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Performance evaluation & network automation. For a triptych QoS, QoE, QiS

Jean-Philippe Georges

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Évaluation de performances & automatisation de réseaux. Pour un triptyque QdS, QdE, QdI

Mémoire de recherche

présentée et soutenue publiquement le 6 mai 2019

pour l'obtention de

**l'Habilitation à Diriger des Recherches
de l'Université de Lorraine**

(mention Génie Informatique, Automatique)

par

Jean-Philippe GEORGES

Composition du jury

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	Jean-Jacques LOISEAU	Directeur de Recherches CNRS, École Centrale Nantes
	Colin PATINSON	Professor, Leeds Beckett University (Royaume-Uni)
<i>Examineurs :</i>	Thierry DIVOUX	Professeur, Université de Lorraine
	Éric RONDEAU	Professeur, Université de Lorraine
	François SPIES	Professeur, Université de Franche-Comté
<i>Invité :</i>	Philippe MIRAMONT	Ingénieur, Centre National des Études Spatiales

Foreword / Manifesto

This dissertation is entitled: “*Performance evaluation & network automation. For a triptych QoS, QoE, QiS*”. The focus is on telecommunication networks (telephony, data, computer, embedded, real-time, Internet, Internet of Things, mobile, etc.). As Robert M. “Bob” METCALFE points out in [Met73b], such networks require both structures to organise computers in highly communicative networks and “*best-effort*” strategies (at least for error recovery and reliability purposes). This notion of effort hence refers to the **performance** of the rendered service/effort. In telecommunication networks, it is actually a set of performance that can characterise the service, and this set is called **Quality of Service (QoS)**.



QoS is the collective effect of service performances that determine the degree of satisfaction of a user of this service. [...] [It] refers to the manner in which packet delivery is provided. This service is described by parameters such as bandwidth, packet delay and packet loss rate. [...] QoS can be characterized by different performance criteria that include basic availability, error rate, response time, the time of connection establishment, data rate, the loss of connection or data due to congestion of the network and the speed of detection and correction of errors.

— Union Internationale des Télécommunications
(Recommendation E.800 approuvée le 23 septembre 2008) [UITo8]

The importance of performance **evaluation** consists in providing a quantitative analysis of the service delivered to the customer. It is even more important for protocols and architectures that do not provide QoS guarantees (i.e. only best or differentiated efforts) or that are simply based on an over-provisioning strategy as detailed in the following document. This is typically the case for one of the protocols I considered in my activities, namely Ethernet (to be noted that Bob METCALFE PhD dissertation was only accepted in 1973 after he attached an analysis part, even if it still offers a best-effort scheme). In this document, the performance will be evaluated according to the metrics defined by the IPPM working group of the IETF, considering additive metrics like one-way delay [RFC2679] of a path, multiplicative metrics like packet loss ratio [RFC2680] and concave metrics like end-to-end bandwidth. The performance evaluation (computer engineering) related studies introduced in Chapter 5 are based on deterministic analysis (mostly through the network calculus theory), simulation and experimentation.

While QoS measurements are objective, it remains network-oriented and does not able to qualify the service perceived by the customer/user (QoSE, QoS experienced) named **Quality of Experience (QoE)**. QoE performance indicators are user-centric and measurements are often subjective since the qualitative component may depend on the user expectations, environmental conditions, psychological factors, application context, etc.

As member of a research centre for control engineering, I have considered an intermediate level of QoE called Quality of Control (QoC). It aims at analysing the performance of real-time systems / networked control systems from the controller point of view. Experience could be described here objectively, for instance in terms of overshoot, response time or stability. Chapter 6 introduces research activities I led with specialists of the control theory, focusing on control over network and control of network. The latter introduces **network automation** where networks parameters (like routing or scheduling) are dynamically configured and algorithms are orchestrated in order to match the QoC requirements. A special attention has been paid regarding the orthogonal experience needs and objectives between end users and network provides. Considering Ethernet networks, I showed how a protocol not designed for such relative QoS and QoE needs, could be from moved from the islands (where it was born), to the enterprise office, to workshops in industry and finally embedded in the space [Ascl.1]. At the end, we introduced (in a similar manner as M. JOURDAIN) the software-defined networking paradigm for real-time systems.

According to the Global e-Sustainability Initiative (GeSI), by 2030, Information & Communication Technologies (ICT) will provide benefits across the triple bottom line, from reducing related CO₂ emissions and resource use, to generating additional revenues, cost savings and wider societal benefits [GeS15]. The concept is simple and its effect will be exponential as quoted by Jaafar ELMIRGHANI (co-chair of the IEEE Green ICT Initiative).



Although ICT currently has an unsustainable carbon footprint, it has the potential to reduce the carbon footprint of other domains by a factor approximately equal to ten times its own carbon footprint as predicted by GeSI. So, for instance, ICT can help smart cities or smart manufacturing to reduce their carbon footprint by 10x ICT's own carbon footprint. And one of the key technologies needed to achieve this favourable impact is IoT, because it is the mechanism for making cities and other domains smarter. So, in a sense, ICT is both a problem and a solution.

Studies have revealed that ICT today generates approximately 2 percent of global CO₂ emissions and is forecast to account for 4 percent of global CO₂ emissions by 2020. Internet use (particularly with the advent of the Internet of Things), which relies on ICT, is forecast to grow 30 percent to 40 percent per year, which results in 30 times its current traffic in 10 years and 1,000 times current traffic in 20 years. At this rate, in ten years ICT will consume about 60 percent of global energy resources, with concomitant emissions and environmental damage. That is the very picture of unsustainability.

The sheer scale of IoT, in terms of the number of connected devices, will create a large draw on electrical power. Projections vary, but guesstimates range between 50 billion to 100 billion active devices. Clearly, we'll need to look at reducing every device's need for power. There's an obvious need for greening in this area.

— Jaafar Elmirghani

(<http://www.energycentral.com/c/iu/how-internet-things-impacts-ict-and-green-ict-efforts>)

Nevertheless, much remains to be done on greening ICT itself, which currently has its own unsustainable carbon footprint. In that field, environmental impacts of information and ICT goods, networks and services are going to be assessed thorough novel standards: ITU-T SG5/Q18, ETSI TC EE TS 103 199 (DTS/EE-00014), ISO greenhouse gas standards comprised ISO 14064-2006; ISO 14065-2013, ISO 14066-2011, or ISO/TR 14069-2013. IEEE Green ICT

Initiative / ComSoc society¹ approved the development of these 9 standards working group, for instance, for a method for calculating anticipated emissions caused by virtual machine migration and placement and for a method to calculate near real-time emissions of ICT infrastructures.

To overcome the strict issue of the energy consumption, I participated to the development (whether in research or in teaching) of the concept introduced by Francis LEPAGE called **Quality in Sustainability (QiS)** [RL10]. Even not yet commonly accepted, QiS (translated as QdI in French – *Qualité d'Intégration environnementale*), it encompasses the three pillars of sustainable development: environmental, economical and ethical contexts. QiS parameters are energy dissipation, CO₂ emission and other greenhouse gases, waste generation (mass of total wastes or hazardous waste mass), visual pollution (not directly measurable) or electromagnetic disturbances (EMF and SAR measurements). While there are metrics and measurements for GHG and radiation, it should be noted that the ethical dimension is still an outstanding issue. A joint metrology would therefore aim at a scientific approach to evaluate both the performance of communication infrastructures and their environmental impact.

Hence, we are convinced that efforts have to be paid to evaluate and control the QiS in a similar way as QoS and QoE. Such green networking will require as will be discussed in Chapter 7 metrics (and measures of effectiveness) to characterise a communication network with respect to environmental problems. Once again I considered the Ethernet protocol and models of the energy consumption of switches. Such metrics will be essential to answer how future networking technologies (e.g. fog/cloud computing, network virtualisation, 5G) will impact ICT and green networking efforts. In addition to the energy consumption / carbon footprint, my research also considers the network architecture life-cycle, bio-mimicry or cradle-to-cradle principles and network automation gathering QoS, QoE and QiS.

The document includes also an activity notice (Part I) and a research project (Part III). This last part develops the short/mid-term research perspectives and opportunities that will form the backbone of my research activities for the next few years. The list of my publications is given in Chapter 4 and is coded differently from the other references listed in the Bibliography chapter.

¹<http://greenict.ieee.org/standards>

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Part I

Activity notice

Chapter 1

Curriculum vitae

Jean-Philippe Georges

November 30th, 1979, REMIREMONT (88 – France), Single

Maître de Conférences (Associate Professor) at Université de Lorraine

Teacher at Collegium Sciences & Technologies, Faculté des Sciences & Technologies

Researcher at Centre de Recherche en Automatique de Nancy (CRAN UMR CNRS 7039)

Department ISET (Sustainable Systems Engineering), Team Green Networking
(*rattaché à la 61e section du CNU*)

Address: CRAN, Campus Sciences, BP 70239, 54506 VANDŒUVRE-LÈS-NANCY cedex, France

Telephone: (+33) 03 72 74 53 03

E-mail: jean-philippe.georges@univ-lorraine.fr

1.1 Education (University)

11/04/2005 **PhD Thesis** in Computer Engineering at Université Henri Poincaré Nancy 1 (spécialité Automatique, Traitement du Signal et Génie Informatique) – Centre de Recherche en Automatique de Nancy

Title: *Networked control systems: Performance evaluation of switched Ethernet architectures (Systèmes contrôlés en réseau : Évaluation de performances d'architectures Ethernet commutées)*

Duration: 09/01/2002 – 11/04/2005, Funding: Allocation de Recherche MENRT

Jury – President: Sirkka-Liisa JÄMSÄ-JOUNELA; Reviewers: Jean-Louis BOIMOND, Jean-Marc FAURE, Christian FRABOUL; Supervisors: Thierry DIVOUX (50%), Éric RONDEAU (50%)

Awards:

- **Prix de thèse** 2005 du club EEA (Club des enseignants et des chercheurs en Électronique, Électrotechnique et automatique), section Automatique
- **Prix des meilleures thèses** du GDR MACS (Groupe De Recherche Modélisation, Analyse et Conduite des Systèmes dynamiques) 2005/2006

2002 **DEA** Contrôle, Signaux & Communication, Université Henri Poincaré Nancy 1, Centre de Recherche en Automatique de Nancy

Msc Thesis: *End to end delays computation in industrial switched Ethernet networks (Calcul des délais de bout en bout dans les réseaux industriels Ethernet commutés)*

Supervisors: Thierry DIVOUX (50%), Éric RONDEAU (50%)

- 2001 Titre d'Ingénieur-Maître de l'IUP Génie Électrique et Informatique Industrielle, spécialité Réseaux Numériques de Communication, Université Henri Poincaré Nancy 1
Maîtrise IUP GEII, spécialité RNC, Faculté des Sciences & Techniques, Université Henri Poincaré Nancy 1
- 2000 **Licence** IUP GEII, spécialité RNC, Faculté des Sciences & Techniques, Université Henri Poincaré Nancy 1
- 1999 DUT Génie Électrique et Informatique Industrielle, IUT Nancy-Brabois, Université Henri Poincaré Nancy 1
- 1997 Baccalauréat S, spécialité Mathématiques, Lycée André MALRAUX, REMIREMONT

1.2 Carrier

SEP. 2005/MAR. 2006 **Attaché Temporaire d'Enseignement et de Recherche** à temps partiel, Faculté des Sciences & Techniques, Université Henri Poincaré, Nancy 1, Centre de Recherche en Automatique de Nancy

MAR./SEP. 2006 **Researcher** at Technological University of Helsinki, Finlande
Post-Doctorat au Laboratory of Process Control and Automation, Chemical Department

SEP. 2006/- **Maître de Conférences (Associate Professor)** de l'Université de Lorraine
Collegium Sciences & Technologies, Faculté des Sciences & Technologies
Centre de Recherche en Automatique de Nancy
(*Concours MCF-1250 : Diagnostic and control of networked control system*)

2013/2018 Recipient of the **Prime d'Excellence Scientifique** (B level)

2018/2023 Recipient of the **Prime d'Encadrement Doctoral et de Recherche** (B level)

Since I was recruited (as ATER and in 2006 as Associate Professor, I am teaching at the département Automatique, secteur Mathématiques, Informatique, Automatique et Électronique of the Faculté des Sciences & Technologies. The faculty belongs to the Collegium Sciences & Technologies of the Université de Lorraine.

I am member of the Research Centre for Automatic Control (Centre de Recherche en Automatique de Nancy (CRAN)). I have contributed early to the research teams "Systèmes Contrôlés en Réseau" and "Systèmes de Communications Contraintes" of the department "Systèmes de Production Ambiants" (SYMPA) and "Systèmes distribués et embarqués réactifs aux défauts" of the department "Sûreté de Fonctionnement et Diagnostic" (SUFDIAG). I am currently involved in the department Sustainable Systems Engineering ("Ingénierie des Systèmes Éco-Techniques" (ISET)), and more specifically in the "Green Networking" team.

My teaching and research activities are in adequacy, focusing in the networking field. I have never benefited (or asked for) CRCT, delegation, secondment (détachement), service discharge or business interruption.

Chapter 2

Research and supervision activities

2.1 Chronological overview

In the following, the publication citations (Acl, AcIn, Ascl, Osc, Acti, Actn, Com, Rap, Bre, The) introduced in this part are given in Chapter 4 and refer to the publications for which I am a co-author (mostly with the Phd/Msc I co-supervised so far). Sections 2.2.1 and 2.2.2 detail the list of publications for each co-supervision.

My research activities can be classified in three categories as shown in Figures 2.1 and 2.2a: (A1) performance evaluation of networks, (A2) networked control systems (NCS) and control of networks and (A3) first contributions in green networking. These three axes are detailed in the Part II. The following paragraphs present my research activities in a - mostly - chronological order.

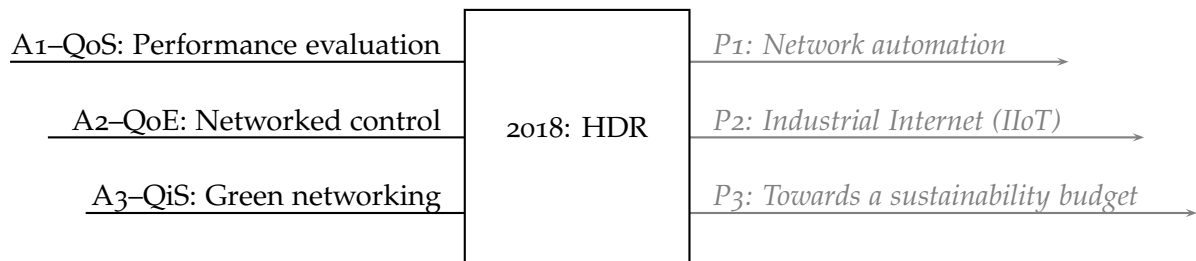
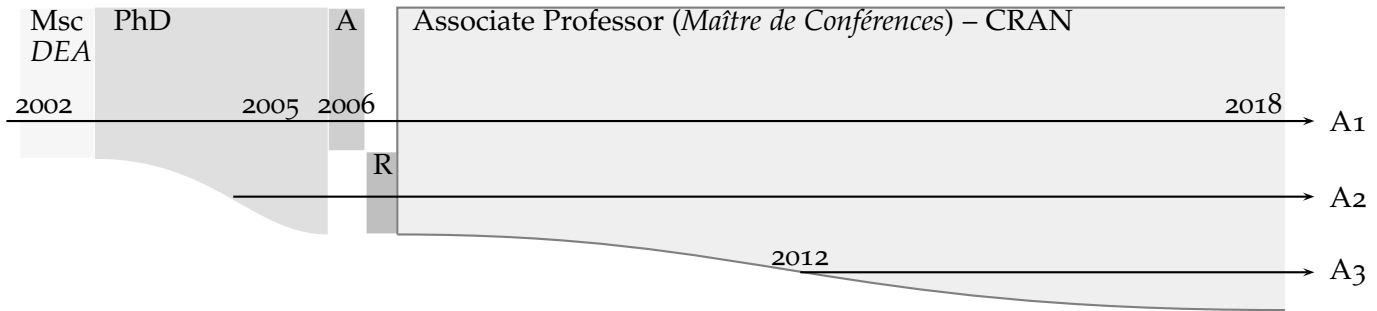
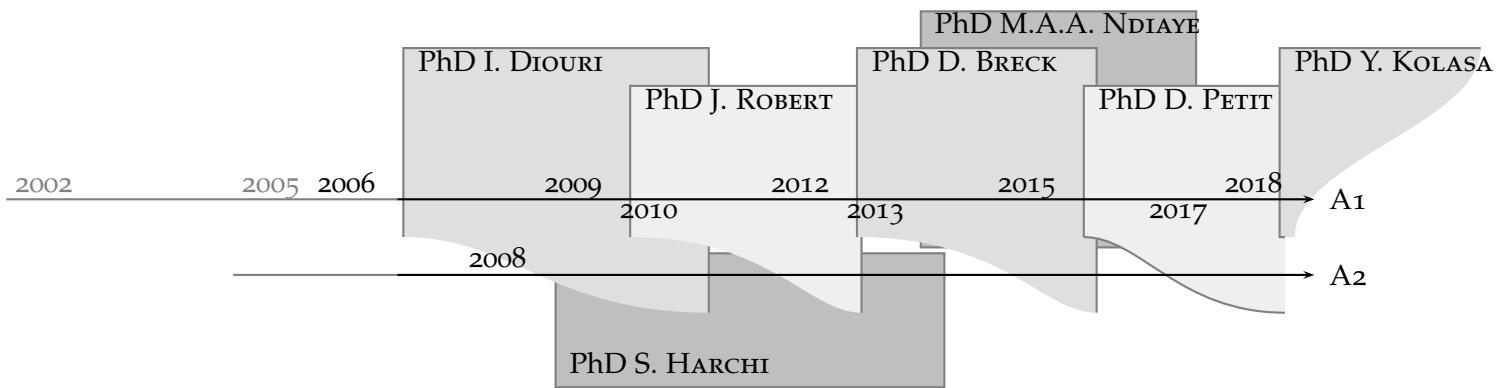


Figure 2.1: Past and future research activities

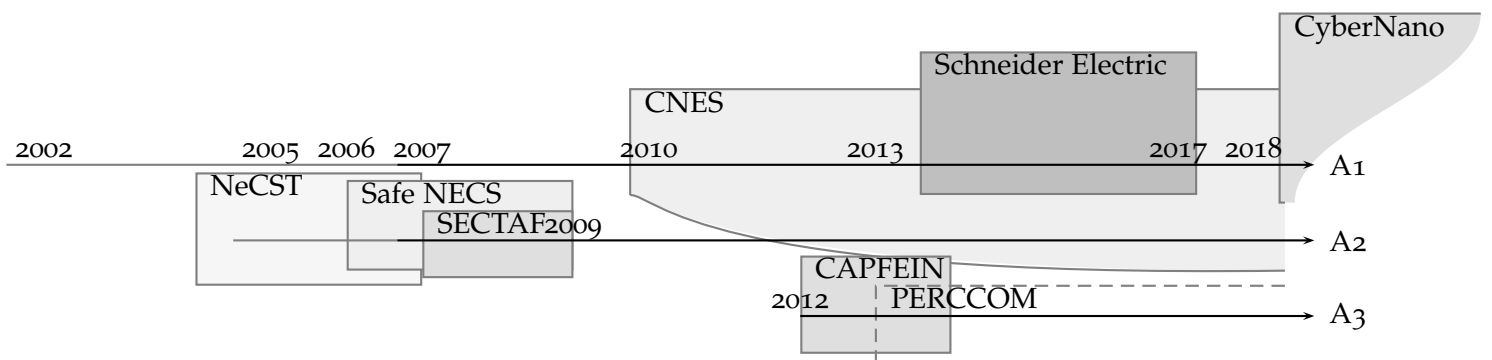
As a continuation of my PhD work, I spent one semester in 2006 at the Technology University of Helsinki (TKK) to work on networked control systems. As a result, we focused, in the framework of the STREP NeCST project (see Figure 2.2c and the list of projects in Section 2.3.3), on co-design of control over network for which the control takes the real network QoS (my expertise) into account. In 2006/2007, we hosted, in Nancy, N. VATANSKI, PhD student at TKK. It leads in 2009 to the synthesis of a robust controller taking into account bounded end-to-end delays computed through the network calculus theory and predictive controller based on delays measurements [Acl.3]. As summarised by the IFAC TC 1.5, researches on networked control systems should also consider the control of the network (QoS). In this respect, we initiated together with É. RONDEAU such research in the framework of the ANR Safe NeCS project, which allowed us to grant the PhD thesis of Idriss DIOURI (the Figure 2.2b shows the list of



(a) Career (A: ATER, R: Researcher at TKK (Finland))



(b) PhD co-supervision



(c) Projects

Figure 2.2: Research activities (A1: performance evaluation, A2: NCS & SDN, A3: green networking).

PhD I have co-supervised), for which we closely collaborated with GIPSA-lab and LAAS. We proposed, as part of this PhD, a controller of the classification of service parameters (priorities, weights, service policies) included in Ethernet switches, whose approach is based both on the delays and the control error signal. The control is based on fuzzy rules [Acl.9]. Finally, as part of the of the CPER SECTAF project, I conducted several collaborations with researchers from CRAN on control engineering, and specifically on studying the impact of network QoS on the performance of FDI/FTC mechanisms for NCS [Acl.4].

In 2007, the French CNES agency contacted the CRAN for two reports, including one about the evolution of real-time networks. The purchased objective was the preparation of the future spatial launchers. I participated to the report, taking charge of presenting the possibility to use Ethernet for real-time networking and the deterministic computation of end-to-end delays through the network calculus theory. It leads to the agreement in 2009 of R&T (*Recherche & Technologie*) activities between CNES and CRAN (that I am still co-managing with T. DIVOUX). The project investigates how Ethernet can be used, in spatial launchers, as an unified embedded network for control and telemetry management purposes. In that framework, I co-supervised with T. DIVOUX the PhD of Jérémy ROBERT. During his PhD and later as post-doctorate, he qualified – based on the network calculus theory – the performance of of a switched Ethernet network based on Ariane 5 traces, compared the industrial Ethernet-based networks in terms of grace time, analysed the clock synchronisation through the IEEE 1588 protocol and proposed advanced reconfiguration protocol and network controllers [Acl.6, Acl.5]. In 2016, we started always with T. DIVOUX the supervision of the PhD of Dorine PETIT. It leads to the definition of a freshness analysis as a preliminary work for network observability and to the foundation of software-defined networking unifying the classification of service, the synchronisation, the reconfiguration of the logical topology or even the traffic reconfiguration [Acti.37, Acti.44]. Those activities correspond to an evaluation of my research on NCS towards generic network automation. One of the achievement in this framework of the contracts with the CNES, deals with the installation of a platform at CRAN that reproduces the launcher communication system [Acti.39].

At the end of the 2008 year, we had the opportunity with T. DIVOUX to develop research on mobile router/sink as a continuation of a Master project I supervised. It corresponds to the PhD of Saïd HARCHI. The key issue that was considered deals with the maintain of connectivity when wireless sensors are deployed and move independently. We applied here our work to oil spill monitoring. The results correspond to the proposal of a novel clustering algorithm for wireless networks and the specification of a session layer enabling to a mobile collector/sink to retrieve the context from clusters and to determine its trajectory [Acl.8]. In 2012, we continued with T. DIVOUX to lead research on wireless network. The PhD of Damien BRECK followed his Msc, whose focus was on frame aggregation mechanisms for telemetry purposes (case study having been provided by the Zodiac enterprise). In his PhD we evaluated the performance of frame aggregation mechanisms included into the Wifi IEEE 802.11n/ac protocols. An analytical review (based on both network calculus and standards analysis) of the inherent QoS was carried out [Acln.2] and extensive simulations over the Riverbed Modeler tool enabled us for proposing algorithms to optimise the aggregation parameters, mitigating the paradox requirements between the end users and the providers.

In 2012, with the beginning of the ANR CAPFEIN and the writing of the EMJMD PERCOM proposal (see section 3.1.2), I started to develop research in the emerging topic of green networking and green ICT (*ÉcoTIC*). It is related until now to the co-supervision (with É. RONDEAU of Msc theses. In Nicolas DROUANT Master thesis [Acl.7], we proposed and formulated

a set of metrics of effectiveness and methodologies for network design, which have been derived from the the commandments of bio-mimetic. In 2015, we proposed energy consumption models of Ethernet switches (we used design of experiments with Md Mohaimenul HOSSAIN [Acti.30] and fuzzy logic with Alifia FITHRITAMA [Acti.29]). We considered also advanced techniques like energy-efficient Ethernet (EEE) during the thesis of Joseph EL KHOURY. Strategies to mitigate the energy consumed by network infrastructures were then developed (with Mohammad Habibullah KHAN [Acti.40]) leading more recently to the foundations for preliminary Software-Defined network architectures for greening Internet communications (Atefe MALEKI [Acti.38]). As part of Dimitar Minovski's Master thesis, we proposed an original approach for reversing the classical analysis for which network devices just need power supply, but rather to use ICT energy consumption for monitoring ICT usage in an enterprise [Acti.34]. Those activities initiated also the evolution of the research team I am belonging since it is now entitled Green Networking.

Finally, we were contacted in 2013 by the Schneider Electric company regarding our research on network performance evaluation. It corresponds to the (CIFRE) Phd of Moulaye A.A. NDIAYE that was supervised by Jean-François PÉTIN (leading activities in control / DES architectures) and myself (taking part of the network architectures). The objective was the performance assessment of industrial control systems (networked distributed control systems) during pre-sales uncertain context. The PhD was achieved in collaboration with Lars KRISTENSEN, maintainer of CPN tool. We proposed here a patented [Bre.1] method for generating a Coloured Petri Net simulation model of an industrial control system (PLC, SCADA and Ethernet switched network). In 2018, I have recently started with Thierry BASTOGNE and the CyberNano startup, the supervision of the (CIFRE) PhD of Yaël KOLASA. It consists of analysis of secure and reliable transfer of cardiac signals over Internet as will be detailed in Part III.

2.2 Supervision activities

2.2.1 PhD thesis supervision (5+2)

Since the beginning of my career as Associate Professor, I have co-supervised 5 PhD thesis (I am currently co-supervising 2 PhD). The co-supervision percentage is given in the following in parenthesis.

Ongoing PhD

Dorine Petit *“Unification des stratégies de contrôle d’un réseau embarqué temps-réel reconfigurable”*
(Unified control strategies of an embedded real-time reconfigurable network)

Supervisors: Thierry DIVOUX (50%), Jean-Philippe GEORGES (50%)

PhD thesis began on October 1st, 2015

Fundings: Fonds propres dans le cadre du contrat CRAN / CNES

Lab./School: CRAN/IAEM Lorraine – Université de Lorraine

Publications²: [Acti.37, Acti.39, Acti.44]

Pending patent application entitled *“Mécanisme de synchronisation de calculateurs sur un réseau Ethernet multi-serveurs asynchrone”*

Young scientist award at 3rd IFAC CESCIT 2018 [Acti.44]

²See complete references in Chapter 4.

Yaël Kolasa “*Transfert fiable et sécurisé de signaux cardiaques sur Internet*” (Secure and reliable transfer of cardiac signals over Internet)

Supervisors: Thierry BASTOGNE (50%), Jean-Philippe GEORGES (50%)

PhD thesis began on May 2nd, 2018

Fundings: Thèse CIFRE contrat CRAN / CyberNano

Lab./School: CRAN/IAEM Lorraine – Université de Lorraine

Departments: Ingénierie des Systèmes Eco-Techniques
ET Biologie, Signaux et Systèmes en Cancérologie et Neurosciences

Publication: [Acti.42]

Completed PhD

Idriss Diouri “*Propositions de méthodes pour adapter le réseau aux contraintes d’applications temps-réel*” (Methods to control networks for real-time constrained applications)

Supervisors: Éric RONDEAU (50%), Jean-Philippe GEORGES (50%)

Date: Defended on October 15th, 2010 (began on October 1st, 2006)

Jury: M. DAMBRINE (president), P. FRAISSE (reviewer), D. SIMON (reviewer),
V. BOMBARDIER, J.-P. GEORGES, É. RONDEAU

Fundings: Contrat européen (50%) et région Lorraine (50%)

Lab./School: CRAN/IAEM Lorraine – Université de Lorraine

Publications: [Acl.9, Acti.10, Acti.17, Acti.18, Acti.21, Actn.4]

I. DIOURI is currently directeur administratif at IGA (école d’ingénieur), Morocco.

Jérémy Robert “*De l’usage d’architectures Ethernet commutées embarquées dans les lanceurs spatiaux*” (Embedded switched Ethernet architectures for spatial launchers)

Supervisors: Thierry DIVOUX (50%), Jean-Philippe GEORGES (50%)

Date: Defended on October 23th, 2012 (began on October 1st, 2009)

Jury: J.-F. PÉTIN (president), A. BARROS-LEFEBVRE (reviewer), C. FRABOUL
(reviewer), P. MIRAMONT, J.-P. GEORGES, T. DIVOUX

Fundings: Fonds propres dans le cadre du contrat CRAN / CNES

Lab./School: CRAN/IAEM Lorraine – Université de Lorraine

Publications: [Acl.5, Acl.6, Acti.24, Acti.27, Acti.31, Actn.6]

J. ROBERT is currently research associate at SnT (Interdisciplinary Centre for Security, Reliability and Trust), University of Luxembourg.

Saïd Harchi “*Un protocole de session dans les réseaux de capteurs sans fils*” (A session layer protocol for wireless sensor networks)

Supervisors: Thierry DIVOUX (50%), Jean-Philippe GEORGES (50%)

Date: Defended on December 6th, 2013 (began on November 1st, 2008)

Jury: B. IUNG (president), T. GAYRAUD (reviewer), F. SPIES (reviewer), K. BEN-
ZAKOUR, A. GUITTON, J.-P. GEORGES, T. DIVOUX

Fundings: Doctorant salarié³ du groupe IGA (Maroc).

Lab./School: CRAN/IAEM Lorraine – Université de Lorraine

Publications: [Acl.8, Acti.26, Actn.9]

³S. HARCHI a continué durant sa thèse ses activités d’enseignement, de correspondant de Masters d’universités

S. HARCHI is currently Directeur Technique du groupe ISGA (école d'ingénieur), Morocco.

Damien Breck “Évaluation des performances du système d'agrégation implémenté dans les réseaux 802.11n” (Performance evaluation of aggregation system in 802.11n networks)

Supervisors: Thierry DIVOUX (50%), Jean-Philippe GEORGES (50%)
Date: Defended on December 4th, 2015 (began on October 1st, 2012)
Jury: D. BRIE (president), S. LAHAYE (reviewer), A. MELLOUK (reviewer), M. WACK, J.-P. GEORGES, T. DIVOUX
Fundings: Allocation de recherche MESR
Lab./School: CRAN/IAEM Lorraine – Université de Lorraine
Publications: [Acln.2, Acti.28, Actn.7, Actn.8]

D. BRECK is currently formateur transition numérique at Alaji.

Moulaye A.A. Ndiaye “Évaluation de performances d'architecture de contrôle-commande en réseau dans un contexte incertain d'avant-vente” (Performance assessment of industrial control system during pre-sales uncertain context)

Supervisors: Jean-François PÉTIN (50%), Jean-Philippe GEORGES (50%)
Date: Defended on March 16th, 2017 (began on July 13th, 2013)
Jury: T. DIVOUX (president), J.-M. THIRIET (reviewer), A. TOGUYENI (reviewer), M. CHETTO, L. KRISTENSEN, J.-P. GEORGES, T. PÉTIN, J. CAMERINI, B. JACQUEMIN
Fundings: Thèse CIFRE contrat CRAN / Schneider Electric
Lab./School: CRAN/IAEM Lorraine – Université de Lorraine
Publications: [Bre.1, Acti.35, Acti.36]

M.A.A NDIAYE is currently system architect in simulation at Schneider Automation.

2.2.2 Msc thesis supervision (17)

M2-R ISC:

Idriss Diouri* “Accommodation dynamique du service offert par le réseau en fonction de l'état du système distribué”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, M2-R ISC 2006. Publications: [Acl.9, Acti.10, Acti.17, Acti.18, Acti.21, Actn.4]. Actuellement directeur administratif chez IGA, Maroc.

Abdellatif Chafik “Implémentation d'un classificateur de service dans un simulateur de système contrôlé en réseau”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, M2-R ISC 2007. Actuellement enseignant chez IGA, Maroc.

Gabriel Berard-Bergery “Développement d'un outil d'aide à la modélisation et à l'analyse de performances d'un réseau sur puce”, Supervisor: J.-P. GEORGES, M2-R ISC 2009.

françaises et de responsabilité pédagogique de filière à l'IGA à Casablanca au Maroc

Sylvain Kubler “Continuité de service sur Ethernet industriel”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, M2-R ISC 2009. Publications: [[Acl.5](#), [Acti.23](#), [Actn.5](#)]. *Actuellement Maître de Conférences à l’Université de Lorraine / CRAN.*

Jérémy Robert* “Analyse de performances de protocoles temps-réel basés sur Ethernet”, Supervisors: T. DIVOUX 50%, J.-P. GEORGES 50%, M2-R ISC 2009. Publications: [[Acl.5](#), [Acl.6](#), [Acti.24](#), [Acti.27](#), [Acti.31](#), [Actn.6](#)]. *Actuellement research associate au SnT / University of Luxembourg.*

Nicolas Drouant “Conception d’architectures de réseaux « green » basées sur les dix commandements d’un écosystème mature”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, M2-R ISC 2012. Publication : [[Acl.7](#)]. *Actuellement chef de projet PIC chef EDF.*

Damien Breck* “Identification du service rendu par un système d’agrégation de MSDU 802.-11n”, Supervisors: T. DIVOUX 50%, J.-P. GEORGES 50%, M2-R ISC 2012. Publications: [[Acln.2](#), [Acti.28](#), [Actn.7](#), [Actn.8](#)]. *Actuellement formateur transition numérique chez Alaji.*

Jean-Baptiste Perrin “Benchmarking des procédures de reconfiguration rapide des réseaux embarqués”, Supervisor: J.-P. GEORGES 100%, M2-R ISC 2014. *Actuellement Ingénieur/architecte réseau chez Phamagest.*

PERCCOM Msc Thesis:

Md Mohaimenul Hossain “Modelling the energy Consumption of a switch using design of experiments”, Supervisors: É. RONDEAU 33%, J.-P. GEORGES 33%, T BASTOGNE 33%, Master Erasmus Mundus PERCCOM 2015. Publications : [[Acti.30](#), [Acti.38](#), [Acti.40](#)]. *Actuellement en thèse au CRAN / Université de Lorraine depuis février 2017.*

Alifia Fithritama “Modelling the energy consumption of a switch using Fuzzy Rule-based classifier”, Supervisors: É. RONDEAU 33%, J.-P. GEORGES 33%, V BOMBARDIER 33%, , Master Erasmus Mundus PERCCOM 2015. Publications : [[Acti.29](#)]. *Actuellement Senior Officer, Managed Network Services, Telkomtelstra, Jakarta, Indonésie.*

Iqbal Ahmed “Green service agreement”, Encadrants : É. RONDEAU 33%, J.-P. GEORGES 33%, A. KLIMOVA (ITMO University, St Petersburg) 33%, Master Erasmus Mundus PERCCOM 2015. *Actuellement assistant part-time researcher à NAIST, Saga University, Japon*

Vitalii Poliakov “Green ICT metrics and Biomimicry”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, Master Erasmus Mundus PERCCOM 2015. *Actuellement en thèse au I3S/CNRS, Université Nice Sophia Antipolis*

Dimitar Minovski “Using ICT Energy consumption for monitoring ICT usage in an enterprise”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, Master Erasmus Mundus PERCCOM 2016. Publications: [[Acti.33](#), [Acti.34](#), [Osc.5](#)]. Award: Green Energy Infrastructure award at SEEDS’16. *Actuellement en thèse à l’Université de Luleå, Suède.*

Mohammad Habibullah Khan “Developing strategies to mitigate the energy consumed by network infrastructures”, Supervisors: É. RONDEAU 50%, J.-P. GEORGES 50%, Master Erasmus Mundus PERCCOM 2016. Publications : [[Acti.32](#), [Acti.40](#), [Osc.4](#)]. *Actuellement enseignant à East West University, Bangladesh.*

Atefe Maleki “Software-Defined network for greening Internet communications”, Supervisors: É. RONDEAU 33%, J.-P. GEORGES 33%, T DIVOUX 33%, Master Erasmus Mundus PERCCOM 2017. Publication: [Acti.38]. Award: Green Energy Infrastructure award at SEEDS’17.

Joseph El Khoury “Assessing the benefit of deploying EEE on commercial grade network switchest”, Supervisors: É. RONDEAU 33%, J.-P. GEORGES 33%, A.H. KOR (Leeds Beckett University) 33%, Master Erasmus Mundus PERCCOM 2017.

Mohammed Mustaqim Rahman “Software consumption learning machine”, Supervisors: É. RONDEAU 33%, J.-P. GEORGES 33%, T. LEBOUQC (GreenSpector) 33%, Master Erasmus Mundus PERCCOM 2017.

2.3 Scientific responsibilities

2.3.1 Responsibilities and participation in working groups

Vice-chair for social media of the **IFAC (International Federation of Automatic Control) Technical Committee 3.3 (Telematics: Control via Communication Networks)** within the period 2017-2020.

Appointed member of the **IFAC TC 3.3** (2014-2020).

I have been charged by the TC chairman to take the responsibility of writing an article about the TC technical contents for the IFAC blog, which will be entitled “Network automation for Internet of Things and Industry 4.0”.

At the national level, I’m actively participating (and engaging the PhD/Msc students I’m co-supervising) from the beginning to the actual GT ARC (Automatique & Réseaux de Communication) of the GdR MACS of CNRS. Previously, I have participated to the former GT StrQds (Systèmes Temps-Réels et Qualité de Service) group of the GdR ARP CNRS.

Member of the IEEE, I participated to the first IEEE Greening Through ICT Summit organised by the IEEE Green ICT initiative in October 3rd, 2017 in Paris.

2.3.2 Scientific outreach

External PhD thesis jury/committee member

Mohamad Haffar doctorat de l’Université de Grenoble, GIPSA-lab, “Approche de co-simulation en vue de la validation et de l’évaluation de performance des systèmes de communication : Application à des architectures de distribution électriques”, September 21th, 2011.

Jury: Didier GEORGES (president), Laurent CAUFFRIEZ (reviewer), Thierry VAL (reviewer), Jean-Philippe GEORGES, Jean-Marc THIRIET (supervisor), Éric SAVARY (supervisor).

Paul-Lou Benedick Member of thesis supervision committee (C.E.T.) of University of Luxembourg, Doctoral School in Science and Engineering. PhD thesis title: “Connectivity & security framework for the Industry 4.0”. Supervisors: Y. LE TRAON, J. ROBERT. Thesis began on January 2018.

Expertise

Scientific expertise for the ANR (National Research Agency):

2012 Scientific expert for the ANR Ingénierie Numérique & Sécurité – INS 2012 programme

2017 Scientific expert for the ANR evaluation process of Generic Call 2017

Membre de comités de sélection:

2011 Emploi “61-MCF-0213” (profil Automatique, diagnostic et sûreté de fonctionnement) de l’Université Henri Poincaré, Nancy 1 / IUT Nancy-Brabois / CRAN

2016 Emploi (sections 61/27) “6127-MCF-GDE” (profil Génie informatique et application à l’infrastructure des SI) de l’Université Paris-Est Créteil Val de Marne

2017 Emploi “61-MCF-0940” (profil Génie Informatique, réseaux, écoTIC) de l’Université de Lorraine / Faculté des Sciences & Technologies / CRAN

Conference chair/TPC/organisation member

Chair functions

Publicity Chair: MED’08 16th IEEE Mediterranean Conference on Control and Automation, June 2008, Ajaccio

Publications & Publicity Chairs: SysTol’10 et SysTol’13 1st and 2nd International Conference on Control and Fault-Tolerant Systems, October 2010 & 2013, Nice

Technical Program co-Chair: ON-MOVE’16 10th IEEE Conference on Local Computer Networks, Workshop On User MObility and Vehicular Networks, November 7-10th, 2016, Dubai, UAE

Publication Chair of SysTol’19 and MED’20

Conference IPC member

- Premières Rencontres des Jeunes Chercheurs en Informatique Temps Réel, 2005, Nancy
- NeCST’06/07 – 2nd and 3rd IFAC International Workshop on Networked Control Systems: Tolerant to Faults – Rende, Italy, 2006 and Nancy, 2007
- SysTol’13 – International Conference on Control and Fault-Tolerant Systems – Nice, October 9-11th 2013
- FiCloud’14/16 – 2nd and 4th IEEE International Conference on Future Internet of Things and Cloud, Track 4: IoT and Cloud Data Management – Barcelona, Spain, August 27-29th 2014 and Wien, Austria, August 22-24th 2016
- TA’16 – 4th IFAC Symposium on Telematics Applications – Porto Alegre, Brazil, November 6-9th 2016

- SEEDS'16/17/18 – Member of the scientific committee of the International Sustainable Ecological Engineering Design for Society Conference – Leeds, UK, September 2016 and 2017 and 2018
- LCN'17/18 – 42nd and 43rd IEEE Conference on Local Computer Networks – Singapore, October 9-12th 2017 and Chicago, US, October 1-4th 2018
- GPC'17/18 – 12th and 13th International Conference on Green, Pervasive and Cloud Computing – and Cetara, Amalfi Coast, Italy, May 11-14th 2017 and Hangzhou, China, May 11-13th 2018
- CESCIT'18 – 3rd IFAC Conference on Embedded Systems, Computational Intelligence and Telematics in Control – Faro, Portugal, June 6-8th, 2018

Conference organisation committee member

MED'08 16th IEEE Mediterranean Conference on Control and Automation, Ajaccio, June 2008

WFCS'10 8th IEEE International Workshop on Factory Communication Systems, Nancy, May 18-21th 2010

SysTol'10/13 1st and 2nd International Conference on Control and Fault-Tolerant Systems, Nice, October 2010 and 2013

MSC'14 IEEE Multi-conference on Systems and Control (MSC'2014), Antibes, October 8-10th 2014

Conference special-session and summer school co-organiser/speaker

- Special session “*Networked control systems tolerant to faults*” (É. RONDEAU, J.P. GEORGES) at 11th IEEE International Conference on Emerging Technologies and Factory Automation, Praha, Czech Republic, September 2006.
- Track “*Green Technologies for a cleaner production*” (É. RONDEAU, J.P. GEORGES, F. MAYER) at World IFAC 2017, Toulouse, July 2017
- Organization committee member of PERCCOM Summer schools: “Green ICT” in 2015 and “Internet of Things & Sustainability” in 2016
- Invited speaker at École d’Été Temps-réel (ETR) (GT AFSEC du GDR ASR) in 2009 [Com.8] and in 2011 [Com.14]
- Invited speaker at doctoral course for Future Automation Systems in Context of Process Systems and Minerals Engineering - MIDICON, Kittilä, Finland, April 2018 [Com.17] Project KIC EIT RawMaterials, Specific Activity: Modern process data analytics by case studies on mineralogy driven control of the production chain from mine to products (Aalto University, Université de Lorraine, Outotec GmbH & Co. KG)
- Co-leader/initiator of 2 CNRS training for enterprises “Ethernet pour applications critiques”⁴ and “TIC et développement durable”.

⁴<http://cnrsformation.cnrs.fr/stage-18240-Ethernet-pour-applications-critiques.html?axe=69>

Reviewing activities

for the journals: EAAI, IEEE Transactions on Industrial Informatics, ISA Transactions, Journal of Intelligent Manufacturing, Algorithms, International Journal of Communication Systems, IEEE Transactions on Automation Science and Engineering, Journal of Network and Computer Applications, Control Engineering Practice, Mathematical Problems in Engineering, Mobile Information Systems, Journal of Intelligent Manufacturing, International Journal of Adaptive Control and Signal Processing. . .

2.3.3 Research valorisation (projects & contracts)

International project

Project FP6 STREP NeCST “Networked Control Systems Tolerant to Faults” (2004-2007)

EU FP 6, priority Information society technologies, STEP n°IST-004303 NeCST (fundings: 2 020 640 €).

Members: CRAN/Université Henri Poincaré Nancy 1 (coordinator: É. RONDEAU), Technological University of Helsinki, University of Duisburg-Essen, University of Hull, PRE-DICT, Neste, SAE Automation.

Participation: researcher (main publications: [[Acl.3](#), [Acti.9](#), [Rap.2](#), [Rap.4](#), [Rap.7](#), [Rap.5](#)]).

National projects

Project ANR Safe NECS “Conception coordonnée des systèmes tolérants aux fautes commandés en réseaux” (2006-2009)

Action de Recherche Amont n°ANR-05-SSIA-0015-01 (fundings: 1 535 286 €).

Members: CRAN, LAG, LAAS, LORIA and INRIA.

Keywords: embedded systems, networked systems, distributed control, fault tolerance, diagnosis, Quality of Service, co-design.

Participation: researcher (main publications: [[Osc.2](#), [Rap.6](#)]) / funds for I. DIOURI PhD.

Project SECTAF “Systèmes Embarqués Communicants Tolérants Aux Fautes” (2007-2009)

CPER Lorraine Modélisation, Information et Systèmes Numériques (fundings: 44 000 €).

Members: CRAN, LICM.

Participation: researcher (main publication: [[Acl.4](#)]).

Project ANR CAPFEIN “réseau de CAPteurs de FormaldEhyde intelligents pour la surveillance de l’air Intérieur” (Network of formaldehyde SEnsors designed for Monitoring of INdoor AIR environments) (2012-2014)

Programme ECOTECH (funding: 567 320 €).

Members: CRAN, LMSPC, LIPHT.

Participation: researcher (main publication: [[Acl.7](#)]).

2.3.4 Industrial collaborations

With the CNES (since 2007)

Since 2007, we lead research with the Centre National d’Étude Spatiales (CNES), whose primary objective is the design of the new communication network intended to be embedded in the future European launchers (especially Ariane 6). The collaboration started by a study of

the new real-time network, followed by R&T (Recherche & Technologie) that I'm co-leading with T. DIVOUX. The following contracts have enabled to fund J. ROBERT and D. PETIT PhD theses.

Veille BUS 2007 "Veille Technique sur les Nouveaux Systèmes de Communication" (25 k€)
[Rap.8]

R&T n°1 (2009-2010) "Réseaux Ethernet pour les systèmes temps réels : application aux lanceurs" (100 k€)
[Rap.9, Rap.10, Rap.11, Rap.14]

R&T n°2 (2011-2012) "Observabilité sur Ethernet et isolation de défauts sur le système en réseaux dans le cas d'une application aux lanceurs" (50 k€)
[Rap.12, Rap.13]

R&T n°3 (2013-2014) "Intégration et démonstration d'architectures Ethernet commutées multi-média, observables et tolérantes aux défaillances" (funding: 100 k€)
[Rap.15, Rap.16, Rap.17, Rap.18]

R&T n°4 (2015-2018) "Ethernet commuté: scénarios lanceurs futurs & Ethernet synchrone" (funding: 250 k€)
[Rap.19, Rap.20, Rap.21, Rap.22, Rap.23]

One of the outcomes of this research consists of increasing the maturity of the usage of Ethernet as the embedded network in future launchers. We installed, at CRAN, a platform (Figure 2.3) that reproduces the launcher's communication system. The goal is to reach the TRL 4 (Technology Readiness Level). This platform consists of the following components (uncured components):

- 9 switches 100 Mbits/s (8 CISCO IE3000⁵ implementing the synchronisation protocol IEEE 1588/PTP and another one for the on-ground sub-network),
- 93 μ -PCs (Raspberry PI) for the traffic generation (86 on-board and 7 on-ground) fitted with two Ethernet interfaces,
- 2 PCs with two Ethernet cards to simulate the on-board computers,
- 8 PCs with two Ethernet cards (one is a IEEE1588/PTP-Meinberg PTP270-PEX⁶) to monitor the communications.
- 124 category 6 Ethernet cables (total length is about 200 m).

The platform was presented during the demonstrator session at IFAC 2017 World Congress [Acti.39].

With Schneider Electric (2013-2016)

Support contract (2013-2016) between CRAN and Schneider Electric

Contrat d'accompagnement CIFRE (45 k€) de la thèse de M.A.A. NDIAYE.

"Évaluation de performances d'architecture de contrôle-commande en réseau dans un contexte incertain d'avant-vente"

Co-responsable with J.-F. PÉTIN. Patent: [Bre.1].

⁵<http://www.cisco.com/c/en/us/products/switches/industrial-ethernet-3000-series-switches/>

⁶<https://www.meinbergglobal.com/english/products/pci-express-ieee-1588-ptp-slave.htm>

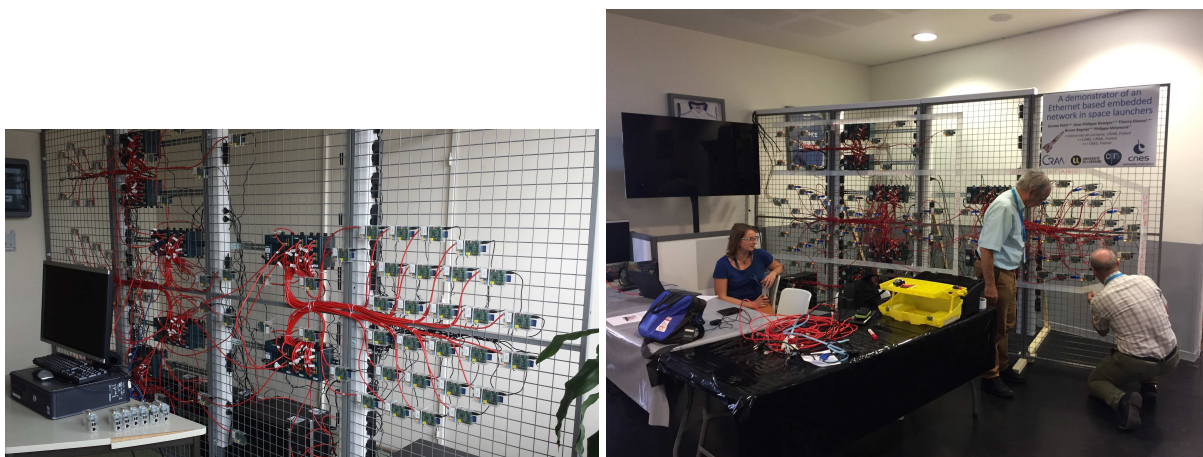


Figure 2.3: Reda6 switched Ethernet benchmark platform at CRAN and in Toulouse during IFAC 2017 World Congress [Acti.39].

With Cybernano (2018–)

Support contract (2018-2021) between CRAN and Cybernano⁷

Contrat d'accompagnement CIFRE de la thèse de Y. KOLASA.

"Transfert fiable et sécurisé de signaux cardiaques sur Internet"

Co-responsible with T. BASTOGNE.

2.3.5 Collective activities at the CRAN laboratory

- Elected member (*représentant du collège des "doctorants, post-doctorants et autres chercheurs"*) at the CRAN laboratory council (2004/March 2006) at the laboratory council bureau (2005/March 2006)
- Named member at the laboratory council (2013/2017).
- Member of prospective commission of the laboratory (2012-2014) and (2015-2018).

⁷Cybernano is a start-up founded in 2013 specialized in Biosignal Processing & Biostatistics

Chapter 3

Education activities

3.1 Presentation

3.1.1 Activities

I do my teaching activities at the (UFR) Faculty of Sciences & Technologies of the University of Lorraine where I am administratively attached. The beginning of my career as Associate Professor coincided with the implementation of the LMD offer at the Faculty (2005). I have been involved in the programmes supported by my department (Automatique) at the bachelor and the master levels. The programmes have evolved, taking into account the new regulatory contours⁸ and changes in the field's professions. I have hence been involved in the following programmes:

Licence EEAR (Habilitation 2005-2009) Electrical, Control and Network Engineering

Licence SPI-EEAPR (Habitations 2009-2012 and 2013-2017)

Sciences for Engineers – Electrical, Control, Production and Network Engineering

Master Ingénierie Système en EEAPR (Habilitation 2005-2009)

Systems Engineering for Electrical, Control, Production and Network Engineering

Master Ingénierie de Systèmes Complexes (Habitations 2009-2012 and 2013-2017)

Complex Systems Engineering

Erasmus Mundus of Joint Master Degrees PERCCOM (2013-2019)

Pervasive Computing & COMMUNICATIONS for sustainable development

I work in different teaching units on communication networks (in line with my research activities) over the LMD cycle from the last year of the Licence diploma (L3) to the last year of the Master diploma (M2). At the beginning of my career, I have taken the responsibility of three teaching units (Unité d'Enseignement - UE) in L3 related to the foundations in networking and in M1 (one relative to the Internet architectures, another to the industrial networks). Within this framework, I ensured the coherence of teaching, the coordination of interventions, the definition of examination subjects and the management of corrections, as well as the representation of the UE in the semester and year juries. Lectures mixed computer class and labs

⁸Arrêtés fixant la nomenclature des mentions des diplômes nationaux de licence (22 janvier 2014) et de master (4 février 2014).

on real equipments (routers, access points, firewalls, etc.) and with professional simulation tools (e.g. Riverbed Modeler). I ensured also practical labs and computer class for other units (in M1 and in M2 / M2-R).

In 2009, I have been charged, within the department and in the framework of the preparation of the new habilitation, to the creation of a LMD curriculum on networking, curriculum that I'm still coordinating. For the undergraduate program, I updated, with the responsible of the Licence, the L3 syllabus in a joint approach with the pedagogical teams of the DUT Réseaux & Télécoms and the DUT Génie Électrique et Informatique Industrielle of the University of Lorraine. It leads to the proposal of a more coherent teaching programme for students. We introduced hence courses (with pre-requisites) on network modelling and simulation, wireless networks and advanced transport/security. As a result, the students of L2 and DUT find, in their University, syllabus taking into account their knowledge and enabling them to prepare themselves for advanced positions as network planner, network engineer or network architect. In addition, it secures the opening of the specialisation in networking (15 students per year in average), for both the Licence and the Master. Since networking is also more and more interesting for other tracks, we added also into the Licence syllabus units to discover networking without pre-requisites. The courses are designed to complement theoretical and technological training in this field of networks.

In Master, I also created (according to a skills/competences approach validated by professionals of the sector) and ensured, the follow-up of a typical track around networks, allowing at the same time a professional insertion (average numbers of 12 to 15 students) and a preparation for a doctoral training (1 to 2 students per promotion). Our standard track on networks (currently named Sustainable Network Engineering) aimed for preparing students for the careers of network architect and network engineer (94% integration of graduates at 18 months). Beyond the disciplinary teachers, we have practiced a System Engineering approach (for which I followed a training of trainers in 2011) in order to present to the students the analysis of needs, requirements and the design of functional and organic architectures. Compared to other programmes in networking, it facilitates the learning skills and competences as defined in the ROME sheets. Besides the different teaching units that I'm responsible (see section 3.3), I am proposing in M2 a unit (UE libre) in distance learning education for the preparation to the Cisco CCNA industrial certification (I followed in 2012 a funded training of instructor for this purpose).

Since 2009, I'm member of the pedagogical teams of the programmes and responsible of the specialisation in Networks & Telecommunications in License and of the specialisation/track in Networking for the Master. The Master track in networking offers possible apprenticeship in M2, combining learning and working in industries. I have also ensure practical training (industrial projects and internships) and the promotion of the training courses (forums, portes ouvertes, etc.). The Master track in networking integrates also an *à la carte* track for students intending a career in research. For that purpose, I am ensuring in M2 courses on network calculus. As responsible of the specialisation, I am assisting them for selecting lectures in the field of their Msc thesis subject, especially for students from engineering schools (ENS Cachan, ENSEM, Polytech Nancy (formerly ESSTIN), Télécom Nancy) that follow the M2 in double degrees. It is important to notice here that all Phd students I have co-supervised was graduated from the Master ISC. Some of them have even followed the full LMD curriculum at the Faculty in networking (D. PETIT, J. Robert, D. BRECK, M.A.A NDIAYE)⁹. The Reda6 platform we installed at CRAN (Figure 2.3) is used here also for teaching as

⁹The full list of Msc thesis I have co-supervised was given in section 2.2.2.

benchmarking platform (Msc thesis of J.-B. PERRIN).

In 2016, I was brought to work for the Networks & Telecommunications sector on the accreditation application files for the License SPI¹⁰ and the Master ISC in preparation for the start of the 2018 academic year. For the Master, following exchanges with professional and the expectations of the CRAN laboratory ISET and BioSiS (Biologie, Signaux et Systèmes en Cancérologie et Neurosciences) departments, we have updated the track in networking to include education in advanced signal processing for machine learning. The objective is the discovery of big data and advanced signal processing for health, biology and environment. The track covers hence Networks, Signals and Green ICT (RESET¹¹). I have also included new units considering evolutions in the networking field, for instance one will be dedicated to Industrial Internet of Things. The transition will be facilitated by the recent recruitment of Sylvain KUBLER (one of my former Msc student) in 2017 as Associate Professor (Maître de conférences) in networking.

Finally, a part of my teaching activities have been also dedicated to internationalisation. From 2006 to 2008, I have given a course in Networking Control Systems at EMSI (École Marocaine des Sciences de l'Ingénieur) in Casablanca and Marrakech, Morocco. The course was included in the outsourced track (parcours délocalisé) Automatique et Traitement du Signal of the Master IS-EEAPR. From 2009 to 2012, I was the responsible of the outsourced track Networked systems "Systèmes en Réseaux Durables" at IGA (Institut du Génie Appliqué) in Casablanca, Morocco. I gave a course on the Internet architectures and I ensured the coherence of teaching, the coordination of interventions, the definition of examination subjects and the management of corrections.

In 2013, É. RONDEAU created an Erasmus Mundus of Joint Master Degrees PERCCOM. The programme is detailed in the next section. One of the idea was that networks would have to be designed differently, taking care of the pollution generated by the infrastructure and more largely speaking, of sustainability. All students were attached to the Master ISC specialization "Ingénierie des Réseaux Durables" for which I was responsible. We propose hence a new unit on green networking in M2 (and introduced even sustainability considerations in all networking courses in Master).

3.1.2 Erasmus Mundus of Joint Master Degrees PERCCOM

The Master ISC, through its specialisation "Ingénierie des Réseaux Durables" (IRD), is involved into the Erasmus Mundus of Joint Master Degrees PERCCOM "Pervasive Computing & COMMUNICATIONS for sustainable development" (<http://www.perccom.eu>). The programme (120 credits) was elaborated by É. RONDEAU (University of Lorraine, Faculty of Sciences & Technologies), and is funded by the European Commission for 5 cohorts (2013-2019). É. RONDEAU is the global coordinator / manager. PERCCOM aims at combining advanced Information and Communication Technologies (ICT) with environmental and circular economy awareness to enable world-class education and unique competences for ICT professionals who can build cleaner, greener, more resource and energy efficient cyber-physical systems.

The students spent a semester at the University of Lorraine, the Lappeenranta University of Technology (Finland) and the Luleå University of Technology (Sweden). At the end of the first academic year, they participate to a seminar at St Petersburg ITMO (Russia). The final semester (for the Msc thesis) takes place at one partner. The associated partners are Leeds Beckett University (UK), University of Chittagong (Bangladesh), University of Applied

¹⁰<https://formations.univ-lorraine.fr/diplomes-et-formations/1630-licence-mention-sciences-pour-l-ingenieur.html>

¹¹<https://formations.univ-lorraine.fr/diplomes-et-formations/2242-master-reseaux-signaux-eco-tic.htm>

Sciences, Harz (Germany), Orange, Facebook, Ericsson, Greenspector and the Fondation Mc Arthur. The programme is a double degree, graduated students get the Master ISC, the Master of Science in Technology (from LUT) and the Master in Pervasive Computing and Computers for sustainable development (from LTU).

Within the consortium, I am the LOCAL COORDINATOR (for the University of Lorraine) and as such, I took part in the application writing and I am in charge of the teaching of the semester of study (in English), the assurance quality at the University of Lorraine. I participate also to the admission committee and the Msc thesis evaluation process. The students (on average 20 students per cohort ≈ 100 students will be graduated at the end, coming the 5 continents¹², including 5 from the University of Lorraine) of this program are enrolled at the University of Lorraine within the Sustainable Network Engineering specialisation for which I am responsible. For the first two graduate cohorts, more than half of the students are currently in thesis, including 2 at CRAN (Dorine PETIT whom I co-supervised and Md Mohaimenul HOSSAIN).

As teacher, I am responsible of a teaching unit Automatic Control for Sustainable Development. With É. RONDEAU, we have equipped a new room named ÉcoTIC at AIPL, allowing, among other things, measurements of the energy consumption of the network architecture. We engage also students into the Design4Green (formerly GreenCode Lab Challenge) 48 hours hackathon (supported by the AGIT (Alliance Green IT)) of eco-design (in particular about green coding). To enforce the quality, professionals in networking (Orange), in circular economy (Foundation Mc Arthur) or in digital transitions (Sensing Vision) are invited for seminars. I participated also to the organisation of two summer schools in Nancy about green ICT smart things & eco-design in 2015 and Internet of Things & sustainability in 2016.

Our vision of education in green networking for undergraduate and graduate students is explained in [Actn.10] (*“Verdir un programme d’enseignement en Réseaux de Télécommunications : marketing ou véritable enjeu scientifique et professionnel”*). Figure 3.1 highlights the expertise and skills gain according to the students during such curriculum.

Finally, I am the responsible for the management of the new EMJMD application (Call for proposals Erasmus+ 2018 – EAC/A05/2017) entitled GreEn NetworkIng And cLoud computing (GENIAL). It focus specifically on green networking and the new networking/computing architectures (IoT, cloud/fog, SDN/NFV). The track RESET of the next accreditation of Master ISC have been structured to support the courses of the GENIAL programme. In addition to the University of Lorraine (Master ISC, track RESET) which is the applicant organisation, the full partners are the Luleå University of Technology and the Leeds Beckett University (Msc Sustainable Computing). The grant total request is 5 432 000 € for 4 cohorts. The proposal has been placed on the reserved list (until the end of 2018).

3.2 Responsibilities

Programmes in French

Bachelor:

Responsable pédagogique L3 Licence SPI-eeapr (2009-2012) for the specialization Networking & Telecommunications (*“Réseaux & Télécommunications”*).

Responsable pédagogique L3 Licence SPI (2013-2017) for the specialization Networking & Telecommunications (*“Réseaux & Télécommunications”*) of the track Digital Systems (*“Systèmes*

¹²<http://w3.cran.univ-lorraine.fr/perso/jean-philippe.georges/perccom/perccom.html>

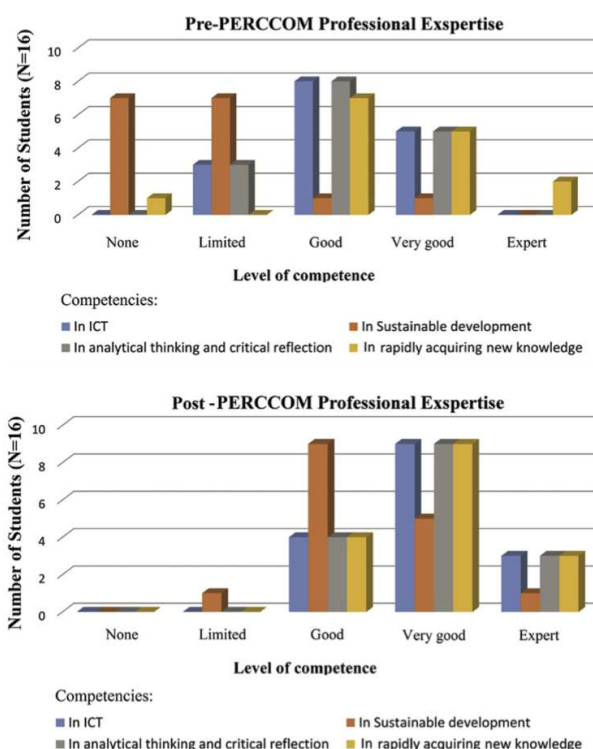


Figure 3.1: Professional skills according to PERCCOM students [Actn.10]

Numériques”).

Responsable pédagogique L3 Licence SPI (2018-) for the specialization Networking & Telecommunications (“Réseaux & Télécommunications”) of the track Digital Systems (“Systèmes Numériques”) and Referent for the track Digital Systems.

Master:

Responsible Master IS-EEAPR (2009-2012) of the outsourced track Networked systems “Systèmes en Réseaux Durables”. Délocalisation de la spécialité “Réseaux, Signaux, Images” (RSI - Networks, Signals, Images) à l’IGA au Maroc.

Responsible Master ISC (2013-2017) of the specialization (parcours) Sustainable Network Engineering (“Ingénierie des Réseaux Durables” (IRD)) of the track Systems & ICT (“Systèmes & TIC”).

Responsible Master ISC (2018-) of the track (parcours-type) Networks, Signals, Green ICT (“Réseaux, Signaux, ÉcoTIC” (RESET)).

Programme in English

Local coordinator of the Erasmus Mundus of Joint Master Degrees PERCCOM (2013-2019)

Into the University councils

Since 2017, elected member of Collegium Sciences & Technologies The collegium is responsible of the 3 UFRs (UFR Faculté des Sciences & Techniques à Nancy, UFR Sciences Fondamentales et Appliquées à Metz et UFR Mathématiques, Informatique et Mécanique à Metz) of the Sciences & Technologies sector of the University of Lorraine. It corresponds to a bit less than 7000 students and around 1100 personnels.

3.3 Summary of the main teaching units

My main areas of teaching concern networking protocols, architectures, QoS, green networking and coding.

Responsibility of teaching units:

- UE (CM/TD/TP) Communications sans fil (Wireless networking), L3 SPI (1 groupe TD). Unit with prerequisites. Topics: WLAN, WPAN, WMAN, WWAN, ad-hoc routing, mobility, transmission channel, propagation models.
- UE (CM/TD/TP) Architectures de l'Internet (Internet architectures), M1 ISC (1 groupe TD). Topics: stack TCP/IP, advanced routing and metrics, multicast, BGP, transport, congestion control, IPv6, SDN.
- UE (CM/TD/TP) Réseaux temps réel & de capteurs (Real-time and wireless sensor networks), M1 ISC (1 groupe TD). Topics: evolution of industrial networks (CAN, industrial Ethernet, AFDX) and wireless networks (802.15.4, 6LowPAN).
- UE (CM/TP) Conception d'architectures de réseaux (Network architecture design), M2 ISC (1 groupe TD). Topics: top-down design, network management, 6sigma/ITIL, green networking.
- UE (online distance learning) Préparation à la certification Cisco CCNA, M2 ISC.
- UE (CM/TP) Automatic control for sustainable development, PERCCOM (1 groupe TD). Topics: smart things, network management, IoT, green coding.

Lectures in other units:

- UE (TP) Informatique industrielle (Coding), L3 SPI (1 groupe TD). Topic: C-language.
- EC (CM/TD/TP) Couches hautes, UE Réseaux et protocoles (Networking for beginner), L3 Licence SPI (1 groupe TD). Unit without prerequisites. Topics: the TCP/IP stack, encapsulation, addressing, routing, transport.
- EC (CM/TD/TP) Transport et sécurité (Advanced transport and security), UE Réseaux haut-débit et réseaux locaux industriels, L3 SPI (1 groupe TD). Unit with prerequisites. Topics: Advanced transport protocols, circuit commutation,

protocols for multimedia, introduction to security (ACL, authentication, autorisations, teleworking infrastructures, VPN, Radius, LDAP).

- UE (TP) Interconnexion des systems (Network modeling) M1 ISC (1 groupe TD).
Topics: hub/switched architectures, addressing, VLAN, STP, routing.
- UE (CM/TD) Ingénierie des réseaux (Network modeling) M2 ISC (1 groupe TD).
Topic: network calculus.
- UE (TP) Qualité de Service (QoS) M2 ISC (1 groupe TD).
Topics: network metrology, architectures IntServ/DiffServ, ressources reservation.
- UE (TP) Communication protocols, PERCCOM (1 groupe TD).
Topics: TCP/IP architectures, addressing, VLAN, STP, routing, transport.
- UE (CM/TP) Quality of Service, PERCCOM (1 groupe TD).
Topics: network metrology, architectures IntServ/DiffServ, ressources reservation.
- UE (TP) Sustainable development & circular economy, PERCCOM (1 groupe TD).
Topics: green networking, metrology of energy consumption.
- UE (CM/TP) Specification definition of Master thesis project, PERCCOM (1 groupe TD).
Topics: thesis topics analysis, bibliography, writing a report, preparing a defense.

Tutor for:

- projects in L3, M1 and M2.
- stages (placements) in M2 and supervisors of Msc thesis in M2 and in PERCCOM.

On a representative basis, my service for the academic year 2016-2017 was divided in 78,5h CM, 134h TD and 100h TP.

Chapter 4

List of publications

- 9 articles in peer-reviewed international journals
- 2 articles in peer-reviewed national journals
- 1 article in educational journals
- 5 chapters in scientific books
- 44 papers in international conferences with a reading committee and proceedings
- 11 papers in national conferences with a reading committee and proceedings
- 17 communications in seminars / workshops
- 23 project deliverables
- 1 patent

Articles dans des revues avec comité de lecture à diffusion internationale

- [Acl.1] J.-P. **Georges**, T. DIVOUX et É RONDEAU : Confronting the performances of a switched Ethernet network with industrial constraints by using the Network Calculus. *IJCS, International Journal of Communication Systems*, 18(9):877–903, novembre 2005.
- [Acl.2] J.-P. **Georges**, N. KROMMENACKER, T. DIVOUX et É RONDEAU : A design process of switched Ethernet architectures according to real-time application constraints. *EAAI, Engineering Applications of Artificial Intelligence*, 19(3):335–344, avril 2006.
- [Acl.3] N. VATANSKI, J.-P. **Georges**, C AUBRUN, É RONDEAU et S.-L. JÄMSÄ JOUNELA : Networked control with delay measurement and estimation. *CEP, Control Engineering Practice*, 17(2):231–244, février 2009.
- [Acl.4] J.-P. **Georges**, D. THEILLIOL, V. COCQUEMPOT, J.-C. PONSART et C. AUBRUN : Fault tolerance in networked control systems under intermittent observations. *AMCS*,

International Journal of Applied Mathematics and Computer Science, 21(4):639–648, décembre 2011.

- [Acl.5] S. KUBLER, J. ROBERT, J.-P. **Georges** et É. RONDEAU : Dual path communications over multiple spanning trees for networked control systems. *EAAI, Engineering Applications of Artificial Intelligence*, 25(7):1460–1470, juin 2012.
- [Acl.6] J. ROBERT, J.-P. **Georges**, É. RONDEAU et T. DIVOUX : Minimum cycle time analysis of Ethernet-based real-time protocols. *IJCCC, International Journal of Computers, Communications and Control*, 7(4):743–757, novembre 2012.
- [Acl.7] N. DROUANT, É. RONDEAU, J.-P. **Georges** et F. LEPAGE : Designing green network architectures using the ten commandments for a mature ecosystem. *COMCOM, Computer Communications*, 42:38–46, avril 2014.
- [Acl.8] T. DIVOUX, J.-P. **Georges** et S. HARCHI : A session protocol for wireless sensor networks. application to oil spills monitoring. *COMPELECENG, Computers & Electrical Engineering*, 2015.
- [Acl.9] V. BOMBARDIER, J.-P. **Georges**, É. RONDEAU et I. DIOURI : Using fuzzy rules for network behaviour identification: application for differentiated services in an Ethernet network. *IJCIS, International Journal of Computational Intelligence Systems*, 11(1):316–329, 2018.

Articles dans des revues avec comité de lecture à diffusion nationale

- [Acln.1] J.-P. **Georges**, É. RONDEAU et T. DIVOUX : Évaluation de performances d’architectures Ethernet commuté. *RSTI, Technique et Science Informatique, Revue thématique "Temps Réel"*, 22(5):621–649, novembre 2003.
- [Acln.2] D. BRECK, J.-P. **Georges** et T. DIVOUX : Évaluation des performances de trafics agrégés 802.11n. *JESA, Journal Européen des Systèmes Automatisés*, 47(4-8):621–649, novembre 2013.

Articles dans des revues sans comité de lecture ou à vocation pédagogique

- [Ascl.1] T. DIVOUX, É. RONDEAU et J.-P. **Georges** : Ethernet : des îles au bureau, puis dans l’atelier. *Revue de l’Electricité et de l’Electronique*, 1:95–101, janvier 2008.

Chapitres d’ouvrages scientifiques

- [Osc.1] J.-P. **Georges**, T. DIVOUX et É. RONDEAU : Evaluation de majorants des délais de transmission pour les systèmes commandés en réseau. *In Systèmes commandés en réseau*, pages 189–230. Hermès-Lavoisier, avril 2007.
- [Osc.2] C. AUBRUN, B. BRAHIMI, J.-P. **Georges**, G. JUANOLE, G. MOUNEY, X. HUNG NGUYEN et É. RONDEAU : QoS-aware dynamic network QoS adaptation. *In*

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- [Osc.4] K.M. HABIBULLAH, É. RONDEAU et J.-P. **Georges** : Reducing energy consumption of network infrastructure using spectral approach. In *Technology for Smart Futures*, pages 235–250. Springer International Publishing, 2018.
- [Osc.5] D. MINOVSKI, É. RONDEAU et J.-P. **Georges** : Monitoring the energy consumed by a network infrastructure to detect and isolate faults in communication architecture. In *Technology for Smart Futures*, pages 219–234. Springer International Publishing, 2018.

Communications dans des conférences internationales avec comité de lecture et actes

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- [Acti.2] J.-P. **Georges**, É. RONDEAU et T. DIVOUX : Evaluation of switched Ethernet in an industrial context by using the network calculus. In *WFCS'02, 4th IEEE International Workshop on Factory Communication Systems*, pages 19–26, Västerås, Suède, août 2002.
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- [Acti.9] J.-P. **Georges**, É. RONDEAU et T. DIVOUX : Classification of service for networked control systems. *In 1er NeCST Workshop Networked Control Systems Tolerant to Faults*, France Nancy, octobre 2005.
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- [Acti.11] É. RONDEAU, J.-P. **Georges**, B. BRAHIMI, N. VATANSKI et S.-L. JÄMSÄ-JOUNELA : Simulation platform for behavioural analysis of networked control systems. *In 13th Nordic Process Control Workshop*, Lyngby, Danemark, janvier 2006.
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- [Acti.23] S. KUBLER, É. RONDEAU et J.-P. **Georges** : Dependability of switched network architectures for Networked Control Systems. In *IEEE International Conference on Mechatronics, ICM 2011*, Istanbul, Turquie, avril 2011.
- [Acti.24] J. ROBERT, J.-P. **Georges**, T. DIVOUX, P. MIRAMONT et B. RMILI : Ethernet networks for real-time systems : application to launchers. In *The International Space System Engineering Conference, DASIA 2011*, San Anton, Malte, mai 2011.
- [Acti.25] J.-P. **Georges**, T. DIVOUX et É. RONDEAU : Network Calculus: Application to switched real-time networking. In *5th International ICST Conference on Performance Evaluation Methodologies and Tools, ValueTools 2011*, Paris, France, mai 2011.
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- [Acti.31] J. ROBERT, J.-P. **Georges**, T. DIVOUX, P. MIRAMONT et B. RMILI : On the observability in switched Ethernet networks in the next generation of space launchers: Problem, challenges and recommendations. In *SPACOMM'15, 7th International Conference on Advances in Satellite and Space Communications*, pages 13–18, Barcelone, Espagne, avril 2015.
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- [Acti.37] D. PETIT, J.-P. **Georges**, T. DIVOUX, B. REGNIER et P. MIRAMONT : Freshness analysis of functional sequences in launchers. In *4th IFAC Symposium on Telematics Application*, Porto Alegre, Brésil, novembre 2016.
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- [Acti.40] É. RONDEAU, J.-P. **Georges**, M.M. HOSSAIN et M. HABIBULLAH KHAN : Is green networking a new workload for ICT engineers? a network topology example. In *20th IFAC World Congress, IFAC 2017*, Toulouse, France, juillet 2017.

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Part II

***Antae annorum* – Contributions**

Chapter 5

Performance evaluation of networked systems (A1 – QoS)

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This chapter introduces a synthesis of my research activities regarding the performance evaluation of (wired and wireless) network architectures. Since my PhD [The.1] (supervised by T. DIVOUX and É. RONDEAU), I have been working on evaluating QoS offered by networks, and particularly in developing deterministic queuing systems calculus for temporal (and capacity) performance. In this respect, I have contributed to the application of the network calculus theory developed by R.L. CRUZ (University of California, US), C.-S. CHANG (National Tsing Hua University, Taiwan), J.-Y. LE BOUDEC (EPFL, Switzerland) to two specific network architectures: switched Ethernet networks and wireless access infrastructures. In both cases, the challenge has consisted in retrieving deterministic QoS properties even though protocols are non deterministic. In addition to the development of deterministic calculus, I have also considered performance evaluation through extensive simulations (with stochastic performances) and experiments (in the framework of the partnership with the CNES agency). The structure of this chapter is divided into three parts, reflecting how I have valued theoretical work in practice and in the industry (research transfer with Schneider Electric and CNES). Even though this chapter focuses on QoS, an original proposal about network observability is made

at the end of the chapter (aiming at evaluating specific metrics like freshness of a networked systems).

Overall, this chapter addresses the following research questions:

- how to qualify temporal performance (upper-bounded delays) of Ethernet architectures (which do not provide QoS guarantees)?
- how to fairly allocate resources (through classification of service (CoS) mechanisms) to protect constrained flows over such networks?
- how to find the good equilibrium between QoS expectations of end-users and requirements of wireless access providers?
- how to assess the performance of distributed automation systems over Ethernet architectures during pre-sales under uncertain context?
- how to evaluate the best candidate among the different Ethernet-based industrial networks for real-time applications?
- how to increase the maturity (TRL) of the design of embedded Ethernet networks?
- what could be network observability? how to track the control application behaviour by only monitoring the network?

5.1 Contributions to deterministic queuing systems calculus

5.1.1 Fundamentals of the network calculus theory

This section aims at providing the fundamentals of the network calculus theory. It will be useful to highlight in the following the different contributions we had accomplished in regards to deterministic (temporal) performance evaluation

The network calculus fundamentals can be found in [Cru91a, Cru91b, Chao0, LBT01]. As noted by [LBT01], it lies in the mathematical theory of dioids, and in particular the Min-Plus dioid also called Min-Plus algebra. In addition to the elementary calculus, several filtering operations are also translated in the $(\min, +)$ setting. The min-plus convolution respectively deconvolution of two functions f and g are hence defined to be:

$$(f \otimes g)(t) = \inf_{0 \leq s \leq t} \{f(t-s) + g(s)\}$$

$$(f \oslash g)(t) = \sup_{u \geq 0} \{f(t+u) - g(u)\}$$

The network modelling is achieved by non-negative and non-decreasing functions (taking their values in the $(\min, +)$ semi-ring), which characterise an amount of data at a given time denoted by t . The set of such functions is given by:

$$\mathcal{F} = \{f : \mathbb{R}^+ \rightarrow \mathbb{R}^+, \forall t \geq s : f(t) \geq f(s), f(0) = 0\}$$

The first use of such functions is for the $R(t)$ input and the $R^*(t)$ output function, which cumulatively count the number of bits that are input to respectively output from a system \mathcal{S} . This corresponds to the real movements of data. Throughout the paper, we assume these

functions to be continuous in time and space. This is not a major restriction as there are transformations from discrete to continuous models [LBT01].

The second use is for the constraints that the real movements of data satisfy. Given a flow with the input R function, an $\alpha \in \mathcal{F}$ function is an arrival curve for R if:

$$\forall t, s \geq 0, s \leq t : R(t) - R(t-s) \leq \alpha(s) \Leftrightarrow R \leq R \otimes \alpha$$

The third use is for the service offered by a system to a flow defined by an input R function, which results in an output function denoted by R^* . Then, the system is said to provide a minimum service curve $\beta \in \mathcal{F}$ if:

$$\forall t \geq 0, R^*(t) \geq \inf_{s \leq t} \{R(s) + \beta(t-s)\} \Leftrightarrow R^* \geq R \otimes \beta$$

In addition, β is called a strict service curve for the system if during any backlogged period $]s, t]$, at least $\beta(t-s)$ data is served.

Let us turn now to the performance characteristics of flows that can be bounded by network calculus. Assume a flow with input function R that traverses a system \mathcal{S} resulting in the output function R^* . The backlog of the flow at time t is defined as:

$$b(t) = R(t) - R^*(t)$$

Assuming first-in-first-out delivery, the delay for an input at time t is defined as:

$$d(t) = \inf \{ \tau \geq 0 : R(t) \leq R^*(t + \tau) \}$$

These arrival and service curves allow for computing the following bounds.

Theorem 1 (The three bounds [Chao, LBT01]). *Consider a system \mathcal{S} that offers a service curve β and that stores input data in a FIFO-ordered queue. Assume a flow R traversing the system that has an arrival curve α . Then we obtain the following performance bounds for the backlog b , delay d and output arrival curve α^* for R^* :*

$$\begin{aligned} b(t) &\leq \sup_{t \geq 0} \{ \alpha(t) - \beta(t) \} = (\alpha \otimes \beta)(0) \\ d(t) &\leq \sup_{t \geq 0} \{ \inf \{ \tau \geq 0 : \alpha(t) \leq \beta(t + \tau) \} \} \\ \alpha^* &\leq \alpha \otimes \beta \end{aligned}$$

Finally, the consideration of the service offered to a flow along a given path may be studied by considering the two following results.

Lemma 1 (Tandem systems [Chao, LBT01, BS14]). *Consider a flow that traverses a tandem of systems S_i , $i = 1, \dots, n$ and that S_i offers a service curve β_{S_i} . Then the concatenation of the n systems offers a minimum service curve $\otimes_{i=1}^n \beta_{S_i}$ to the flow.*

Lemma 2 (Residual service – Blind multiplexing [Chao, LBT01, SZFo8]). *Consider a node offering a strict service curve β and two flows entering that server, with respective arrival curves α_1 and α_2 . A service curve for the flow 1 is:*

$$\beta_1 = (\beta - \alpha_2)^+ = \max(0, \beta - \alpha_2)$$

The last Lemma is also presented by [BS14] as:

Theorem 2 (Left-over service curve). Consider a system S that offers a strict service curve and that serves two input flows, f_1 and f_2 with arrival curves α^{f_1} and α^{f_2} , respectively. The minimum service f_1 is guaranteed to receive is lower bounded by the so-called left-over service curve $\beta^{l.o.f_1}$. In case of arbitrary multiplexing of flows crossing S , it holds that $\beta^{l.o.f_1} = \beta \otimes^{ARB} \alpha^{f_2}$ with $(\beta \otimes^{ARB} \alpha)(t) = \sup_{0 \leq s \leq t} (\beta - \alpha)(s)$.

These first results enabled us to validate the method to determine time performance bounds in spite of best effort protocols. However, it was only limited to simple networks. In fact, first results mainly address the tandem systems shown in Figure 5.1a thankfully Lemma 1. The pay bursts only once principle enables here to tight the bounds rather than computing each time the output arrival curve (as defined in Theorem 1). For rate-latency services curves, [LBT01] shows that the composition of rate-latency curves (the most employed) correspond to another rate-latency one. It gives also delays bound expression for affine arrival curve.

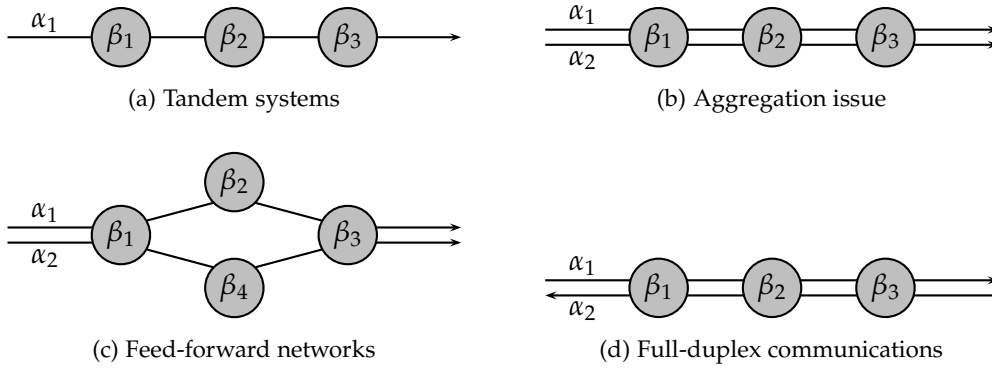


Figure 5.1: Flows mapping on switched topology.

Next step consisted in considering the aggregation issue shown in Figure 5.1b for acyclic networks. If the service curve β is for the whole service offered by a system (i.e. a switch) and not dedicated to a given flow, it means that bounds could be only computed for the aggregated traffic ($\alpha_1 + \alpha_2$). Due to inter-flow dependencies, multiplexing of a flow depends on other flow and *vice versa*. To obtain bounds for a given flow (for instance α_1), the scheduling policy of the system should be taken into account in order to define an appropriate service curve β' from the initial curve β . For this topic, Lemma 2 gives an interesting result known as blind multiplexing or residual service. It is equivalent to consider that in the worst case, a given flow will be served in an equivalent manner as a low priority traffic for a strict priority scheduler. [BGLT08, LMS08, SZF08] detail next how this lemma can be used in conjunction with the pay bursts only once principle in order to catch the pay multiplexing only once principle. For affine function and rate-latency functions, it is shown that the path service curve offered to the traffic α_1 is given by $(\beta_1 \otimes \beta_2 \otimes \beta_3 - \alpha_2)^+$. A complete study is given in [BGLT08] about the conditions required to use this result and also how to compute more tight bounds. Associated network topologies are related to the feed-forward property (see Figure 5.1c) defined by [SZM06] as a network in which nodes can be labelled in such a way that the path of every flow is composed of an increasing sequence of node labels. Different methods have been proposed as the least upper delay bound [LMS08]. Here the end-to-end service curve in a tandem is computed by iterative removing interfering flows. Recent developments about this topic can be found in [BJT10]. It gives an algorithm that computes the maximum end-to-end delay for a given flow for any feed-forward networks under blind multiplexing with concave arrival curves and convex service curves.

However communications in a realistic network might be more complex than the acyclic network illustrated in Figure 5.1b. Figure 5.1d shows more complicated studies. This one is typical in an industrial context where a calculator might send a control update to an actuator/sensor while the sensor is sending the feedback. In such a case, previous results cannot be applied such that it might be not possible to identify the service guaranteed by a path for a given flow. As a consequence, it is not possible to use the pay bursts only once principle for instance, and only local upper-bounds delays (i.e. the delay for crossing one switch) will be computed according to the output arrival functions given in Theorem 1. This means that studies deal with total flow analyses.

The network calculus has been used for IETF DiffServ architectures on Internet [LBT01], industrial Ethernet networks [Acl.1, JNTW02], avionics networks [Grio4, BFo8, BNF12, HGO15], wireless sensor networks [SZT07] or networks on chip [TCG⁺01]. Next sections show how this theory has been applied until now in the framework of the performance evaluation of Ethernet based real-time communications. It introduces what kind of additional information could be integrated in the application of the network calculus theory. It shows also where blind multiplexing issues are remaining.

5.1.2 Performance evaluation of 802.1D switched Ethernet networks [Acl.1, Acl.2, Acti.25]

The Ethernet standard [IEE08b] is a standard solution for interconnecting industrial devices despite its intrinsic drawbacks, particularly its non deterministic medium access method. A new trend endorsed particularly by the IAONA (Industrial Automation Open Networking Alliance) consortium was to promote the Ethernet network as a standard for industrial communications. The expected benefits are less costly network installations, because equipment is available off-the-shelf, and the avoidance of interoperability problems, because Ethernet technology is broadly used. Other advantages are that Ethernet is a well-known protocol, widely implemented, and its performance improves continuously with technological evolution (especially bandwidth). However, access to the Ethernet medium relies on the non deterministic CSMA/CD algorithm [IEE08b], which applies a stochastic method to resolving collisions and cannot guarantee that message transmissions will be received in bounded time. Consequently, the native Ethernet protocol cannot be directly implemented in a plant with severe time constraints, and many Ethernet-based solutions ([IECo6a, IEC06b], AFDX [ARI03] or TTEthernet [SAE11]) have been proposed to overcome this issue, as mentioned in [ATVoo, Deco5, Deco1, Felo5] (this has resulted in the specification of a large number of fieldbus standards and a “fieldbus war” as described in [FS02, FS04]). However, if these Ethernet-based solutions are adapted to industry requirements, they lead to two types of problem: (i) different solutions are not interoperable because different fieldbuses are developed by each manufacturer; (ii) time performance is insufficiently evaluated or compared.

Since my PhD thesis, I have considered the analysis of pure native Ethernet standard switched (IEEE802.1D/Q standards [IEE04, IEE06b]) architectures in order to maintain the promise of interoperability. Among several COTS networks, it is the most cost and mature effective solution [MFF07]. As detailed in [Acl.1], full-segmented switched architectures [IEE97] enable to translate the problem of stochastic Binary Exponential Backoff to additional congestion into switches, and this congestion is going to be analysed through the network calculus theory. The objective is to compute upper-bounded end-to-end delays.

In [JNTW02], the network calculus theory is employed in order to bound delays by simply

assuming that the service provided by switches is following rate-latency functions. It enables to compare efficiency of line vs star topologies. Switched Ethernet topologies in a real-time context are not only appropriate to the factory area, but covers also embedded systems like the EADS A380 aircraft. In [Grio4, BFo8] the modelling of AFDX networks (switched Ethernet with admission control techniques) was achieved thankfully the network calculus theory.

The research lead by [Grio4] was related to the qualification of the usage of Ethernet networks in EADS A380 aircraft for the first time by computation rather than measurements. We share the same approach in our joint work with CNES for launcher), but rather than considering specific protocols and hardware (i.e. AFDX), we only considered IEEE802.1D/Q switches. Compared to [JNTWo2], our modelling is based on a functional analysis of switching principles that extends the switch modelling in a more detailed manner rather than the simple indication of a $\beta(t) = R(t - T)^+$ switch service curve. More information is provided in [Acl.1].

It may be noticed that switched Ethernet networks correspond to a particular case study: paths are *a priori* known (defined by spanning tree algorithms). Moreover switches have multiple input/output ports, meaning that two levels of aggregation should be discussed: between flows entering by different ports and between flows entering by the same input port. Moreover, flows entering by the same input port are not necessarily exiting a switch by the same output port.

Our switch modelling is based on 4 components (Figure 5.2): a multiplexer to access a shared memory queue, a demultiplexer for the forwarding plane and an output queue limited by the outbound port capacity.

For a given flow i , we considered concatenation of affine functions in order to take into account the link capacity such that:

$$\alpha_i(t) = \min(Ct, \sigma_i + \rho_i t)$$

where C corresponds to the link capacity, σ the maximum burst and ρ the long term arrival rate. For a flow i , we note σ_i^j the burst level after crossing j switches. When a flow i enters a network, its burst is upper-bounded by σ_i^0 .

An issue is that the parameter (σ, ρ) are only known at the input of the network (σ^0, ρ^0) . As shown in Figure 5.2, the problem is here that the the graph is cyclic: σ_1^1 depends to σ_2^7 and therefore to σ_2^1 , which is itself related to σ_1^7 (i.e. σ_1^1). As a consequence, it is not possible in a general framework (i.e. without considering particular topologies) to apply the pay bursts only once principle (and consequently Lemma 1).

We therefore applied the technique developed by [Crug1a], which is based on the bound related to the output arrival curve (Theorem 1) $\alpha(t) \circ \beta(t)$ when the upper-bounded delay is finite and:

$$\beta(t) = \delta_{\overline{D}} = \begin{cases} 0 & \forall t \leq \overline{D} \\ +\infty & \text{else} \end{cases} \quad \forall \overline{D} < +\infty \quad (5.1)$$

We proposed then in [Acl.1] an upper-bound delay for each switch component. For instance, for two flows entering into a multiplexer, the delay for the flow 1 is hence upper-bounded by:

$$\overline{D}_{mux,1} = \frac{1}{C} \min \left\{ \sigma_1 + \rho_1 \frac{\sigma_2}{C - \rho_2} + (C - \rho_1) \frac{L}{C}, \sigma_2 + \rho_2 \frac{\sigma_1}{C - \rho_1} + \rho_2 \frac{L}{C} \right\}$$

The delay is computed here as the time required to served the maximum amount of backlog into the component. Therefore, if the long-term arrival rate remains constant, the delay generates additional burst ($\sigma_1^1 = \sigma_1^0 + \rho_1^0 \overline{D}_1$) as shown in Figure 5.3.

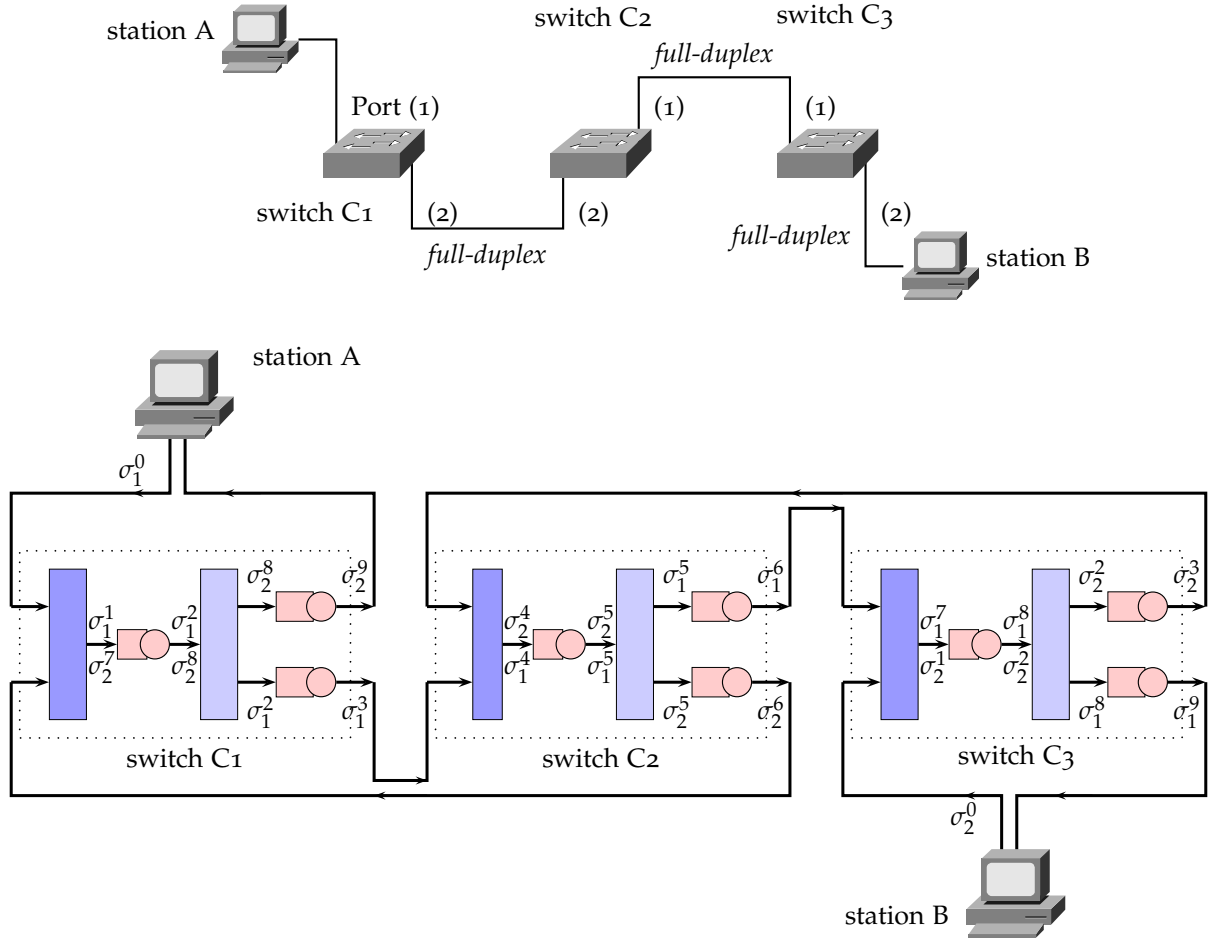


Figure 5.2: Flow inter-dependency (2 flows, 1:A→B and 2:B→A)

For feed-forward network, it could be hence easy to determine the end-to-end delay just by summing the delay for crossing each component along the path. But since switched Ethernet networks may lead to cyclic network in a general manner (see Figure 5.2), we have simply proposed the following methodology (even if for some configurations, it might lead to not tight upper-bound delays):

1. for each flow, determine the initial parameter (σ_i^0, ρ_i) . The traffic is assumed known or constrained by a leaky/token bucket (DiffServ) or a GCRA (ATM) controller;
2. identify the path for each flow (according to the spanning tree protocol);
3. for each component of each switch and for each flow, define the output burst as $\sigma_i^{j+1} = \sigma_i^j + \rho_i \bar{D}$;

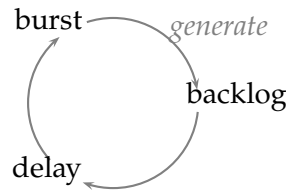


Figure 5.3: Relation between burst and delay

4. resolve the following equation system:

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & & & \vdots \\ a_{n1} & b_{n2} & \dots & a_{nn} \end{bmatrix} * \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix}$$

5. compute the burst for each flow on each component;

6. compute end-to-end upper-bounded delays as:

$$\overline{D}_i = \frac{\sigma_i^h - \sigma_i^0}{\rho_i}$$

with h the number of components over the path minus one.

Experiments [Acl.1] have shown that the computed upper-bounded delays remain tight, even if it corresponds to worst-case situations (i.e. sparse). Obviously, the methodology could be improved with the last results for acyclic networks as discussed in the following.

The methodology has been applied to real testbed in the framework of the study of Ethernet networks that will be embedded in the next generation launchers. It will be used also in the following chapter for the design of networked control systems. With N. KROMMENACKER, I have also included it in a design process of hierarchical switched Ethernet architectures according to real-time application constraints [Acl.2]. It corresponds to a method based on genetic algorithms to minimise end-to-end delays by providing a good distribution of the devices on the network switches. The objective function is defined by using the above methodology. This approach enables to valid the network topology and propose a distribution of the industrial devices that respects the temporal application constraints, even if this heuristic does not provide the best solution.

5.1.3 Weighted round robin scheduling for 802.1D/Q classification of service [Acti.17, Acti.25]

Classification of service in switched Ethernet networks

The evolution of Ethernet to segmented architectures and the definition of the *Virtual Local Area Networks* (VLAN) have led to the birth of a new standards set (802.1D/p, 802.1Q [IEEo4, IEEo6b]) in which new encapsulation fields are added to the native frame format. One of these fields defines priority levels (8 levels being supported in relation to the 8 types of applications: voice, video, network management, best effort, etc.). Currently the scheduling policies implemented on switches [IEEo4] are often limited to strict priorities (SP) and the weighted round robin (WRR).

With the PhD thesis of *i. DIOURI*, we aimed at refining the results obtained previously in order to support such classification of service (CoS) mechanisms. We are still interested in the delays for each flow according to whether the policy of the switch is SP or WRR.

In the following, it is assumed that the size of a frame is upper-bounded by L . The notion of flow corresponds here to the set of traffic sharing the same priority and exiting the switch by the same output port (i.e. the traffic entering by a common input port of an output multiplexer on Figure 5.4b). We assume also that the capacity of the inputs and outputs are relatively fixed at C_{in} and C b/s. Each flow $i \in \mathbb{N}^*$ is (σ_i, ρ_i) upper-constrained with $\sum_{j=1}^n \rho_j < C$ where $n \in \mathbb{N}^*$ is the number of priority/class and a weight ϕ_i is given to each flow.

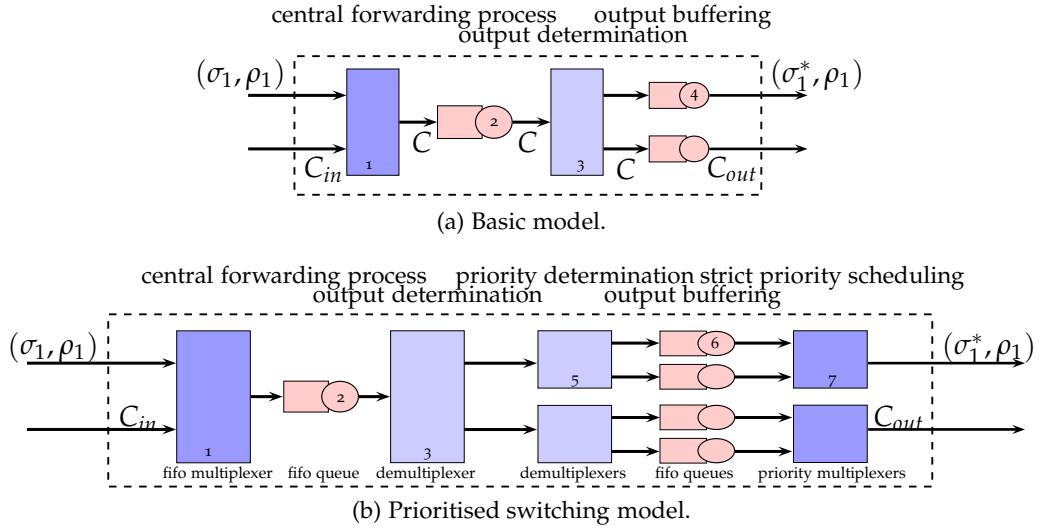


Figure 5.4: The prioritisation mechanism modifies the output buffering at output ports.

Strict priority

The strict priority policy guarantees to the packets of the flow with the highest priority (here, flow 1) to be selected first. But, since the forwarding of a packet on the network cannot be preempted, packets of the flow 1 might have to wait the complete forwarding of a packet with a lower priority. Also, the service curve associated to the flow with the highest priority is given by :

$$\beta_1(t) = R(t - T)^+ \quad T = L/C, R = C \quad (5.2)$$

Obviously, packets of flow 2 are served before packets of flow 3, but they have to wait that there is no packet of flow 1 that is waiting before to be served. So there is a first latency corresponding to the processing time of the initial bursty period of the flow 1. Moreover, like above, it will not be possible to preempt the forwarding of a packet of flow 3 in order to serve a packet that has just arrived from flow 2. Finally, since the node will serve first packets of flow 1, the forwarding rate will be limited to $C - \rho_1$. A packet of flow 3 will be served only if there is no packet of flows 1 and 2 waiting. That is to say that the service has a first latency period defined by the processing time of the initial bursty period of the union of the two others flows.

We have hence proposed the following service curve for a flow $i > 1$:

$$\beta_i(t) = R(t - T)^+ \tag{5.3}$$

$$T = \frac{\sum_{j=1}^{j=i-1} \sigma_j}{C - \sum_{j=1}^{j=i-1} \rho_j} + L/C, \quad R = C - \sum_{j=1}^{j=i-1} \rho_j$$

The service offered to one flow depends on the other flows and the service offered to the flow with the lowest priority may tend towards zero.

Fair queueing and weighted round robin

The Weighted Fair Queuing, initially proposed in [DKS89], also known as the Packetized Generalized Processor Sharing (PGPS), is based on the conceptual algorithm called the Generalized Processor Sharing (GPS) [PG93]. However practical implementations of WFQ in today’s switch products are based on a Weighted Round Robin (WRR) which is simpler. The WRR [DKS89, PG93] manages the network performance by adjusting the number of frames forwarded for each queue according to its weight. It serves all the queues in a cyclic way, from the one with the highest priority to the one with the lowest. The weight associated to a given port i is defined by ϕ_i (with $\phi_i \in \mathbb{N}^*$). In other words, it means that no more ϕ_i flits might be successively served per round robin cycle for a port i . The maximum number of frames served during a round robin cycle is defined by $\Phi_n = \sum_{j=1}^n \phi_j$.

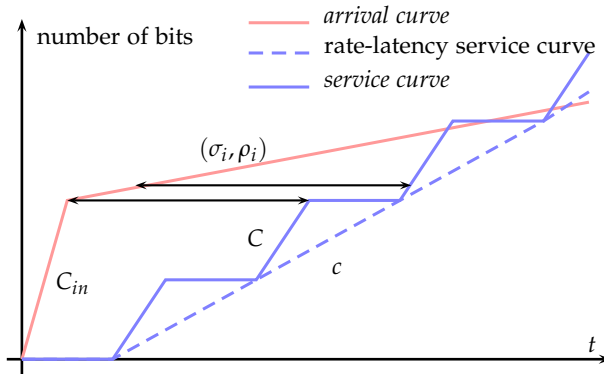


Figure 5.5: Service curves *weighted round robin*.

Regarding Figure 5.5, we have considered first an update of the service curve proposed by [Chao] for GPS policy. It corresponds (the dashed line) to the rate-latency service curve:

$$\beta_i(t) = R(t - T)^+ \quad R = C \frac{\phi_i}{\Phi_n}, \quad T = \frac{\sum_{j \neq i} \phi_j}{C} \tag{5.4}$$

A local improvement of the delays bounds deals with the definition of the second service curve is shown in Figure 5.5. The main idea is hence to take into account that it is the access to the switching fabric which is shared between the input ports, not directly the forwarding capacity. In fact, this service can be seen as the composition of the service offered by each cycle. Indeed, for a cycle n , the curve corresponds to a constant plus a rate latency $nK + \beta_{R,nT}(t)$ as shown by Figure 5.6.

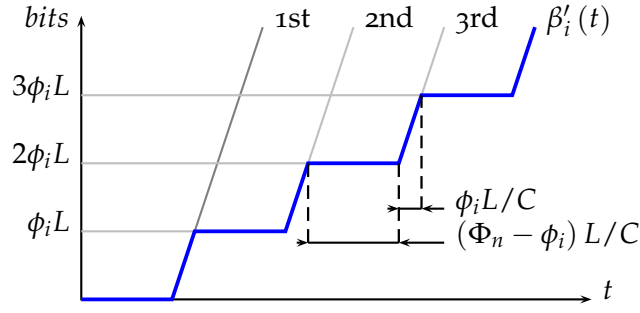


Figure 5.6: Composition of service for each round-robin cycle.

We then proposed to replace (5.4) by:

$$\begin{aligned} \beta'_i(t) &= (1\text{st}) \wedge (2\text{nd}) \wedge (3\text{rd}) \wedge \dots = \inf_{k \in \mathbb{N}} \{kK + \beta_{R,kT}(t)\} \\ &= \inf_{k \in \mathbb{N}} \left\{ k\phi_i L + C(t - \Phi_n(k+1))^+ \right\} \end{aligned} \quad (5.5)$$

Different properties might be given for equation (5.5). Considering Lemma 2 and [SZMo6], we have proposed the following result. It enables to distinguish the service offered by a WRR scheduler to two flows with the same priority / belonging to the same class.

Definition 1. Consider a switch serving two flows, 1 and 2 entering into the switch by the same input port i with some unknown arbitration between the two flows. Assume that the switch guarantees a strict service curve β_i to the aggregate of the two flows. Assume that flow 2 is α_2 -smooth and that $R > \rho_2$. The service curve offered to the flow 1 is defined by:

$$\beta_1(t) = \inf_{k \in \mathbb{N}} \left\{ K' + R'(t - T')^+ \right\}$$

with $R' = R - \rho_2$, $T' = \frac{\sigma_2 + T\rho_2}{R - \rho_2}$, $K' = (K - \sigma_2)^+$ and K , R and T defined as in equation (5.5).

According to the Lemma 1, we proposed also [Acti.25]:

Definition 2. Assume a flow traverses switches 1 and 2 in sequence. Assume that each switch offers a service curve of β_i , $i = 1, 2$ to the flow. Then the concatenation of the two switches offers a service curve:

$$\beta_1 \otimes \beta_2(t) = \inf_{k_1, k_2 \in \mathbb{N}} \{K + R(t - T)\}^+$$

with $K = K_1 + K_2$, $R = \min(R_1, R_2)$ and $T = T_1 + T_2$.

By applying Theorem 1, I. DIOURI highlighted in [Acti.25] that the forwarding rate offered to the packet with a lower priority will tend to zero in the strict priority scheduling (famine). This problem does not appear in the weighted round robin policy, since the forwarding rate will only depend on the weights values. Such results will be used in the next chapter to automatically configure the weights for each flow.

5.1.4 Frame aggregation in wireless 802.11n/ac [Bre15, Acti.28]

| With the PhD of D. BRECK, we have studied the A-MSDU frame aggregation system introduced with the standards 802.11n and 802.11ac [IEE12, IEE13].

Overview

Aggregation could have two advantages: improve lifetime by reducing the number of transmissions (and thus the number of competitions to gain the medium) and minimise the consumed bandwidth. Many improvements have been made in the physical layer to achieve this goal. Nevertheless, frame aggregation remains one of the major enhancements that enables this standard to reach the 100 Mb/s [IEE12] data throughput objective at the Medium Access Control (MAC) layer. Some authors have studied 802.11n aggregation performance using various theories, including:

- Queuing theory (throughput, channel utilisation, aggregate latency) [LWo6, KDo6b].
- Analytic study (throughput) [GKo7].
- Simulations (channel utilisation, aggregate latency) [SNC⁺o8, WWo9].

Nonetheless, the above works suffer from several drawbacks. First, chosen performance indicators are macroscopic, as they mainly deal with the delay for an aggregate to cross a given topology. It is then impossible to quantify the impact of the aggregation system on one of the aggregated flows. Aggregating is not always appropriate, especially when considering critical applications. Indeed, some frames are voluntarily delayed in order to wait for others with which they will be aggregated. Furthermore, many authors provide average values for performance indicators (delay, throughput), when worst case values may be required. Obtaining *a priori* bounds is necessary for critical applications. Some authors computed them like [GKo7]. However, their results need a detailed knowledge of incoming traffics which is often impossible to get in practice. Indeed, even in a simple case study, the number of scenarios increases quickly without any hypothesis on the input flows (packets size, inter-arrival, jitter, ...) and on the system thresholds. D. BRECK purpose was therefore to compute a service curve for a 802.11n aggregation system. This curve represents the service provided to a particular input flow. Our study highlights the limitations of the residual service (Lemma 2).

The aggregation system aggregates several MAC Service Data Units (MSDU) to form an Aggregated-MSDU (A-MSDU) encapsulated in a 802.11n frame (Figure 5.7). Cumulative data is sent in the network according to two criteria. On the one hand, if cumulative data reaches a size threshold and, on the other hand, if the associated class gains the medium or if the time spent in the system by the first collected frame reaches a temporal threshold. Figure 5.8 represents the aggregation system with the size threshold s and h the temporal one. This enables to not delay the transmission of a packet, unlike other aggregation mechanisms for which a temporal threshold is defined [IEEo9a].

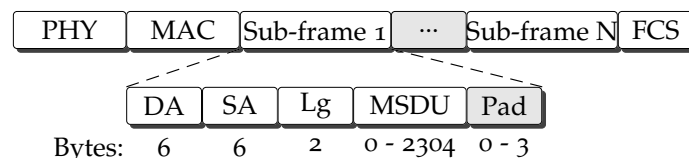


Figure 5.7: A-MSDU frame format

We are restricting here the study to an aggregation system that only considers the maximal size threshold S .

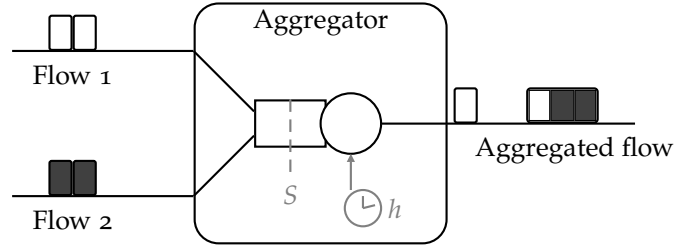


Figure 5.8: Functional model of aggregation system

Aggregate departure

Let us consider the aggregation system of Figure 5.8. Assume first that the incoming traffic is merged in a "super flow" formed by the two flows such as $R(t) = R_1(t) + R_2(t)$.

Proposition 1. *The aggregation system sends an aggregate with a throughput C when its backlog is greater than or equal to a maximal size threshold S . The aggregate size varies between $S - l_{max}$ and S , with l_{max} the maximum packet size at the system input.*

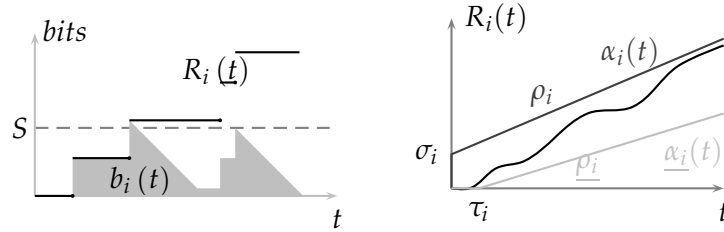


Figure 5.9: Backlog and incoming traffic envelopment

As shown in Figure 5.9, the backlog varies with frames arrival and decreases only when reaching the critical size S , i.e $R(t) - R^*(t) \geq S$. Consequently, this system is non work conserving and its service varies with data arrival (unlike the systems with a constant bit rate service $\beta(t) = Ct$). As sending an aggregate depends on the amount of input traffic, D. BRECK proposed to low-bound the input flows with a minimal arrival curve like in Real-Time Calculus [TCNoo]. We assume to consider only affine arrival curves (Figure 5.9). Thus $\forall 0 \leq s \leq t$:

$$\begin{aligned} \underline{\alpha}_i(t-s) &\leq R_i(t) - R_i(s) \leq \alpha_i(t-s) \\ \underline{\rho}_i(t-s-\tau_i)^+ &\leq R_i(t) - R_i(s) \leq \sigma_i + \rho_i(t-s) \end{aligned} \quad (5.6)$$

The model of the service offered to the "super flow" is given below.

Proposition 2. *Given an aggregation system with two input flows. Each of them is constrained by two arrival curves $\underline{\alpha}_k(t)$ and $\alpha_k(t)$ with $k = 1, 2$. The service curve $\beta(t)$ becomes:*

$$\beta(t) = R(t - \Delta)^+ \quad (5.7)$$

with a rate $R = \underline{\rho} = \underline{\rho}_i + \underline{\rho}_j$ with $i = \arg \min_{i=1,2} \tau_i$ and $j = \arg \max_{j=1,2} \tau_j$, and a latency $\Delta = \tau_i + S/\underline{\rho}_i$ if $S/\underline{\rho}_i \leq \tau_j - \tau_i$ or else $\Delta = \tau_i + (S + \underline{\rho}_j(\tau_j - \tau_i)) / (\underline{\rho}_i + \underline{\rho}_j)$.

Two variables must be computed in this model, the service rate R and the latency Δ . Our reasons for choosing an rate-latency service curve and the computation of R and of the maximal time between the departure of two aggregates, Δ can be found in appendix in [Acti.28].

Service dedicated to a flow

After having formulated the service offered to $R_1(t) + R_2(t)$ (Proposition 2), D. BRECK identified a service curve noted $\beta_1(t)$ for $R_1(t)$ only. As our service curve from proposition 2 is strict by definition of Δ , applying the residual service (Lemma 2) leads to the following proposition [Acti.28].

Proposition 3. *The aggregation system defined in the Proposition 2 offers to the flow $R_1(t)$ a minimal service curve:*

$$\beta_1(t) = (\underline{\rho}_1 + \underline{\rho}_2 - \rho_2)(t - \Delta_1)^+ \quad (5.8)$$

Since the forwarding rate might be inferior to the arrival rate (i.e $\underline{\rho}_1 + \underline{\rho}_2 - \rho_2 \leq \rho_1$) a stability condition is necessary: $\underline{\rho}_i = \rho_i$. So, the service rate for the flow 1 becomes ρ_1 . It means that the worst service rate is obtained when an flow is alone. Besides, the delay Δ_1 does not ensure that data from flow 1 was arrived. Furthermore, Δ_1 is increased by a flow 2 burst which does not appear in the expression of $\beta(t)$. To avoid the pessimism introduced by these observations we propose to replace Δ_1 in equation (5.8).

We search $\Delta'_1 \geq \Delta$, the maximal inter-leaving time between two aggregates that contain data from flow 1. Following the FIFO delivery, if the flow 1 arrives before flow 2 ($\tau_1 < \tau_2$), then $\Delta'_1 = \Delta$. Otherwise, it means that we can have $\Delta \leq \tau_1$ and it is necessary to wait for the next aggregate (sent after τ_1). This new inter-leaving time Δ'_1 consists in two parts: the delay time τ_1 and the departure date of the first aggregate including at least a packet of the flow 1. This last part depends on the threshold S , on the maximum number of aggregates only based on the flow 2 $\lfloor \frac{\tau_1 - \tau_2}{S/\rho_2} \rfloor$, and on the quantity of data of the flow 2 continuously arriving $\rho_2(\tau_1 - \tau_2)$. It gives:

$$\delta'_1 = \tau_1 + \frac{S - \rho_2(\tau_1 - \tau_2) + \lfloor \frac{\tau_1 - \tau_2}{S/\rho_2} \rfloor S}{\rho_2 + \rho_1}$$

We have all the elements for a new proposition.

Proposition 4. *The aggregation system defined in the Proposition 2 offers to the flow $R_1(t)$ a minimal service curve:*

$$\beta'_1(t) = \rho_1(t - \Delta'_1)^+ \text{ with } \Delta'_1 = \max(\Delta, \delta'_1)$$

[Acti.28] compared, over a simple case study and according a trace mentioned in [CKT03], the proposals 3 and 4. It shows that for this scenario, the proposal 4 is the closest to the simulation. Residual service leads here to a modelling pessimism. System performance for an user-flow are better when other flows give traffic. The residual service only considers other flows as rivals. This leads to a pessimistic approximation of the service for one flow, which is why we propose an upgrade of the residual service that reduces the pessimism for such systems.

Delay and backlog bounds

Let us now compute backlog and delay bounds using Theorem 1. Figure 5.10 shows that backlog and delay bounds are respectively vertical and horizontal maximal distances between arrival and service curves.

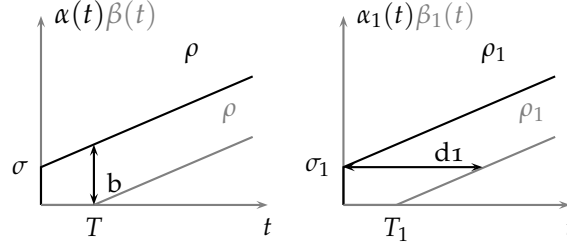


Figure 5.10: Backlog and delay bounds computation

The vertical distance is maximal at $t = T$ as shown in Figure 5.10. Hence $T = \Delta$, and the backlog bound is then,

$$b = \alpha(\Delta) - \beta(\Delta) = \sigma_1 + \sigma_2 + \Delta(\rho_1 + \rho_2) \quad (5.9)$$

We want to compute the delay bound crossing the aggregation system. It is computed for each sub-frame of the aggregate using the service curve dedicated to a flow. As shown in Figure 5.10, the delay bound is:

$$d_1(t) \leq \sup_{s \geq 0} \{ \inf \{ \tau \geq 0 \mid \forall t \geq 0, \beta_1(s + \tau) \geq \sigma_1 \} \} = \frac{\sigma_1}{\rho_1} + \Delta_1$$

[Acti.28] illustrate the bounds pessimism for the same kind of system as [GKo7]. It emphasised that applying directly residual service might lead to large pessimism depending on the tightness of the arrival model and the difficulty to recover the worst case scenario considered by the network calculus theory. The lower the gap between maximal and minimal arrival curves, the greater the precision of the delay bound. Refining the residual service property significantly reduces for such frame aggregation system the pessimism introduced when modelling it.

This type of system is particularly useful at the border between two networks having different capacities. The aggregation is realised in the gateways, such as in 802.11 access points. The performance gap between Ethernet and Wi-Fi makes the aggregation interesting for the bandwidth optimisation. Indeed, it enables a station to transmit more users' data when it gains the medium. So it is expected a better service for the concerned application. But what is the impact for the concurrent applications? Do all the applications benefit from this system when they are aggregated together? Do they compete for the available space in an aggregate? What about the stations that compete for the medium access with a station which aggregates? All these questions have also been addressed in D. BRECK PhD thesis, as will be presented in Section 5.2.1.

5.1.5 Minimum cycle time analysis of Ethernet-based real-time protocols [Acl.6]

As mentioned earlier, many Ethernet-based commercial solutions available on the market guarantee time performance. This means that user selection of one particular solution is a critical decision, but the choice often depends more on political strategies with an industrial device manufacturer than on the intrinsic performance of Ethernet-based interfaces. The objective of J. ROBERT PhD thesis was to provide a formal behavioural analysis of each Ethernet-based solution, in order to facilitate comparison.

With J. ROBERT, we improved and refined the analysis developed by [JSWo7, Pryo8] of the Ethernet-based solutions that incorporate new scheduling features in ASIC/FPGA: EtherCAT and Profinet IRT. We also extended to two other well-known industrial Ethernet products, namely to Modbus/TCP and Ethernet/IP solutions.

Minimum cycle time

The general objective of this study was to compare the time performance of the major industrial Ethernet products available on the market. We considered a communication scenario, based on one controller (for example, a PLC), interconnecting sensors, and actuators in an Ethernet network. The controller was treated as the communication master that initiated all dialogues with slave nodes (sensors and actuators). The controller is characterised by its controller cycle time period, which was divided into three steps as shown in Figure 5.11: - the sensor data refresh time, in the controller memory, - the processing time, and - the actuator update time.

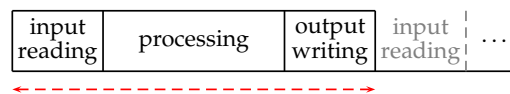


Figure 5.11: PLC cycle time

Steps (1) and (3) represent communication periods, which should be less than the difference between the controller cycle time period and the processing time period. Thus, the time performance of each Ethernet product was compared according to a constraint named *minimum cycle time*, which was defined as:

Definition 3 (Minimum cycle). *The minimum cycle time Γ was the communication time required by the controller to both collect and update the data memories of all sensors and actuators.*

In the following section, the analytic models of minimum cycle time are provided for the four protocols (details can be found in [Acl.6]). These models all used the following parameters: the transmission delay τ , the network device latency ℓ , the propagation delay δ , the link capacity C , the payload x (bytes), and the number of slaves n . It was assumed that there were no transmission errors and that the network was dedicated to the PLC application and was not shared with other applications.

EtherCAT

The EtherCAT network was developed by the Beckhoff company (type 12 in standard IEC 61158, [IECo6a, IECo6b]). A frame is sent by the master and slaves can read and write data *on the fly*. The duration of reading or writing operations corresponds only to the network device latency ℓ , which is independent of frame size and the same for all slaves.

Proposition 5 (EtherCAT). *The minimum cycle time is:*

$$\Gamma = (2n - 1) \ell + 2n\delta + \frac{8}{C} \left(40k + (k - 1) n_{max} (12 + x) \right) + \frac{8}{C} \max \left(44, (n - (k - 1) n_{max}) (12 + x) \right) \quad (5.10)$$

with $n = n_{max} = \lfloor \frac{1500 - EH}{12 + x} \rfloor$ and $k = \lceil \frac{n}{n_{max}} \rceil$.

Similar results are given in [JSW07] but, in contrast to this earlier work, expression (5.10):

- takes into account the *on the fly* minimum cycle time mechanism proposed by EtherCAT; the main advantage of this is that a device can begin frame forwarding before complete reception of a frame (in contrast to, e.g., store-and-forward mode), which significantly reduces the forwarding time,
- considers the use of padding, as defined by Ethernet,
- integrates the time required to forward the information sent from devices to the controller, and
- considers cases where the number of slaves and their payload requires the utilization of several frames.

The accuracy of the EtherCAT synchronization mechanism was reported in [CBS+10], which shows that this issue need not be considered because it was estimated as equal to a few nanoseconds.

Profinet IRT

The Profinet protocol was developed by the Siemens company (type 10 in standard IEC 61158, [IECo6a, IEC06b]). Profinet IRT is based on the time-slice mechanism, which specifies two modes, the asynchronous mode and the isochronous mode. Only the isochronous mode was analysed [JE04]. In this study, the Profinet IRT used the *slipstreaming effect*, where the controller began by sending frames to the most remote slave in the line topology, and then to the second remote slave and so on, until it reached the nearest slave. This mechanism enabled a reduction in the cycle time by minimising the transmission time. The *slipstreaming effect* was also applied to exchanges from slaves to the controller. The links were set up in full-duplex mode.

Only the positive characteristics of the *slipstream effect* were considered. This required that $\tau \geq \delta + \ell$, as noted by [JSW07].

Proposition 6 (Profinet IRT). *The minimum cycle time is:*

$$\Gamma = \delta + \ell + n \frac{8}{C} \left(38 + \max(46, 6 + x) \right)$$

Modbus/TCP

Modbus is a serial communication protocol developed by Modicon in 1979. Modbus/TCP is a variant of the Modbus protocol (type 15 in standard IEC 61158, [IECo6a, IEC06b]), which uses the Ethernet physical and link layers [MIo6]. Because EtherCat and Profinet IRT were

previously analysed using a master/slaves model, this model was also used for Modbus/TCP evaluation. In this study, we considered only write requests and because the byte count field was stored as a single byte, this indicates that the date field length was limited to $x \leq 255$ bytes.

Proposition 7 (Modbus/TCP). *The minimum cycle time is:*

$$\Gamma_{10h} = n \left(8 \frac{181 + x}{C} + 2(2\delta + \ell) \right). \quad (5.11)$$

EtherNet/IP

EtherNet/IP (IP, Industrial Protocol) is a network developed by Rockwell Automation in 2001 and supported by ODVA (Open DeviceNet Vendor Association) [Broo1, Scho6]. EtherNet/IP (type 2 in standard IEC 61158, [IECo6a, IECo6b]) uses the Common Industrial Protocol (CIP) for off-the-shelf Ethernet products and TCP-UDP/IP stack. Ethernet/IP is a connection-based network.

In this study, a linear switched topology was selected. It can be viewed as an extension of the experimental set-up considered in [ASV07], where the number of switches varied according to the number of ports per switch. In order to compare the other protocols with Ethernet/IP, a similar exchange scenario was proposed. The controller sent a frame to each slave device and each slave device produced data that were sent to the controller.

Proposition 8 (Ethernet/IP). *The minimum cycle time is:*

$$\Gamma = 2\delta + \ell + 8n \frac{84 + x}{C}. \quad (5.12)$$

Comparisons

Based on that proposals, we compared the performances of each protocols according to constants defined in [JSW07, Pry08] and for two bandwidths: 100 Mb/s and 1 Gb/s. Figure 5.12 shows the minimum cycle times (in ms), according to the number of slave devices with a payload equal to 100 bytes

The general conclusion was that all Ethernet protocols perform suitably with a bandwidth of 1 Gb/s for interconnected real-time systems. At 100 Mb/s, special attention is required by engineers in the selection of Ethernet-based protocols.

5.2 Modelling and assessment through extensive simulations

Previous section was dedicated to the proposal of deterministic properties. In my research work, I have also focused on simulations for two main reasons. The first reason lies in the shortcomings of the results obtained by computing upper-bounds for specific system as aggregator. The second reason is the study of networked systems with uncertainties, as explained in Section 5.2.2.

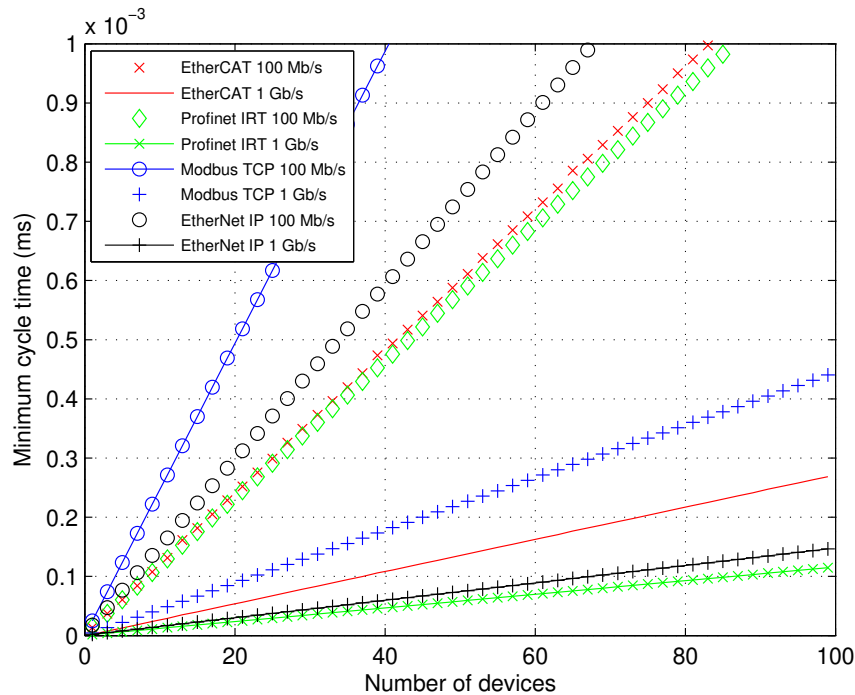


Figure 5.12: Minimum cycle time as a function of the number of devices with a constant payload of 100 bytes per device and two bit rates of 100 Mb/s and 1 Gb/s

5.2.1 Simulations through Riverbed Modeler and configuration of 802.11n aggregation system [Actn.8, Bre15]

In Section 5.1.4, we concluded on the limits over the modelling due to the gap between maximal and minimal arrival curves and the difficulty to consider other flows as rivals. To overcome that issue, D. BRECK, in a second part of his PhD thesis, have led to a large simulation campaign for different configurations of such systems and numerous traffic scenarios.

Most of the previous works used NS2 and Riverbed Modeler. Some authors also used self-made simulators, which is not interesting for us because we do not propose any modification of the standard. We used Riverbed Modeler and its generic models, especially because they were written for the verification of the 802.11n standard [SNC⁺08]. It natively implements the 802.11n aggregation mechanisms and it is a suitable tool to deeply study the influence of the aggregation parameters. In [Actn.8], we computed through an analytical model of the standard [IEE12] the sending time of an aggregate and identified the number of frames included in one AMSU. We have hence shown ([Actn.8]) that the Riverbed Modeler tool complies well with the specifications of the standard (at least on the case study under consideration), with an aggregation function that depends on the medium access policy.

Our objective was to evaluate the influence of the aggregation parameters on some QoS indicators. To achieve this goal, we firstly consider the system as a “black box” configured by an operator, receiving users’ flows. As depicted in Figure 5.13, the system is defined as the dynamic of a queue associated to a MAC service class. Entering this “black box”, the users’ flows are specified according to the size and the inter-arrival of the packets (constant or exponential distribution). Each flow will be alternately considered as the interesting one, and

the influence of different aggregation configurations will be evaluated on itself, but also on its competitors. This is the novelty of our research compared to the current state of the art.

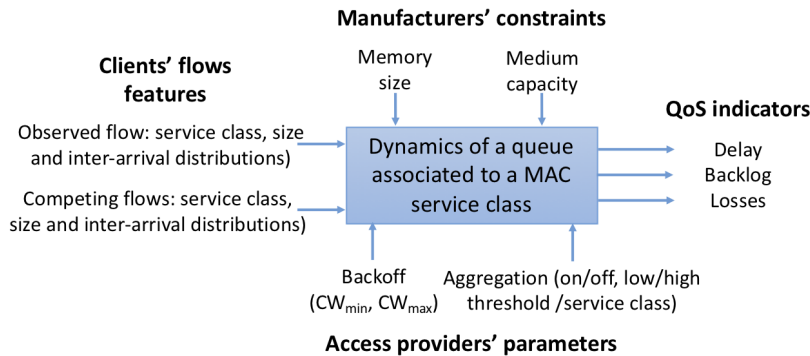


Figure 5.13: The aggregation system black box representation

Our study focused on constant periodic processes firstly, and then to processes following a Poisson distribution (exponential on the packets inter-arrival and the packets size). As a propagation model, we have chosen the default one (free space), which ensures no corrupted packets due to small distances (excepted those which are lost due to collisions). To take into account the burst issue previously identified, we have used a traffic profile that is based on bursts, while giving enough time to the system to proceed at least to a part of that burst. For instance, Figure 5.14 shows such a flow of 100 packets of 500 bytes emitted every 50 μs . This inter-arrival has been obtained by trial and errors in order to stress the system (just before having packets drops due to memory overflow).

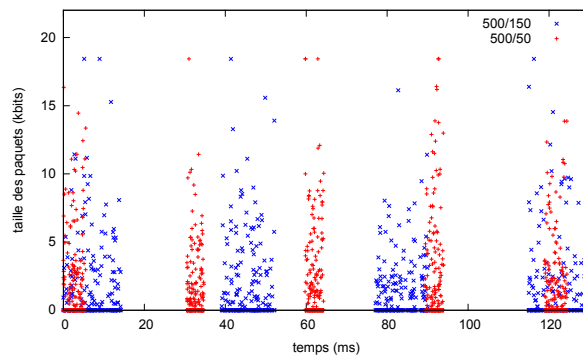


Figure 5.14: An example of a flow entering the MAC layer

Simulations focused on the delay between the arrival of a packet in the MAC layer and the departure of the aggregates which contains it and the backlog which will be compared with the memory size imposed by the device constructor. If it is greater than this size, packets will be dropped. In order to control the system, it is possible to aggregate or not a queue dedicated to a service class; to choose the aggregate size threshold (3 839 or 7 835 bytes).

Reflecting the numerous parameters offered by the MAC and physical layers, we have restricted this study by fixing some physical ones (frequency, bandwidth...), and some MAC others (AIFS, the bounds CW_{min} and CW_{max} between which the backoff is randomly drawn, or the TXOP duration) or the memory size. From these competition locations, we considered three simulation scenarios (Figure 5.15) for two aggregated flows in a same service class; in

two different service classes inside a same station and in two different service classes belonging to two different stations.

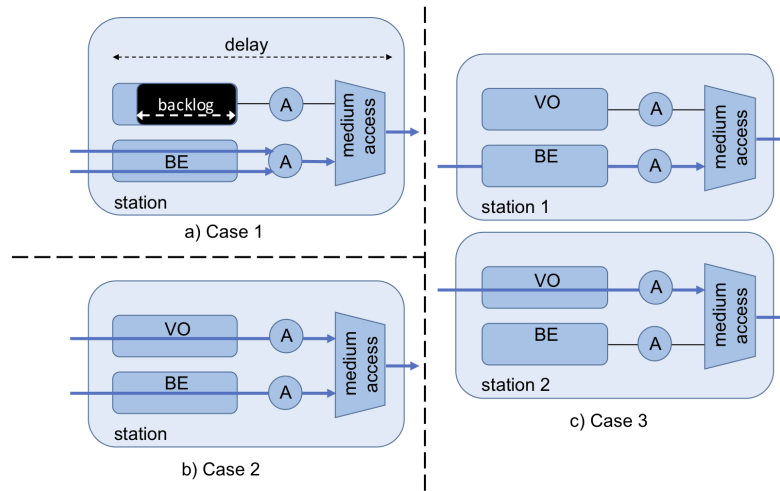


Figure 5.15: The 3 studied scenarios

After more than 15 000 simulations [Bre15, Chapter 3, pp. 55-121], we know that aggregation always improves the application bitrate for the aggregated flow. This enables to reduce the backlog, and thus the drop risk, thus reducing the delays. Nevertheless, the competitor flow is often penalised: if a low priority flow aggregates, the other flow has to wait for the whole aggregate to be transmitted, and its delay and backlog increases. On the other side, high priority flows are always aggregated at the expense of their competitors due to the long transmission time of the aggregates, which inevitably increases the waiting duration to try to gain the medium again and decreases the remaining backoff decrementing speed.

This reduction is added to the 802.11e mechanisms that already limited the medium access probabilities for the low priority classes. Some applications do not use the Classification of Service, which could lead to *Voice* packets to be proceeded as *Best Effort* packets. In this case, aggregating affects the performances of these critical applications.

Excepted for the two specific cases described above, aggregating improves the performances. If the high priority flow is aggregated, its competitor will also benefit because the medium will be free earlier. If the low priority flow is aggregated, it has the possibility to transmit a greater amount of data when it gains the medium. As a conclusion, we can claim that it is globally interesting to activate the aggregation on all queues. Indeed, the high priority flow processes its backlog more quickly, and that offers more space for the low priority flow. From all these observations, we proposed several configuration recommendations:

Claim 1. When a lower class flow reaches the famine, upper classes flows have to be aggregated in order to reduce the average delay and the maximum backlog.

Claim 2. If the delay and the backlog remain unsatisfactory, the considered flow has to be aggregated in order to reduce the average delay and the maximum backlog.

Claim 3. When the backlog of an upper class increases up to the memory limit, the aggregation has to be disabled on the lower classes flows in order to reduce the backlog and the average delay of the upper class flow.

Claim 4. For small size packets (less than 500 bytes), there is no need to modify the aggregate size threshold to reduce the maximum backlog and the delays.

Claim 5. For large size packets (1500 bytes and more), flows have to be aggregated at the maximum threshold in order to reduce the maximum backlog and the delays.

For the client, other clients are enemies, since they consume provider's resources and so may reduce the offered service. But numerous clients are absolutely necessary for the provider to make its infrastructure profitable. So, the provider has to find a balance for satisfying the greater number of clients. It can be found through a good configuration of the aggregation system which can significantly influence the performances offered to the clients, in particular with the classification of service. Indeed, clients are not equal: the more a client pays, the more the offered service is good. That limits the weight of the individuals or the small enterprises, in opposition to the service providers.

Based on the recommendations resulting from the simulations, we proposed Algorithm 1 enabling to choose dynamically who aggregates, and to set the aggregation parameters, from Quality of Service requirements given by both the client and the provider. Compared to [BRS11, SS10, SOSH12, DKB⁺10], our objective was to evaluate the performance of the aggregation system, without any modification and for a specific flow. The algorithm has been included in the HCF part of a new wireless station model into the Riverbed Modeler simulator. With Algorithm 1, each class adapts now its behaviour (aggregation or not, size threshold) each time it wins the medium, regarding the states of all the station classes (normal or alert) and taking into account the higher priority classes' states, just before the transmission.

Algorithm 1: The algorithm to configure the aggregation

Data: $ac \in 1, 2, 3, 4$: the class priority (1 the highest priority); \widetilde{b}_{ac} backlog requirement; b_{ac} backlog measurement; p an anticipatory factor; $alert[ac]$ class status

Result: decision $E_{agg}[ac]$ to not aggregate $noagg$, aggregate at the low threshold agg_{sb} or the high threshold agg_{sh}

ac got the medium access

```

foreach  $i \in [1, ac[$  do
    if  $b_i \geq p\widetilde{b}_i$  then  $alert[i] \leftarrow 1$  ;
    else if  $b_i < p\widetilde{b}_i$  then  $alert[i] \leftarrow 0$  ;
     $\Sigma_{alert} \leftarrow \Sigma_{alert} + alert[i]$ ;
if  $\Sigma_{alert} > 0$  then  $E_{agg}[ac] \leftarrow noagg$  ;
else if  $E_{agg}[ac] = noagg$  then  $E_{agg}[ac] \leftarrow agg_{sb}$  ;
else if  $E_{agg}[ac] = agg_{sb}$  et  $b_{ac} \geq \widetilde{b}_{ac}$  then  $E_{agg}[ac] \leftarrow agg_{sh}$  ;
    
```

Similar simulations have been launched [Bre15] in order to evaluate the performance of the proposal. When the competition between the classes is managed with a simple strict priority scheduling, the algorithm activates the aggregation at the high threshold, on all the classes. No modification of the aggregation for the low priority classes is then efficient: they cannot access the medium while high priority class queues are not empty. From the provider point of view, the best (minimising the backlog) is to keep this situation with all classes which aggregate independently of the clients' requirements (in case of shared memory). A possible enhancement is to find a compromise between both the clients and the provider requirements: since those of the clients are already taken into account, it is possible to add a condition to the algorithm in order to force the aggregation on all classes if the global backlog rises the limit. In case of dedicated classes' memories, it is possible to manage them differently: for example,

one may be saturated without having drops for another.

Our algorithm is particularly advantageous when requirements are strong on upper classes and weak on lower ones: for example, if delays and backlog are constrained for a *Voice* class when the *Best Effort* one accepts great delays and even drops.

Unlike other proposals available in the literature, our algorithm respects the 802.11n standard and only acts on the levers it offers: activation/deactivation of the aggregation, size threshold. The other novelty of this algorithm is also to make possible the deactivation of the aggregation regarding information coming from the competitors.

5.2.2 Practical use of Coloured Petri-Nets for the assessment of distributed automation architectures during pre-sales uncertain context [Acti.36, Acti.35]

In 2013, I was contacted by the Schneider Electric for a joint work about the performance assessment of Distributed Automation System (DAS) during pre-sales uncertain context. In that framework, I co-supervised with J.-F. PÉTIN (leader of the dependability and discrete-event systems research group in CRAN) the PhD thesis of M.A.A. NDIAYE.

The objective was the design and assessment of DAS architectures that are composed of several processing devices such as: Supervisory Control and Data Acquisition (SCADA), Programmable Logic Controllers (PLC) or I/O devices (actuators, sensors, transmitters) implementing all required functions for controlling and monitoring an industrial system. The problem is that during the pre-sale phase of an automation project, system integrator (SI) defines DAS proposals that fulfil specifications contained in customer's call for tender.

The main challenge encountered in the pre-sales context is related to the uncertainty modelling. This uncertainty covers several aspects of the timed behaviour of the DAS architecture [SVZ09, ZW89]:

- the features of the DAS architecture are not precisely known: the behaviour of the component and the use context of the control system can only be approximately estimated by the SI (for instance, the processing time of PLC depends on the execution of embedded software, which can only be approximated at this stage, through a uniform distribution for example);
- the events occurred on the DAS architecture (messages emitted by sensors and actuators, control actions sent by the human operators, ...) have to be considered as random events in order to model several operating modes; these random events are spatial (the DAS components exchanging information are not precisely known) and temporal (the occurrence time when a device initiate a communication is not known neither).

Consequently, the formalism to be used for performance assessment must enable the characterisation of timed behaviour, including random input parameters with probability laws distribution, some of them may be non-exponential (uniform distribution, Poisson, Weibull, ...). Furthermore, due to the complexity of industrial process, DAS architectures are structured into hierarchical levels and components providing same services can operate with slight behavioural differences when providing them. Those points lead to additional requirements for the formalism that has to support:

- a hierarchical representation of the ICS: high level model representing the ICS topologies, definition of generic models for all ICS components;

- the modularity, re-usability and parametrisation of the models.

Performance assessments of DAS architecture have been studied during these past years. Many methodologies have been developed through two main families: analytic evaluation and simulation. Analytic approaches (like network calculus, real time calculus, trajectory approach or (max+) algebra or the model-checking [CGJ⁺01, WVHFM06]) assume however deterministic knowledge of the traffic exchanges. Other approaches that rely on probabilistic models, such as Markov Chain theory [Jaco0], providing analytically an estimation of the response time if system models are homogeneous to a Markov or Semi-Markov processes (mainly while using only exponential distributions). This limitation, with regard to the probabilistic features of the DAS requirements, makes this method unsuited for this context. Simulation consists of an event-driven or real-time execution of the model. Modelling a DAS architecture basically relies on models from the Discrete Event System (DES) theory (timed automata, Petri Nets, DEVS, ...). In case of probabilistic model, several traces must be executed to compute statistical information about the performance. It is generally done using Monte-Carlo simulation using probabilistic state-based models. Among many methodologies that have been studied, Petri Nets have already proven their efficiencies on modelling and assessing DAS performance. In particular, Coloured Petri Nets (CPN) [JK09, Jen94] have proven their efficiencies of modelling and assessing performance of DAS. In [MDL07], the models focus on DAS control devices whereas network performances have been retrieved from experimental benchmark studies and in [BRA08], the modelling is extended to specific network devices (Ethernet switches). Main benefit of using CPN (instead of GSPN) in our case is that these distributions laws are not limited to exponential ones, the drawback is that, our models will be limited to the use Monte-Carlo simulation.

For all these reasons, CPN appears to be an efficient choice for the pre-sales software tool to be developed. The work was supported by CPN tool [JK09] (in collaboration with L. KRISTENSEN from the Bergen University College) for modelling, simulation and performance assessment. Thereby functions defined by , use the CPN tool formalism through the Standard ML programming language [MTHM97] (even if the CPN definition is independent of the concrete inscription language). The main result in [Acti.36, Acti.35] relies on the definition of a modelling framework that enable automatic generation of CPN models for performance assessment.

Proposal of a CPN holder, parametrisation, instantiation and automatic generation of the model

CPN manual modelling of DAS architecture is complex and time consuming due to the variety of network topologies and also to the number of connected components on a topology. However, despite network topologies variety and process type, DAS architectures involve the same families of components (SCADA, PLC, I/O devices, network, ...). Starting from this statement, a generic modelling approach has been proposed [Acti.36].

It is based on a generic hierarchical CPN model representing common topology structure of DAS architecture. It is able to represent any type of DAS topology. This hierarchical CPN model is the CPN model holder during the automatic model generation and will be called *CPN holder* (Figure 5.16).

The *CPN holder* model is based on defining generic links between several component families. A family gathers generic components involved in DAS architecture (SCADA or PLC

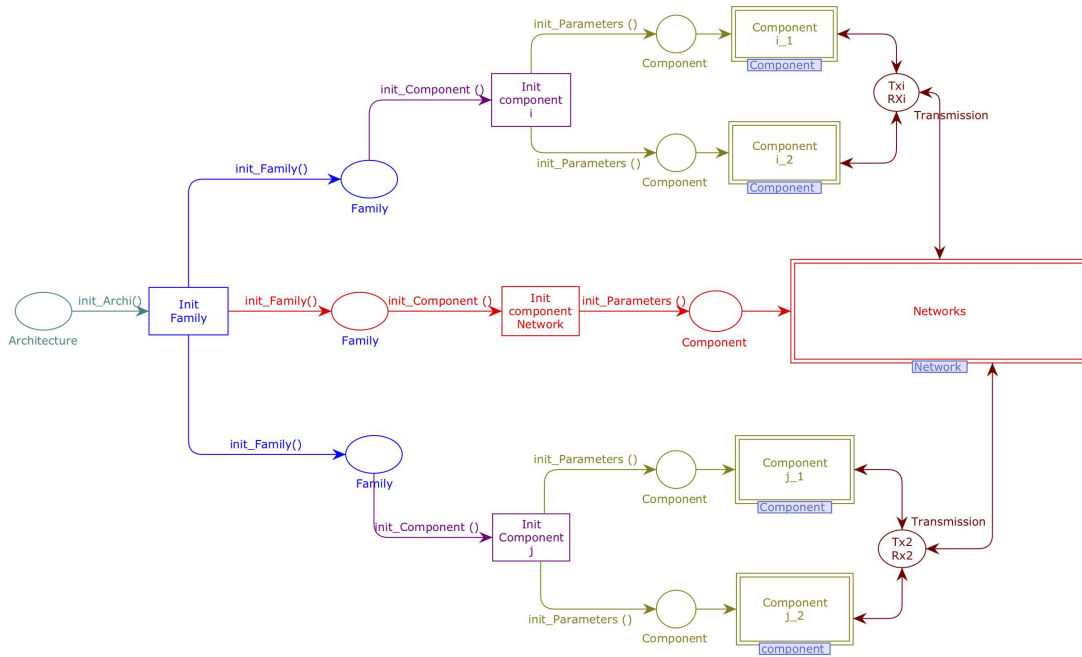


Figure 5.16: CPN holder

for example). A family may embed several different components through an instantiation process. At last, a family instantiates some generic CPN models of elementary components. Components having similar behaviour and operating mode are modelled using a unique CPN generic model. Those CPN models are customisable by using a set of parameters defining their specific features (for example, two PLC of the same family may be able to process different amounts of requests per scan). Each component is modelled with a generic interface (*Tx* places for outgoing messages from the components and *Rx* places for incoming messages) respectively connected to an output buffer and an input buffer.

[Acti.36] detailed the internal generic structure (with assessment transition for supporting performances monitor, the traffic generation and the substitution transition that explicits the “component behaviour”) and the sub transition called *Network*. We considered here only the modelling of Ethernet layers (used in Schneider Electric solutions) with a specific attention to the the forwarding plane.

Parametrisation of the model and instantiation of components used in the families, as well as families used in the DAS architecture, are done through the token and colour set declaration as detailed in [Acti.36]. The basic idea is to define a generic and hierarchic CPN structure using substitution transition, which is customisable for a given DAS thanks to the initial marking. The initial marking within the place *start* is automatically generated from a Standard Generalized Markup Language (SGML) [GR90] describing the DAS architecture.

Based on the rationales for modelling, instantiation and parametrisation presented above, Figure 5.17 provides an overview of the DAS model generation. It summarises and schedules the different tasks to perform the transformation of an informal description of DAS architecture into a CPN model as required for its performance assessment.

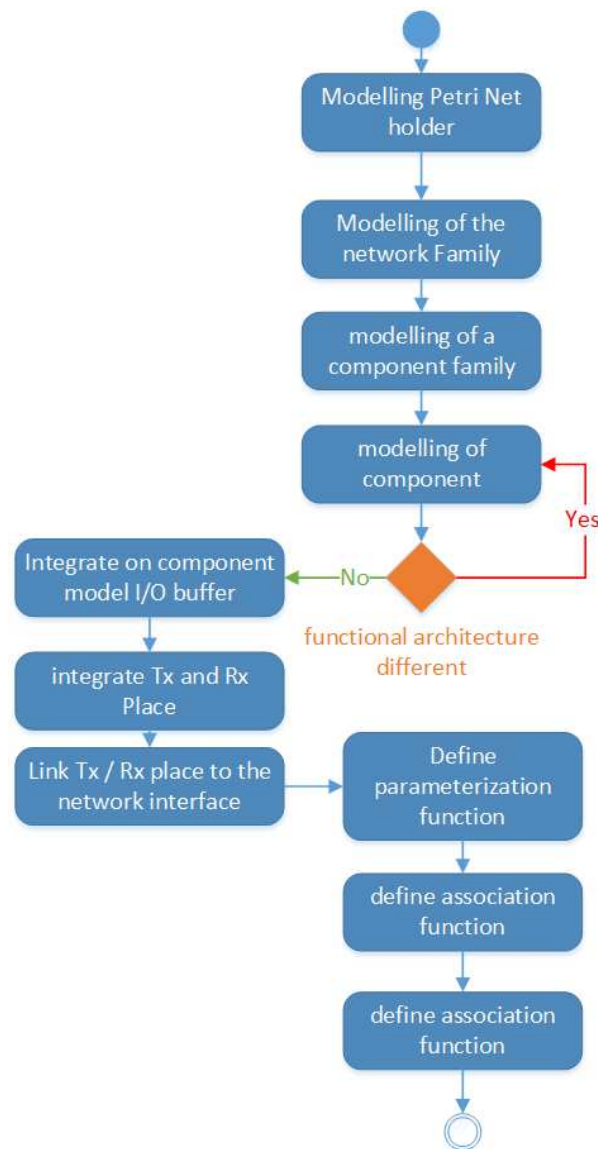


Figure 5.17: Overview of DAS CPN model generation

Performance assessment and development of a software tool

In the framework of M.A.A. NDIAYE, Schneider Electric has developed a software tool illustrated in Figure 5.18. The input of the tool is the description of the DAS architecture through domain specific language (DSL) [vDKVoo] that will be provided by the System Integrators. It contains the description of commercial components that are involved in DAS architecture, the material links between these components and the main information flows that are exchanged. This description also defines DAS performance that must be assessed according to the methodology (patent [Bre.1]) and the CPN model defined in our research work.

Two case studies (a small linear full-segmented architecture, using Schneider Electric component for water treatment in small size cities and a mid-size architecture for cement plant separated into three communication layer) have been selected to illustrate the generation of DAS models [Acti.36]. In order to evaluate its efficiency, an experimental reference has been

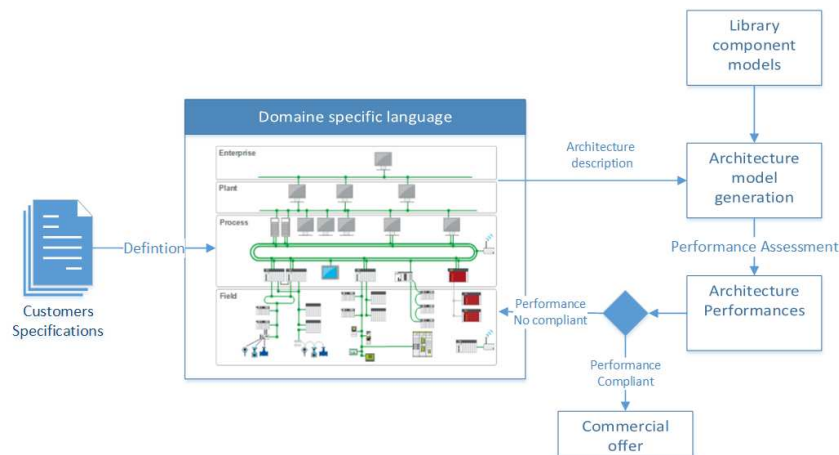


Figure 5.18: DAS performance assessment tool

deployed in laboratory in which performances have been measured. Experimentation focuses on the end-to-end delay, i.e. the time for the message to go from the client to a device through the PLC.

It shows how fast and easy is the generation of CPN model of any DAS architecture regardless its size, complexity or topology. The performances assessed by the simulation tool are close to the results retrieved from the laboratory. However, the maximum values are a little bit more important for the experimental run; it is mainly due to the firmware load on the PLC which is basically modelled as distribution law and to the limitation of our CPN model of the network.

To resume, our work is a relevant solution based on the automatic generation of a CPN model. This automatic generation has 3 main advantages: the CPN model holder and the library of CPN component models are done only once, a user without experience on CPN modelling can easily with parametrization generate CPN models through SGML description and finally, our approach allows testing a wide range of architectures without spending time on the modelling phase.

5.3 Retrieval of network observability/freshness from testbed

This section gathers the research works that I have led (also in the framework of J. ROBERT and D. PETIT PhD thesis) in collaboration with the French space agency CNES since 2007. It corresponds to Research & Technological activities for real-time, reconfigurable and embedded switched Ethernet networks in the next generation of space launchers (long-term objective for the future European unmanned launchers).

The objectives are the reduction of the total cost of the launch system by the use of a unique COTS technology (switched Ethernet), the avionics mass reduction by unifying the different embedded networks [MGS12] (Ariane 5 is based on a MIL-STD-1553B [Dep78] for exchanging control data and a dedicated/proprietary bus for telemetry data flow [Not14]) and avionics performance improvement (with at least the same reliability).

During this long collaboration and in a framework of a transfer of my theoretical researches over performance evaluation, I have worked on the worst-case analysis (a set of PBOO/PMOO network calculus results applied for bounding ETE delays [Rap.9, Rap.10, Rap.11, Rap.14] for

different switched architectures. Those studies focused also on the ability of the network to be robust and to reconfigure itself in real-time when a failure occurs or in launcher specific case of stage separation [Rap.15, Rap.16] and the network capacity in order to retrieve the acceptable level of additional background traffic.

However I will focus in the following of two original concept we introduced: the network observability and the freshness analysis. To increase the readiness level of Ethernet as the network to be embedded in launchers, we have developed a demonstrator Reda6 in CRAN. The objective is to reach TRL_{3/4} (ISO/DIS 16290 [ISO13, Man95] Technology Readiness Levels 3/4: technology development and demonstration), i.e. to constitute a “proof of concept” in a laboratory environment (component and/or breadboard validation in laboratory environment).

5.3.1 Proof of concept of switched Ethernet as embedded network for next generation launchers – Demonstration platform Reda6

Theoretical studies were leaded, and it was expected by the CNES to validate the academic results through real experiments, based on which the results should be confirmed. A demonstrator [Acti.39] has been designed at the CRAN facilities as mentioned in Section 2.3.4. The main issue here is that the demonstrator might be used to validate architectures of either future launchers for which the control law is not already defined or of past launchers without knowledge of the control law.

Figure 5.19 describes the topology itself. There are two switches per stage and per booster, each one linked both to its “redundant” and to another stage/booster. Consequently, the dual chain topology has been given up but the network remains at least 1 fault-tolerant. In order to improve the reliability, the on-board computers (OBC) which are the only end-systems to send commands are connected to two switches. The platform supports application (payload) traffic: class control and class telemetry (periodic, event-triggered); background traffic (video, etc.); mirroring traffic (“hyper” observability); synchronisation traffic (PTP, NTP); layer-2 topology routing/control traffic (STP, RSTP) or management traffic (SNMP, etc.).

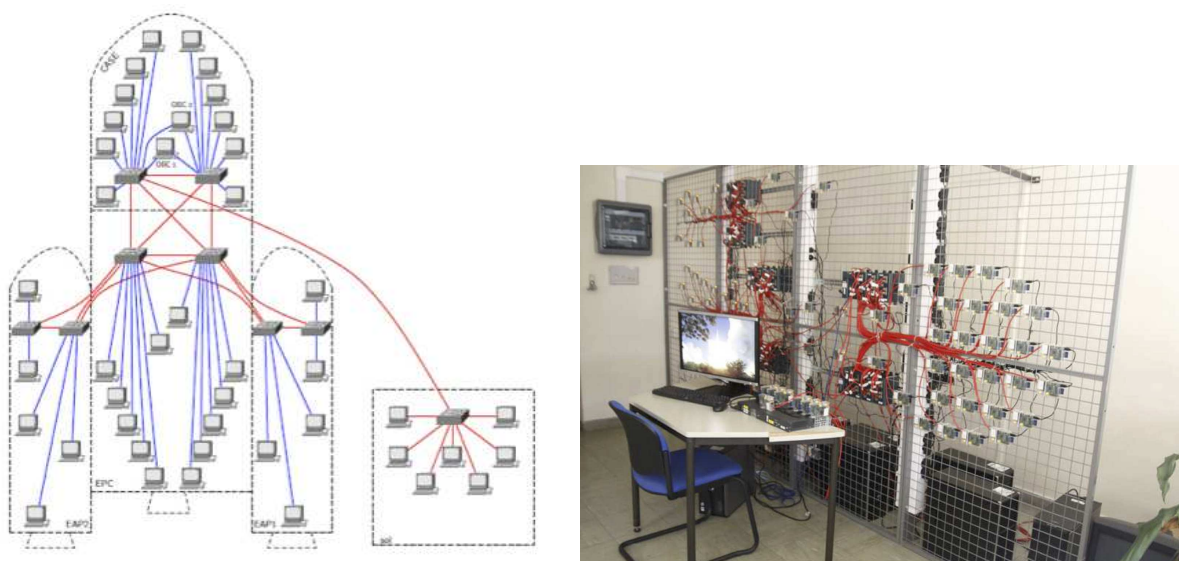


Figure 5.19: Topology of the network

This configuration is very challenging in as much as the number of end-systems and switches is much bigger than the strict need but it allowed us to test more easily the limit of the system on that “sizing” configuration. For the definition of the traffic, the software (the control law) of the avionics is not available at this step. Consequently, a specific one has been then developed (in C programming language) to retrieve a similar behaviour by retro engineering of previous traces (analysis of the messages exchanged on the current MIL-STD-1553B during a recent flight) and/or defined by experts. The details of the architecture are provided in [Acti.39].

Finally, in the spatial domain where the system is lost after its mission, it is mandatory to observe all the traffic in order to replay (reproduce from original data of a flight), to test and to analyse on ground the exchanges. Collecting traces are important in launchers since they are the single source available to deduce, after the flight, if the expected behaviour the system control has been followed. Metrology is also important for the qualification of systems [Acti.24, KZST11] (non availability time, packet loss ratio, non observed frames ratio).

5.3.2 On the network observability [Acti.31]

Besides conventional network management systems (which focus only on network states), I focused on the observability issue defined as the ability to monitor the satisfaction of the application quality of performance (especially in terms of time constraints and frames sequence). It consists to obtain a real picture of the communications (without additional supervision traffic) at any given time and location in order to get a network monitoring that acts as an observer of the control state. In [Acti.31], we defined the observability as the ability to determine dynamically how the sequence (set of control/measure messages) requirements are satisfied (including the ordering of events). A question might be *is the word w_j successfully forwarded by the network at the time $t_j \pm \delta_j$* .

In a conventional communication technology (i.e. specific buses), it is easy to collect all exchanges on the physical wire with a dedicated device. But, it is not possible anymore on a switched network (the traffic is confined to different segments whereas several frames may be simultaneously forwarded around the network). The port mirroring technique and many monitors (using the tcpdump¹³) are therefore implemented. Even if multiple (network) observers are used, a centralised overview of the current frames exchanged by the network has to be determined (this centralised overview is important for launchers where the control state information have to be transmitted to the ground via the telemetry channel). To merge all the local traces, it needs a global reference time with synchronisation offsets have to be as small as possible. We have shown that the maximum offset between two monitors can be expressed as $off_{max} < \tau + \delta$ with the propagation delay δ (which can be negligible on the short Ethernet links) and the transmission time $\tau = \min(L_{frame}) / C$ where C corresponds to the link capacity and L_{frame} the length of the Ethernet frames. The underlying question is therefore the time synchronisation method [Lam78].

In switched Ethernet network, the clock drift can be limited by using a synchronisation protocol as IEEE1588 - Precision Time Protocol (PTP) [IEE08a]. However, the timestamping uses the date of the kernel clock and not the one of the PTP card (cf. tcpdump operation) as shown in Figure 5.20. To do that, we proposed to use Network Time Protocol (NTP) [Mil91] at stratum 0 to synchronize the kernel clock with the PTP card (to our knowledge, PTP cannot be implemented locally yet). The performances (variation of the offset) of the two control loops

¹³<http://www.tcpdump.org>

(as shown in Figure 5.20) have been measured on each monitor.

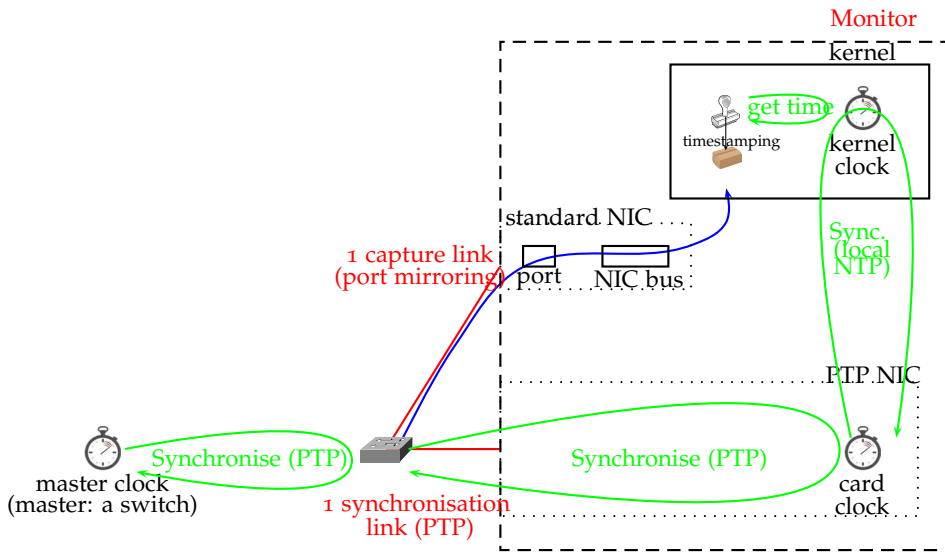


Figure 5.20: Experimental time-stamping mechanism

J. ROBERT showed that if such an architecture enables to verify the temporal respect of the events sequence (to a single destination and crossing a unique switch), it is clear that this is not possible to detect the ordering of events in a consistent manner (too large offsets). To overcome this issue (clock synchronisation and multiple observability points), we proposed in [Acti.37] to rely on the multicast functionality. We will assume that each message is sent over the network in multicast. The destination address corresponds to a group that gathers the original destination and the address of a PC that will be called the observer o (in charge to forward the underlying trace to the ground via the telemetry channel).

5.3.3 Freshness analysis based on traces [Acti.37]

Avionics requires to verify different properties that encompass not a single (like in network calculus, trajectory approach [BSF10], real-time calculus), but a sequence of frames mapping a functional command. With D. PETIT, we then have proposed a method to validate end-to-end freshness inside a network as part of an observability analysis. The main novelty consists in achieving such validation for launchers just based on a single frame capture file that will be monitored through a ground-board communication.

An important property is to test if the end-to-end freshness is satisfied as defined in [LEBP11] (processing time of each task will not be taken into account in this study). A δ -freshness requirement may be defined such that a data d_n is "globally" produced from data d_i themselves produced not earlier than δ time units before. From a traffic capture point of view, a functional sequence would be observed according to the frames $F_1 \dots F_n$ (that respectively corresponds to the transportation of data $d_1 \dots d_n$). A functional sequence is defined as a set of frames $F_1 \dots F_n$ sent by m devices ($m \leq n$). In launchers, three kind of devices can be distinguished: the sensors, the actuators and the controller. To simplify, the functional sequence $s \xrightarrow{X} c \xrightarrow{Y} a$ is now considered. It corresponds to the periodic transportation of a measure X produced by a sensor s and of an action Y computed by the (on-board) controller c for an actuator a . Figure 5.21 details the exchanges, with the copy to the observer o .

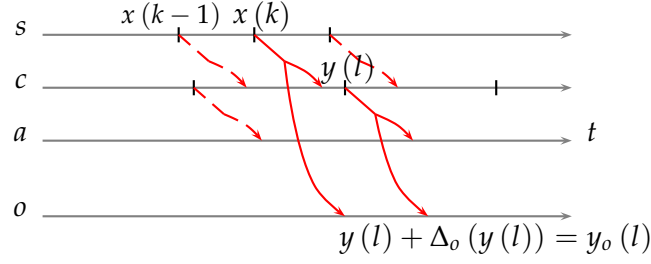


Figure 5.21: Functional sequence and freshness

We note $x(k)$ the date at which the sensor is sending the k -value of the measure and $y(l)$ the date at which the controller is sending the l -value of the command. An end-to-end freshness requirement means here that the value X , that has served to compute the value Y sent at $y(l)$, has to be received before but not δ time units before ($x(k) \geq y(l) - \delta$). Assume now that the delay of the frame sent at $x(k)$ is noted $\Delta(x(k))$. End-to-end freshness for a command $Y(l)$ will be satisfied if it can be found a measure $X(k)$ such that:

$$\forall l \in \mathbb{N}, \quad \exists k \in \mathbb{N} \mid y(l) - \delta \leq x(k) + \Delta(x(k)) \leq y(l) \quad (5.13)$$

The existence enables also to take into account potential frames losses and oversampling. The problem is that both $x(k)$ and $y(l)$ are local values, based on different clocks. From the point of view of the observer (that will receive each frame), available timestamps are slightly different. Dates are modified according the Quality of Service offered by the network, such that timestamps available are $x_o(k) = x(k) + \Delta_o(x(k))$ and $y_o(l) = y(l) + \Delta_o(y(l))$ where $\Delta_o(z)$ corresponds to the delay to send frame z to the observer. $y_o(l)$ represents the date at which the command $Y(l)$ has been captured by the observer (the timestamp in the trace). And since the path between the sensor and the controller is not the same as between the sensor and the observer, delays may be different ($\Delta(x(k)) \neq \Delta_o(x(k))$).

Since only the dates in the capture file are known, we introduced a new proposal (the proof is given in [Acti.37]).

Proposition 9. *The end-to-end freshness for a command $Y(l)$ ($l \in \mathbb{N}$) will be satisfied if it can be found a measure $X(k)$ such that:*

$$\exists k \in \mathbb{N} \mid y_o(l) - \delta + \Delta_{max} \leq x_o(k) \leq y_o(l) - 2\Delta_{max} \quad (5.14)$$

where Δ_{max} corresponds to the maximum delay of any frame in the network. The proposition is valid for $\delta \geq 3\Delta_{max}$.

Figure 5.22 shows that it may contain measures not relevant for a given command $Y(l)$.

Figure 5.22a highlights a situation in which a frame $X(k)$ is captured before a frame $Y(l)$ whereas this command was not computed from this measure since it has been received after on the controller. In Figure 5.22b, a frame $X(k)$ seems to be not earlier than δ time units before the frame $Y(k)$ but it was received before on the controller such that it was not considered to produce the command. Figure 5.23 summarizes the validity domains of the measures that will refresh the command.

Hatched areas in Figure 5.23 correspond to measures out of the scope of a command $Y(l)$, while the white area contains valid (useful) measures. Gray areas correspond to domains that need to be excluded too since they are ambiguous (might contain both valid and not valid

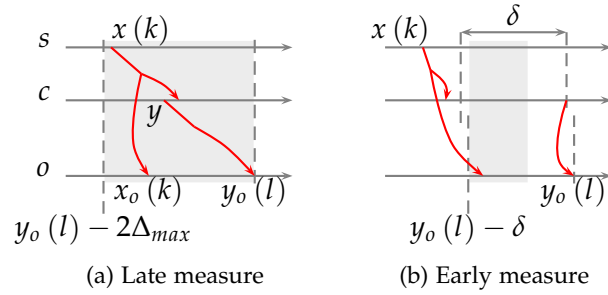


Figure 5.22: Ambiguous situations ($Y(l) \neq f(X(k))$)

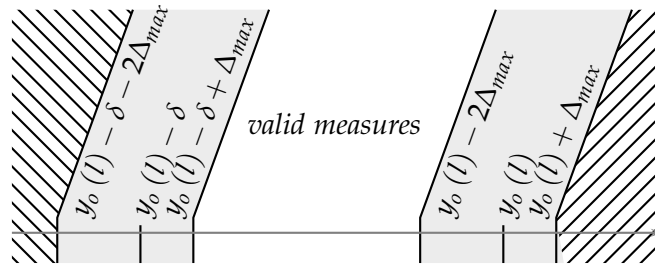


Figure 5.23: Excluded time windows

measures). Considering periodic measurements and commands, it means from there that measurement period has to be less than $\delta - 3\Delta_{max}$ (regardless clocks synchronisation). It is important to note here that the width of the ambiguous domains is related to the maximum delay Δ_{max} . Figure 5.23 is important for avionics since it provides a way for engineers to be sure at the earlier step of the control design that the control observability will be possible after a flight. We have shown furthermore that if someone wants to check the frame arrival order between two measures or commands, it is necessary as shown, in Figure 5.22a, that the second value is received at the observer at least after $2\Delta_{max}$ time units (if the sending inter-arrival time is larger than Δ_{max}). The maximum delay is proposed to be computed through the network calculus theory as defined in the beginning of this chapter. It is also important to note that our analysis is not limited to switched networks with additional features (like in AFDX [BJRSF14]) or knowledge of the traffic.

We provided in [Acti.37] algorithms to process a given trace file and determine if the sequence freshness requirements has been satisfied. It may be noticed that a similar algorithm might be defined to check the ordering property of the frames of a given type. Such algorithm will check that the sequence number is increasing all along the trace and that the time difference between two consecutive numbers is at least $2\Delta_{max}$ (to avoid ambiguous situations).

Figure 5.24 shows that we were able to verify the satisfaction of the freshness requirement, both in a nominal case and under a link failure case, on a real benchmark detailed in [Acti.31, Figure 5].

Figure 5.24a shows that at least one fresh measure is available to compute a command in the framework of (5.14). The variation of the freshness is due to the non synchronisation of the two flows and to the jitters. Regarding the freshness analysis (see Figure 5.24b), no measure $X(k)$ is received and hence enables to satisfy the freshness requirement during the link failure (for $l \in [30, 123]$). However a second sensor and a second network (the dashed

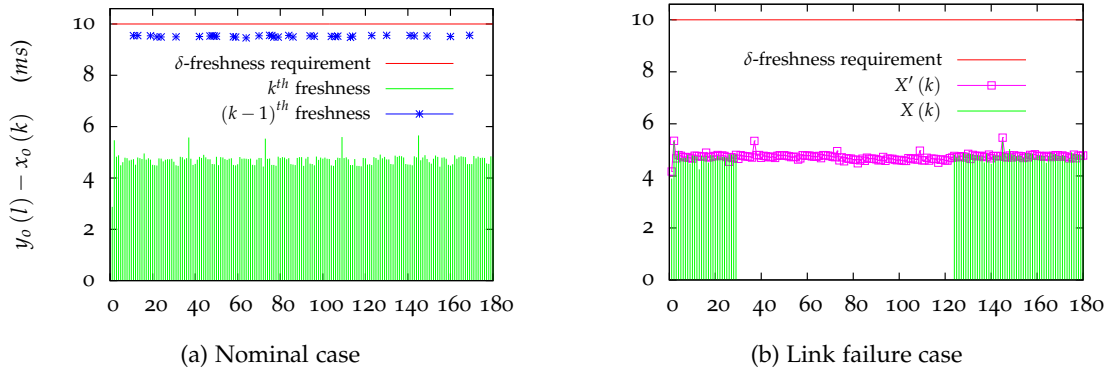


Figure 5.24: Freshness of each measure valid for a command. Abscissa gives the sequence number l of the command

lines) will sent the same type of data, such that the controller might use it to compute a new command. The proposed algorithms enable to verify that this redundancy will also be able to satisfy freshness requirements.

Chapter 6

Networked control systems, a first step to network automation (A2 – QoC)

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After my PhD thesis and after having analysed the QoS offered by different networked systems, I have focused my research to explicit how QoS impacts on QoE in distributed application settings. As member of a research centre for automatic control, I have been interested in a specific QoE: the Quality of Control (QoC) (also called Quality of Performance). It mainly corresponds to effect of the QoS to the stability of the control and to the research field of networked control systems. Hence, I have worked with specialists of control engineering on the co-design of control over network, and also the diagnosis over network. I applied here the results obtained by the network calculus theory and simulation of wireless network. When the QoS offered by the network, a possibility relies on the control of network as introduced by the IFAC TC 1.5. Here, I proposed specific algorithms to control the scheduling on networked devices and strategies to increase the availability, especially in case of failures. Finally, this last point led me (especially in the framework of my collaboration with the CNES) to propose centralised algorithms to control the network, strategies that are today known as software-defined networking.

The chapter addresses hence new research questions:

- how the QoS offered by the network impacts the QoC?
- how to design a control of a given system in taking into account the QoS?
- how to dynamically adapt/improve the QoS in regards to the control requirements?
- how to reconfigure a network in case of failures and how to anticipate failures?
- how to maintain a connection when the physical connectivity is broken?
- what could be the benefits of a centralised control of the network?

6.1 Introduction to networked control systems

6.1.1 A problem at the crossroads of several communities

Bringing together QoC and QoS is a problem that founded at the beginning of the 1980s. In France, it was initiated by few precursors at the origin of the "local industrial networks" community (G. JUANOLE, F. LEPAGE, J.-P. THOMESSE and extended then by institutional working groups gathering different communities (time delay systems, real-time systems, networked systems): from the former AFCET (*systèmes de communication industrielle*) group in 1996 to the current group ARC (*Automatique et Réseaux de Communication*) of the GDR MACS (that gathers among others researchers from CRAN, CRISTAL, GIPSA-lab, LAAS, LS2N)¹⁴. In fact, their study requires, on the one hand, to have a deep knowledge in automatic control, computer science and communication networks, and on the other hand to capture the interplay between these disciplines. In 2005, I attended at the IFAC World Congress in Praha to the kickoff of the IFAC TC 1.5 Networked Systems. It confirms the duality *control of the network* and *control over network* explained below. It led also to several research projects like the European project FP6 STREP NeCST and to the French project ANR Safe NECS and SECTAF for which I participated as research scientist.

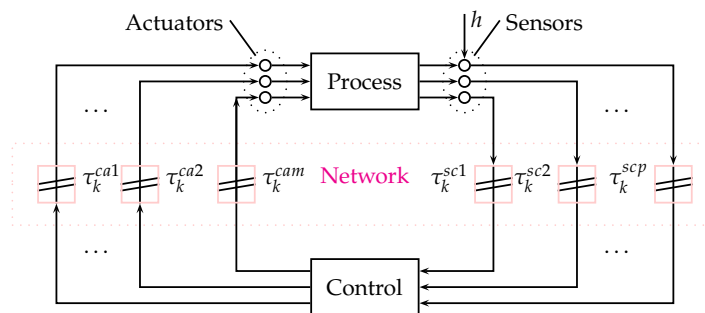


Figure 6.1: MIMO distributed control over a network [Nil98]

Networked Controlled systems (NCSs) are composed of actuators, sensors and controllers distributed over the network. A NCS is a control system in which the regulation loops are closed by the communication network [ZBP01, Rico3, HFM04, LWS02, TCo3, Yano6, Zamo8]. However, it is necessary to ensure the stability of the process control, taking into account the performances of the network [BLP03]. The main problem of the NCSs is the network induced delays shown in Figure 6.1. These delays can degrade the performances of the systems; they

¹⁴It corresponds also to the groups involved in the two book I have contributed for [Osc.2, Osc.1].

can even lead to an unstable behaviour, especially for hard time-constrained processes. Thus, it is necessary to take into account these delays in the design of the control law [CHL⁺03, LMT01].

Activities in the area of NCS can be categorised into two major fields: control of networks and control over networks as shown in Figure 6.2. Control of networks [Masoo, Wito5, JMo6, WYBo2, NTo4] is mainly concerned on providing a certain level of performance to a data flow, while achieving efficient and fair utilisation of network resources. In the area of control of networks major problems of interest are call admission, scheduling, routing, flow control, power control, and various other resource allocation problems. The objective is to provide quality of service (QoS), while achieving efficient and fair utilisation of network resources. Control over networks deals with the design of control strategies which are adapted to the effect of unreliable communication links through which the control data are exchanged (like the typical example of remote operation Figure 6.2b). Here the network is considered as a "black box".

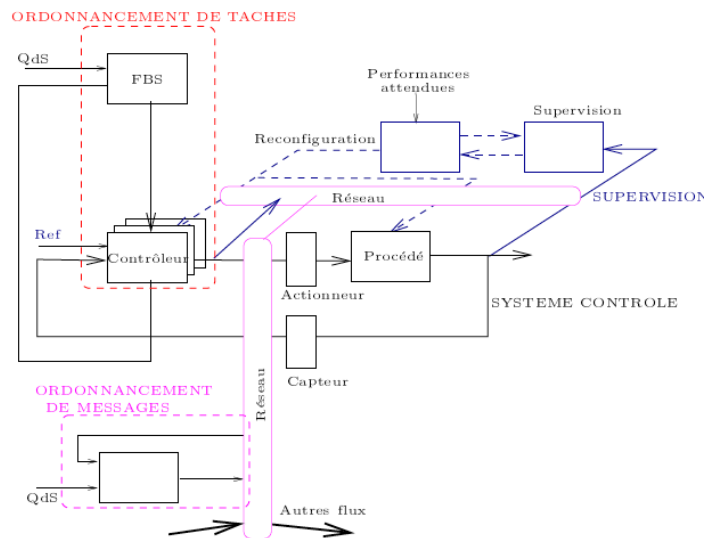
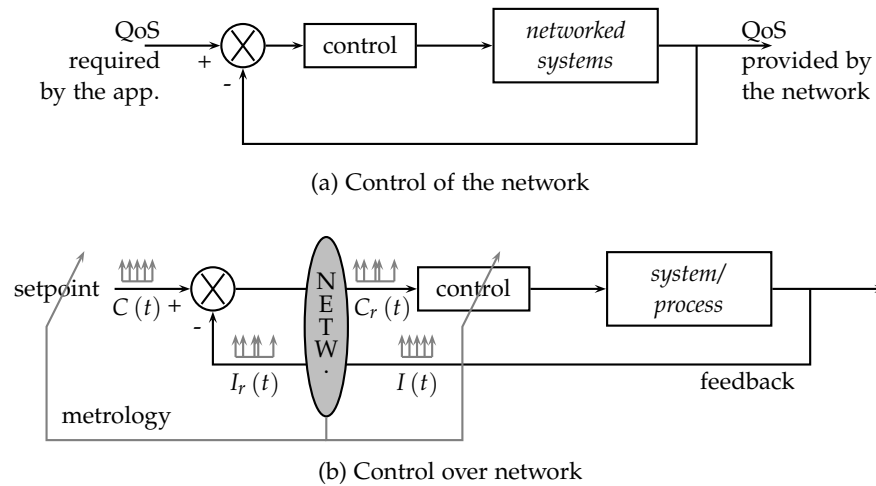


Figure 6.2: Activities in the area of NCS [RD07]

The foundation of my research relied in that field on the observation that if observers have been defined for time delays systems, they are based on delays claimed known (or sometimes constant or following an arbitrary law). The issue is that they do not provide the delay analysis or do not consider the network engineering point of view, especially in the case where the network behaviour is difficult to analyse and to predict. Hence, I have applied here the results of my activities about performance evaluation. One important characteristic is that I have considered shared networks (when the control shares the network with non real-time applications) that did not offer intrinsic QoS guarantees. This is typically the case in the next section that deals once again with the non determinism of Ethernet.

6.1.2 The problem illustrated: the control of a quad-rotor over Ethernet [Acti.21]

To illustrate the impact of delays in NCS, I am introducing here the results of a joint work I realised with researchers of the GIPSA-lab (S. GENTIL, S. LESECQ) in the double framework of the project ANR Safe NECS and the PhD Thesis of I. DIOURI [Acti.21].

We worked together on the co-design of an UAV (Unmanned Aerial Vehicle), namely a 4-rotor helicopter (Figure 6.3) using Matlab/Simulink simulations as benchmark. The control law of this system is non linear and its observer uses data provided by an Inertial Measurement Unit [TGT⁺07].

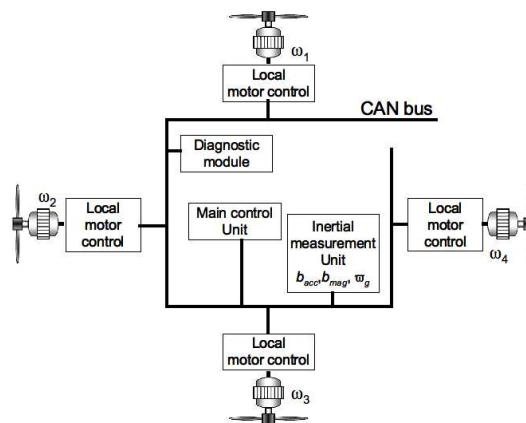
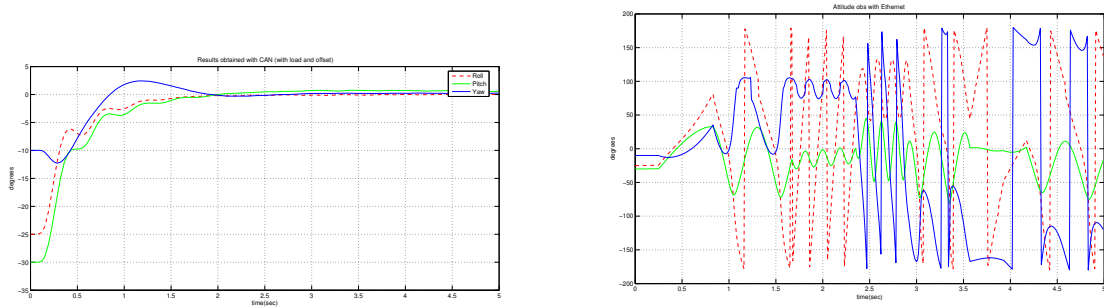


Figure 6.3: Quadrotor architecture with the embedded network [BLGT07]

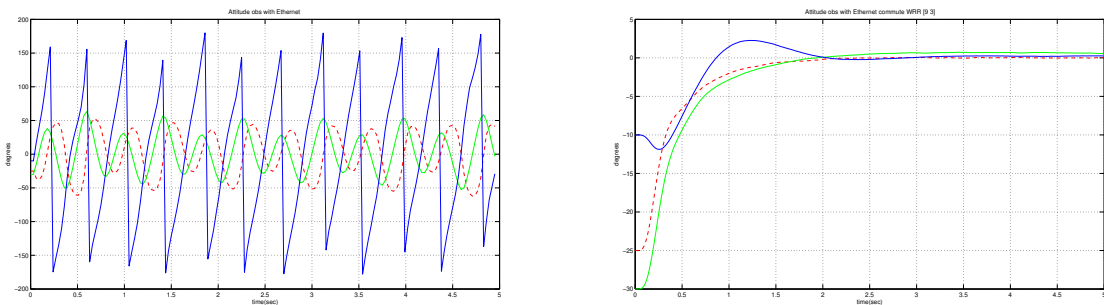
We compared the impact of a shared/switched Ethernet network to the traditional embedded CAN network through simulation based on the TrueTime library [AHC07]. If shared Ethernet was able to offer enough QoS without background traffic, it fails to support an additional video application Figure 6.4b whereas the CAN network, even with a capacity 10 times less, is able to maintain the system stable (even if the QoE of the video is poor) Figure 6.4a. Switched Ethernet improves the delays, but not still enough as shown in Figure 6.4c.

To increase the QoS offered by the switched Ethernet network, we applied the CoS mechanism and the WRR scheduler introduced in Section 5.1.3. As explained in [Acti.21], we updated the TrueTime kernel in order to allow the simulation of the WRR over switched Ethernet networks (that was not supported at that time). Based on our previous studies [Acti.17], we fixed the weights for the control and the video traffic such that upper-bounded end-to-end delays satisfy the control requirements. Figure 6.4d shows that we were hence able to retrieve the same profile as for CAN from the control point of view while maximising the bandwidth



(a) CAN 1 Mb/s with load, non synchronised exchange

(b) Shared Ethernet 10 Mb/s, with load



(c) Switched Ethernet 10 Mb/s, with load

(d) WRR CoS Switched Ethernet 10 Mb/s, non synchronised load

Figure 6.4: Influence of the network on the system output

offered to the communications non involved in the control (the QoE of the video was here acceptable).

6.2 Control over network

6.2.1 Co-design of networked control with delay measurement and estimation [Acl.3]

During my post-doctorate, I started a joint work with the Aalto University (Laboratory of Process Control and Automation) and especially N. VATANSKI and S.-L. JÄMSÄ-JOUNELA on networked control with delay measurement and estimation. It is important to note already that this collaboration leads today to new perspectives that will be presented in my future projects.

Two delay compensation methods were studied, adaptive Smith predictor approach and robust control approach, in the framework of NCS while considering the protocol specifications. The Smith predictor based approach is proposed for the control over a network when accurate delay measurements are accessible and the robust control based approach is proposed when only the estimate of the upper bound end to end delays are available.

Adaptive Smith predictor based on delay measurement

The coupling between QoS parameters and the controller design was performed on the basis of the delay measurements and the adaptive Smith Predictor based approach. The delay measurement was obtained via a synchronisation step of all the computers' clocks by using the IEEE 1588 standard described in the previous chapter. The originality of the proposed approach is related to the accuracy of this estimate, especially compared to RTT measurements. In fact, this accuracy is emphasised in the context of switched topology. The clock synchronisation facilitated the delay measurement and allowed the delay variations to be dynamically obtained with respect to the intrinsic properties and activities of the network. This information was utilised by the Smith Predictor based controller.

Consider a SISO, open loop, stable linear process. The adaptive Smith predictor configuration scheme that integrates the measurement information is shown in Figure 6.5.

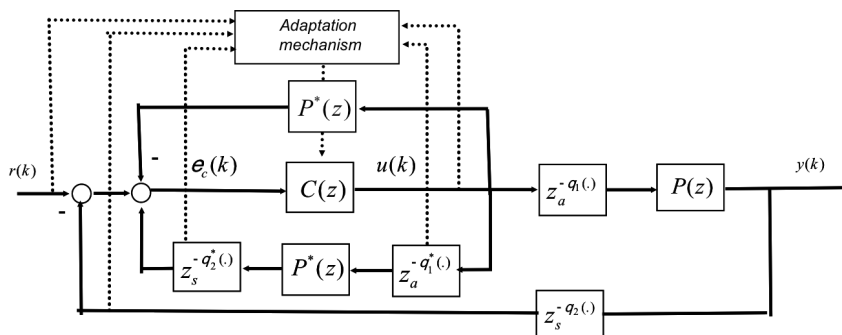


Figure 6.5: An adaptive Smith predictor for compensation of the sensor path network induced delay

The minor compensation loop, consisting of a sensor path delay measurement $z_s^{-\theta_2^*(\cdot)}$, a plant model $P^*(z)$ and an actuator path delay measurement $z_a^{-\theta_1^*(\cdot)}$, is introduced around the nominal controller $C(z)$. In [Acl.3] we have shown that in the general NCS case, the commutativity assumption (regarding $z_a^{-\theta_1^*(\cdot)}$ and $z_s^{-\theta_2^*(\cdot)}$) for the linear system and a time variant delay does not hold. Only the sensor path delays can be eliminated [BSP01]. Even though the elimination of the actuator delay is not possible, this effect can also be reduced by an adaptive mechanism, for example by gain scheduling as the "Adaptation mechanism" block in the scheme in Figure 6.5. The main drawback of the Smith predictor scheme is that the technique was originally developed as a method to handle open loop stable systems with fixed time delays. The performance is often sensitive to model mismatch, either in the delay or in the rational plant part. In the face of small delay measurement errors, the Smith predictor may perform poorly because the error between the real value is amplified by the high controller gain. In order to ensure the robust stability and performance of the system, the adaptation will be achieved by changing the nominal controller parameters according to the changes in the delay value error. We introduced hence a limiting criterion from [MZ89] that gives the necessary and sufficient conditions for systems for controller gain, including the Smith predictor, to remain robustly stable in the presence of a small mismatch in delay.

The effectiveness of the proposed control over a network configuration using the measured network delay has been illustrated through an example via MATLAB simulations, and also on the experimental platform developed for behavioural analysis of the NCS. In order to cope with real time requirements, the sampled versions of the process model and the controller

were directly programmed using C- language and, to further reduce the calculation period, real time programming was necessary and performed through the RealTime Application Interface (RTAI) ¹⁵. The platform consisted of a switched Ethernet/IP/UDP network with a PTP daemon is implemented on each computer to ensure online the synchronisation.

We concluded, both from simulations and experiments, that the performance of the system was improved significantly and that the control becomes less sensitive to the delay effect produced by the network. However under delay measurement error conditions, only the adaptation procedure was able to regain some of the performance, although the adaptation strategy at some point also becomes inadequate. It shows that the performance of the closed loop system is closely related to the quality of the measurement of the delay used in the time delay compensation design. Therefore, when an (accurate) measurement of the induced network delay is not available, control design should be based more on techniques such as network modeling for evaluating its performance. In [Acti.16], we had completed the design of a Smith predictor controller by integrating upper-bounded delays computed through the network calculus theory. It enabled to conclude that upper bound delay estimate is an important measure of networked control system that can also be used design and synthesis of the control system.

Robust control for delay tolerance based on upper-bounded delays

The information about the bounded delay obtained with network calculus according to the methodology for 802.1D switched Ethernet networks I have detailed in Section 5.1.2. It was used to obtain a control law that satisfies the design specifications, and to maintain the system performance even in situations during which the delay equals the upper-bound (worst-case uncertainty). The network delays are quantified in terms of an uncertainty around the nominal plant, and a mixed sensitivity based robust controller design approach is implemented.

We considered then a system G_p , to be a combination of the nominal plant (assumed to be fixed and certain) and uncertain (unknown, but bounded) dynamical effects of the network. It is hence assumed that the dynamic behaviour of G_p is described not only by a single linear time-invariant model but also by an uncertainty set Π of possible linear time-invariant models. The norm-bounded uncertainty description set Π is generated by allowing H_{inf} norm-bounded stable perturbations caused by the network to the nominal plant. With the weighting functions, w_I , and normalised perturbations, Δ_I , the expression for the networked controlled plant G_p becomes:

$$G_p(s) = G(s) (1 + w_I(s) \Delta_I(s)); \underbrace{|\Delta_I(j\omega)| \leq 1}_{\|\Delta_I\|_{\text{inf}} \leq 1} \forall \omega$$

The information about the upper bound network delay is utilised in creating the weighting functions w_I . The weight determination procedure consists of selecting the transfer function of a nominal plant $G(s)$, and determining at each frequency the smallest radius $l_I(\omega)$ which includes all possible plant and network combinations Π .

For the SISO system, the smallest radius $l_I(\omega)$ for all possible plant and network combinations where the actuator path delay and the sensor path delay are combined (lumped) into a single multiplicative complex uncertainty weight can be presented as:

$$l_I(\omega) = \max_{G_p \in \Pi} \left| \frac{e^{-j\omega(\delta_a + \delta_s)} G(j\omega) - G(j\omega)}{G(j\omega)} \right| = \left| e^{-j\omega(UBD_1 + UBD_2)} - 1 \right| \quad (6.1)$$

¹⁵www.rtai.org

where UBD_1 is the upper bound delay for the packet transmission in the actuator path, and UBD_2 the upper bound delay in the sensor path. The following weight was considered then to be a good approximation of the delay for the H_{inf} synthesis [WLS94]:

$$w_I(s) = \frac{(UBD_1 + UBD_2)s}{1 + (UBD_1 + UBD_2)s/3.465} \quad (6.2)$$

It was obtained experimentally from the complex Pade approximation by increasing its values at higher frequencies without changing the value at low frequencies. The controller synthesis problem was finally solved in a straightforward manner since, in the case with one complex multiplicative perturbation. The robust performance (RP) problem

$$RP \iff \max_{\omega} (|w_P S| + |w_I T|) < 1 \quad (6.3)$$

was approximated as a weighted mixed sensitivity problem, where the robust performance condition is slightly strengthened [SP05]:

$$\left\| \begin{array}{c} w_P S \\ w_I T \end{array} \right\|_{\text{inf}} = \max_{\omega} \left(\sqrt{|w_P S|^2 + |w_I T|^2} \right) < \frac{1}{\sqrt{2}}$$

where w_P is a weight for the sensitivity function S (usually an approximate of an integrator), and T is the complementary sensitivity function. As the obtained controller is of relatively low order, there is little need for model reduction techniques. For MIMO systems the situation is different, and more advanced controller synthesis techniques such as μ synthesis are required, in addition to the model reduction techniques.

To verify the validity of the proposal, we evaluated it through Matlab simulations and platforms experiments. In the simulation of the network, the transmission delays over the network in the sensor and on the actuator side were assumed to vary randomly between zero and the upper delay value estimate. The H_{inf} optimal controller for this mixed sensitivity problem was found using the MatlabTM Robust control toolbox.

In [Acti.16], we have concluded that the performances obtained in simulations and with the experimental prototype correspond well to the expected results and are not influenced by the delay variations. Also there is no significant difference between the consecutive responses, as was observed in the Smith predictor case. However, this approach provides relatively conservative results in terms of performance compared to the Smith predictor based approach, especially when the overall network delay is short.

6.2.2 Fault tolerant control under intermittent observations [Acl.4]

In addition to the delay criterion, I have also analysed the impact on NCS dependability of packet losses. In the framework of the Project CPER MISN SECTAF, I have worked with scientist of control engineering in CRAN (mainly D. THEILLIOL and C. AUBRUN) on the analysis of wireless transmissions QoS.

When wireless networks are concerned, the quality of service of the communications can be relatively low compared to wired networks. Actually, different protocols are proposed. Their relevance has been studied by [Deco2, DPMVZo6, WMW05, WKHW02]. Nevertheless, most of the standard wireless protocols remain basically non deterministic. Consequently, technologies commonly used in wireless local networks do not offer real guarantees of the proper transmission of information.

Overhead travelling crane

In order to achieve realistic studies of wireless networked systems, an experimental platform of overhead travelling crane in the CRAN facilities was considered. The Figure 6.6 shows the synoptic view of the plant. A metal bar is positioning along a six meters length axis by two linear motors. An embedded calculator is fixed to each motor, and the communication between the mobile calculators is achieved thanks to the use of a IEEE 802.15.4 wireless network [IEEo6a] whereas the communication between a calculator and its associated variable-frequency drive was supported by a CAN wired network.

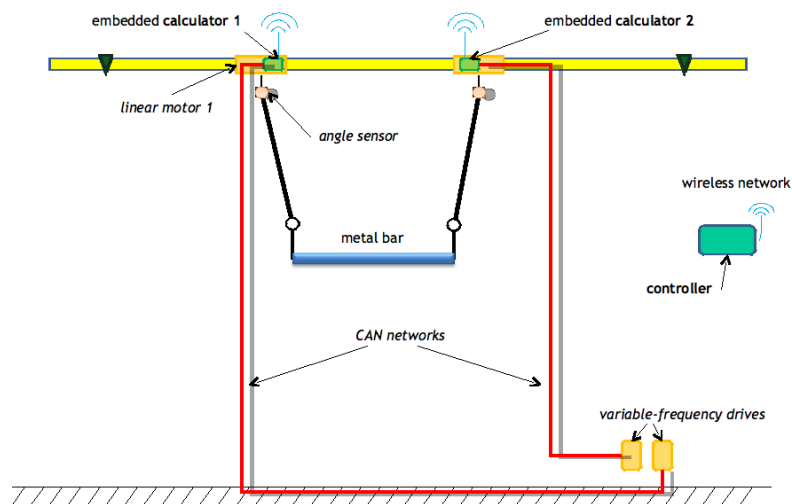


Figure 6.6: View of the overhead travelling crane benchmark

Packet losses sources and prediction

In order to be able to isolate the packet losses occurrences, a special attention has to be paid to the wireless channel models. Rather than making the assumption that the noise is white gaussian or using the popular Gilbert/Elliott model (see for instance [WKHW02]) since such models do not enable to characterise packet losses ratio dedicated to each communication, we proposed to use channel noise models in order to simulate bit errors on a wireless communication sketch. Our method was based on experimental measurements achieved on the real plant. In [Com.6] a measurement survey (done both in nominal and transitional operation in the 2.4 to 2.5 GHz band with the assistance of researchers of LICM in Metz) was carried out in order to draw the map of the electromagnetic disturbances induced from the environment and originating from the process equipment itself. The first finding was that the disturbances originating from the system itself are negligible. An important observation was that the noise affecting the communication is mainly impulsional noise, consisting in a series of impulses of varying duration and amplitude (mainly due to the 2.4 GHz band hosts IEEE 802.15.3, 802.15.4, 802.11, and possibly other systems).

These results were then introduced as environmental noise in a global simulation of the NCS by using the TrueTime library [COH07, AHCo7]. We patched the wireless network block (that uses a fixed level white gaussian noise [AHCA05]) with an externalise *noise block* delivering a signal modelling the impulsional noise due for instance to the co-existence of wireless technologies in the same frequency band to be taken into account in the SNR ratio.

The patch consists also of a new output to indicate the packet losses occurrences (and hence the rate probabilities).

The TrueTime library (and its updated wireless network block) was used next to simulate the whole system [Com.6], i.e. in integrating the plant dynamics described by a linear model and the LQR-control/measurement tasks.

A promptness indicator (like in like WorldFip [CEN96]) was also added on the controller in order to produce packet losses traces. It might be view as a healthy indicator of the network. Based on it, the controller might know if a new value has been received and adapt hence its computations. To note here that it might also highlight situations when network induced delays are larger than the sampling time such that none measures were received. Simulations enable us to classify three modes: no losses, intermittent losses for a given traffic and a special case corresponding to a wireless network out of order. The promptness computation algorithm was extended in order to determine dynamically a probability to move from one situation to another, i.e. a transition probabilities matrix Π that represents the probability to move from one mode to another. This matrix might be computed at each sampling time thankfully on the promptness indicators. At this point, the problem might be hence resumed as: to detect and isolate measurements errors (channel errors or packet losses) on the controller equivalent to sensor failures and finally to reconfigure the control.

Fault detection, isolation and estimation module

In the spirit of the fault diagnosis, we looked in [Acl.4] to reconstruct the state of the system from the subsets of measurements in the presence of intermittent loss of package which corresponds to channel error or network congestion and causes a straight packet loss. The objective was to build a bank of filters where each filter is based on a “faulty” model under the knowledge of a transition probability matrix from one mode to another mode.

As proposed by [ZL98] in the multi model framework with the Interacting Multiple Model (IMM) algorithm [BBS88], such linear system in the presence of faults/failures can be considered as a stochastic hybrid system. The system mode sequence is then an indirectly hidden Markov chain where a transition probability matrix Π from the mode i to mode j is a design parameter.

According to the dynamic behaviour of a packet lost, which is similar to a fault on a sensor, we considered sensor failures to represent network failures in the fault diagnosis approach. Classically we modelled a sensor (i.e. a network) failure by setting to zero the appropriate column of the output matrix C .

Compared to [ZL98] or to [TRP08], which have extended the Interacting Multiple Model algorithm to nonlinear system, we took into account not only a single fault but a set of faults defining the faulty model. It also extend the Interacting Multiple Model algorithm, developed by [ZL98] under network problem. The four steps of the interacting multiple model algorithm are provided in [Acl.4].

Sensor fault masking

For this study, a linear quadratic regulators (LQR) was considered to design the controller of multi-input and multi-output system. Since the feedback control can only guarantee the stability and the dynamic behaviour of the closed-loop system, a complementary controller is required.

Different techniques have been developed to achieve steady-state tracking of the reference input. Among them, a feed-forward control law based on a command generator tracker [Zj02] can be considered such as:

$$u^{nom}(k) = -K_{forward}^{nom}r(k) - K_{feedback}^{nom}\hat{x}(k) \quad (6.4)$$

where $K_{forward}^{nom}$ is synthesised on the basis of the closed-loop model-following principle and $\hat{x}(k)$ represents the state estimation obtained classically for instance by mean of a Kalman filter. However, in the presence of sensor faults, the faulty measurements corrupt directly the closed-loop behaviour. Moreover, the controller aims at cancelling the error between the measurement and its reference input. But in this case, the real outputs are different from the desired value and may drive the system to its physical limitations or even to instability.

Sensor fault-tolerant control was obtained by computing a new control law using a fault-free estimation of the faulty element to avoid faults to develop into failures and to minimise the effects on the system performance. From the control point of view, sensor fault-tolerant control does not require any modification of the control law and is also called “sensor masking” as suggested by [WTZBo6]. The performance of the proposed FTC is discussed in [Acl.4].

6.3 Control of network

After working with specialists of the control design, I have worked on control of network strategies in order to adapt the performances of the network to the QoC requirements as shown in Figure 6.2c. In a similar way as for control over network, I have focused of two QoS metrics: temporal and dependability performances.

6.3.1 Control of CoS mechanism parameters [Acl.9]

In Section 6.1.2, we introduced the idea that WRR CoS mechanisms (defined in Section 5.1.3) are fundamentals for (switched) Ethernet networks to support NCS requirements. However the configuration of the weights remains difficult when we aim at avoiding famine situations for background traffic sharing simultaneously the network. During his PhD thesis, I. DIOURI proposed hence four strategies as depicted in Figure 6.7.

Considering two flows (real-time (RT) and best-effort (BE)), weights are fixed:

1. by measuring delay (based on clock synchronisation through the IEEE 1588 protocol): when the RT delays increases and exceeds a given threshold, the bandwidth weight for RT messages has to be incremented with a step of 10. The interest of this approach is that it is a predictive method since it makes the corrections on the network before the occurrence of process instability matters.
2. by observing errors: the control of network depends on the difference between the reference and the response of the system. The network is modified only when a system dysfunction is observed (the error threshold chosen is 5 %) but anticipation is not anymore possible. The algorithm to control the network consists then in progressively incrementing the background traffic weight and decrementing the RT traffic weight when the error is less than the threshold and inversely if it is higher than the threshold. If the observation is based only the error and the matter is not due to the network, the compensation action has no effect to improve the system performance.

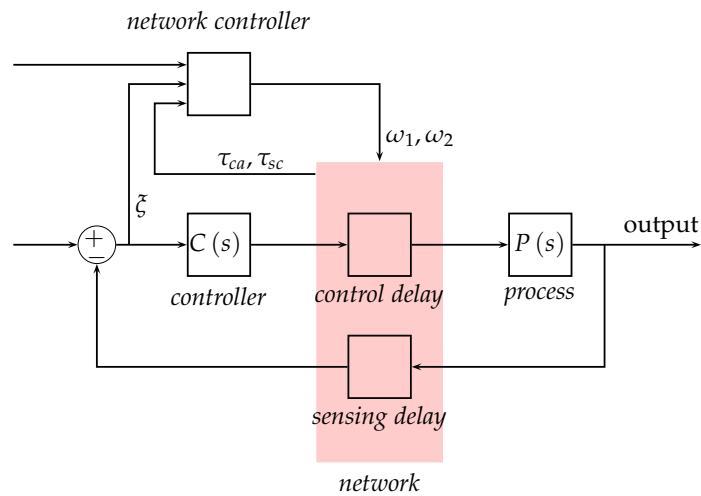


Figure 6.7: Control of network strategy

3. by considering both RT delays and the overshoot: combination of the two previous approaches enables to both anticipate system degradation by analysing the delay variations and to adapt network according to the current system state. Figure 6.8 shows the overall behaviour.

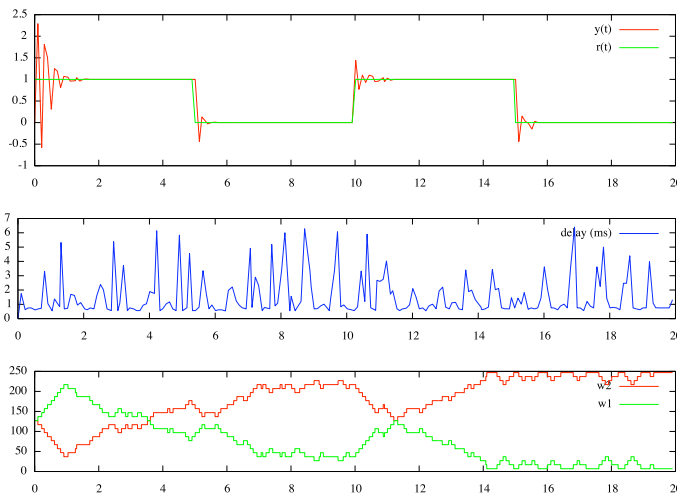


Figure 6.8: Case of delay and error compensation

4. using the network calculus theory: it corresponds to the strategy applied in Section 6.1.2. The algorithm consists then on progressively incrementing the background traffic weight and on decrementing the RT traffic weight if the error and the delay thresholds are not reached and if the delay supported by the control traffic is decreasing.

Consider now the results shown in Table 6.1. If strategies 1 and 3 works perfectly, they suffers from the difficulty to implement one-way delay measurements. The strategy 2 is not able to anticipate QoC degradation. Finally, the approach based on a worst-case model (strategy 4) does not really enable to increase the bandwidth offered to the best-effort traffic.

Table 6.1: Comparison of control of WRR strategies

<i>CoS based on</i>	<i>delays average (ms)</i>	<i>maximum overshot (in %)</i>	<i>bandwidth (Mb/s)</i>
without	2.27	793.8	–
delay	1.73	94	9.94
error	1.75	72	9.96
delay + error	1.52	44	9.8
delay + error + network calculus	1.5	42	8.1
network calculus (fixed CoS)	–	–	1.9

We looked hence to propose another approach for estimating QoS values during the investigation and identification phases of modelling the network. We analysed the network as a black box, where the inputs are both QoS controllers and incoming traffic and the outputs are QoS values. The main interest of this approach is to consider, *de facto*, all of the mechanisms implemented in the network in the modelling step. Fuzzy set theory [Zad65] was selected for three reasons. (1) A rapid preliminary study on the relationship between the delay and weight assigned to a WRR scheduler showed non-linearities. (2) The relationship between the users and the communication network, such as the Quality of Experiment (QoE) model [HEESGo8] and QoS provisioning, as regards Service Level Agreement (SLA), can be easily described as shown in [Acl.9]. (3) The fuzzy set theory both enables the identification of the network behaviour and reuses this identification to control the QoS tuning.

QoS identification using fuzzy rules

The QoS criterion used in this study is the delay. The objective of network delay identification is to be able to determine the relationship between the delay for crossing a switch and the weights of the WRR scheduler. As a novelty, we determined the fuzzy rules of the controller based on automatic modelling rather a human expertise and its identification of network behaviour using series of numerical simulations generated using the Riverbed Modeler network simulation tool. For the data set generation, 314 weight configurations (with 30 runs with different seeds) have been tested for different (background) traffic loads. Each simulation required five minutes to complete an analysis of the end-to-end delay in steady state. The identification of the delay was based on the mean delays with a confidence index of 90%. The results detailed in [Acl.9] highlight the impact of the weight tuning on the communication's temporal behaviour and show non-linearities that justify the use of fuzzy logic in the identification phase.

The main idea was first to apply pattern recognition or the classification methods that are used in the image processing domain to the network domain. Then, the weights of the WRR scheduler are considered primitive inputs, and the delay is considered an output of the classification method.

The required interpretability does not permit the use of black box methods such as Neuronal Networks (NNs) [TTL09] or Support Vector Machines (SVMs) [HCT07]. We choose to use a rule-based system, [NK98, NK99, RSA03] which seems to be more appropriate in the network context. The obtained rule set will provide knowledge about the delay behaviour, with each rule set describing the perceived delay relative to the system tuning. We used the deductive reasoning mechanism because the system outputs depend on the system inputs.

The analysis of the simulation data for delay identification is based on conjunctive possibility rules [Jon07]. There are many methods that obtain their rule sets from data, including Decision Tree Methods (DTMs) [MSTC94] and Genetic Algorithms [CGH⁺04]. Due to the small set of data that can be obtained because of the excessive computing time, we chose the Fuzzy Rule Classifier (FRC) method, which is well adapted for modelling a system with a reduced data-set [BS10]. To identify the rules of the network relation between the scheduler weights and the delay, we use the training step of the FRC method. This step is divided into two levels: the fuzzy linguistic variable definition (fuzzification) and the fuzzy rule generation, which requires an iterative step for model adjustment.

The WRR scheduler weights w_1 and w_2 correspond to the input of the system to be identified. In this study, the delay is described using three terms: Target Delay (TD), Intermediate Delay (ID) and Unacceptable Delay (UD). The Trapezoid-Triangular membership functions are used because they generally give better results [BS10].

The output of the system must also be fuzzified. Based on the definitions of Unacceptable and Target delay, we create the term Intermediate delay. The threshold between Unacceptable and Intermediate delay and the initial limit between Target delay and Intermediate delay correspond to the application constraints determined from network simulation tool (Riverbed Modeler). However, the second threshold limit has been empirically changed to improve the recognition rate.

The Fuzzy Rule Classifier (FRC) that we use here is based on Ishibushi's Algorithm. The final output is obtained by privileging the rule giving the highest response. Each rule is activated in parallel, and a disjunction operator is used to aggregate the partial conclusions and determine the final decision. The disjunction operator selected is the maximum.

The rule set obtained in [Acl.9] has been adjusted by associating a Confident Factor (CF) with each rule. The adjustment step corresponds to the iterative part of the algorithm [NIT97]. If the classification rate is inferior to a predefined threshold, the iterative procedure tunes the model. If the current sample does not match the rule, the CF coefficient decreases. Otherwise, if the sample confirms the rule, CF is increased.

Fuzzy controller step

The goal of this phase is to propose a controller capable of maintaining the end-to-end delay for the high-class traffic that is acceptable according to the application requirements. At the same time, the controller has to maximise the bandwidth for other traffic. Based on the fuzzy rule modelling, we chose to implement these rules in a fuzzy controller [Zad73, Sug85].

The strategy for reconfiguring the weights can be expressed in the following way. When the high class traffic delay is 100% unacceptable, rule 2 is applied to retrieve the target delay value. Rule 2 consists of a High w_1 and a Low w_2 . The control consists otherwise of incrementing or decrementing the weights with a maximum step of 5 (or -5).

The fuzzy controller is implemented in the simulation Riverbed Modeler tool for its evaluation. The fuzzy controller was tested for the Cisco 2924XL switch model contained in the Riverbed Modeler model library. A specific link (statistic wire) has been added, which enables the time required to cross the switch to be obtained. The fuzzy controller is located at the core Cisco 2924XL switch model and is written in C++ code.

The controller was validated through two simulations that compared the network behaviour with *a priori* fixed weights (like described in Section 6.1.2) and with weights that are dynamically tuned with the fuzzy controller. Without the fuzzy controller, [Acl.9] showed an important drawback (in addition to the network expertise level required): because weights

are fixed without considering the evolution of the background traffic, other traffics suffer from the large and potentially excessive reservation guaranteed to the real-time traffic. The simulation showed hence the interest in dynamically tuning the network bandwidth relative to both the load variation and the application requirements. However, it was noticed that the fuzzy controller does not guarantee the high class traffic delay stays in the acceptable areas (peaks in the delay are still possible, especially in case of traffic burst). Finally, it is important to note here that this work could be reuse today for the configuration of new Ethernet standards gathered as TSN as discussed in my project to be discussed in the following Part.

6.3.2 Control of a mobile sink/collector through a session layer [Acl.8]

In the framework of S. HARCHI PhD thesis, I have introduced researches when the global connectivity over the topology is broken. In order to illustrate our work, we have chosen an application of oil spills observation.

From the beginning of the oil spill, many wireless sensor nodes are randomly scattered to observe it. The topology of the network is going however to be dynamic: a connected system can evolve into a clustered system that presents a break of the global connectivity. Using a mobile collector which will regularly visit the disjoint clusters enables to restore a discreet connectivity. The major difficulty is to cope with the dynamics of the system (like wind, waves, and the Coriolis force) which implies a variation of the network topology (and communication interruptions). It may lead to a partial or total loss of connectivity for one or several nodes, and so to the inconsistency of the global information system (non-connected communication graph). A session layer protocol was originally proposed [Acl.8] to reconstitute a consistent global information system. It enables the collector to reconstruct the communication context with the previously visited clusters, knowing they could have moved, merged, or have split. It mixes hence control of the trajectory of a mobile system (a gateway from the networking point of view) for a control of a wireless sensor networks.

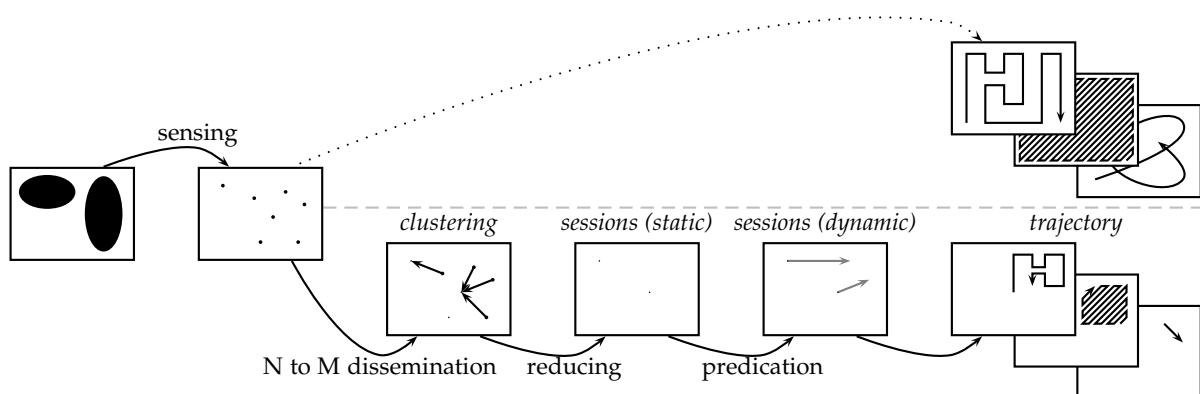


Figure 6.9: Role of the session protocol in the simplification of the collector trajectory

A particular interest of this session protocol and the original idea of our work are shown in Figure 6.9: the mobile sink should move all along the monitored area in order to collect the data disseminated in the sensor nodes (upper part of the figure). However, in order to increase the refreshment frequency of the global information system, it should avoid covering the whole area (especially when the distribution of the nodes is not uniform). Clustering is used as a first step to disseminate data of a set of nodes into a single node (and reduce yet the

number of points to visit). The session protocol will then check that the information stored in clusters is enough representative regarding the application requirements (here, regarding the size of the oil slick). If it is not the case, the related point on the trajectory will be once again removed. It will also contribute to improve the trajectory of the mobile sink as follows: the contextualisation performed by such session layer will be used in order to predicate future nodes location and hence ensures the communication capability between the collector and the nodes. It leads finally to a smaller subarea to cover regardless of the trajectory strategy used. We present in the following the main features proposed in S. HARCHI PhD thesis (details can be retrieved from [Acl.8]). This proposal is quite original and is a real novelty in the field of sensor networks. It is distinguished from the work on the DTN (Delay Tolerant Network) [DF09, Fal03] or on the data-mules [SRJBo3, JSSo5, PB08]. Indeed, beyond the data collection, it takes into account the informational context we seek to preserve during the successive visits of the collector.

Clustering

The number of nodes, their low capacity of transmission and processing, their mobility, and their limited energy, do not enable each one to communicate directly with the "sink" where all the data must converge. A cluster is a subset of connected nodes, and clustering is the process for grouping nodes into disjointed clusters. A particular node called Cluster Head (CH), allows to coordinate the members of its cluster, to aggregate and/or process the measured data and to transmit them to the data collector. In [Acti.26], after having studied and analysed the numerous metrics which are available in the literature [AY07, NALo6, KDLS08, LGFo8, MST⁺09, TV08], we have proposed an algorithm for the election of the cluster head. It includes the following parameters: residual energy, density and mobility of the nodes. Our application with an high dynamics suggests that we choose to elect the cluster head in the smallest possible k -neighbourhood. The metric is based on a 1-density (like in [Mito6]), and so, cluster members will be at most 2 hops from the head.

Proposition 10 (Clustering metric). *The metric for the cluster head election is expressed as:*

$$m_i(t) = \frac{(1 - \alpha) M_i(t)}{\epsilon_i(t) \alpha \rho_{i,1}(t)} \quad (6.5)$$

with:

α an application dependent parameter, $\epsilon_i(t)$ the residual energy of node i ,

$\rho_{i,1}(t) = \frac{N_{i,1}(t-\Delta t)}{N_{i,2}(t-\Delta t)}$ the node i density [MBFo6],

$N_{i,k}(t)$ the number of k -hops neighbors of the node i ,

$M_i(t) = \frac{|d_i(t) - d_i(t-\Delta t)|}{\Delta t}$ the mobility of the node i , with:

$$d_i(t) = \frac{1}{|N_{i,1}(t)|} \sum_{v \in N_{i,1}(t)} \text{dist}_{i,v}(t) \text{ and } \text{dist}_{i,v}(t) = \sqrt{(x_i(t) - x_v(t))^2 + (y_i(t) - y_v(t))^2}.$$

[Acl.8] provides the distributed algorithm implemented in each node. Messages enable the cluster head and an ordinary node, to propose to join the cluster and to accept this proposal.

Sessions: definitions and operators

With a session layer protocol, even with discrete connections when it visits the cluster heads, the collector can rebuild a consistent information system over the former established connections. For example, in the case of a merging of clusters where the head is changing, the

collector may give it a session identifier deducted from those given to the heads of the former merged clusters.

Definition 4 (Session). *A session represents the exchange of an informational subset of the global information system $S(k)$ between a collector and the groups of nodes G_i . It therefore has a spatial and temporal dimension. k evolves at each new visit of the collector, and therefore represents the discretisation of the global sensor network connectivity.*

In order the collection to be efficient, the exchange has to be informationally significant. Therefore it can be limited to a group of nodes (cluster) of sufficient size ($|G| \geq n$). A too small cluster will thus not be associated to a session thanks to this size threshold n . The association of a session to a cluster enables to limit the trajectory of the collector to the cluster heads. We considered that for each visit of the collector to the cluster head representing a group of nodes G_i , this latter can provide the cluster data.

We introduced then an inheritance relation which is essential, because it will enable the continuity of the context between two collector visits, even if the cluster heads have changed. Indeed, a cluster may have lost or gained some nodes, may have elected a new head, may have merged with another, or may have been divided into several other clusters. We defined the inheritance relation as:

Definition 5 (Inheritance).

$$G_i \in S(k+1) \text{ inherits from } G_j \in S(k) \Leftrightarrow \exists g \subset G_i / g \subset G_j \text{ and } |g| \geq \xi n$$

ξ represents the variation of the number of defectors around the minimum size to form a group. It is positive and can be less than 1 to avoid the creation of a new session when defectors from several groups merge to form a new group (double inheritance).

Definition 6 (Merging/Splitting). *A session is a merging of other sessions if it inherits from at least two sessions. The merging represents the case where a significant part of two or more groups merge to create a new group. A session is split into two or more other sessions if each one inherits from the original session when the group with which it was associated is divided in groups of sufficient size.*

Definition 7 (Session creation/deletion). *A session is considered as newly created if it is associated with a group of sufficient size and if it does not inherit from any existing session. A session disappears if no session inherits from it, or if the group it belonged to no longer contains at least n nodes.*

The service offered by the session layer is defined in the standard [ISO96b]. As mentioned in [Nus91, Nus90] synchronisation points are used to identify parts of the data stream with the double aim to isolate the various logical parts of the dialogue, and to allow recovery in case of error or incident. We associated the concept of incident with the break of the network connectivity, and the dialogue was resumed at each cycle of the mobile collector at the end of cycle. The major synchronisation points are used to completely separate the parts of the communication which precede and which follow a new collector cycle. They define a dialogue unit and correspond to the snapshots of the network established at each cycle of the collector. According to [Nus91, Nus90] minor synchronisation points enable to structure each dialogue unit. In our protocol, the minor synchronisation points will be associated to the exchanges between the collector and each sensors group which is represented by a session. The Figure 6.10 illustrates the concept of synchronisation point. It shows that the major synchronisation points correspond to the view of the information system at each return of the collector to its "base camp", when minor synchronisation points correspond to each of the exchanges between the collector and the visited cluster heads. State-charts, sequence diagram and messages detailing the session protocol are available in [Acl.8].

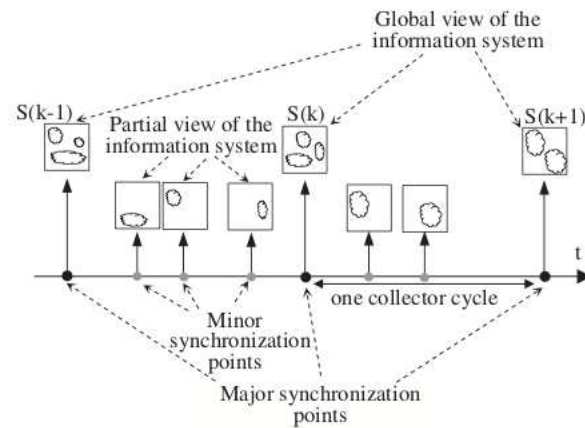


Figure 6.10: The synchronisation points

Trajectory of the mobile sink

Finally, the collector will thus have a view of the dynamics of the network and will update its trajectory to reach the sufficiently representative groups. This trajectory may be planned as in [WCBLP07] or [GY⁺14]. Numerous strategies can be envisaged, such those proposed in [GRCP14, VZF09] or gathered in the surveys written by [FBC09, TIDE14] about distributed mobile sink routing in wireless sensor networks. We defined the following sketch.

Initially (at the beginning of the disaster), when all nodes are concentrated in a single slick, the collector could follow a spiral path in order to detect the cluster heads and collect their locations from which it will compute the next trajectory. Then, in the steady state, it could update the following visit by using a predictive method (an Ambrosini method for example) which takes into account the knowledge of the last information system instances $S(k), S(k-1), \dots, S(0)$ (position of the cluster heads and their assumed motions regarding the weather conditions such as the wind speed and direction, ocean currents...). Then the minimal Hamiltonian path can be calculated (thanks to an appropriate heuristic) in order to visit all these cluster heads (exactly once). The uncertainty of the prediction should be commensurate with the range of the cluster heads.

We validated the algorithm into a node model under the network simulation Riverbed Modeler environment. All nodes are in conformance with the non-slotted and non-beaconed IEEE 802.15.4 MAC layer. The energy model we have chosen was proposed by JURČÍK and ΚΟΥΒΑΑ, and is described in [AME13]. Then we have selected the Random Waypoint mobility model proposed by [JK07], and refined by [BMJ⁺98]. Even it has been criticised in [BMJ⁺98], it is certainly the most used: after its movement, a node stops during a finite time, chooses randomly a destination, moves again, and so on until the end of the simulation. At the beginning, all nodes are concentrated in one corner of the square monitored area. The considered nodes speeds correspond to realistic weather conditions. In [Acl.8], we analysed the performance of the proposal through 2880 simulations according to the number of sessions (number of significant clusters to visit), the number of out-session nodes (static aspect of our network and ability to cover the entire area to monitor), the number of new sessions between two visits of the collector (dynamic aspect of the network) and the area covered by the nodes. It enabled to find by simulation the optimum values of n and ζ for a given disaster. To finish, one may noticed that this work might also be seen as a contribution to greening with ICT approach.

6.3.3 Dual path communications over multiple spanning trees [Acl.5, Acti.23]

We introduce here a strategy developed by S. KUBLER and J. ROBERT to anticipate failures over a switched Ethernet network in case of a NCS with high dependability constraints. Compared to previous control of network, the optimisation is planned here offline.

The problem comes from the too long reconfiguration time in case of failures (FDI and FTC) of the Spanning Tree Protocol (STP [IEE04]) and derivatives like the Rapid STP (RSTP, IEEE802.1w [IEE04]). We aim here to decreasing this time to nil by anticipating the failures. It consists of duplicating frames and of forwarding them on different paths. This is supported by the possibility of defining as many trees as possible as Virtual Networks (VLAN, IEEE 802.1q) through techniques like MSTP (Multiple STP, IEEE 802.1s) or PVST (Per-Vlan STP, Cisco proprietary protocol).

These are related works [HGM10], but our approach differs from to the network technology. Firstly, we study switched Ethernet architectures not considered in [JRY09, LPDL07]. Secondly, our main objective is to maintain the continuity of service in respect of the standards defined for switched Ethernet, without defining additional (STP) mechanisms [QMCLo8, KWKW09, IJW10]. The work developed by [FBB11] is quiet similar to our proposition, but their fitness function is expressed according to time constrained and not on a reliable criterion. Moreover, our chromosome modelling avoids the generation of unviable solutions in opposition to [FBB11]. In our approach, we rely on the MSTP protocol to define several trees for interconnecting NCS equipment. This strategy consists of implementing a static procedure of forwarding as many frames as defined trees. Thus, if a path is down, the sink node receives the information by at least one of the others paths.

The first work is to define an expression formalising the problem of the redundant paths between a source generating traffic and its destination node. A path consists of a series of network components. A network component represents either a network node (switch) or a link. The failure probability of a path depends on the number of network components constituting the path. More network components that are used, higher the path failure probability. Moreover, the failure probability of redundant paths can be correlated when a same network component is used in several paths. Failure of this network component affects the behavior of not only one path but of several paths. Each network component is assumed to have the same failure probability.

Network dependability with independent/overlapping paths

We define α_i as being the number network components composing the path i . A network component is a link or a device network (switch). Let λ be the failure probability per hour of any network component and $\mu = 1 - \lambda$ as being the non-failure probability. The failure probability of a path i (P_{Path_i}) is given by (6.6). The failure probability of the network (P_{Net_j}) composed of j independent paths is given then by (6.7).

$$P_{Path_i} = 1 - (1 - \lambda)^{\alpha_i} = 1 - \mu^{\alpha_i} \quad (6.6)$$

$$P_{Net_j} = \prod_{i=1}^j P_{Path_i} = \prod_{i=1}^j (1 - \mu^{\alpha_i}) \quad (6.7)$$

The assessment of (6.7) is studied according to the SIL specifications (Safety Integrity Level, IEC 61508 standard [Int05]). The analysis is based on the choice of network components with

SIL 4 (with $\lambda = 10^{-8}$). We found that a network architecture implementing two paths would be a good arrangement between dependability and cost.

Let α_i be the number of exclusive network components composing the path i . An exclusive network component belongs only to one path. Let β be the number of common network components used in both paths. As a matter of course, the total length of a path i equals $\alpha_i + \beta$. By relying on the equation (6.7), the whole network failure probability can be determined by (6.8) which is defined as our fitness value.

$$Fitness = 1 - (1 - (1 - \mu^{\alpha_1})(1 - \mu^{\alpha_2}))\mu^\beta \quad (6.8)$$

Equation (6.8) will act as the expression formalising the problem of the redundant paths between a source generating traffic and its destination node. In the following, the issue will be to search for pair of trees such that the paths between two nodes minimise the fitness value. Let L be the number of links and N be the number of nodes in a graph. Firstly, consider a cyclic graph (where $L = N$ for $N \geq 3$) which is a simple case. The search space for one tree is equal to N . As a result, the search space of our problem which consists by exploring all pair of trees among the total number of trees might be limited to C_N^2 . Secondly, consider the complex case of a complete graph (where $L = \frac{N(N-1)}{2}$ for $N \geq 3$). This time, the search space for one tree is equal to N^{N-2} as detailed in [YN93]. As a result, the search space of our problem might be equal to $C_{N^{N-2}}^2 = \frac{N^{N-2}(N^{N-2}-1)}{2}$. That is clearly a combinatory problem. Moreover, this issue is a subclass of problem studied in [JRY09] which is described with complexity order $O(|L||N|)$.

Genetic algorithm heuristic

There are three main classes of heuristics: the constructive methods (greedy algorithm, pilot method), the local research methods (simulated annealing, taboo search) and the evolutionary methods (Genetic Algorithm, ant colony optimisation). In these works, we notice that for a similar problem, the GA gives the best results and is the solution retained.

Let us focus on the coding of spanning trees. There are several methods of spanning tree representation of graph [ERI⁺06, NSKI92, ZT02, RKR03, RESI05, LCT00, YYSY05]. We retained the coding method explained in [ERC⁺08] (for power systems) which is based on the representation in the co-tree (i.e. digital coding of open branches designed in [RKR03]). The interest of coding the open branches is to limit the size of the coding compared to the elementary coding in which each branch is identified with '0' or '1' if it is opened or not. The remaining issue deals with the selection of the branches to open. Since a tree aims here at eliminating potential loops, the solution consists in analysing each fundamental loops [LCT00]. A fundamental loop is defined such that it does not contain other loops. However, it is necessary to check a given branch is not opened in two distinct fundamental loops (since otherwise, it will not guarantee a fitted tree). Each branch is identified by a digit. The "digital coding of opened branches" in each fundamental loop consists finally in a vector composed by the digit of the opened branches. Accordingly, the digital coding of open branches in each fundamental loop is implemented in our algorithm which serves as basis for the coding of the population members. It will avoid the determination of fundamental loops allowing the validity of the resultant topologies after crossover and mutation processes in the genetic algorithms to be tested. We proposed two algorithms aimed at checking if the graph is connected and identifying the nodes along a path

According to the type of coding previously cited, the crossover and mutation operators might generate more or less invalid individuals compared to the topological constraints. We retained the crossover and mutation strategies based on the graph theory approach developed in [ERC⁺o8] (the *co-cycle* approach is however not implemented since it does not guarantee that resulting individuals will be in line with the topology constraints). The conventional GA parameters [Gol89] were adjusted with the same approach as [Acl.2] as explained in [Acl.5].

To test the validity of the proposal in the framework of NCS, specific nodes were developed in the Riverbed Modeler network simulation tool in order to simulate the control and the plant of a simple process (gathering a controller, a sensor and an actuator; i.e. two paths). The topology relies on a switched Ethernet architecture consisting of 31 switches and 56 links. We launched simulations for two cases study. The first one uses the classic solution with the Spanning Tree Protocol (STP). The second one applies the method proposed by implementing two (VLANs) paths obtained from GA. Two VLANs are defined and two trees are created respectively for each VLAN by using MSTP. In practice, spanning trees will be configured by adapting the switches' ports priorities and the link costs. Furthermore, the controller duplicates the control messages on both trees and it receives twice the sensor state. Rapid STP is activated on the simulation tool for defining both trees.

Simulations show that in case of failure occurrences, no impact on the process control were detected (in contrary to the single STP case for which instability periods were observed) [Acl.5]. However, when failures occur simultaneously on both paths, performances of the communication will correspond to those provided by RSTP protocol. It may be noticed that the frames duplication generates desynchronisation since the duplicated messages do not arrive at the same time at the destination nodes. This trouble can be suppressed either by numbering or timing the messages and discarding all messages containing "old" numbers. Once again, it is interesting to note that the last amendments of Ethernet named TSN promotes mechanisms similar to the strategy we proposed here.

6.4 Centralised controller for the next generation of space launchers

In the framework of our collaboration with CNES, I introduce studies aiming at highlighting the benefits to implement centralised control of network approach in launchers.

6.4.1 Toward self-reconfiguration of switched Ethernet architectures [Acti.27]

Considering the robustness limitations of the previous strategy (two failures might directly lead to an interruption of service) and the requirements of the launcher, we worked with J. ROBERT to increase the robustness of switched Ethernet architectures up to (at least) the same reliability level than with MIL-STD-1553B.

We suggested to refer (see IEC SC65C WG15 and [Har09]) to a "redundancy in the network" solution (network topology with redundant links and switches) in which the network can reconfigure itself to ensure the continuity of service. It may be noticed that Automatic Repeat reQuest (ARQ) protocols can improve the reliability, but regarding the real-time requirement, none are considered here. To face with a failure of the local interconnection point of a device, "redundancy in the [end] nodes" will be used even if full solutions as PRP, CRP, BRP, HSR) are not considered here. Our objectives are therefore to have a reconfiguration mechanism transparent for the application point of view, and to minimise the time of the

reconfiguration action (and so the losses). It corresponds to a real-time requirement for the reconfiguration strategy [Pry06], and will be qualified in the following as:

Definition 8 (The (recovery) recovery time [IECo8]). *The time necessary to switch to a backup solution and ensure the continuity of service. An application can tolerate a limited time of interruption of service, called grace time [Felo8].*

Many solutions [HGM10] rely on redundancy management for physical meshed architecture (Figure 5.19). Relevant protocols in this category, Media Redundancy Protocol (MRP) [Felo8] and RSTP are based on two main steps: fault detection and topology reconfiguration. Fault detection is typically achieved by the asynchronous periodic transmission of particular frames between switches. Recovery time issues for real-time systems are coming from these exchanges and from the asynchronism due to the distribution of the algorithm. In order to reduce the recovery time, MRP protocol considers a centralised approach, but only for a ring topology. For all these reasons, we suggest a novel centralised approach for the physical topology supervision and the logical topology reconfiguration for any physical meshed topology.

The core idea of our proposition detailed in [Acti.27] is to reject the logical trees to control all paths in a deterministic way. It is suggested to apply a layer 2 routing to control the “route” taken by each flow. We suggest to introduce a central agent capable of detecting any failure and reconfiguring an active logical topology. This agent has a global view of the network (and so of the network state). This view can be obtained by requesting all switches periodically (*via* Simple Network Management Protocol - SNMP). Indeed, any switches store the states of its ports in a specific database called Management Information Base (MIB). This information is updated thanks to a physical link integrity function (defined in the standard 802.3) on any switches.

In a formal way, we consider a network graph $G = (X, A)$ where X is the matrix containing the state of all switch ports and A the matrix representing the physical connectivity between the switches. Let n the number of switches in the architecture and m the number of ports that a switch has (in this paper, it is assumed that all switches have the same number of ports). The element of X is written as $X_{i,j} \in \{0, 1\}$ which represents the state of switch $j \in \{1, n\}$ port i with $i \in \{1, m\}$. X is defined such as $X = [X_1 \dots X_j \dots X_n]$ where X_j represents the port states of switch j . The element of A is noted as $A_{(i,j),(i',j')} \in \{0, 1\}$ represents the physical capacity to communicate between the port i of the switch j and the port i' of switch j' . This network graph will have to be updated periodically as written in line 3 of Algorithm 2. Indeed, in monitoring the states of ports (the matrix X), the network graph is accordingly modified. It is important to note that the performance of our solution will depend on the value of this monitoring period. This criterion will be evaluated in the next section.

Let us remember that our goal is to fill in or update the forwarding table. For that, we have to look for the output ports associated to each destination on all switches. A list D of all stations (represented by their MAC addresses (@MAC)) is defined. It is necessary to know on which port of which switch are located the end-stations. A matrix D' is thereby defined to contain the network attachment of the different stations such as $D'_{i,j} \in D$ represents the connection of end stations (with MAC address @MAC) on the port i of switch j . As a matter of course, for each switch and for each MAC address in the list D , we can identify on which switch j' is located an end-station (see lines 4-6 in Algorithm 2).

This information and the updated network graph are the inputs of the well-known Bellman-Ford routing algorithm (see line 7 in Algorithm 2). The result of this step is the next hop to reach the destination. Knowing the switch to cross and the physical connectivity (the matrix

Algorithm 2: Reconfiguration algorithm

Data: $G = (X, A_{(i,j),(i',j')})$: the network graph;
 D : the list of all stations;
 D' : the network attachment of the different stations;
Result: the vector $R_j = \langle @MAC, i \rangle$ with $@MAC$ the destination and i the output port to reach $@MAC$ (next hop) from the switch j

```

1 begin
2   periodically
3      $G \leftarrow \text{update}(G)$ ;
4     foreach switch  $j$  do
5       foreach  $@MAC \in D$  do
6          $(i, j') \mid D'_{i,j'} = @MAC$ ;
7          $R_j \leftarrow \text{Bellman-Ford}(j \rightarrow j', G)$ ;

```

A), we can deduce the output port to fill in the forwarding table. Of course, if it is concerned by the failure, it is modified (see lines 8-9 in Algorithm 2) in the forwarding table.

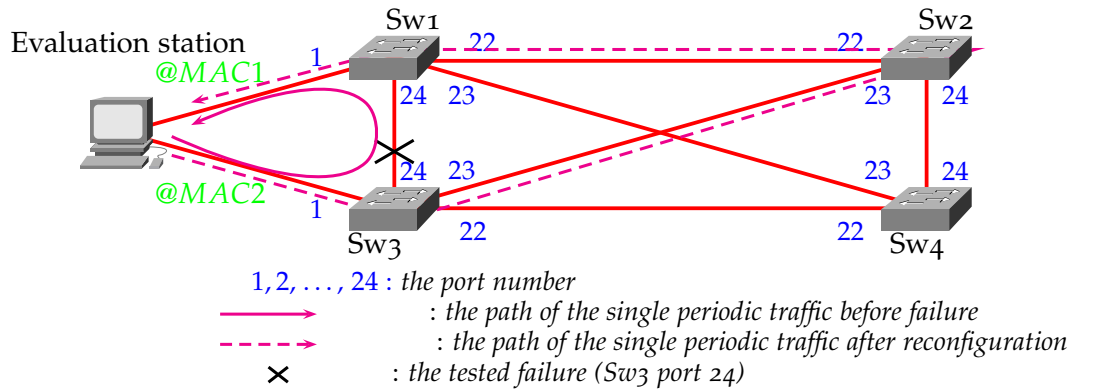


Figure 6.11: Architecture of the preliminary experimentation

We experimentally tested the algorithm feasibility and its performances over the platform described in Section 2.3.4. We observed that the variation of the interruption time is mostly due to the detection time of "link_loss" which is between 50 ms and 150 ms (as defined in the standard [IEEo8b]), plus the reconfiguration time and the update time in the MIB. Among the tested monitoring period, the 100 ms period is the closest to the detection time. The reconfiguration time is around 20 ms. Finally, the increase of the delay for the recovery solution is proportionally limited (relatively to the service interruption time). Experimental measurements have hence shown that the recovery time has been decreased and the number of losses is lower compared to RSTP (although it is still non-null especially for the flow with a small period).

One may noticed that the proposal of a centralised controller came early and corresponds today to the concept of software-defined networking and that the idea to introduce a layer 2 routing taking into account temporal performances is currently implement in Ethernet TSN standards.

6.4.2 A strategy to implement a software defined networking [Acti.44]

With D. PETIT, we pursued the idea of a centralised controller to dynamically take control decisions on a network embedded in a space launcher. The feasibility and the challenges of SDN in the domain of industrial Ethernet and embedded systems are discussed in [HWJ16a, TE16, HGO15, GSCS17].

In the case of a space launcher, two types of events can lead to the modification of the configuration: physical topology evolution events and flow evolution events. Physical topology evolution events correspond to (i) failures (link or device) and (ii) the stage separation where some devices are lost. Flow evolution events correspond to phase changes where new flows are transmitted and others are not anymore. Our controller configures the paths, i.e., implements a forwarding plane, depending on traffic and topology events. The objective function verifies that the real time constraints concerning end-to-end delays (i.e. to guarantee bounded delays) at each phase changes and stage separation [Acti.44]. Our work do not require bandwidth reservation mechanisms.

Figure 6.12 shows the steps to the proposed SDN controller architecture.

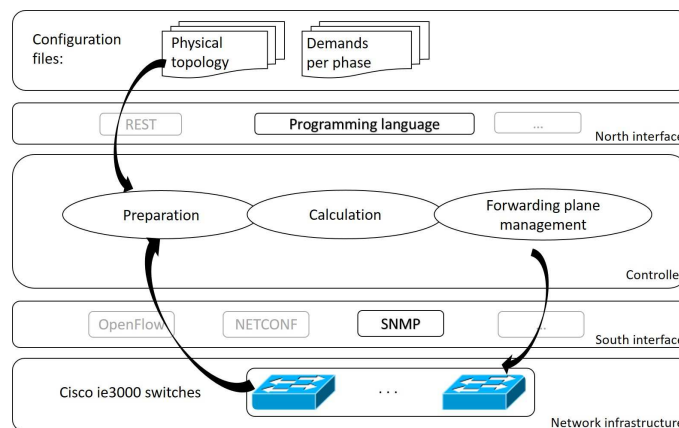


Figure 6.12: Supporting network controller architecture for embedded network

The centralised simplified algorithm that takes place in the controller consists of selecting a good forwarding plane and proceeds as follows (more details are given in [Acti.44]):

1. Define candidate paths for each demand
2. Generate related forwarding planes
3. Select a forwarding plane as candidate
4. Evaluate it according to the objective function (compute the end-to-end delays)
5. Apply the plane if requirements are satisfied ($\text{delays} \leq \text{threshold}$) and exit. Go back to step 3 otherwise.

The collection of the information is implemented periodically in order to detect, through a south interface based on the SNMP management protocol, topology and demands changes. The detection of phase changes from south interface uses messages called broadcast TOP which states the flight phases. The controller uses these messages to learn the current phase and the relative requirements. Since no device are added during the flight, the information

describing the nominal physical topology is static and given by the north interface. When the forwarding plane is selected, the controller implements the solution in the network infrastructure using SNMP south interface as described in the previous section.

The objective function corresponds to the end-to-end delays computation. Hence, the calculation step computes delays. We decide to calculate the delay for each flow using the network calculus theory taking into account that a flow is split, at least, in two demands and the algorithm calculates all the paths for all these demands in advance. This increases the problem complexity because more traffic is added to the computation of the paths.

In order to apply then the network calculus, the forwarding plane is transformed in a virtual server graph in order to calculate the delay as explained by [BS16].

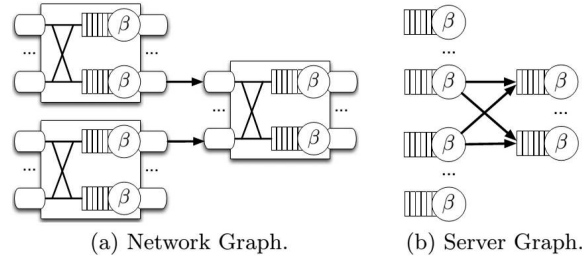


Figure 6.13: A graph of network devices with output buffering (a) and its server graph connecting the devices' queues (b) [BS16]

In addition, the use of network calculus depends on the type of the architecture, nested or non-nested. [LMS08] define a nested tandem $[1, N]$ as the non-existence of two flows $(i, j), (h, k)$ such as $i < h \leq j < k$ with $i, j, h, k \in [1, N]$ and $(i, j), (h, k) \neq (1, N)$ the flow of interest. Said in others words, let us consider two flows $(i, j), (h, k)$ with $(i, j) \neq (h, k)$ and $i \leq h$ then either $j < h$, or $k \leq j$. In the first case, the two flows do not cross the same set of nodes. In the second case, it says that (h, k) is nested in (i, j) . A non-nested tandem is a tandem that does not correspond to this definition. The Figure 6.14 represents among other things a nested and non-nested tandem. In the case of non-nested tandem, it is necessary to transform the tandem in a nested one since otherwise the theorems cannot be applied.

In the case of non-nested tandem, it is necessary to transform the tandem on a nested one to apply Least Upper Delay Bound (LUDB) [LMS08] methodology to compute end-to-end delay. In the example of the non-nested tandem from Figure 6.14, [LMS08] proposes to split the tandem $T = \{1, 2, 3\}$ into two sub-tandems $T_1 = \{1, 2\}$ and $T_2 = \{3\}$ and then to sum the end-to-end delays calculated on these two sub-tandems. In this case, the arrival bounds of flows $(1, 3)$ and $(2, 3)$ have to be calculated on node 3, in addition of flows $(1, 2)$ and $(1, 3)$ on node 2.

In order to calculate less arrival bounds, we proposed, from the same example, to split the flow $(1, 2)$ at the input of node 2 to create a flow $(1, 1)$ and a flow $(2, 2)$ and come back to a nested tandem. Only one arrival bounds of the flow $(2, 2)$ has to be calculated using the output arrival curve theorem like that : $\alpha_{(2,2)} = \alpha_{(1,2)} \circ \beta_1 = \rho_{(1,2)}t + \sigma_{(1,2)} + \rho_{(1,2)}T_1$. The Figure 6.14 shows the transformation of non nested tandem to nested tandem using our proposition and then the LUDB methodology is applied.

This approach enables at the end to compute end-to-end delays through the PBOO and PMOO (Lemmas 1 and 2) in an iterative way in order to bound the end-to-end delays. For the calculation, our controller implementation use the network calculus calculator DiscoDNC [BS14]. The simplicity of the network architecture enables to use brute-force search to calculate

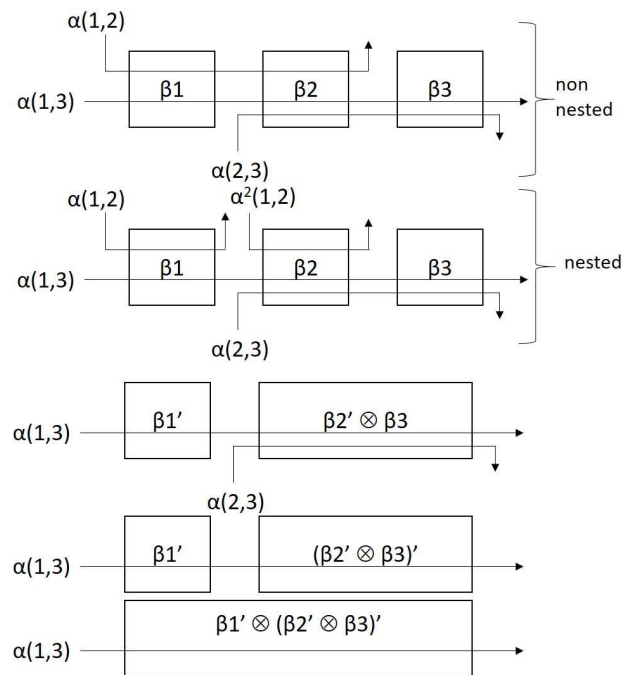


Figure 6.14: LUDB methodology, from nested to non-nested

all the possible paths. In fact, forwarding planes are selected one by one such that the first one that fulfil all requirements is applied and the algorithm stops. It can happen that none of the forwarding planes respect the constraint and so no solution is found.

Chapter 7

First contributions to green networking (A₃ – QiS)

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In 2012, considering the report of the Climate Group which noted that energy consumption by ICT activities represented 2 % of global human activity in 2009 [GeSo8], I initiated, with É. RONDEAU, activities in the field of green (ICT) networking. It corresponds also to my involvement as local coordinator of the Erasmus Mundus of Joint Master Degree PERC-COM. This chapter introduces therefore some results we obtained with Master students. It is interesting to note that green networking can be view as networked control systems considering additive QiS constraints: environmental and ethics considerations. Similarly to control over/of network, works are classified in that field over two issues: greening with ICT and greening ICT. The results presented in this chapter correspond to the last one and focus two issues: network design and energy consumption. In both cases, this first contributions aim at defining measures of effectiveness (MoE) of network architecture.

The chapter addresses hence different research questions:

- how to improve network sustainability?
- how to translate the lessons of mature ecosystem in networking?
- what is the pollution generated by network components (mainly in term of carbon emissions)?
- is green networking a new workload for ICT engineers?
- how to optimise the usage of network and mitigate its footprint?

7.1 Designing green network architectures using the ten commandments for a mature ecosystem [Acl.7]

A new challenge for ICT engineers is therefore to be able to design ICT more efficiently by considering environmental constraints. In the ecology domain, J.M. BENYUS' book "Biomimicry" [Ben02] proposed ten commandments for mature ecosystems. With N. DROUANT and in the framework of the project ANR CAPFEIN, we showed how to apply these commandments to ICT, by focusing on green network architecture design.

In the final chapter of this book, "How will we conduct business", J.M. BENYUS defines ten commandments for mature ecosystems. An ecosystem¹⁶ is a complex of living organisms, their physical environment, and all their interrelationships within in a particular unit of space. She says that "over billions of years, natural selection has come up with winning strategies adopted by all complex, mature ecosystems". The ten commandments are defined (a complete definition is given in [Acl.7]) as:

1. use waste as a resource,
2. diversify and cooperate to fully use the habitat,
3. gather and use energy efficiently,
4. optimise rather than maximise,
5. use materials sparingly,
6. don't foul their nests,
7. don't draw down resources,
8. remain in balance with the biosphere,
9. run on information, and
10. shop locally.

The evolution of ecosystems generally occurs in two phases: the developing stage and the mature stage [AC94]. Our goal was to check if philosophical concepts from ecology make sense when considering a technical system as a network. To design a technical system, a systemic approach is recommended, which takes into account all requirements and constraints of the global system [POA⁺11]. In this systemic approach, the design of the system (in this paper, the network architecture) must be evaluated according to two points of view, namely the project-system and the system-of-interest. We proposed metrics for both these views.

7.1.1 Ten commandments for designing network architectures

The specification of guidelines for designing green network architectures is complex because they must cover different requirement specifications (network, ecology) and must integrate unrelated criteria, criteria that are mutually contradictory, and criteria that are mutually reinforcing. System engineering [INC15, MPZM03] splits the assessment into two parts, namely

¹⁶<http://www.britannica.com/>

the project-system and the system-of-interest parts. The purpose is to be able to use different metrics for evaluating these two parts.

The problem is that, even if a new green network technical solution appears interesting as a local solution, it could have negative effects in terms of the global environmental system. Therefore, the objective is to translate the ten commandments for eco-mature systems into network technical terms, thereby filling the gap between ecology and network domains.

The objective of the project-system assessment is to define guidelines for designing green network architectures. All its procedures have to be verified to ensure that the methodology of the design has been met by the network designer. Here, the check-list principle is used [Acl.7, Table 1]. Two possible answers (Yes or No) are used to check the degree to which ecological criteria are considered in the project-system. The solution that achieves the most "Yes" responses is the one that most respects the environment. This table is not exhaustive and is an initial set of recommendations that should be updated continuously. We introduced also additional concepts like those defined in the book "cradle to cradle" [MBo2] (in which raw materials are separated into biological nutrients and technical nutrients) or circular economy.

An analysis of these lessons in [Acl.7] showed that the majority of the commandments could be translated to network system requirements except for the commandment "Remain in balance with the biosphere". This commandment corresponds to a particular network application (monitoring the environment) but is not directly related to the problem of network architecture design.

7.1.2 Green measures of effectiveness for system-of-interest

The objective of the system-of-interest assessment is to develop metrics that enable evaluation of different network architecture solutions in terms of the ecology criteria. This is a quantitative evaluation, measured in terms of CO₂ emission or the percentage of product recycling, for example. In system engineering, these metrics are called the Measure of Effectiveness (MoE). In general, the MoE will reflect approximately the impact of a given action on the environment.

N. DROUANT specified hence five MoEs are specified. This list is not exhaustive (a metric regarding how manufacturing waste are disposed would have to be also considered) and the equation expressing each MoE can be refined. However it demonstrates a general framework for designing green network architectures. The network architecture is analysed here in consideration of two main factors:

- the impact on the environment of the manufacture of network equipment (router, switch, etc.)
- the impact on the environment of each phase of network use.

Table 7.1 lists the notations that will be used to formulate the MoEs described below.

Definition 9 (MoE on recyclability ("Use waste as a resource")).

$$\Gamma = \frac{\sum_{i \in \overline{X}_r} \rho_i}{|\overline{X}_r|}, \quad \overline{X}_r = (X \cup X_S) - X_r \quad (7.1)$$

Definition 10 (MoE on energy consumption ("Gather and use energy efficiently" and "Don't draw down resources")). *The energy consumption associated with the network architecture is defined*

Table 7.1: Notations

Symbol	Description
X	Set of equipment for the architecture
$ X $	Number of items of equipment in the architecture
X_s	Set of substitute equipment
X_r	Set of repackaged equipment: $X_r \in (X \cup X_s)$
\overline{X}_r	Set of used equipment never repackaged: $\overline{X}_r = (X \cup X_s) - X_r$
ρ_i	Recyclability rate for an item of equipment i
Γ	Recyclability rate of the whole architecture
E	Energy consumed by the whole architecture
E_m	Energy consumed by the equipment's manufacturing process
E_u	Energy consumed by the whole architecture during its use phase
P_u	Power consumption of the whole architecture during its use phase
E_d	Energy consumed during the dismantling phase of \overline{X}_r
δ	Power consumption gain (relative to the traffic profile)
ω_i	Traffic load for a switch port i
ϵ_i	Power consumption of an item of equipment i
\emptyset	Power consumption of a switch in the idle state (no traffic)
σ	Power consumption of a busy switch port (full load)
Φ	CO ₂ emission for the whole architecture
α	Multiplicative gain between energy consumed and CO ₂ emission by country
τ	Multiplicative gain caused by energy transportation losses

as:

$$E = E_m + E_u + E_d = E_m + \int_{t=0}^{\text{end of lifecycle}} P_u(t) dt + E_d \quad (7.2)$$

considering the model for Energy Efficient Ethernet switch [RSZ+12]:

$$P_u = \emptyset + \sigma \sum_{\text{port } i} \min(1, \delta \omega_i) \quad (7.3)$$

Definition 11 (MoE on pollution ("Don't foul their nests" and "Shop locally")). *The estimate of CO₂ pollution considering the full life-cycle (manufacturing, use or dismantling) is then obtained by:*

$$\Phi = \Phi_m + \Phi_u + \Phi_d = \alpha_m E_m + \alpha_u E_u + \alpha_d E_d \quad (7.4)$$

If we consider the sources of energy (in particular renewable energy), it comes an MoE on CO₂ emission:

$$\Phi = \sum_{s=m,u,d} \sum_{\text{energy source } i} \frac{\alpha_{s,i}}{\tau_{s,i}} \times E_{s,i} \quad (7.5)$$

where $E_{s,i}$ represents energy-source component i consumed during the stage s and τ represents the additional rate for transporting energy.

Definition 12 (MoE on relevance to user needs ("Optimize rather than maximize", "Use material sparingly" and "Run on information")). *There are therefore two main aspects:*

- The network performance in terms of classical Quality of Service criteria such as responsiveness and reliability,

- Its environmental performance, corresponding to the MoEs on pollution and recyclability.

A radar diagram is proposed to represent both the network performance and the network specifications.

Green MoE interest is highlighted through a case study in [Acl.7]. It considered three candidate architectures compared according to the following user requirements: reliability, recyclability, and CO₂ emission. The network performance (QoS) is here limited to the reliability, but obviously, additional metrics like service capacity and buffer in capacity may be also considered. A radar diagram is proposed to summarise the various MoE results regarding the initial specification defined by the customer. A major issue is the adjustment of multiple MoEs, which are often strongly correlated and can therefore have opposing effects on the whole system.

7.2 Mitigating the energy consumption

At present, one of the main concerns of green network is to minimise the power consumption of network infrastructure. Hence, we looked for modelling the energy consumed by networked devices at the access level. In particular, I aimed at completing the QoS model of the Ethernet switch with power consumption models. Those models were obtained by design of experiments and fuzzy logic. Models were used then to optimise offline the topology of access networks and to control online the routing at core networks.

7.2.1 Energy consumption modelling of an Ethernet switch

We focused now on the measurement and modelling the power consumption of an Cisco Ethernet Catalyst 2960-X switch during its runtime considering various types of input parameters with all possible combinations. This switch was chosen because it has been analysed to be one of the “greenest switch” in the market that consumed 55 % less energy in Watts/Gb/s and saves (at that time) over 50 % in annual energy operating costs compared to the industry average.

By design of experiments [Acti.30]

M.M. HOSSAIN applied design of experiment (DoE) to obtain adequate information on the effects of each input parameters on the power consumption. For the experiment, three input parameters are chosen. They are bandwidth, traffic and number of connections. The output to be measured is the power consumption of the Ethernet switch.

In [Acti.30], two models are proposed for measuring the power. First model is based on full factorial which provides model with less number of experiments and for more elaborate experimental model linear regression model is used. Statistical analysis methods have been applied to identify the most influential parameters affecting the power consumption of the Ethernet switch within the range and domain of these experiments.

Our target was to review Ethernet switch as a black box and observe its behaviour in different scenario. Because of that we have only considered those parameters which are directly in relation with Ethernet switch. Regarding port capacities, three different values have been used 10 Mbps, 100 Mbps and 1000 Mbps. As Ethernet switch has 24 link ports, number of active connections are varied from 2, 4, . . . , 22, and 24 connections to cover the whole range.

Power consumption is measured for different combination of bandwidth and number of PC and traffic.

The experiment was designed in a way as every two PC is acted as a pair. One PC of the pair is sending data and another one receiving data. In this experiment, Powerspy2 sensor is used to measure the power consumption of the monitored switch. JPerf was used for traffic generation. Variation of traffic is done by changing maximum segment size and window size. Maximum segment size varies between 256, 512 and 1518 bytes. And window size varies from 1 to 123 kilobytes. Each experiment was run for 10 minutes in order to observe a stable and steady value.

Full factorial method generates a model for power consumption of Ethernet switch based on number of PC connected and link capacity. The model provides a rather long equation which considers all the possible 2-way interaction [Acti.30]. However, a general formula can be deployed because for a given scenario only four terms from the equation will be used.

$$\text{Power}(W) = 35.3642 + \alpha X + \beta Y + \gamma (X \times Y) \quad (7.6)$$

where X is capacity (Mb/s), Y is number of active PC connected and α, β, γ are the co-efficient of the variables.

After doing full factorial, multiple linear regressions analysis was done and it gives (with Z the traffic (Mb/s)):

$$\text{Power}(W) = 33.2585 + 0.000389Z - 0.001006X + 0.06646Y + 0.000213X \times Y \quad (7.7)$$

Random scenario was chosen in order to validate the model. Measured value and predicted value from the model were closed to each other. By comparing the two equations provided by two different model, it can be observed that, for full factorial the model was rather complex where for each combination there was different co-efficient even though all of them are not used simultaneously. However in regression analysis model the equation was rather simple. Furthermore full factorial model provide a rather mean value of the power consumption for a given scenario however regression analysis provide different value for different traffic.

Thorough fuzzy logic [Acti.29]

A. FITHRITAMA proposed a fuzzy rule-based model (because a switch presents non-linearity and uncertainty behaviour under different operating condition) of energy consumption based on the result of same experiments. The switch is analysed as a black-box system with unknown characteristics and fuzzy logic is used to map the relation between input and output variables.

For the experiment, four input variables are chosen; namely capacity, traffic-load, number of connections, and hibernation-mode while the output variable to be measured is the energy consumption of the switch. The last input corresponds to Cisco SHM (Switch Hibernation Mode) feature which puts the switch in sleep (ultra low power mode) during periods of idle or very-low traffic.

The model which consists of a set of fuzzy rules produced from iterative adjustment procedure is given in [Acti.29]. In total, there are 54 if-then rules in the set. However, after eliminating the rules with unknown results and the ambiguous rule with low CF (less than 0.7), only 24 rules are left as described in Table 7.2.

Table 7.2: Model for prediction and estimation consists of 24 fuzzy rules

Rule	CF	Hibernate	Bandwidth	PC	Traffic load	Energy
1	0.878215	<i>off</i>	<i>high</i>	<i>med</i>	<i>med</i>	<i>high</i>
2	1	<i>off</i>	<i>high</i>	<i>high</i>	<i>med</i>	<i>high</i>
3	0.970118	<i>off</i>	<i>high</i>	<i>med</i>	<i>high</i>	<i>high</i>
4	0.98648	<i>off</i>	<i>med</i>	<i>high</i>	<i>high</i>	<i>high</i>
5	1	<i>off</i>	<i>high</i>	<i>high</i>	<i>high</i>	<i>high</i>
6	1	<i>on</i>	<i>low</i>	<i>low</i>	<i>low</i>	<i>low</i>
7	1	<i>on</i>	<i>med</i>	<i>low</i>	<i>low</i>	<i>low</i>
8	1	<i>on</i>	<i>high</i>	<i>low</i>	<i>low</i>	<i>low</i>
9	1	<i>on</i>	<i>low</i>	<i>med</i>	<i>low</i>	<i>low</i>
10	1	<i>on</i>	<i>med</i>	<i>med</i>	<i>low</i>	<i>low</i>
11	1	<i>on</i>	<i>high</i>	<i>med</i>	<i>low</i>	<i>low</i>
13	1	<i>on</i>	<i>low</i>	<i>high</i>	<i>low</i>	<i>low</i>
14	1	<i>on</i>	<i>med</i>	<i>high</i>	<i>low</i>	<i>low</i>
15	1	<i>on</i>	<i>high</i>	<i>high</i>	<i>low</i>	<i>low</i>
16	1	<i>off</i>	<i>low</i>	<i>low</i>	<i>low</i>	<i>med</i>
17	0	<i>off</i>	<i>med</i>	<i>low</i>	<i>low</i>	<i>med</i>
18	1	<i>off</i>	<i>high</i>	<i>low</i>	<i>low</i>	<i>med</i>
20	0.788996	<i>off</i>	<i>low</i>	<i>med</i>	<i>low</i>	<i>med</i>
22	1	<i>off</i>	<i>med</i>	<i>med</i>	<i>low</i>	<i>med</i>
25	1	<i>off</i>	<i>med</i>	<i>high</i>	<i>low</i>	<i>med</i>
26	1	<i>off</i>	<i>low</i>	<i>low</i>	<i>med</i>	<i>med</i>
29	1	<i>off</i>	<i>med</i>	<i>low</i>	<i>med</i>	<i>med</i>
30	0.886023	<i>off</i>	<i>low</i>	<i>med</i>	<i>med</i>	<i>med</i>
31	1	<i>off</i>	<i>med</i>	<i>low</i>	<i>high</i>	<i>med</i>

Because the model obtained in this study covers all possibilities of inputs, this energy consumption model can be used for prediction and estimation. This model will be useful for network architects to design and optimise the configuration for a green network.

A. provided also a fuzzy control that aims at taking into account the users' usage of the network. It is based on the user activity in a day described in Table 7.3.

By using fuzzy rules to control the switch behaviour according this case study, it was possible to save 36 % of energy consumption compared to the worst case scenario where the devices is always up 24/7 [Acti.29].

7.2.2 Principles to optimise network architecture in an enterprise [Acti.40]

All the new recommendations, new standards and new technical solutions are perceived for ICT Engineers as new constraints and additional activities in their busy workday. The traditional tasks of ICT Engineers are to develop and propose solutions respecting stakeholder requirements usually expressed in terms of time performances, reliability, security and not in environmental term. This new problematic can discourage ICT actors to take actively part in Green ICT concept and just generate the well-known symptom of green fatigue. Our approach is to avoid to change radically the ICT engineer habits and to continue to design ICT solutions in considering the users' requirements and not only environmental issues. We intro-

Table 7.3: Daily activity pattern of the users on weekdays and weekends

Time	Duration	Network usage
<i>Weekdays</i>		
7:00 9:00	2 hours	Early morning, few people, low network activities
9:00 12:00	3 hours	Morning, many people, high network activities
12:00 14:00	2 hours	Lunch break, few people, low network activities
14:00 15:00	1 hour	Afternoon, video conference meeting, high network activities
15:00 17:00	2 hours	Late afternoon, many people, medium network activities
17:00 19:00	2 hours	Evening, few people, low network activities
19:00 23:00	4 hours	Night, system backup, high network activities
23:00 7:00	8 hours	Midnight, no activity, idle
<i>Weekends</i>		
7:00 7:00	24 hours	No activity

duced hence a research work to evaluate how the consideration of the energy consumption may affect the design of switched topologies used as access networks in enterprise.

The Ethernet switch architecture optimisation is divided in two methods: the clustering and the serialisation. One heuristic (spectral algorithm) is interesting for realising both clustering and serialisation and is based on the analysis of Laplacian matrix. It is one of the most successful heuristics for partitioning graphs and matrices. We applied the classical approach, considering as defined in [DH73, Fie73, Fie75a, Fie75b], the second smallest eigenvalue λ_2 and its associated eigenvector named Fiedler vector as a good cut size. We considered also the Recursive Spectral Bisection (RSB) [Sim91] for the splitting value and the serialisation method defined in [ABH99]. Our proposal consists in “colouring” the value that represents a message sent between two stations in the exchange matrix. In [Acti.40], the red colour indicates that the traffic is sent 24h/7 and the black colour specifies the traffic is generated only during the working hours (during 8h). In addition, a weight of 3 is applied to red traffic in the exchange matrix to increase its importance regarding the black one. The considerations of the green requirements remain hence very limited.

The benefit of the methodology is analysed in [Acti.40] for a given case study. Figure 7.1 shows the initial and the optimised solutions.

Both solutions were evaluated in terms of QoS (simulations of the delays by using the Riverbed Modeler simulation tool) and of energy consumption. The power consumed is estimated by the (7.7) without considering the traffic which is considered as negligible. For mitigating the network power consumption, the end devices communicating only during the working hours are put in sleeping mode for the entire night. We showed that a network architecture optimised in term of delay can also generate a green solution. By turning off both end devices and Ethernet switches during their non-activity period, the method based on spectral algorithm can mitigate the network energy consumption by 16.5%. In addition, the optimised solution enables to easily find more environmental-friendly solutions with a slight degradation of delay. For the example took in [Acti.40], the mitigation of network energy consumption is more than 33% compared with the initial configuration. It explicits our idea: well design a

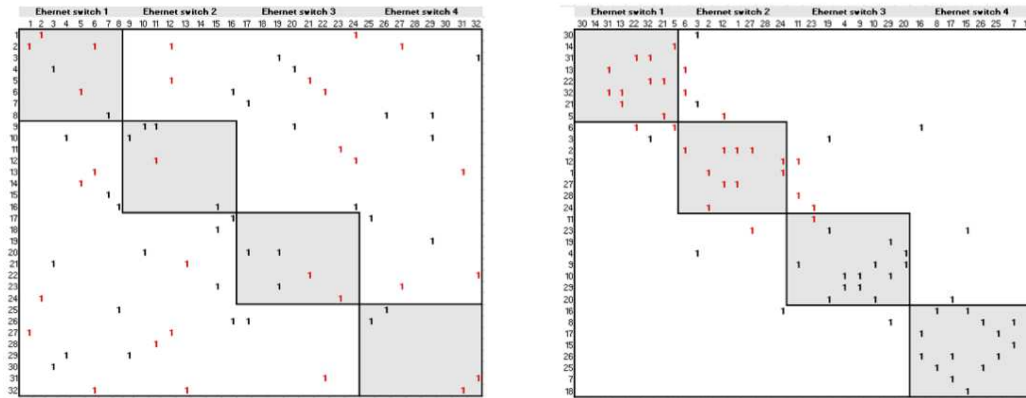


Figure 7.1: Exchange matrix for initial and optimised cabling solution

network, a software, an ICT-based application should conduct to obtain green solutions.

7.2.3 A software-defined networking perspective for core networks [Acti.38]

A. MALEKI developed a controller in order to avoid network designers to over-provision resources to satisfy the needs during peak usages. Resources such as bandwidth, processing power, and memory are prepared oversized to handle high traffic loads, however, most of these devices are underutilised during the non-peak times and this unlocks the potential to optimise the energy consumption of the resources proportionally to its actual traffic utilisation. Considering European GÉANT2 network¹⁷, she proposed a method by which we can remove up to 41% of the link during the peak time traffic and save.

The GÉANT network is the largest and most advanced research and education network in the world by gathering 38 NREN partners. It's connecting over 50 million end-users at 10,000 institutions across Europe. The backbone network is operating at speeds of up to 500 Gb/s and links to research network in other world regions covering over 100 national networks worldwide.

In [Acti.38], we proposed a model representing the energy consumed over such network. The model is discussed in the next chapter. The problem is formalised as a classical routing one, taking into account flows throughput requirements, link capacities and redundant paths. It consists hence as computing the global forwarding table of the entire network that minimised the total energy consumed by the architecture. The power consumption of the devices is based on the model previously described [Acti.30].

A. MALEKI proposed to route the traffic by using the used path while satisfying the constraints mentioned above. Nevertheless, by violating any of the constraints a new path with enough capacity will be calculated to accommodate the flow with using the minimum number of resources. We named this approach Shared Path First (ShaPF). For the first flow the shortest path is chosen.

In order to evaluate the method in the GÉANT network, we considered the data sets SNDlib¹⁸ which represents the dynamic traffic of a subset of nodes with the granularity of 15 minutes. By applying SPF, we could save up to 41% of the links compare to the shortest path approach. We could fulfil the constraints and successfully transfer the flows by using only 21

¹⁸Available at <http://sndlib.zib.de/home.action>

out of 36 links. Since all the nodes were sending traffic it was not possible however to turn off any node for this specific data-set.

Part III

***Post habilitatio* – Project**

Chapter 8

Project overview

8.1 General considerations

Regarding our previous research, I've become convinced that both the design and the management of networks will require more and more analytic characterising their performance evaluation and supporting the incoming advanced network automation. This renewed interest of network automation is engaging since it comes over the years after that (European) full-integrated protocols like ATM (with a full support of the QoS support and the control, data, management planes) were forsaken for the benefit of the basic (best-effort) IP. During the last decades and complementary to over-provisioning techniques, efforts have been pushed to add tricks over IP to retrieve QoS support. However it has led to unsound architectures that suffer from a non native understanding of the network management over the layers. The recent development of Software-Defined Networking have reemphasised the needs for (centralised) automatic control. As carried within it, I've convinced that we are not looking for a single protocol stack, but instead, for (centralised or distributed) algorithms that will both evaluate the overall performance of the networked systems and support automatic reconfigurations of the architecture regarding the users/providers' needs. The change is even more deep since it will require more engineering for graduates students and it will led to software robots for configuring network devices (whereas it might be still achieved by technicians, device per device).

Network performance evaluation is necessary as new (e.g. 5G) protocols or amendments (TSN) are currently in standardisation and request for comments over their performance. We are however not limited to protocols since we think the overall performance is more related to the new architectures (SDN/NFV or the intensive use of Pub/Sub in IoT). It would also call for overtake the well-known QoS, by highlighting the QoE (or Quality of Performance in control) and by pushing forward the QiS concept. QiS would be more and more important and, as shown previously, Green Networking shall not be reduced to energy consumption/savings even if it is a ongoing concern¹⁹. We want to develop performance evaluation based on an integrated view (and model) of this triptych (QoS, QoE, QiS). Our work should find interests for different protocols/architectures and lead to a resource budget concept. It even more important since we are witnessing an upsurge of network convergence. After hosting the voice, data networks are coming to be jointly designed with smart power grids and to deliver lighting and power in smart buildings. And networks will be also at the foundation of the

¹⁹Taking Internet as a country, it would be classify as the fifth biggest electricity consumer according to Gary Cook of Greenpeace

infrastructure for artificial intelligence (AI).

One of the current move in network architecture is related to the support of Internet of Things. It is an important topic since networks are here one of the foundation to develop smart things (Global e-Sustainability Initiative (GeSI) SMARTer 2030 report²⁰ [GeS15]) and Future Internet, Industry 4.0 or Industrial Internet (of Things). Previously, we have shown how (with novel performance evaluation and network automation) Ethernet could be used for everyThing (at least from the office to the factory plant). We aim hence at achieving similar studies in the IoT field. To ensure that the full architecture (network, computing, storage) will be able to support flexibility and dynamics reconfigurations will require facilities (network automation) and guarantees (performance evaluation) whatever it would be achieved through centralised or distributed algorithms. The QiS concept is here interesting regarding the question raised by some writers to know if Industry 4.0 is really the 4th industrial revolution (since no novel energy resource is introduced). QiS will obviously enable to take care of energy saving, but also the circular economy and sustainable development pillars (People, Profit, Planet) – the 5th revolution? We will take significant effort to make networks really “green” through advanced network automation for IoT (without leaving the QoS and QoE metrics). In fact, it is on the trend of Roberto SARACCO’s future vision for 2030-2050 of 6G²¹:

6G networks will embed planning into the network itself, meaning that the network will become aware of the way it is being used, what is actually required by its users at this specific moment and what it is likely to be required at a later time and it will be able to plan for its evolution by reconfiguring its resources and by “asking” vested parties to provide additional resources coming up with a convincing reason and a convincing business plan.

To reach this achievement, I propose hence to develop first research on network automation covering network optimisation for core networks, proportional energy consumption networks, clustering/slicing techniques. The mean would be here to apply control theories to network control and management planes (like the research done in the ARC group of the GDR MACS). Our second proposal is to apply those results in IoT and in particular IIoT, where communications are constrained. Considering real plants/platforms, we will deal with smart factories, telemedicine and smart grids. Those topics are here related to the IFAC TC 3.3 over Telematics and we are convinced that control and network specialists should work together at it occurs in the past with the NCS research field. Finally, and before 6G networks, we would like to develop a concept of resource budget for Quality in Sustainability. We would looking also for evaluate the performance of NFV/VNF deployment at the core of networks and the blockchain technology for smart contracts.

8.2 The project

The project that I am forming is thus in line with my previous activities while opening up to new technologies under development/standardisation as shown in Figure 8.1. It is built on the same idea, that QoS, QoE and QiS will have to be all considered at once as an essential triptych. My research is intended to be decoupled in three fields.

P1 with the axis network automation, I intend to continue to develop new algorithms for the control of network (A2). Regarding the technologies under development, it aims at

²⁰<http://smarter2030.gesi.org>

²¹<http://sites.ieee.org/futuredirections/2018/01/25/lets-start-talking-about-6g/>

looking on SDN/NFV technologies with a control engineer point of view. Obviously, I will still lead network performance evaluation activities (A1), viewed as the core of my skills. Preliminary expectations are presented in Chapter 9.

- P2** the axis Industrial Internet of Things is viewed as the next evolution of the former concept of networked control systems (A2) with a specific focus on novel wireless solutions as LPWAN and mostly 5G and evolution of cloud computing (fog/edge) infrastructures. It encompasses also the Industry 4.0 concept and the evolution of telematics systems.
- P3** the axis towards a sustainability budget is the extension of the first contributions for green networking (A3). It consists of the maturation of the concept of resource budget and smart contracts and will consider here benefits of future technology like blockchain.

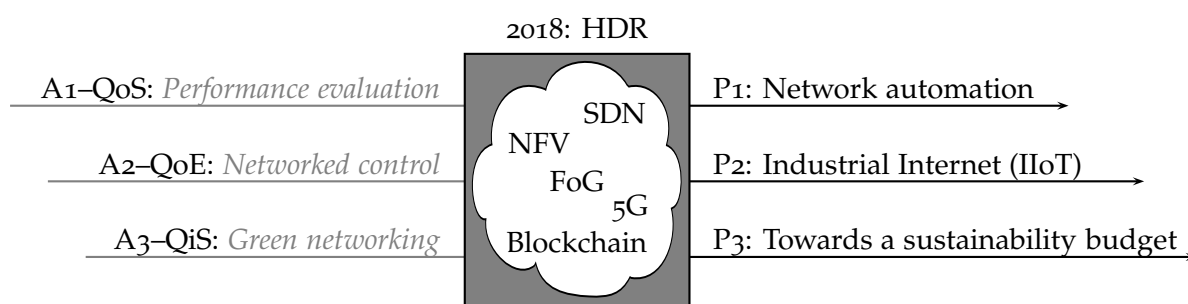


Figure 8.1: Past and future research activities

Table 8.1: Table of the future research topics

Topic	P1	P2	P3	Section/Page
PhD#1: SDN automation for Time Sensitive Networks	✓	✓		8.3.1
PhD#2: Secure and reliable transfer of cardiac signals	✓	✓		8.3.2
Control the energy consumed by an architecture	✓			9.2
Daytime policies and network clustering	✓		✓	9.5
NFV/VNF deployment scenarios at the core of networks	✓		✓	9.6
Blockchains for smart contracts	✓		✓	9.7
Vision of IIoT for factory of future		✓		Page 143
Framework for connectivity & security		✓		10.1.3
Rethink electricity distribution without load following		✓	✓	Page 146
Budget of LPWAN and 5G architectures		✓	✓	10.1.5
Eco-design based on resource budget			✓	Page 152

To support this project, I am considering a specific scheduling. Since I had starting to work on software-defined networking and since it will lead to solutions for the problem that will be encountered in the two other axis, the axis P1 is considered as the short-term perspective. Since axis P2 is the fruit of opportunities for collaboration, I am planning a longer time range (even if preliminary activities might start in parallel to P1 as the ongoing PhD described in Section 8.3.2. The concept introduced with P3 will need even more maturation. As a consequence, P2 and P3 stand for mid-term perspectives, described in the last Chapter 10.

Figure 8.1 may highlight a risk of vertical (the networking protocols and techniques) and horizontal (the axis) silos. However, my project contains a lot of gateway (a given protocol would not be limited to one axis and results in one axis will be used in another one) and is even opened to the solutions that will appear in a mid-term horizon (like the 6G introduced in the previous section). From that point, I am convinced that 5G is going to profoundly change wireless communications (hypothetically replace Wifi for humans?) and will, with TSN, be the expected universal connectivity solutions.

In the next section, I am going to introduce the 2 PhD thesis that I'm going to supervise in 2018 (PhD candidates and funding are secured – contracts with an institution and a company – for each of them). The following chapters contain also other research topics. The Table 8.1 summarises this proposal such that it can be used by the reader to directly navigate to related description.

8.3 Novel PhD supervision activities

8.3.1 Software-Defined Networking automation for Time-Sensitive Networking

Supervisors: T. DIVOUX, J.-P. GEORGES. In collaboration with CNES.

Context:

In time and reliability constrained networks, the various industrial (proprietary) protocols (IEC 61158/61784, 62439 and ARINC 664) are being supplanted by Ethernet-based networks. Previous work has focused on recovering - by analytical calculation - guarantees of Quality of Service (QoS) even though Ethernet does not natively support these requirements (time and reliability). However, most of these protocols include an overlay that modifies the operation of native Ethernet and/or impose different topologies. In the same way, centralised solutions (and singular) allowing to control these architectures were proposed to improve the reconfiguration (real-time) of the paths in case of failure, the prioritisation of the flows, the clocks synchronisation, the management of crazy station or the allocation of bandwidth by flow (and *in fine* the control of the periods of polling). This thesis focuses on two notable developments. On the one hand, in order to devote Ethernet to networks with time and reliability guarantees, its standardisation has been and is enriched by several amendments^a (IEEE 802.1AB, AS, ASbt, AQ, CB, Qca, Qaz, Qat, Qav, Qbv, Qch, Qci, Qbu, Qcc, Qbp, Qbz), amendments grouped under the term *Time-Sensitive Networking* (TSN). On the other hand, the notion of control and data plane decoupling and dynamic network control have been conceptualised under the Software-Defined Networking paradigm (SDN). The combined use of TSN standards and SDN architecture for centralised QoS control should make it possible to dynamically ensure the integrity of these networks (even in the event of congestion).

Problem:

The objective of this thesis is to study the efficiency of TSN automation through SDN architectures. The various TSN amendments introduce a large number of parameters (priorities, VLAN identifiers, credits, cycles, etc.) for which optimisation (at least avoiding over-sizing situations) is necessary in order to satisfy time / reliability constraints. This is all the more delicate as the result of this optimisation depends on the characteristics of

the flows (destination, frequency, size, requirements) which can vary (as can the topology) dynamically over time. In addition, some amendments require resource reservation protocols ((M)SRP or ISIS TLV) that clarify the need for a network controller, and therefore the use of SDN architectures. If the opportunity of the SDN is legitimate, this thesis aims to study the capacity of these architectures to meet the requirements of TSN networks. A first study will thus consist in ensuring that the optimisation functions implemented within the network controller are achievable in times consistent with the system dynamics. A second axis concerns the assurance that the reliability of the network is not compromised by the centralisation of the control (multi-controller architectures with interfaces “east/west” will have to be analysed). Second, it’s important that communications south (OpenFlow, SNMP, NetConf, MSRP, etc. protocols) enable changes in topologies/requests to be detected and reconfigurations to be applied in equally compliant times. Finally, from a control engineer point of view, it will be a question of proposing filtering mechanisms making it possible to avoid the network becoming incoherent (i.e. to ensure the stability of the network control). A particular task will be to identify correlations and conflicts between the different TSN amendments. A unified vision of these amendments is therefore expected.

In the end, the aim of this thesis is therefore the definition of the TSN algorithms/-functions to implement within an SDN controller, the proposal of SDN-type architectures as well as the performance evaluation of the control chain (from detection to reconfiguration). An originality of these works will aim not only at mastering a network, but also at considering the notion of network observability introduced in D. PETIT thesis. The aim here is to ensure that the network control does not call into question network analysis functions, allowing both the detection of network anomaly and the supervision of the controlled system. Finally, and to support time / reliability requirements, virtual machine migration support (Network Function Virtualisation (NFV) concept) would be applied to optimise function deployment on the architecture (802.1Qbg : *edge virtual bridging*).

Experiments:

Previous studies will be validated through experimentation. CRAN has an industrial Ethernet platform with 8 Cisco industrial switches (with PTP support) and a hundred μ -PC. This platform will be enhanced with Cisco Industrial Ethernet 4000 switches supporting the latest generation TSN and SDN protocols. All single/multi controller functions and architectures will be implemented on this platform. Design of experiments will thus make it possible to prototype and benchmark all the proposals formulated in the thesis.

^a<http://www.ieee802.org/1/pages/tsn.html>

I am also considering in the future to integrate to this work the results of the ongoing standardisation activities of IETF DetNet ²²: deterministic networking over Internet.

8.3.2 Secure and reliable transfer of cardiac signals on Internet

PhD candidate: Yaël KOLASA.

Supervisors: T. BASSTOGNE, J.-P. GEORGES. In collaboration with CyberNano.

²²<https://datatracker.ietf.org/wg/detnet/documents/>

Context:

This thesis topic emanates from a double context: thigh throughput analyses in pharmaceutical studies and the increasing use of connected objects for monitoring patients' health status. In both cases, the objective is to be able to transmit cardiac signals for remote treatment. In recent years, the technological evolution of measurement systems in pharmaceutical laboratories has considerably increased the accuracy and quantity of data produced during preclinical analyses. Real-time cellular impedance-metry, field potential electrode chips and high-resolution fluorescence video-microscopy are all measurement tools that generate files from a few GB to a few hundred GB with each experiment. This inflation in data size has two direct consequences: the problem of data storage and the problem of data sharing. In addition, there is a constraint because some of this data may contain sensitive information, the confidentiality of which must be preserved.

In parallel with the development of new measurement technologies in laboratories, more and more portable consumer goods are available and allow daily monitoring of cardiorespiratory activities over long periods, much longer than a simple ECG (10 s) or a Hölder test (24 h). The size of these long tracks also poses transfer problems to which are added network connectivity constraints. In summary, in both cases file sizes can quickly lead to long transfer times and dissatisfaction with the quality of the user experience.

Problem:

We wish to develop new applications in monitoring cardiac activity at home. Regardless of the new technology used and the final application targeted, the collection of cardiac activity measurement signals requires a sampling period between 200 Hz and 1 kHz which rapidly leads to the production of large measurement files whose final processing is centralised. A reliable, safe and quality transfer (in the QoS and QoE sense) requires first estimating the effects of all the technical parameters involved in the transfer. Once identified, the second issue to be addressed consists in designing the architecture and setting of accessible parameters to optimise the three responses of interest: service quality, reliability and security. In response, we wish to implement an approach combining modelling and simulation of network solutions under the OMNeT environment and digital experiment planning for robustness analyses and multi-criteria optimisation. This subject is part of the logical continuation of the research master's subject currently being carried out by Y. KOLASA.

In the IoT field, several architectural and protocol solutions are currently being defined or even standardised by different organisations (IEEE Internet of Things, Open Group, W3C, etc.). These solutions are attached to all or part of the OSI model. These include M2M Machine-to-Machine protocols (MQTT, AMQP, CoAP, LoRa, 802.15.4, 6LoWPAN, TRILL, etc.), protocols addressing the Back-End Data-Sharing Model through standardised and open APIs (O-MI/O-DF, Big- IoT/WoT, SensorThings API, etc.), or those related to the Semantic Web. Generally based on Web services type solutions, these solutions, by nature adapted to the instantaneous publication of measurements (limited volumes) on a central storage architecture, are relatively different from transport protocols designed for transporting multiGB files. Congestion control is thus limited to basic Internet solutions (i.e. TCP/UDP) without taking into account the specificities of a wireless local loop. A transport not adapted here can result in a failure of the transmission (due to the non-recovery of packet losses) or an increase of the transfer time (of several tens of minutes) requiring the maintenance of the connection.

It is therefore important to benchmark here all the solutions (protocols and parameters) currently proposed that could adapt to the cardiac signal framework. Performance will be based on QoE criteria such as end-to-end transfer time or reliability. And since sensors can have computing and storage resources, this study must identify a trade-off between immediate data transfer (requiring continuous connectivity) and temporary local storage before transmitting a large file. If work exists within the framework of large file transfer for health on the Internet, the quality of data transport such as cardiac signals on an IoT architecture has not yet been taken into account (except at the semantic level such as the HL7 vocabulary for health). The aim is to propose, depending on the context, the reference transport architecture to be implemented and to specify the QoE for users (patients, laboratories, doctors).

8.4 Collaborations and involvement in scientific communities

First circle of researchers in CRAN I intend to work with belong to the green networking team: Professors T. DIVOUX, É. RONDEAU and Associate Professor S. KUBLER. As my project share different topics (mainly IoT) with the department Sustainable systems engineering, I will look for collaboration with researchers of the department, in particular in the field of Industry 4.0. As mentioned in the following, I'm planning to work jointly with researchers of the departments Control, Identification, Diagnosis (CID) and Biology, Signals and Systems in Oncology and Neuroscience (BioSiS) (like in the framework of the PhD detailed in the previous section).

At the national level, my project in line with the GT Automatique et Réseaux de Communication (Control and Networks) of the GDR MACS. At the international level, I will pursue collaboration with different researchers of the EMJMD PERCCOM (Luleå University of Technology, Leeds Beckett University, ENEA). In the framework of the project KIC EIT RawMaterials, I am planning also to work on 5G networks with Aalto University. I am also working with J. ROBERT, researcher scientist at the Interdisciplinary Centre for Security, Reliability and Trust in Luxembourg, on connectivity issues in IIoT.

As Vice-Chair, I am also engaged in the IFAC Technical Committee 3.3 (Telematics: Control via Communication Networks). Finally, I planned to associate to my project P₃ the community of the IEEE Green ICT initiative and engineers from Orange (M. VAUTIER) and Infovista (R. LERBOUR) companies.

8.5 Teaching project

As Associate Professor, I formed a teaching project in line with my research perspectives. As mentioned in Chapter 3, I was brought to work during the academic year 2016/2017, for the Networks & Telecommunications sector on the accreditation application files for the License SPI and the Master ISC in preparation for the start of the 2018 academic year. For the licence, it consists of the specialisation Networking & Telecommunications into the track Digital Systems and for the Master of the track Networks, Signals, Green ICT ("Réseaux, Signaux, ÉcoTIC" (RESET)).

The syllabus that I have designed aims at preparing students according to the skills and knowledge in networking mentioned in the ROME sheets M1804 (Études et développement

de réseaux de télécoms)²³, M1801-3 (Systèmes d’information). Roughly speaking, the Table 8.2 shows the mapping of the units in networking and the activities defined in the M1804 sheet.

Table 8.2: Mapping of the units in networking and the activities defined in M1804

		A1	A2	A3	A4	A5	A6	A7	A8
S7	Networking			☒	☒				
S8	Architectures IoT		☒	☒	☒				☒
S9	QoS/QoE <i>Green ICT</i>	☒	☒			☒	☒	☒	

The RESET track shares also the vision for green networking and QiS according to the M1804 sheet (Conseil en organisation et management d’entreprise | Chef de projet green IT). To note that the track includes also a discovery of data-science/data-mining.

The fitness of my future teaching activities with my research project is also emphasise if we considered some units I integrated in the syllabus and for wich I will serve as teacher (and even responsible):

- UE Wireless communications & Mobility (teaching of LPWAN and 4/5G), L3 SPI: P2
- UE Internet architectures (with introduction to SDN/NFV): P1
- UE Internet of Things, M1 ISC : P2
- UE Quality of Service & Quality of Experience, M2 ISC
- UE Green networking (with introduction to QiS), M2 ISC: P3

Finally, I an engaged in the future to reinforce the collaboration between the Licence (at FST) and the department R&T of IUT Nancy-Brabois and between the Master (FST) and the engineering schools in the University of Lorraine.

²³<http://candidat.pole-emploi.fr/marche-du-travail/fichemetierrome?codeRome=M1804>

Chapter 9

Short-term perspectives: Network automation, control and data planes (P1)

This chapter is organised as follows. Section 9.1 introduces a general formalisation of network automation issue. It is based on the framework of Software-Defined Networking (SDN) that is defined, by Open Network Foundation (ONF), as a new network architecture where the network control, directly programmable, is separated from the data plane. The purpose of SDN is hence to abstract the network in order to simplify its use and its configuration. [XWF⁺15] and [KRV⁺15] present two surveys on SDN. Next, expectations are detailed for two single issue: mitigating the energy consumption (Section 9.2) and maximising the QoS (Section 9.3), and an unified issue taking into account daytime policies and network clustering (Section 9.5). After that, I am planning to consider two (future) technologies: visualisation (NFV/VNF) vs (energy) consumption (Section 9.6) and blockchain (distribution over peers) vs SDN (centralisation) (Section 9.7).

9.1 Control, forwarding and management planes

The topology

Assume a network architecture. The physical topology is defined by a directed graph $\mathcal{G} = (V, E)$, comprising a set V of vertices $i \in \{1, 2, \dots, |V| = n\}$ together with a set E of edges (i, j) , which are 2-elements subsets of V .

For a simple graph with vertex set V , the adjacency matrix is a square $|V| \times |V|$ matrix A such that its element $A_{i,j}$ is 1 when a link exists between two nodes i and j and 0 when there is no edge. The diagonal elements of the matrix are all zero, since edges from a vertex to itself (loops) are not allowed in simple graphs. In the framework of Software-Defined Networking (SDN) and more generally speaking network automation, we would consider that the topology is redundant, which means that several paths (i.e. more nodes and links are added - offline - to the physical topology) are available. As a consequence, the forwarding and the management planes might be logically controlled and optimised (and some parts of the topology would be configured in an hibernation mode...). One may note here the relation with Cyber-Physical Systems (CPS) in which the system is over-actuated...

The capacities of each link are gathered in a (square $|V| \times |V|$) matrix C . $C_{i,j}$ represents

hence the capacity of the link (in Mb/s) between nodes i and j . It might be seen as the weight of the edge. To note here than however we are not going to directly work with a weighted graph in which the weight is directly given by $A_{i,j}$ as we will assume in the following that this capacity might be controllable when other parameters, i.e. \mathcal{G} , are not. The value of $C_{i,j}$ is expected to be part of a predefined set that contains the different capacities (for instance, we might have $C_{i,j} = 0$ if $A_{i,j} = 0$ -no link exists-, 10 for a 10 Mb/s link or 100 for a 100 Mb/s one).

The data plane & a first (QoS) flow (SLA) requirement

The graph \mathcal{G} represents the static part of the network. We introduce now the dynamic part, i.e. the traffic demands. We are given a set $\mathcal{K} = \{1, 2, \dots, K\}$ of Origin-Destination pairs. Let s_k and t_k be the origin and the designation of pair k and let $\lambda_k \in \mathbb{R}^+$ be its traffic demand (equal here to the throughput in b/s).

The control plane consists for each demand to define for each node the next hop to reach a given node. In a redundant topology, several paths can be available for a given origin-destination pair. However only paths satisfying both the throughput demand and the capacity limitation can be considered. We introduce then a set Π that will gather the forwarding decision (i.e. the routing strategy) for all flows over all nodes. Π is defined such that $\Pi_{k,v}$ gives the node $v + 1$, i.e. the node adjacent to the node v into the path p_k ($\Pi_{k,v} = v + 1$) or \emptyset if the flow is not going to be forwarded by node v . A path $p_k \subseteq V$ can be hence easily retrieved from Π_k since $p_k = \{s_k, \Pi_{k,s_k}, \Pi_{k,\Pi_{k,s_k}} \dots, t_k\}$.

Obviously, different paths are possible such that several forwarding planes are available. The matrix Π , i.e. the global forwarding (routing) table, should however respect the following constraint for a demand i :

$$\forall v \in \{p_i - t_i\}, w = \Pi_{i,v}, \text{ such as } \sum_{k \in \mathcal{K} \mid \Pi_{k,v}=w} \lambda_k \leq C_{v,w} \quad (9.1)$$

It ensures that only existing links are considered and that all links will be able to support the associated total throughput. This QoS requirement will be hence only reached if a control plane satisfied the previous constraint exists. Obviously Π_k has to be checked in order to ensure it corresponds to a valid simple elementary path, but we are not going here – for simplicity – to mention the relevant constraints.

A control plane

In addition to the data plane Π , we assume now that the link capacities can be controlled. More exactly, it is assumed that the capacity of a link can be switched over different values, from the maximum capacity defined by C to 0 (i.e. both end interfaces are shutdown). We gather those decisions into the matrix Γ (initially, $\Gamma = C$) and we replace C by Γ in equation (9.1). $\Gamma_{i,j}$ value can only be retrieved from the set defined above. Since it governs the forwarding of a frame, we will call Γ the control plane (even we know it might be confused). Obviously, it is expected that if $\Gamma_{v,w} > 0$, traffic should be forwarded from v to w or the reverse.

The management plane

Consider the 7 nodes network shown in Figure 9.1a. Regarding the 3 demands and the links capacities, control and forwarding possible planes are respectively shown in Figure 9.1b and 9.1c. The management plane is in charge of the configuration of the nodes according Π and Γ . For instance, it will limit the bandwidth on the link between nodes 1 and 7 to 10 Mb/s and it will shutdown each interface of the link between nodes 1 and 2 since it is not anymore useful.

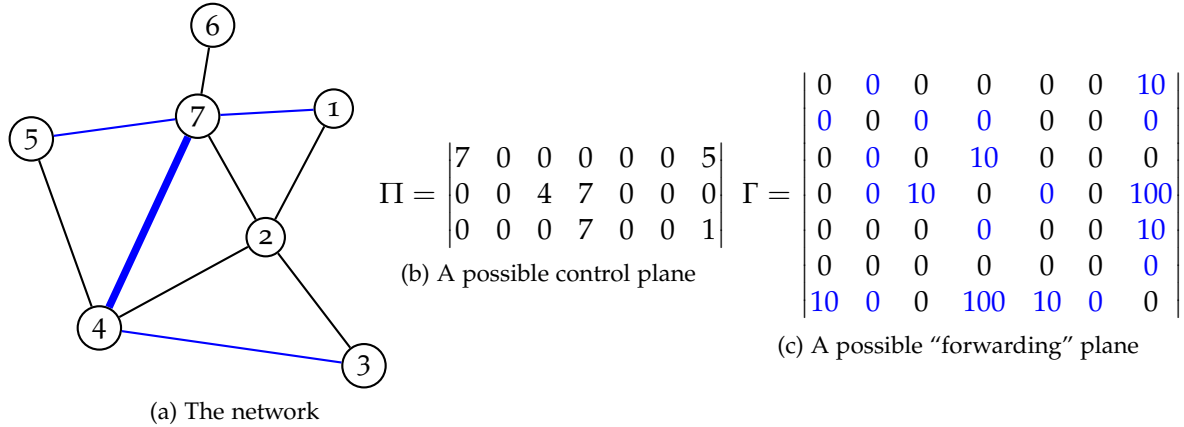


Figure 9.1: Planes for 3 demands: $\mathcal{K} = \{\{s_1 = 1, t_1 = 5, \lambda_1 = 5 \text{ Mb/s}\}, \{3, 7, 9\}, \{4, 1, 3\}\}$. All links are full-duplex, 10/100 Mb/s

Each time a control/forwarding plane will change (due to a demand or a topology change), configurations will be required such that the relevant complexity (of the management plane) need to be consider as a penalty. This is in fact linked to the control objective that is considered (and the cost of a plane). We propose hence to focus in the following on two issues: a first one typical from green networking, a second one more related to traditional QoS considerations.

9.2 Problem #1: the energy consumption

The first problem that is important to focus on concerns the minimisation of the energy consumption of the network architecture.

We introduced this problem with the Msc Thesis of A. MALEKI [Acti.38] (Section 7.2.3). We are going to develop it with the PhD Thesis of Md M. HOSSAIN²⁴ who is supervised by É. RONDEAU and T. DIVOUX at CRAN (Software Defined Network for greening internet communications)²⁵.

To formalise the cost of a control plane in terms of energy consumed, we present a simple model of energy consumption of each active device.

The energy consumption modelling

The model will be used to predict the overall energy consumption and to optimise the forwarding table. Previously, we have modelled the energy consumption of a typical network device

²⁴http://www.cran.univ-lorraine.fr/detailsujetpublic.php?appel=form_rech&codetheme=07&codelangue=EN&codesujet=01016

²⁵We are working currently on optimising the energy consumption of the European GÉANT2 backbone [Acti.38].

(Cisco Ethernet switch) by design of experiments (Msc Thesis of Md M. HOSSAIN [Acti.30]) and fuzzy logic (Msc Thesis of A. FITHRITAMA [Acti.29]). Similar models can be nowadays found in the literature, even for different devices. To simplify, it is assumed here that a node v energy consumption follows the linear model:

$$\mathcal{E}_v(t) = \int_0^t \left(\alpha_v + \sum_{w \in V} \delta_{v,w} \beta_{v,w} \right) t \cdot dt \quad (9.2)$$

where \mathcal{E}_v in W , α the switch power consumption (when no interfaces are activated), $\delta_{v,w} = 1$ if $C_{v,w} > 0$ and 0 else (to know if the interface to the neighbour w is used) and $\beta_{v,w}$ the power consumption of the interface port itself. The model consists hence of two parts: a fixed/static one that has to be paid each time the node is turning on and a dynamic one that will depend to the control plane.

Based on that model, we are considering a green strategy that consists to turn off any nodes and links not used by the routing strategy.

The plane cost & the objective function

In terms of energy consumption, the cost of a control plane corresponds hence to the sum of the energy consumed by each node involved in the routing strategy. Consider the two following binary variables:

$$\delta_{\Pi}^v = \begin{cases} 1 & \text{if } \sum_{k \in \mathcal{K}} \Pi_{k,v} > 0 \text{ or } v \in \Pi \\ 0 & \text{else} \end{cases}, \quad \delta_{\Pi}^{v,w} = \begin{cases} 1 & \text{if } \exists k \in \mathcal{K}, \Pi_{k,v} = w \text{ or } \Pi_{k,w} = v \\ 0 & \text{else} \end{cases}$$

A node v is used in the control plane if it forward ($\sum_{k \in \mathcal{K}} \Pi_{k,v} > 0$) or receive ($v \in \Pi$) frames and its interface to the node w is used if v (and respectively w) is the next hop for at least one demand k . The cost of a control plane Π can be hence computed as:

$$\mathcal{E}_{\Pi}(t) = \int_0^t \sum_{v \in V} \delta_{\Pi}^v \left(\alpha_v + \sum_{w \in V} \delta_{\Pi}^{v,w} \beta_{v,w} \right) t \cdot dt$$

According to the selected paths, it means some nodes and some links might not be used by defined as previously. If no *green* (turning off - put in hibernate/sleep state - non used devices) policy is applied, the previous (equation) statement will stay true (whatever the traffic load, no daylight policy) since the (physical) topology will run until its dismantlement. We are then going to apply a simple green policy: *any switch and any link unused will be turned off*. Not used nodes/links will correspond to the ones not involved in the forwarding plane. If a switch has more interfaces (even not used by the physical topology), they will be turned off too.

In previous works, we have shown that network devices are not acting yet as energy-proportional computing since the traffic load has a very limited (negligible) impact on the overall consumption. Furthermore, turning off nodes and even links is not always possible like in the core network backbone (as the GÉANT2 network) due to end-hosts that demand high availability and full-time connectivity even if the network is not used [GCNS08].

We propose hence to investigate here the two main approaches defined in [HO17], both exploiting the lower charge periods to either put to sleep some hardware elements (sleeping) or adapt the network rate to the actual traffic level (rate adaptation). The first one is related

to the standardised Low Power Idle (LPI) mode [CRN⁺10] (norm IEEE 802.3az). The basic idea of this Energy-Efficient Ethernet (EEE) standard consists in sending packets as fast as possible and entering a low-power idle state when there is no data to transmit. The second one most famous implementation is Adaptive Link Rate (ALR) which has been studied in [ZSGRG08, HO17, GCNS08]. It consists of decreasing the link capacity in order to benefit of a low power consumption.

The objective will be here to develop joint (routing and forwarding) strategies that will extend the previous studies that have focused on the individual performances (like latencies) of each mechanism. In the ALR case, the matrix Γ gathers the decisions (for instance, Figure 9.1c shows that the link capacity between nodes 1 and 7 has been decreased to 10 Mb/s), such the power consumption $\beta_{v,w}$ will now vary according to the link capacity. Hence, the problem is, while satisfying the demands requirements (elementary paths, throughput, links capacity limitations), as follows:

$$\left(\hat{\Pi}, \hat{\Gamma}\right) = \arg \min_{\Pi, \Gamma} \int_0^t \sum_{v \in V} \delta_{\Pi}^v \left(\alpha_v + \sum_{w \in V} \delta_{\Pi}^{v,w} \beta_{v,w}(\Gamma_{v,w}) \right) t \cdot dt \quad (9.3)$$

We propose here to consider for illustrative purpose that $\beta_{v,w}(\Gamma_{v,w} = 10 \text{ Mb/s}) = 0.1 \text{ W}$ when $\beta_{v,w}(\Gamma_{v,w} = 10 \text{ Gb/s}) = 21 \text{ W}$. More models could be also identified (especially in the specific case of wireless links for which it exists a direct link between the capacity and the sending power).

We would also take into account a third plane, the management plane, that gathers the functions used to control and monitor devices. It covers the network automation/management protocols like the historical SNMP, the famous SDN OpenFlow or even more recent like Net-Conf (there are usually associated to the south interfaces). Issues to be taken into account concern real-time requirements [SGMP17], detection and reconfiguration latencies, additional energy costs, controllers placement and actions ordering. Such protocols are both in charge to refresh the list of the demands \mathcal{K} , to turn off/on (which remains a technical challenge) or put in hibernate/sleep state nodes/interfaces and to apply any new routing rule and capacity command (respectively from Π and Γ). From a control engineering point of view, it will address also the stability of the command to switch from a plane to another one. It will lead to a new objective:

$$\left(\hat{\Pi}, \hat{\Gamma}\right) = \arg \min_{\Pi, \Gamma} \int_0^t \sum_{v \in V} \delta_{\Pi}^v \left(\alpha_v + \sum_{w \in V} \delta_{\Pi}^{v,w} \beta_{v,w}(\Gamma_{v,w}) \right) t \cdot dt + \Omega(\Pi, \Gamma) \quad (9.4)$$

$\Omega \geq 0$ will hence correspond to the cost to switch from the actual control and forwarding planes (Π_0 and Γ_0) to the optimal new ones ($\hat{\Pi}$ and $\hat{\Gamma}$). This management plane cost (or reconfiguration penalty) could correspond could be related to energy consumption or latency and Ω might be seen as a penalty function.

One way to address this reconfiguration penalty would be as a filter at the output of the controller, filter that will decide to apply (or not) the reconfiguration. One idea will be to apply it only if the current plane does not satisfy the demands and/or if the new solution has a gain (in terms of energy) superior to the cost to reconfigure and/or if the stability is not going to be engaged. This output filter would be the place where the stability issue is tackled.

Expectations

Due to the number of edges, vertices, flows, capacities parameters, etc.; the solution will hence probably be built with heuristics and techniques like (Mixed) integer linear programming (ILP) or other methods like genetic algorithm (as currently investigated in Md Mohaimenul HOSSAIN PhD thesis) or spectral algorithm.

Basically, the idea is that the demands share as much as possible common paths, such that a maximum number of nodes and links would be turned off. It acts as the problem of building tree over a graph. However, there is here no constraint to get one single tree (since such objective might maximise the number of nodes) and the problem to find the best tree (i.e. the STEINER tree) is NP-hard. We would investigate the algorithms (protocols) developed for multicast routing (for instance RPF with Pruning or CBT) as a tentative to build faster multiple trees satisfying equation (9.4) and spanning all demands.

In order to take into account the load, we propose also to formulate the cost of an architecture when the LPI mode is activated. A key question to be answered is: when the ALR and/or the LPI modes would be used? As a tentative, we can already suggest that ALR is interesting when the load of a given link is closed to a bottleneck situation (for one of the capacity supported) whereas LPI would be more related to low traffic load, when bursts mode can be supported. For LPI, we would be also interesting in mixing network calculus delay analysis with arrival curve dedicated to energy. The idea is to develop here energy curve in focusing more on max-plus analysis.

9.3 Problem #2: the demands' throughput and end-to-end delay

We are considering here a second problem that is more dedicated to conventional QoS issues.

We introduced this problem with the PhD thesis of D. PETIT [Acti.44] and we will worked jointly during her Postdoctorate (100 % ATER) in CRAN during the academic year 2018/2019.

In the framework of an embedded network, the goal is to provide as much as possible throughput to all flows, under a minimal constraint and a maximum end-to-end delay performance.

The admission control

The objective is here to control the load of the network by the means of the throughput of each demand using admission control on each device over the network.

It is assumed that each node supports a mechanism to regulate the traffic. It may consist in a Class-Based Weighted Fair Queuing (CBWFQ) fitted with a drop policy (that limits the throughput for a class in terms of rate and burst). Whereas such policy exists over switched Ethernet networks, other mechanisms like RED AQM, MPLS-TE Tunnel-Based Admission Control, BAG in AFDX or meter in OpenFlow v>1.3 networks can correspond to that definition. It enables to ensure a minimum / maximum bandwidth service to a flow (when a class is equal to a flow). The weighted round robin guarantees the minimum service and the dropper discards the packets when the flow tried to send more than the agreed arrival curve (such mechanism will be also interesting to manage storm control policies or even crazy station in embedded networks like the Ariane launcher).

The idea is even to offer to each demand the maximum admissible throughput (adaptive sampling), i.e. to offer, for a demand k , a rate superior to λ_k . Each demand is also associated to

a constraint regarding a minimal throughput requirement λ_k and a maximum end-to-end delay Δ_k . We will use the network calculus theory to compute worst end-to-end delays regarding the control plane Π and to take into account (non-)nested architectures, the TFA/SFA analysis. An arrival curve (σ_k, λ_k) is hence associated to each demand such that greedy sources (supporting an adaptive sampling mechanism) will send in average no more than λ_k . We consider also that each intermediary node along the path defined in the plane will limit the throughput to the same value λ_k .

The plane cost & the objective function

Each path in the plane should offer a throughput superior or equal to the demand's requirement and inequation (9.1) has to be verified.

Solving such problem (maximise the service offered) would be perceived differently from the customer or the provider. Each source expect the maximal throughput for itself whereas the provider want to satisfy the maximal number of sources. We would hence be interested in considering fairness services. We propose firstly to consider a linear utility function:

$$(\hat{\Pi}, \hat{\lambda}) = \arg \max_{\Pi, \lambda} \sum_{(v,w) \in E} \frac{\sum_{k \in \mathcal{K}} \delta_{\pi_k}^{v,w} \lambda_k}{C_{v,w}} \quad (9.5)$$

Equation (9.5) leads to use all links of the physical topology at their maximum capacity, i.e. the maximum value (the number of links $|E|$) would be reached in case of bottlenecks links. If we would not be interesting in balancing the traffic over the full architecture maintained by the provider (the client point of view), the problem would be relaxed as:

$$(\hat{\Pi}, \hat{\lambda}) = \arg \max_{\Pi, \lambda} \sum_{v,w \in V^2 \mid \delta_{\Pi}^{v,w} > 0} \frac{\sum_{k \in \mathcal{K}} \delta_{\pi_k}^{v,w} \lambda_k}{C_{v,w}} \quad (9.6)$$

Here only the links used in the plane Π are considered.

Compared to the previous problem, it may be noticed that the list of the rate limitation λ_k offered by each node to each demand would correspond to the control plane (i.e. Γ).

The value λ_k would hence depend on the plane, since the more a demand is in competition with other demands, the more it will have to share the capacity (even if a single demand would ask for $\lambda_k \geq \min_{v,w \in V^2 \mid \delta_{\Pi_k}^{v,w} > 0} C_{v,w}$).

Expectations

As for the previous problem, solutions would be built *via* heuristics. We would be interesting to evaluate both approaches, first the control plane and then the throughput limitations and the reverse. We propose to use the network calculus to ensure the delay requirements rather than a weighted graph approaches that will not enable to tackle end-to-end performances and phenomena like pay bursts/multiplexing only once [BS14]. Considering the delay, algorithms like DIJKTRA or YEN could be interesting. But considering the throughput allocation and equation (9.5), we are committed to study FORD-FULKERSON (or modified solutions giving the n -best solutions of the maximum flow problem) since disjoint paths could offer more bandwidth.

Regarding the throughput allocation, it acts as a discussion about fairness. Obviously, equality would not provide the best results, so we would study the linear, proportional

(for instance to the path length) and max-min fairness (though algorithms that will increase λ_k for each demand until it leads to a dip in other demands performance). We would also support traffic priorities (classification of service), enabling to reserve more resources to specific demands.

9.4 Towards a full set

It is finally important to note here that if an online optimisation heuristic is the core of the solution, computation times have to be considered here, especially since optimisation will have to be relaunched each time that an input (flow requirements) changed. It may lead to unstable control law, issue that should be solved. The placement of the controller(s) would be also a challenge that as not yet so much be studied (especially in the following case of observability).

With the development of LPI technologies (and especially in the context of wireless networks like LiFi and InfraRed communications), we think that the two previous problems would have to be merged. Here, we would also take into account the packet aggregation mechanism (previously studied in D. BRECK Phd Thesis [Bre15] for its temporal performances with the duality between the client and the provider point of views) and other advanced load balancing mechanisms. We are convinced here that control engineering theory might help to develop control law that will be able to tackle the complexity and the stability of the architectures.

Requirements for resiliency would also have to be supported. The problem presented previously at the control plane as the finding of single unicast path for each demand would be here updated. Planes would have to consider multiple routes for each demand (the nominal plus backup routes that could be used simultaneously for real-time systems). Furthermore, multicast path could be challenging when a demand as to reach several destinations [SZWB17]. This is typically the case in the Ariane launcher embedded networks in which a monitoring station collects a copy of all frames over a switched architecture. This leads us to propose a new line of research that we are calling observability. The idea is that the health of a system (and its control) would be only checked by analysing the simple presence of packets over the network. We would study here the possibility to develop new services/functions over the controller (NOX) that would run algorithms (based for instance on finite automata). Observing the network activity would hence enable to track the activity generated the control system plus the network states. We would expect recorder applications able to “replay” a networked system. Such application would be also interesting for understanding a faulty scenario and even to qualify future networked architectures. To our knowledge, this problem of (network) observability in a centralised approach have not been really fully studied and it would be sensitive to different parameters: specific latencies requirements, placement of controller(s), etc.

9.5 Dynamics: daytime policies and clustering/slicing

At the same time, the source of energy generation (and as a consequence the CO₂e pollution) changes along the day. Even if solving the problem #1 and the equation (9.3) would take it into consideration, we are interesting in developing algorithms that will identify

specific patterns for which precomputed planes will have been offline computed. It is expected here that methods enabling to take into account *a priori* knowledges would be useful (we may be interesting to reuse our previous study based on fuzzy logic developed in [Acti.29]).

Secondly, to avoid the spreading of the load over a topology and to limit the congestion domain, clustering study could be performed in order to regroup nodes highly connected. A similar issue occurs when a tuning off policy is applied (to save energy). It will be only possible to turn off a node if it is not anymore sending/receiving traffic to/from its neighbours. It leads to identify cluster of nodes for which a common activation policy would be applied and such that a full cluster of the architecture could be turned off. We would hence study clustering techniques for an architecture. More particularly, we are interesting in adding the support of the time evolution of the cluster whereas clustering has been studied in networks to solve the initial physical interconnection of the end-to-end devices to the infrastructure. We would consider hence techniques like spectral algorithms. Clustering would be also studied in the case of NFV (Network Function Virtualisation). Here a service can be virtualised over different machines, and the question of the allocation of the clients over the different virtual servers remains a trick, which is here not limited to "geographical" considerations. The same occurs when an architecture is sliced in different parts (that might be recovered), for security purposes for instance.

9.6 NFV/VNF deployment scenarios at the core of networks

The following topics correspond to the proposal of a PhD thesis for an EJD application. I wrote it with M. VAUTIER from Orange and it is related to the project Clearwater²⁶.

To evaluate the benefits of network virtualised functions, we propose an evaluation of the electrical power consumed by a Network Functions Virtualisation deployment.

First, we will focus on the Hosting Infrastructure Services deployed by an IT provider. In order to fully take benefit of a demand network and services transformation leveraging Software-Defined Networking (SDN) and Network Functions Virtualisation (NFV) facilities ("self-care" and automated delivery of corresponding services), a standard and shared hosting IT infrastructure, called Hosting Infrastructure Services (HIS), is defined to allow agile and rational deployments of various workloads and use-cases.

The HIS architecture design depends on (i) the nature of the workload (service platform, information systems, network), (ii) the nature of the data centre (regional, national, local) and (iii) the nature of the final service deployed (centralised in one data centre or distributed). Consequently, different HIS design *scenarii* are considered to answer these different possibilities. Among them is the so called "Design Scenario 3" design, mainly aiming at supporting virtual network use-cases (e.g. virtual Evolved Packet Core) which topology is distributed by nature. A "Design Scenario 3" cloud covers a national landscape with multiple Points of Presences (POPs), either centralised or geographically distributed closer to the end-user. Basically, centralised POPs handle service control functions such as Virtual Network Function (VNF) manager, service and resource orchestration. VNF workloads can be supported on both centralised and distributed POP. On top of the virtual infrastructure, the HIS is completed by a centralised common services layer, managing multiple POPs, which provides common infrastructure services such as web proxy, re-

verse proxy for web flows, firewall, and so on.

The goal to be reached consists then in developing different methodologies to assess the maximum energetic impact of existing virtual network (order of magnitude) including also the technical environment. It will require obviously measurements of electrical dimensioning for each NFV deployment scenario.

Secondly, we will focus on data centres that require a tremendous amount of supplied electrical energy to operate. Even if the main part is related to cooling issues, network power consumption can account, in certain scenarios (energy vs load), for nearly 50 % of the overall data centre power consumption [AMW⁺10]. For [MSG⁺16], NFV will yet likely make data centres an integral part of telecommunication networks and therefore, there is an urgent need to study whether NFV will meet its energy savings expectations, or whether –like the NFs– the energy consumption will just be transferred to the cloud; and in definitive, to the data centres. In the context of energy efficiency, [MSG⁺16] report some works focusing on mainly measurements on the effect of transferring network and user functions to the cloud and on simulation of possible energy saving resulting from NFV. However current approaches on power consumption suffer from not taking account the state of the service regarding its life cycle.

We would like hence to address the whole service life cycle assessment in considering their carbon emission and encompass the scale variation of the usage of a service. It would lead to an eco-design of the different network functions driving by a resource budget (gathering QoS, energy and business costs) associated to each demand/service. The optimisation of the network should now take into account the state of the service and to respect its associated budget. The analysis would have to consider the different nature of data centres (regional, national), of the final service deployed (in one data centre or distributed), of the workloads (computationally intensive or data-intensive, distributed load, data-driven load) and finally of the network architecture (two-tier, three-tier, BCube, DCell [FKBZ17]). Results are hence expected here about energy-aware function placement chaining and consideration of inter-data centre communications. Solutions would also taking into account advanced metric like communication network energy efficiency, network power usage effectiveness, and energy proportional coefficient. The budget could be completed by new power consumption models for the energy efficiency, especially to asses each deployment scenario. Other notions like state-full data planes approach and trust (and its impacts on network design) could be also integrated in the budget notion. Design pattern and filtering solutions could be also studied to face with the stability of the network control. We expect to consider validation of the results though simulation (for instance, GreenCloud [KBK12]).

Finally, to reach the resource budget concept and the life cycle assessment, we would consider how NFV operations focus on IT Information Library (ITIL) processes and the Enhanced Telecommunications Operations Map (eTOM) framework.

9.7 Blockchains as silos' breakthrough and for smart contracts of a new economy

I have worked with S. KUBLER since his recruitment as Associate Professor at CRAN in 2017. The following includes parts of his proposal: CONCERTOs: Towards efficient bLOCKchain-based SDN arChitEctures in IoT ecOsystems.

One of the remaining challenges in network automation is related to trust and account-

ability across controllers/domains (that should be taken into account in the infrastructure budget). The blockchain paradigm has created a whole new playing field, offering powerful tamper-proof logging and auditing capabilities that can help tackle such issues and challenges. An interesting feature of blockchain is that trust and control is not centralised, but rather decentralised, making it possible to validate transactions without requiring a central trusted authority. It should enable the consideration of third parties software apps (that could be for instance embedded in an SDN controller) or even third parties infrastructures (INTERconnected NETworks). We plan to develop research both for facilitate cooperation between IIoT network silos and for improving the confidence in automatic SLA sensors (measuring service level objectives (SLOs)).

As shown previously, a large set of IoT protocols and technologies are already available. As a consequence, an organisation can aggregate different networks. It can be explained by a limited deployment of an innovative technology to a part of the plan and not uniting resulting data islands (because of the cost of a total restructuring of the infrastructure or machines obsolescence) or simply, by a non convergence of industrial and enterprise networks. Companies and their stakeholders could be also spurred to share their (data) infrastructure, but for tactical or trust issues are not doing so. At the end, each silo could be governed by specific and autonomous (non cooperative) SDN controllers.

To eliminate such network silos (especially in IoT ecosystems, where hundreds to thousands of SDN controllers/apps may need to cooperate/interact), blockchain could be used to improve to the authentication and the accounting of the east/west transactions between controllers (i.e. silos). However, research dealing with using blockchain capabilities in SDN networks, has essentially focused on functionality and architectural detailing so far, and not on the impact that the proposed solution may have on the end-to-end system performance and SLA (/SLO) guarantees. We are hence interesting in analysing, identifying and mitigating the impact(s) of blockchain on multi-SDN app/controller-powered applications. In particular, we want to formalise the end-to-end "latency" for converging towards desired system states (QoS metric). We would like also to evaluate the excess electricity consumption (QiS metric) introduced by the blockchain (will require to develop new models, taking into consideration traffic exchange and miners processing). Such evaluation will be achieved through design of experiments to tackle the broadcasting parameters (block size, interval, ...), the underlying consensus algorithm, the network topology characteristics and QoS parameters, the SDN-app logic and functions (routing, attacks' detection, provisioning), etc. In the long run, it would lead to self-adaptive blockchain broadcasting strategies (like off-chain consensus algorithms) and clustering issues to optimize the ressources reservation over the fog (or even at the edge).

With more confidence and accounting in transactions, we think that blockchain could be helpful then to develop automatic SLA (/SLO) measurements robots. In fact, we aim at simplifying and automate the verification of the service level defined in the contract between the client and the provider. Robots monitoring QoS metric are available, but each contractor will not trust measurements given by the provider and will conduct its own measurements. This lack of trust could be filled with blockchain as it will certify the validity of the data and even provide historian. It will lead to smart contracts, smart because automatically verified in both side agreement.

To fulfil the resource budget concept, we would however extend existing sensors for sustainability achievement through Green SLA. GSLA would be a formal agreement incorporating all the traditional commitments respecting the ecological, economical and ethical

aspects of sustainability. Such contract will hence incorporate the resource budget and metrics (like those defined in [RSR⁺17] - 12 greenness metrics) mentioned in the GSLA or rules like those introduced in Janine BENYUS in her book "Biomimicry" Biomimicry: Innovation Inspired by Nature (the ten commandments of ecomature system).

Finally, eco-sustainability assessment, providing end-users (both developers and citizens) with dynamic and easy-to-use solutions helping them to understand, and most importantly to evaluate the budget/cost when combining data/services in terms of the three pillars of sustainability (ecological-economic-ethic). Ellen MacArthur Foundation explained the advantages in terms of recycling management, energy harvesting and societal perspectives. It is hence important, when making data available and turning that data into useful knowledge, to enrich the raw data with transparent information about its sustainability, understandable by all citizens (B2C) and developers (B2B) and to offer tools enabling to globally assess the sustainability of IoT. For that, specific metrics must be elaborated and smart sensors must be developed in IoT as mentioned early. Such indicators might be seen as reputation indicators and incentive actions (like the people ranking in web brokers like Booking or), for business and citizens to select the more eco-sustainable providers. It could be in a similar way applied as additional context of information accessible on IoT marketplace that enable to discover available data, to publish data, to manage billing services, to retrieve vendors information (and hence open a P2P session). However, it will require a high-confidence level (not always the case in web brokers. . .) such that a blockchain securing the smart sensors measurement as it would bring the necessary trust and accounting levels.

Chapter 10

Mid-term opportunities: IIoT (P₂) and mature QiS (P₃)

This chapter introduces the mid-term perspectives of my research project. It is divided in two parts: Industrial Internet of Things and emergence of a resource budget concept for advanced QiS. In both cases, the project is based on (recurrent and novel) collaboration opportunities with researchers in Nancy and abroad with whom I have worked during my previous activities or that I had encountered during the writing of this dissertation. Those collaborations define in a way the working research team that I am engaging for the success of my project.

10.1 Contributions to Industrial Internet of Things with support of Telematics and Edge/Fog/Cloud Computing

The presentation of this axis starts by a state of art and an overview of research activities in the field (Section 10.1.1). It states the positioning of my project. In the next section, I'm reducing the perimeter in terms of factory of future / smart manufacturing and relatively to my involvement in the IFAC TC_{3.3} about Telematics. According to this statement, I highlight in the following sections several applications. The reader might follow the following list to navigate directly to each one.

- A general vision of IIoT for smart manufacturing is provided in page 143.
- Opportunity to work with J. ROBERT (Univeristy of Luxembourg) on frameworks for IoT connectivity & security is discussed in Section 10.1.3.
- Opportunity to work on IIoT & SDN for smart grids is described in Section 10.1.4, with a particular focus to the Interreg North-West Europe RED WoLF application.
- Opportunity to work with Aalto University anf future (5G) wireless technologies as described in Section 10.1.5.

10.1.1 A tour of the IIoT landscape

We are now introducing the second angle of our proposal. Generally speaking, it is related to the digital transformation of industrial process. It encompasses national (as well as European and international) Future Industry efforts²⁷ [All18] and in AI²⁸ [Vil18] as novel business plans for Internet actors like Cisco²⁹. More specifically, we are interested to formalise how network management/automation novel solutions (SDN/NFV) could improve Internet of Things (IoT) relatively to industrial (IIoT) and sustainable (Green ICT) requirements. All items are graduated initiatives of the IEEE Future Directions group³⁰.

To underline the importance of IoT, let's consider some figures. By 2020, the International Data Corporation³¹ estimates that connected IoT will see around 30 billion endpoints. That number could exceed 80 billion by 2025. And, by 2019, 43 percent of IoT data will be processed at the edge.

Industrial automation will use more and more the IIoT networks (we are gathering here the notion of industrial Internet, Machine-to-Machine, Internet of Everything, embedded Internet, Web of Things, Smart Things) [XHL14]. The idea is not here to work on the usage of IIoT (and even to rethink factories, grid, logistics), but to work on the core of IIoT itself, since it faces challenges that let future usages probably unsure. It is interesting to note that the notion of IoT is even not well defined as reported in [IEE15]. This report shows that the main standardisation groups (IEEE, ETSI, OneM2M, ITU, IETF, NIST, OASIS and W3C) all consider a different definition! We can mention from IEEE "A network of items—each embedded with sensors—which are connected to the Internet", from ETSI "Machine-to-Machine (M2M) communications is the communication between two or more entities that do not necessarily need any direct human intervention. M2M services intend to automate decision and communication processes" and from ITU "Available anywhere, anytime, by anything and anyone". Our contribution will hence focus on enabling technologies, system and software architectures and management. We will look for contributing to the three following issues.

Industrial networks have been through different battles (or even fieldbus war [FS02] and more recently, industrial Ethernet war [FS04, Fel05]). In wired networks, the trend is the study of the so-called Time-Sensitive Networking (TSN)^{32,33} that gathers several standards. It is interesting to note that actually, a quite similar kind of battle seems to occur for wireless sensor networks between the *de facto* standard, the IEEE 802.15.4 (and its extensions IEEE 802.15-e [KSKT18], 6TiSCH [TPE15, BNO⁺17]) and specific ones like IEC 62591 (WirelessHART), IEC 62734 (ISA100.11a), and IEC 62601 (WIA-PA) or even the Wifi 802.11ah/ax amendments. Investigations about the real-time performance are still required and the challenge of exploiting network-related effects on the automation control is still going on. Therefore, we are not focusing on a particular communication technology (wired as wireless, Ethernet TSN, LP-WAN, LiFi, etc.), but rather, looking for algorithms enabling to tackle the interoperability between those ecosystem vendor solutions and to monitor and optimise their performances. The final objective is to achieve Internet at the speed of light (as defined by ACM in 2013) or Tactile Internet network (as defined by ITU in 2014 – end-to-end latencies to 1 *ms*) without over-provisioning the network at least 50 percent link utilisation for deterministic traffic flows (as

²⁷<https://www.economie.gouv.fr/nouvelle-france-industrielle/industrie-du-futur>

²⁸<https://www.aiforhumanity.fr>

²⁹https://www.cisco.com/c/fr_fr/solutions/industries/manufacturing.html

³⁰<https://www.ieee.org/about/technologies.html>

³¹Source: IDC Dawn of the DX Economy and the New Tech Industry, doc #DR2017_GS1_FG, February 2017

³²<http://www.ieee802.org/1/pages/tsn.html>

³³even the Internet devices vendor Cisco is proposing Industrial Ethernet 4000 switches

ruled out by IETF).

Another point that IIoT is going to develop is the remote control/monitoring. It is the main step before a full closed control loop. Data are currently collecting over batch process, then analyse even through machine leaning techniques, and finally human decide (or not) to apply (pre-computed) control actions. It corresponds in a sense to the research achieved into the IFAC TC 3.3 (Telematics: Control via Communication Networks). It is currently the trend for IoT for BMS and corresponds to tele-presence, tele-operation, tele-maintenance, tele-diagnosis, remote sensor data acquisition, tele-medicine, tele-education, traffic control, robots for hazardous environments, remote industrial automation, maritime and aerospace systems, automotive systems and smart homes. It enforces the need to analyse communication (including the Internet, wireless communication) and the needs for appropriate theory, methods, proof of concepts and standardisation as well.

The final point deals with the deployment at data analysis (and storing) on edge and fog nodes in distributed networks rather than into the cloud as natively introduced for remote monitoring applications. As detailed in the following, it is likely that IIoT needs tools to simplify development, deployment and operation of processing storage, analytics, or any combination of micro-services and to decrease the energy usage (through optimised workflows) over the (local and external) infrastructure. The challenge is to decide where that data should go and be analysed (to power better business decisions) and it claims for the ability to apply rules to data in motion (with taking care of data ownership, privacy and security). As detailed in the next sections, it needs an architectural framework to extend fog processing to multiple tiers: east-west (fog to fog) and north-south (hierarchical processing leveraging network topology). It can be coupled with virtualisation in order to deploy virtual services faster and at lower cost (leading to NFV infrastructures). It aims here at automating network fabric provisioning for both virtual and physical infrastructures.

Among the different needs for IIoT infrastructures, 6 hot topics are usually mentioned. The first one consists on determining the optimal frequency (avoid unnecessary data pulls high frequency when the data will be consumed a low frequency and hence avoid network congestion). Algorithms to identify automatically the needs and to adapt the polling have to be defined as well to sleep down the network usage (think of duty cycles in wireless communications). Then, prioritisation (or classification of service) is required to ensure integrity of critical/sensitive traffic. Next, it is important to determine the right place for data processing according to the real-time and constrained data requirements. Decoupling hardware from operating systems and hardware (virtualisation) is also a huge topic since resources (processing, storing, networking) have to be adjusted to the data requirements in order to guarantee a relevant service level. The mapping of those resources should be also orchestrated in a consistent way, aware to the machine/process control logic. Finally, it is important nowadays to be able to report online (visibility/observability) on the current operation states of the network, enabling to identify correctly the plant (is it an OT or IT issue?).

In IIoT, a strong network architecture is hence critical for bridging the gap between IT and OT. From our point of view, advanced network automation (centralised or distributed) is the missing technology to bring the ability for IIoT to adapt plant floor network (provision devices for timeliness, security, reliability, scalability and deploy policies) to industrial business varying requirements (assurance and compliance), to contain costs, to decrease the infrastructure complexity, to simplify the management (o-touch deployment), to support the various protocols (converged plant network through a common control/data plane) and to enable supervision and visibility (observability) of the infrastructure state.

Nevertheless, separating the design of the controllers and coders can be very sub-optimal,

incurring some severe performance losses and significant additional costs. We will aim at a strong cooperation (co-design) and composability of control and network logics, since we are turning in aligning the network to OT and finding the best equilibrium between those.

The aim of this section is to cover different topics related to networked control, including for instance issues related to: communication delays, tele-operation, sampled data control, event trigger control, self-trigger control, quantisation effects, etc., as well as applications of networked control on robotics and embedded systems.

10.1.2 Industrial Internet for the factories of the future: smart manufacturing

In the previous section, we have detailed the different researches that we are going to lead in the framework of network automation (mixing QoS considerations as green – energy consumption – networking considerations). We are convinced that the upstream development in network engineering (from the physical to the application layers) is going to (already) lead to new industry. We are talking here about the so-called Industry 4.0, *Usine du Futur*, robotic factories, smart manufacturing, etc. In the past, different specific networks have been designed to face with real-time and reconfiguration requirements. Later, co-design (control and network) approaches have been studied in the framework of networked control systems and cyber-physical systems. However, the design remained at that time fixed for the system life-time or a predefined mission. Manufacturing plants are nowadays asking for more flexibility and agility, such that a plant could be used to build new products, involving different sensors, actuators and calculators. These requirements impose major development challenges, particularly when non-functional properties must be enforced, such as real-time response (high speed isochronous horizontal flows), traffic isolation and reconfigurability. In fact, it may even reach the infrastructure limits in terms of complexity, wide-range information requirements, high bandwidth (vertical flows of process monitoring), complex configurations, etc.

In this context, certain technologies gain particular relevance, such as Industrial Ethernet protocols, particularly Real-Time Ethernet protocols, and synchronisation protocols such as the Precision Time Protocol. More recently, standardisation efforts such Time-Sensitive Networking promise to lay the grounds to efficiently support traffic with highly heterogeneous requirements. Another related framework is that of Software-Defined Networking which is making its way from the telecommunications world into other domains such as industrial automation. Traffic over the network will change, claiming for a new qualification of the QoS performance of the service offered by the network.

Industrial automation systems should rethink through the software-defined paradigm. In the field of the adoption of Ethernet based technologies for factory automation, first works have mainly focused on the real-time performances requirements in the framework of Industry 4.0, Cyber-Physical Systems and Industrial Internet. [ABGS15] introduces a so-called SDN Profinet networks whereas [HDSD16] developed a first proof of concept for Real-Time Ethernet (RTE). [HWJ16b] present the features of future industrial networks by means of SDN. More recently, [SZWB17] introduces a prototype SDN controller for direct multicast routing of industrial traffic in a cyclic switched Ethernet network using the Ryu SDN framework. The implemented function consists of a direct routing of UDP multicast traffic in a ring topology (proactive forwarding approach, shortest path for all members of the appropriate multicast groups, experiments in an IEC 61499 compliant development environment about the performance penalty introduced by switch-controller-communication are performed). Results shows how SDN supports a flexible and reliable network setup in the automation industry and is suited for real-time traffic. Similar approaches exists also, relying on Time-Sensitive Network-

ing (TSN).

We may noticed the idea to consider SDN to manage industrial networks is justified by the fact that historical networks access medium and QoS prioritisation policies were (static) based on centralised planes (TDMA or token-bucket strategies) and even controller (i.e. the bus arbitrator in WorldFIP). It remains however that SDN (that brings reconfiguration capability) has not yet shown its full adequacy in the industrial networks area since we still agree with [HWJ16b] that “most of the requirements were either not sufficiently investigated till now or were only reviewed in the non-industrial area” as it emerged from the area of campus and data centre networks.

This is all the more valid if we consider now Internet of Things network. Inbreeding with best effort Internet, it suffers from the best effort policy (and hence no QoS guarantees) such that engineers turn around over-provisioning techniques (and hence decrease the overall performance). In that way, [Szy16] proposes to create virtual links (similar to those in AFDX) IIoT over the core network in order to support deterministic machine-to-machine (M2M) services. In the fact the idea is to get closer to the “Tactile Internet” network proposed by the International Telecommunication Union (ITU) in 2014 or the “Internet at the speed-of-light” developed by the IETF. However, if it may add a new dimension to human-machine interaction, it contributes to improve the core and do not consider the last mile. This part of the network relies more and more on wireless communications. The IETF has hence created a Working Group, 6TiSCH, to incorporate IEEE’s time synchronised channel hopping (TSCH) wireless standard into the IP infrastructure, however, for flexibility the standard does not specify the scheduling algorithms (time slots reservation and frequency hopping) to be deployed in a centralised approach. More generally, [KAMH17] give a survey on software-defined wireless sensor networks and show that “most of the studies are still unriddling the architectural framework”. In fact, there will be a need to move some of the processing closer to the devices to improve network response efficiency.

In fact, today’s design patterns are biased by the historical progress from steam machines to electric control and field-bus networks. They rely on controlled environments, custom communications protocols, and media with a narrow area of application. This leads to static and application-specific configurations that require high engineering effort, effort done once at the factory initial design stage.

In an industrial Internet area, we are considering that the planes will not have to be only defined once but should be very flexible to evolution of the production requirements (to support a growing number of different products and product variations, multi-purpose manufacturing resources, as well as shortening lot sizes and product life cycles). And rather than trying to support such evolution of the production over a manufacturing plant through scalability issues, we think that the network should be controlled and reconfigured dynamically according to the current operation that the plant is intended to operate. It means that specific northbound interfaces have to be developed in order to interconnect the production controller to the network controller (and retrieve the set of demands \mathcal{K}). Such interface will have to be based on universal API in order to suit a variety of applications, such as machine control, audio-video transmissions, or automotive networks. Thankfully to such northbound interface, it will be possible to reconfigure networks (connectivity, availability, paths, redundancy, ... and other QoS metrics) by applying network automation functions introduced in Chapter 9 and by slicing the network for different simultaneous operations (separated plants, maintenance vs critical missions) or by synchronising different sites (or line productions). A first effort is given in [PSA⁺16], working on network interfaces for the SDN controller based on the OPC Unified Architecture. A similar effort will be required in case of multi-agent system.

Over the longer term, we are committed for defining a co-design approach where the design of the network controller would be achieved jointly with the design of the plant (/system) control. The idea would be to consider a CPS plant, with over-provisioned resources (sensors, actuators, programmable logic controller (PLC)). The network is also considered as enough redundant to be able to propose different paths between devices. Considering those devices as computing resources, it will be similar in the Internet area to the deployment of web servers over different hosts. According to the processing, storing and networking requirements, a machine (or several) is selected and the relevant paths are reserved. If the demand change, it may generate a migration of the (virtual) machine to another one (and the network is reconfigured as well). If the design of the operational architecture of a control system and relevant optimisation issues have been already studied ([LDF⁺11] – allocation of the control functions on controllers regarding capabilities, specific constraints or cost), there is a lack in supporting (and optimising) the information (network) architecture. The problem is that reallocate a control function without considering its network requirements and the network capacity increase the risk that the information architecture will not satisfied the control function needs. The challenge is hence for smart manufacturing to dynamically find (at the minimal cost considering both controllers of plant control and networks) the best paths over the physical topology - see the graph \mathcal{G} and the matrix C – (also in terms of security) and allocations of the control functions over the (static) computing resources (for which new matrices need to be introduced). Once again, the trick is that SDN have not been designed to support reliability, dependability and real-time performances specific to these systems and we will analyse the stability and the convergence time of such combined (re)allocation. A point is that we would not looking for a global optimum but for any implement satisfying operational architectures and computing requirements (as introduced in section 9.3). Another point concerns also transient situations (for instance, what will happened if a controller expects to receive a data from a sensor whereas the sensor is still sending the information to another machine and if the path towards the new controller has not be already configured?). An idea would be to considered also techniques like those defined with the new management protocol NetConf (and its Yang model) that enables (compared to the historical SNMP or the SDN OpenFlow protocols) a better support for robust configuration change using transactions involving a large number of devices. Such southbound interface dedicated to factories should taking care of the synchronisation of the activation of configurations and probably support a transient stage during which both (the old and the new ones) planes will work. It is in fact the verification of the functional testing of the control logic that will need to be tested before to be applied in production environments. In fact, a full management of the life-cycle of the associated services and configurations is required. It will lead to support network function virtualisation as well as plant function virtualisation. Figure 10.1 shows this convergence of the information and the operational architectures.

We share hence the vision of software-defined industrial networks of [LZZ⁺16], depicted in Figure 10.1. Here the idea is that industry systems such as distributed control system (DCS), manufacturing execution systems (MESs), and enterprise resource planning (ERP) are pushed over a cloud service platform (kind of PaaS) as it starts to be implemented in industry. To go further, we think that such federative approach should be balanced with edge computing and NFV techniques. The SDN controller should be also able to maintain control function as closed as possible to the plant (edge computing) and functions implemented into the plant (like in PLCs) could be virtualised across the different computing resources. If the mission of the plant has to be reconfigured, the control function will be dispatched by the SDN controller to the best suited computing resources and the SDN controller will configure the network

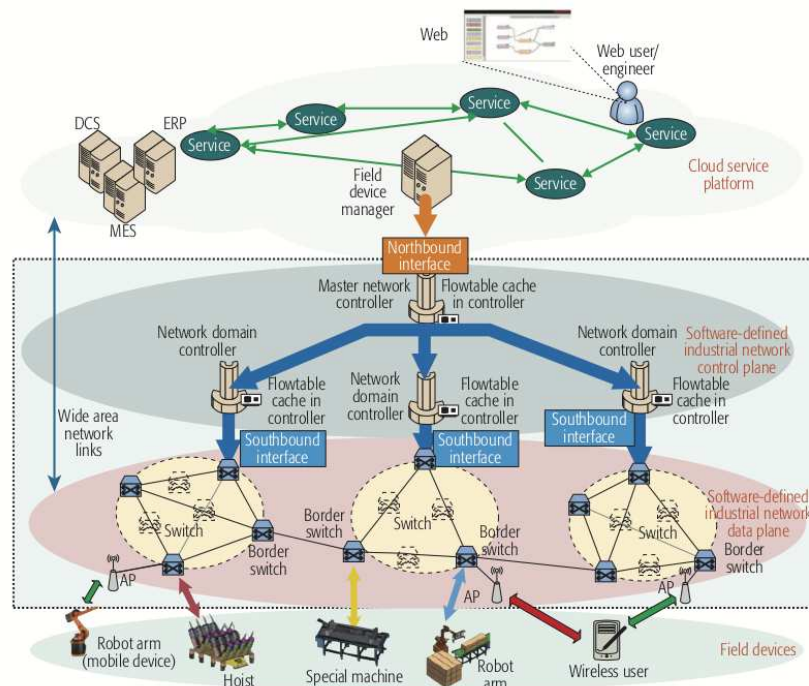


Figure 10.1: Co-design networking and manufacturing control by the means of SDN/NFV [LZZ⁺16]

devices such that a sufficient QoS will be guaranteed (and hence a sufficient QoE for the plant control). The main challenge remains here the transient steps, since networks would have to be reconfigured with a convergence time satisfying the requirements (whereas until now the network design is achieved one – mainly offline – and never dynamically reconsidered). One lesson learnt from the past, especially from the research in the field of networked control systems (NCSs), concerns the co-design of the control and the network. Previously, we have working on robust control over the network. We will consider now a dynamic co-design (and its convergence time and stability) supporting the current advanced IIoT platforms.

When the factory integrates several line productions or different islets/machines (acting as silos), it may leads to multiple local controllers working independently. To improve the flexibility, we are also interested in defining a upper control layer. We propose to compare the usage of a federative multi-domain SDN controller to the east/west interfaces across the controller. In the first scenario (hierarchical control), the central controller will define the image and the functions to be implemented in each controller. [GH16] have hence proposed a novel SDN controller to increase the security and resilience of communication infrastructures in such context (the developed ILP problem encapsulates a shortest path routing objective and harmonises ICS flow requirements including quality of service, security of communications, and reliability). In the second (collaborative approach), decisions regarding forwarding, flow control, deployment of applications will be negotiated among the controllers. Efforts will be here pushed out to ensure the stability of the infrastructure and also to reduce transient inconsistencies. The objective for such “edge controllers” is to eliminate the possibility of instability and transient inconsistencies in the network. We hence are looking for seamless services that will support in definitive the real and effective Industry 4.0 paradigm.

The deployment of computing resources is even more sensitive when the industrial automation system requires storing capabilities or have to support tele-maintenance (or more largely speaking remote monitoring) applications. In that case, data coming from the sensors and actuators are stored in data centre. In fact, Industrial Internet of Things (IIoT) has paved the way to real-time big data storage, access, and processing in the cloud environment [TS16, KGA⁺18]. It corresponds in fact to the essor of the cloud computing PaaS as shown in Figure 10.1. However, the transfer of the data companies to the cloud could be sensitive (privacy issues), critical in terms of availability (centralisation) and it consumes a huge level of resources (see Section 10.2.2). A trend consists of keeping the data as closed as possible and in a distributed manner. It corresponds to the fog computing conceptualised by Cisco in 2012 [Cis15b]. Fog computing is used for monitoring or analyzing real-time data from network-connected things and then initiating an action. The action can involve machine-to-machine (M2M) communications or human-machine interaction (HMI). Compared with the cloud, it enables to support time-sensitive requirement (to verify that control loops are operating properly). A fog node receives feeds from IoT devices using any protocol, in real time; runs IoT-enabled applications for real-time control and analytic, with millisecond response time; provides transient storage, often 1–2 hours and sends periodic data summaries to the cloud. At the same time, cloud platform receives and aggregates data summaries from many fog nodes; performs analysis on the IoT data and data from other sources to gain business insight (historical analysis, big data analytic, and long-term storage) and can even send new application rules to the fog nodes based on these insights [Cis15b].

It should not be confused with edge computing which extends fog computing in essence further to the end devices. Some edge devices embed nano/micro data centres and light computing resources such that services could be offer through single-hop communications (as considered by IEEE/IETF with the 6LowPAN) without a connection to the cloud. Edge computing make the “cloud close to the ground” such that it appears hence for us much more promising for industrial networks as a enabler of Industry 4.0 or IIoT. Figure 10.2 shows some differences, even if it will not be a competition, but they will act as complementary solutions.

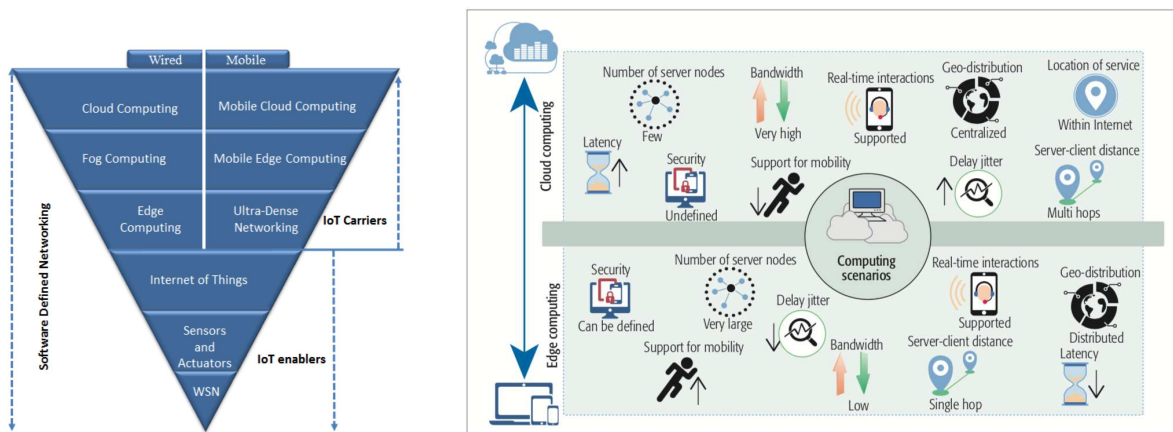


Figure 10.2: Current and future network computing technologies [KAMH17] and comparison of cloud and edge computing [KGA⁺18]

Edge devices may consume high energy such that an efficient cooperation between cloud and edge and an optimal workload allocation scheme are required for energy saving. For instance, in [KGA⁺18], an SDN-based edge-cloud interplay is presented to handle streaming

big data in IIoT environment, wherein SDN provides an efficient middleware support. In the proposed solution, a multi-objective evolutionary algorithm using Tchebycheff decomposition for flow scheduling and routing in SDN is presented. The proposed scheme is evaluated with respect to two optimisation objectives, that is, the trade-off between energy efficiency and latency, and the trade-off between energy efficiency and bandwidth. [AKZR18] propose an efficient workload slicing scheme for handling data-intensive applications in multi-edge-cloud environment. To provide cost-effective inter-DC migrations, the SDN-based control scheme provides energy-aware network traffic flow scheduling based on a multi-leader multi-follower Stackelberg game. One again, we think however that a co-design is needed, namely to enforce the cooperation between the production (and the field device) manager and the network controller. As a result for the network controller, it will at least increase the *a priori* knowledge and hence enabling to find in a easier and a faster way the relevant configurations for the network. It should also be completed with advanced duty-cycles methods and data/frame aggregation as presented previously.

In addition to such energy minimisation work, we are interesting in solutions for reducing SLA violations. We would like to study algorithms for SDN/NFV that will improve the overall network performance. One of the key point deals with the centralisation level required, since data plane extension control could be preferred to improve the reliability and decrease the network overload. It concerns also (SDN) controller as well as nodes (sensors, actuators and computing) optimum placement for different topologies, flow scheduling techniques (like those defined by TSN) and slicing of jobs between edge, fog and cloud platform. Hence sensing as a service would be possible and real-time data processing supported (taking care of delay-sensitive as well as delay-tolerant communications). Moreover, interoperability between field device manager and SDN controller should be improved through rules enabling to prevent policies clashes, to support backward configurations (as originally introduced by the NetConf protocol) and to support new addressing scheme (like the anycast approach in IPv6) underlying by the use of VMs. Finally, we would also working on the big data effect: various sources are going to generate a continuous growth in size of data that have to be transported to the cloud, i.e. over the Internet network while it has not designed for (i.e. the TCP behaviour) and usually in an inconsistent way to the SLA offered by the ISP.

To resume our motto is that if communication (P2P) technologies exist (for a while), the support of online reconfiguration mechanisms of multi constrained networks (like in industrial automation with control loops and real-time monitoring) are still lacking. However industrial are more and more (discovering? and) wondering to use the new advanced network technologies (Internet of Things). The risk comes from both the fact those technologies have not been specified for such usage and that industrial automation designers are not always aware of the technologies issues. It is similar to the situation before the introduction of NCS. We are convinced that network automation (based on SDN/NFV pillars), whatever the communication technology used (wireless or wired), is the key to solve those concerns of dynamic, reliable, efficient and sustainable digitalisation. We aim hence at bringing data, communications, process, and control all together in one single co-design process for INTERconnected NETwork control systems (iNCS). There is here a new opportunity to put together people from control and network communities considering different points of view of the same problem.

In the next sections, we will present some specific applications, not limited to the smart factory case. We are here considering issues like interoperability, big data and energy efficiency, each time through an industrial case study.

10.1.3 Framework for connectivity & security

The following topic is related to the PhD thesis of P.-L. BENEDICK in connectivity & security framework for the Industry 4.0. I am member of the evaluation committee of the PhD thesis which is co-supervised by J. ROBERT at University of Luxembourg. It is in part of a research contract within an upcoming industrial partnership, which involves one industrial partner (in the automotive sector) and one startup (in the R&D in live analytic). The partnership takes place between 2017 and 2021.

The issue studied here is relevant to the network interoperability, aiming at providing a seamlessly connect factories and endpoints. In the industrial sector, companies have independently developed on-site technologies, systems and processes resulting in non-interoperable and proprietary systems, making an integrated factory expensive to manage and maintain. Obviously one may decide unilaterally to substitute all protocols with one common standard like Ethernet TSN (and replace all machines by new ones) or gingerly to move data through gateways on a common technology acting as an universal bus. However, it's going to come up against practices/routines (and lessons learnt from the past) in Industry. In fact, we would study a smooth interoperability, enabling systems to easily and efficiently connect, communicate and understand each others.

The goal is to provide the technological foundation at the communication and interoperability levels for information source publication and consumption around open standardised APIs. It may include the evaluation of different real-time communication protocols, the definition of specific QoS (Quality of Service) frameworks and the study of a software-defined network (SDN) paradigm applied to the manufacturing.

The complexity comes from the large set of industrial (low layers) protocols (wired and wireless, IP4/6) previously introduced. It is even more complex when we are going to consider in addition the messaging and service description protocols (above layers) used for IIoT. The last ones embed the IoT most-used^a, namely HTTP, COAP, MQTT protocols completed by the OPC Unified Architecture (OPC-UA) and OMI/ODF [RKTF16, BRLTK18] initiatives. Such interoperability will require the development of gateways, converters, extra wiring, piggy backing extra sensors to get at data, multiple vendors, adding wifi or cellular, adding security, data storage & computational horsepower. It should also encompass the communication models (remote procedure call (RPC), restful operations, client/server and/or publish/subscribe) [Hu15] and the underlying service/data discovery^b. Consequently, it means also ensures the interoperability between protocols based (or not) on brokers and bulk exchanges (supporting compression), different data semantics and working in a synchronous/asynchronous fashion. It is hence important to plan such interoperability, and hence to propose novel solutions since the field is not covered (especially for IoT protocols). To note that it is even not limited to internal (into the plant, machine-to-machine communications) interoperability IIoT (which interact with the physical and external world), require a consensus on how to implement, manage and most importantly comply with security, privacy and trust standards. The question to be addressed is where to locate the gateways/agents? At devices, at IIoT edges?

^a<https://iot.ieee.org/newsletter/march-2018/i-iiot-protocols-for-beginners>

^bTo note here that a co-design of industrial control systems as introduced previously should be able to select and to take care about the data collection mechanism settled over the network infrastructure

If IEC 61499 provides rules for systems/applications to be portable, it is mostly related

to multi-software and -vendors solutions, management commands. It does not cover the direct translation/traduction of the low and high protocols that is required to ensure real-time communications as required in IIoT.

It is expected that such researches lead to the development of proofs-of-concepts while taking into account the management of end-to-end control of what is shared, with which peer systems, when and how. Solutions will be gathered in a middleware for heterogeneous devices, delivered with a performance analysis and energy optimisations. Such middleware will also introduced a set of control/command messages to facilitate services to register and declare their capabilities with the gateway and ensuring here the deployment of translation services. It may include also the definition of new models of security for preventing from cyber-attacks.

10.1.4 IIoT, SDN, Smart Grids: a call for one more network convergence step

Previously, we have already introduced the need for dynamic balancing between energy production and consumption in ICT. We want now to directly focus on electric grids, and more specifically on smart grids (with real-time monitoring through meters and devices and automation systems). By taking into account interdisciplinary fields such as information and communication technologies, computer science and automation, smart grids can provide auto recovery, consumer empowerment, higher resiliency to natural disaster and cyber attacks, energy quality, new markets, integration of distributed generation and distributed storage, and reduced environmental impact.

IETF has already expressed the needs for deterministic communications and control for utilities such as the smart power grid. [Szy16] shows how a deterministic U.S. IIoT network controlled by an SDN control plane can meet a 10 *ms* delay constraint over distances of about 2,000 *km*, and the jitter is less than 10 μ s. Communication profile with compliant services and topologies are usually according to IEC 61850 standard for smart grid. The benefits to use advanced network automation and SDN (or Multi-Agent Systems (MAS) based solutions) for smart grid has been detailed in [DKW17]. Using a typical transmission grid scenario, [DKW17] discuss the relevant aspects of security, reliability, transmission paradigms, topology detection and configuration effort. The usage of an SDN IIoT platform for smart grid resiliency is even more detailed in [ARKNA17]. The goal is to react immediately whenever a failure occurs to recover smart grid networks using real-time monitoring techniques, in fact by detecting a consecutive failure into the IT network as shown in Figure 10.3.

Any failures or disturbance in the power system can cause dissatisfaction on large number of energy consumers, such that the SDN controller defines a new route in case of discover any occurrence of network fault or communication failure. Figure 10.4 shows the structure and the functions of the SDN controller.

This approach (use bidirectional forwarding detection protocol between SDN witches to discover failure under the hypothesis that a communication failure acts for a failure over the power system). To detect a failure of the power grid by analyzing the status of the IT network is complementary to our previous researches achieved in the scope of Dimitar MINOVSKI Msc Thesis (i.e. monitoring the energy consumed by a network infrastructure to detect and isolate faults in communication architecture: power-based network management systems). In [MRG16], we provide algorithms to receive reports for the changed state of the network in an energy-efficient way by following the energy consumption of the network infrastructure. The approach of monitoring the power consumption directly from the PDU, instead of P2P communication with every device, brings own complexity as the network grows. For instance,

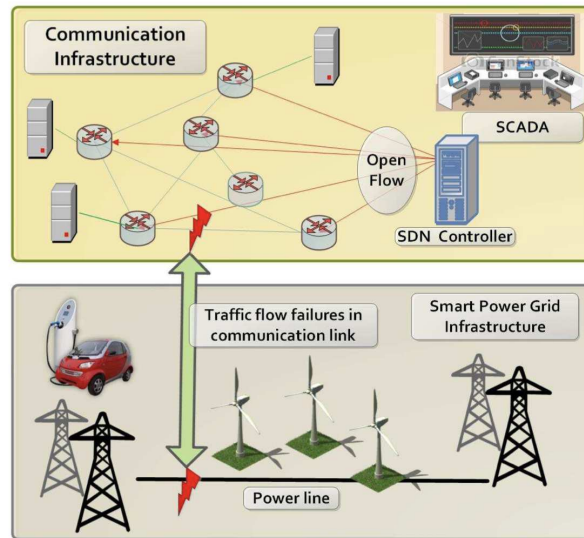


Fig. 1. SDN platform enabling fault detection in smart grid [4].

Figure 10.3: Smart grid monitoring

in a scenario of multiple faults happening simultaneously, the FDI concept presented in this paper is able to cope with the occurring situation. As future work, we envision a deployment of the proposed application as part of a SDN controller, that will complete the structure shown in Figure 10.4 (with specific measurement devices like Raritan PDUs), will enable to predict network failures (and ask for new routes to achieve seamless reachability) and to better integrate mix of renewable energy resources.

Previously, we have also shown the importance to develop south interfaces in order to support advanced grid metrics (and hence visibility, control and monitoring of the energy usage) and interoperability between SDN controller and grid devices. In [VRG17], an extension of Cisco Energywise MIB is proposed to include other metrics covering all the facets of sustainable development directly available from smart grids. It should expand SNMP as an universal protocol to interact both with network and grid devices (especially compared to the OpenFlow protocol and its limited set of statistics regarding energy). In future works, we would like to study and apply such approach to the novel NetCONF NMS protocol and its associated Yang modeling. Hence the SDN controller would not be only able to exchange with IT devices like in Figure 10.4, but also directly from the grid. We would also determine if metrics coming from the power grid field could be useful to describe the QoS and QiS performances of the network. We expect that metrics like those defined in [RSR⁺17] for sustainable data centres could also be translated in IIoT (and even IoT in general). We aim here at guidelines to choose the correct metric(s) and at developing the relevant software sensors. [RSR⁺17, Appendices] detail hence up 132 metrics (covering different fields like green, network or financial topics).

The following topic comes from an Interreg North-West Europe project proposal for which I had contributed. It is entitled “Rethink Electricity Distribution Without Load Following” (RED WoLF) (Priority Axis 2 Low carbon). It is led by Leeds Beckett University (G. COLANTUONO). The project at the writing time has passed step 1 (see <http://www.nweurope.eu/>).

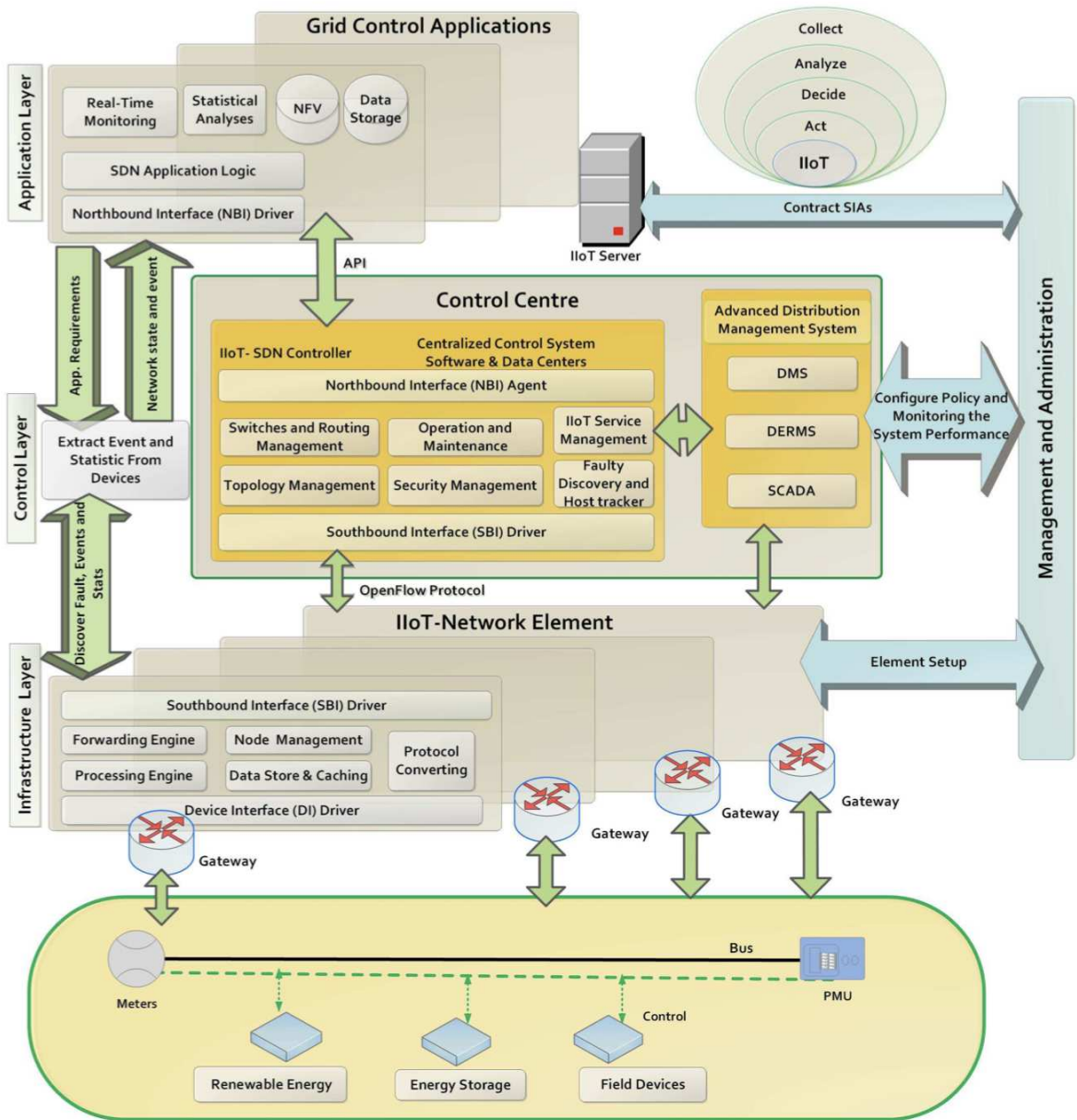


Figure 10.4: SDN architecture based IloT for grid resilience [ARKNA17]

Such efforts will permit to retrieve from the grids both internal information of the system (battery energy level, energy mix rate, energy needed – especially for peak consumption detection, carbon emission) and external information (weather, user behaviors, daily activities). Based on that, we expect hence, as future works, to design software models that will smartly drive electricity from renewable sources like PhotoVoltaics and grid to Hybrid Storage Systems thermal and electric reservoirs, among others for smart city. The challenges cover the placement of smart sensors, the specification of the networking architecture, the communication availability and the representation of the information in the specific context of micro- and smart-grids for house, renewable energies and batteries. Obviously, the Quality of Service offered by the network would have to be assess in terms of delay, reliability and security, while taking into consideration (i) the implemented communication technologies (wire, wireless), (ii) scalability issues (e.g., when seeking to interconnect a number of houses in a micro-grid), (iii) application specifications and constraints for transporting or sharing energy (both from a quantitative and qualitative point of view). At the end, novel smart driver adaptable to the local conditions, from demand pattern to the energy mix available on the local grid would be added to the structure of SDN controller like the one depicted in Figure 10.4.

Finally, those outcomes leads us to consider that a general convergence between ICT networks and smart grids would be more and more required. That call for one more convergence is not even limited to power grid but would encompass lighting grid. This assertion comes from our current effort to develop for teaching a curriculum to deliver light in rooms (and hence buildings) through IT technologies, switched Ethernet network and Power-over-Ethernet. It corresponds to new industrial products like those developed by the Cisco-Philippps joint venture. Such convergence brings new issues for the network (like previously convergence between data and voice networks) like the decoupling the delivering of power to the (STP) port state and a centralisation of control (in a SDN fashion). It can even go one step further if luminous tiles are coupled with Visible Light Communications or LiFi networks in order to provide both data and light or InfraRed communications during the daylight. And it can be also, from the centralized control plane, linked with indoor presence systems in order to save energy. It leads to the motto of the next section, envision the deployment of infrastructure with a global cost view, computed according a budget.

10.1.5 Budget of LPWAN and 5G architectures

I am finally considering the future wireless technologies (as 5G) since there are going to be largely deployed. For this topic, I am considering exchanges with R. LERBOUR of Infovista (in order to retrieve the provider point of view) and a closed work with Aalto University as an outcome of my involvement in the project KIC EIT RawMaterials (S.-L. JÄMSÄ-JOUNELA and J. KORTELA).

A part of IoT platforms are based on emerging technologies and in particular Low-Power Wide-Area Network (LPWAN). LPWAN family acts as a response to specific requirements and environmental constraints. Those constraints, complementary to the traditional QoS indicators, cover questions that has not been really addressed. How to prevent communications to smash the energy waste? How to ensure a practical, sustainable and easy integration of the devices in a specific environment (like in the context of the instrumentation of Paris Place

de la Nation³⁴)? How to ensure a robust communication if it is used for V2V or emergency shutdown systems? The open issue is hence to identify how each LPWAN technology answer those questions, to determine the real cost of the IoT technology to be used and will satisfy a common budget. And regarding all the metrics part of the budget, a new metrology should be proposed to monitor the budget satisfaction.

We have already started to analyse the efficiency and the environmental integration costs of LoRa and Sigfox networks. However, telco (big) providers (historically supporting human communications) do not want to let the M2M communications outside from their business, so cellular technology LTE (Long Term Evolution) is currently (standardisation process) adapted to the IIoT. It will hence be relevant to compare not only LPWAN technologies like LoRa and Sigfox, but also to include in the survey 3G/4G/5G solutions. Even if they may not have been designed specifically for LPWAN, they might be used and should hence be considered, especially when derived technologies NB-IoT (Narrow Band IoT) and LTE-M or CAT M1 will be standardised. In the case of 5G [KNS⁺17], it is interesting to note that the prototype products are looking for high-bandwidth and not really on energy consumption, even if it was one initial expectation. More generally, we are convinced that cellular networks for mobiles could be used as conceptual starting models.

In IoT wireless networks are subject to throughput limitations due to the usable total bandwidth and range limitations due to consumption. Moreover, transmit power may be limited by a constraint on the electromagnetic radiation. These three constraints are in addition to the imperative of good propagation of the communication signal. These four constraints can lead to placing the gateways towards the wired network in an optimised way if the sensors are dense and talkative. The possible presence of a descending channel can further increase the constraints. Further, with the expected increasing number of IoT devices there is a need to be able to prioritise between motes when performance suffers due to e.g. interference and colliding frames, so that more important IoT devices will be able to transmit. Hence, there is a close relationship between wireless communication performance, amount of devices and the importance of data. Depending on the LoRaWAN class (A,B or C), this might be treated differently. The scientific objectives is first to model constraints. Then, to design an algorithm for placing gateways on a territorial area equipped with sensors parametrised in stream of data sent and received. Further, as study and proposal will be included about a possible solution of how to manage priorities of IoT devices.

In fact, we are here going also to retrieve the (wireless) challenges of green industrial networking, i.e. energy consumption, batteries life-cycle, coexistence, mitigation of wireless interference, soberness... Obviously, we will have to ensure that such technologies may act as wireless TSN (not only delays and bandwidth, but also clock synchronisation, reliability) and security (confidentiality, users and devices authentication, privacy)!

The originality of this work would be to guide users in selecting the appropriate technology regarding they needs. It will be based on dashboard on experiment platforms gathering indicators of QoS and QiS (with a limited impact to the running architecture) and on computation of the whole life-cycle economic and environmental cost of a specific IoT sensor using the chosen LPWAN technology. The last challenge will be to tackle the 'opposite' point of views between IoT carriers / telco companies and IoT users. Both would like to optimise

³⁴http://www.cisco.com/c/m/fr_fr/never-better/core-networking.html

the network through different objectives; a common resource budget will be hence the only means to bring them closer together.

10.2 Towards a resource budget concept for Quality in Sustainability

This last chapter deals with the introduction of a resource budget concept which is defined in the next section and is coming from exchanges with M. VAUTIER of Orange in the framework of PERCCOM. In one word, budget should be cornerstone for incentive actions taking into account QiS (and not only energy consumption). The budget will be also formulated on the basis of results of several activities previously detailed (as shown in Table 8.1).

10.2.1 The concept

We are finally introducing now long-term perspective. It is mainly linked to the idea that energy consumption is just one metric of Green ICT, and sustainable IoT will need to aggregate a large panel of metrics and KPI indicators. Our view is hence to contribute to the Quality in Sustainability (or *Qualité d'intégration Environnementale*) introduced in [RL10]. Even if it is not fully used/admitted in academia, we think that it is the key to tackle at one and the same time environmental, economical and societal issues generated by networks. The goal is to go further than the carbon footprint (total amount of greenhouse gas emissions that goes in the atmosphere, caused here by a network architecture, indicated with CO₂e).

During the last first Greening Through ICT Summit in October 2017 in Paris³⁵ [Des17], it was clearly stated that if IoT might improve the efficiency of one smart city app, app are usually designed without taking care of the other app and the city management such that smart city does not always mean sustainable. In fact, it reflects the lack of a common budget that will enable to identify the real contribution of each app/silos. It is also a conclusion of the ADEME³⁶ technical report [ADE17] entitled how to combine digital transformation and energetic and ecologic transitions in Future Industry? It is really important that the good characteristics of Internet of Things would not be adversely affected with disregard for human and social needs (leading to an Internet of Nothing).

This concept of resource budget (will be more detailed in section 10.2.2) is linked with the ten commandments of ecomature system defined in Benyus' book "Biomimicry" (and preliminary applied in networking as defined by N. DROUANT). It encompass also the efforts in [RSR⁺17] to provide a multitude of metrics (energy efficiency, cooling, greenness, performance, thermal and air management, network, security, storage, and financial impact) available to analyse individual key performance indicators. It corresponds in addition to the upcoming IEEE standards for greener information and communication technology³⁷ [Pre16] (green community control, environmental product assessment, energy efficiency, renewable energy generation, energy-efficient communications network protocols) and an upcoming trend for IoT [ZLSN15]. The definitive goal of such budget will be to reduce the recurring cost (and soberness) of Information Technology (IT) and facility management. In fact, Green ICT

³⁵<http://greenict.ieee.org/summit/gtict-summit-2017>

³⁶Agence de l'Environnement et de la Maîtrise de l'Énergie

http://www.ademe.fr/sites/default/files/assets/documents/Industry-numerique_2017-synthese.pdf

³⁷<http://theinstitute.ieee.org/resources/standards/standards-for-greener-information-and-communication-technology>

benefits the environment by improving energy efficiency, lowering carbon footprint and greenhouse gas emissions, using renewable resources, and by encouraging reuse and recycling. It should hence go further than the Power Usage Effectiveness (PUE) indicator currently used in data centre although it is not enough to describe the overall (QiS) sustainability performance and it was never intended to be used as a comparison metric. This should be also complementary to efforts in green industrial networking [AYA⁺16] for energy-based research work (adaptive link rate, interface proxying, energy-aware infrastructure, and energy-aware applications) mitigating wireless interference, testing product quality and environmental conditions and taking care of product Life Cycle Accounting.

We will focus on metrics for planning, designing, building and operating networks. It will lead to the development of an automated process, achieved by connecting numerous sensors together to create one IoT platform As mentioned in [RSR⁺17], such a platform can potentially discover new correlations between data sets. The data can also be used to decide whether the existing technology and equipment can be used more efficiently, e.g., improved scheduling algorithms, or whether it is better to replace them with the latest, most efficient technology or equipment. One issue concerns here the modelling of network hardware and software life-cycles.

We will also consider here two additional IEEE Future directions³⁸: blockchains and 5G. These technologies should enable to overcome the differences between the user, provider, and society expectations; the (technological) silos (for instance IT versus OT; the proprietary/vendors silos).

10.2.2 Software services eco-design based on resource budget

For a given IT company, the challenge is to improve the energy efficiency consumed by its software applications in order to mitigate both the electricity bill and the carbon emission. The complexity to globally analyse the software environment according to ecological and business indicators requires to develop new support decision tools to guide software/network engineers all along the design process of new services.

Today, there are many proposals, standards and software to assess the life cycle of physical products and processes in considering their carbon emission (ex: European Standard in sustainability of buildings, CEN TC350). However, Life Cycle Assessment (LCA) applied to software services is a new research topic. Today, the main contributions in this domain deal with best practices and patterns to eco-design software coding. They also highlight the complexity of software development process. The services life cycle can be independent or can be integrated in more global complex services. Moreover, the software services can be implemented in the customer side or in provider side. Finally, the software services use hardware components and eco-design approach requires to understand the relationships between energy consumption and CPU, memory, ...

Thus, the objective of software service LCA tool is to identify the relevant actions to eco-design new services. The main issue of developing such tool is its acceptance by both companies (and sub-contractors) and software engineers. Indeed, the software service LCA tool cannot be only oriented on environmental issues, but must integrate the business point of view to analyse the additional costs and/or the benefits of such approach. M. BRAUNGART and Mc DONOUGH clearly explained in their book on circular economy the importance to eco-design systems or products in studying together ecological and profits criteria.

³⁸<https://www.ieee.org/about/technologies.html>

The originality of research in that area is then to drive software eco-design process by the budget (which is the traditional indicator in business world) and not directly by environmental indicators. One solution is to translate software/network resource consumption in term of budget. A budget will hence collect the resource consumption of CPU, memory, networks relatively to a domain such as a function, a software block, an architecture level, etc. For example, the energy consumed by a software (especially in mobile computing) could be defined by physical entities (screen, CPU, network, etc.) or according to architecture levels (eg. OS, web browser, web server). The interest of resource budget concept is to allocate consumption by domain and to monitor this allocation during the software process. A budget threshold overrun enables to plan corrective actions (based on budget constraints for the whole stakeholders): changing the initial budget allocated to development team, optimising existing software to respect the budget, substituting functionalities by new ones or discarding new functionalities.

| The following topic correspond to exchanges with M. VAUTIER from Orange. It is also related to exchanges with engineers of the Greenspector company.

The goal of our own research will be to develop a support decision tool integrating the concept of resource budget, focusing on network infrastructures (hardware and software). For the software, we aim at making a link between dynamic consumption of software code and the network usage through communications API calls (or at least patterns). It would lead first to a comparison of the communication modes (client/server, RPC, publish/subscribe) that are intensively used in IoT and then to rules to select the best modes for a given service. We propose here to use the Greenspector tool [PAL14]^a that is able to detect dirty patterns in source code in several languages based on unitary measured rules and that is able to measure resource consumption based on automatic tests. The challenge is here to go further than merely taking into account the data rate as generally considered. It will require detection of dirty patterns through dynamic measures, retrieving context knowledge, achieving precise static analyse (to avoid false positives) and even conceive learning machine. For the software part of the infrastructure, we would integrate virtualised functions scattered throughout the network (in an SDN controller or in a NFV way as considered in the next section). For the topology, we will translate the different metrics (already known and to be defined as mentioned previously) to such resource budget. Budget will be preliminary defined for specific services (apps), according to architecture type and requirement specifications and available tools and metrics monitoring ability. The models and patterns implemented in the support decision tool would be individually verified to check their accuracy and more globally to analyse their interdependence.

^a<https://greenspector.com/en/>

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Résumé

Les utilisateurs de réseau partagent un besoin d'indicateurs de la Qualité de Service offerte et d'un contrôle du degré de satisfaction de la Qualité de l'Expérience. L'émergence de la thématique Éco-TIC a mis en évidence l'effet non durable causé par la croissance constante des réseaux, notamment leur empreinte carbone. Notre contribution vise à développer l'évaluation de performances et l'automatisation des réseaux en tenant compte d'un concept de Qualité d'Intégration environnementale.

Nos activités sur l'évaluation de performances ont pris en compte des réseaux sans garanties de QoS ou qui sont simplement basés sur une stratégie de surdimensionnement. Nos travaux portent sur l'analyse déterministe (dont la théorie du calcul réseau), la simulation et l'expérimentation. Pour les systèmes contrôlés en réseau, nous avons élaboré des algorithmes de contrôle de QoS. Enfin, de premières contributions en Éco-TIC ont porté sur la modélisation et l'atténuation de la consommation d'énergie.

Le projet que nous formons repose sur l'idée que la QoS, la QoE et la QiS devront toutes être considérées à la fois comme un triptyque essentiel. Notre proposition s'articule selon trois axes : (i) l'automatisation des réseaux, le contrôle et les plans de données, (ii) l'Internet industriel des objets (évolution de l'ancien concept de systèmes de contrôle en réseau) et (iii) la QiS mature (maturation du concept de budget des ressources et des contrats intelligents).

Abstract

Users of networked applications share a common need for indicators of the Quality of Service offered by the network and a control of the degree of satisfaction of the Quality of Experience. Recently, the emergence of green ICT highlighted the unsustainability effect caused by the constant growth of networks regarding for instance its carbon footprint. Our contribution aims at developing performance evaluation and network automation considering a larger concept of Quality in Sustainability.

Our research activities on performance evaluation have considered networks that do not provide QoS guarantees or that are simply based on an over-provisioning strategy. Our work deals with deterministic analysis (mostly network calculus theory), simulation and experimentation. Then activities devoted to networked control systems have led to control laws and software-defined QoS metrics. Finally, first contributions in green networking have considered energy consumption modeling and mitigating.

The project that we are forming is built on the idea that QoS, QoE and QiS will have to be all considered at once as an essential triptych. Research is intended to be decoupled in three fields: (i) network automation, control and data planes, (ii) Industrial Internet of Things (viewed as the next evolution of the former concept of networked control systems) and (iii) mature QiS (maturation of the concept of resource budget and smart contracts).