



# Mobility as a Primitive to Improve Communications in Wireless Networks

Enrico Natalizio

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Enrico Natalizio

**MOBILITY AS A PRIMITIVE TO IMPROVE  
COMMUNICATIONS IN WIRELESS NETWORKS**

Habilitation à diriger des recherches



Presented on: November 15<sup>th</sup>, 2017



Université de Technologie de Compiègne  
Rue du Dr Schweitzer  
Compiègne, 60200  
FRANCE

Habilitation à diriger des recherches

# Mobility as a primitive to improve communications in wireless networks

Enrico NATALIZIO

November 15<sup>th</sup>, 2017



HDR presented on November 15<sup>th</sup>, in front of the committee, composed of:

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# Acknowledgements

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Finally, I would like to thank all the members of my dissertation committee who accepted to be part of it. I greatly value your involvement and scientific expertise.

Thank you all!



Part I.

Activities report

# 1. Curriculum Vitae

---

## Civil Status

Enrico Natalizio

Born on 06/10/1976

Divorced, no kids.

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## 1.1. Current Position

**Maître de conférences** classe normale (CNU 27) at the Université de Technologie de Compiègne.

Member of the Sécurité, Communication, Optimisation (SCOP) of the UMR UTC-CNRS 7253 Heudiasyc.

## 1.2. Education

2002-2005 **Ph.D.** in Computer Science and System Engineering - Università della Calabria - Cosenza, Italy.

Ph.D. Thesis on *New Algorithms of Mobility and Resource Management for Wireless Networks*.

1995-2001 **M.Sc.** in Computer Science Engineering (Magna cum laude) - Università della Calabria - Cosenza, Italy.

M.Sc. Thesis on *Improvements of Radio Resources Management in a Cellular Hierarchical System*.

1990-1995 **High School for Science Disciplines** - Liceo Scientifico G. B. Scorza - Cosenza, Italy.

## 1.3. Professional career

From 2012 **Maître de conférences** - Section CNU 27 - Université de Technologie de Compiègne - UMR UTC-CNRS 7253 HEUSIASYC - Compiègne.

- Currently in **Délégation CNRS** at the Heudiasyc Laboratory.
- Holder of the **Prime d'Excellence Scientifique** from 2013.

2010-2012    **Postdoc researcher** - Inria Lille - Nord Europe - France.

2006-2010    **Contract Professor and Postdoc researcher** - University della Calabria - Cosenza, Italy.

2001-2002    **Junior Consultant** - Value Partners Technology - Cosenza, Italy.

## 2. Supervision activities

---

### 2.1. Postdoc Supervision

#### Postdoc in progress

**Milan ERDELJ**, financed by the FUI AIRMES project (started in July 2016): *Fleet of heterogeneous cooperating drones*. Codirection with Bertrand DUCOURTHIAL (UTC-Heudiasyc).

Supervision quota: 50%. Enrolled at: UTC.

**Publications:** [S3].

#### Postdoc completed

**Nicola Roberto ZEMA**, financed by the Labex MS2T in the framework of the DIVINA team activities (October 2015 - March 2017): *Control and communication of multi-robot system for visual navigation*. Codirection with Isabelle FANTONI (UTC-Heudiasyc).

Supervision quota: 50%. Enrolled at: UTC.

**Publications:** [J3, J6, S1, C2, C3, C4, C7, C8, F1].

Currently: Postdoc researcher at IFSTTAR Lille.

**Michal KROL**, financed by the Region Picardie IMATISSE project (May 2016 - December 2016): *Device-to-device communications in crowdsensing for flood monitoring*.

Supervision quota: 100%. Enrolled at: UTC.

**Publications:** [J1, C7].

Currently: Postdoc researcher at UCL (UK).

**Milan ERDELJ**, financed by the Region Picardie IMATISSE project (January 2015 - July 2016): *Wireless sensor and robot networks for flood monitoring*.

Supervision quota: 100%. Enrolled at: UTC.

**Publications:** [J1, J7, J8, S3, C10].

Currently: Postdoc researcher at UTC.

## 2.2. Ph.D. Supervision

### Ph.D. in progress

**Arbia RIAHI SFAR**, Ph.D. in cotutelle with the Ecole Polytechnique de Tunisie (started on September 1st 2014): *Privacy protection in the IoT: an approach based on game theory*.

Codirected by: Yacine CHALLAL (Ecole Nationale Supérieure d'Informatique d'Algerie), Abdelaziz SAMET (Ecole Polytechnique de Tunisie).

Supervision quota: 33%. Enrolled at: UTC and Ecole Polytechnique de Tunisie.

**Publications:** [J5, S2, S4, C6, C20, I3].

**Nesrine MAHDoui**, financed by the Labex MS2T in the framework of the DIVINA team activities (started on October 1st 2015): *Vision based cooperative mapping and exploration using a swarm of robots in GPS denied environments*.

Codirection : Vincent FREMONT (UTC-Heudiasyc).

Supervision quota: 50%. Enrolled at: UTC.

**Publications:** [C1, C11].

### Ph.D. completed

**Lotfi ZAOUCHE**, French Ministry of Education grant (October 2013 - February 2017): *Security and reliability of communications in swarm networks*. Codirection with Abdelmadjid BOUABDALLAH (UTC-Heudiasyc).

Supervision quota: 50%. Enrolled at: UTC.

**Publications:** [C16, I2].

Currently: ATER at UTC.

**Nourhene MAALEL**, CIFRE Ph.D. with the CEA (September 2011 - June 2014): *Reliable routing in highly dynamic networks*. Cosupervision with Abdelmadjid BOUABDALLAH (UTC-Heudiasyc) and Mounir KELLIL (CEA-LIST).

Supervision quota: 33%. Enrolled at: UTC.

**Publications:** [C21].

Currently: Project manager in industry.

**Karen MIRANDA**, hired on the ANR RESCUE project (January 2011 - April 2014): *Adaptive self-deployment algorithms for mobile wireless substitution networks*. Cosupervision with Tahiry RAZAFINDRALAMBO and David SIMPLOT (both Inria Lille - Nord Europe).

Supervision quota: 33%. Enrolled at: Inria Lille - Nord Europe.

**Publications:** [J17, C25, C30].

Currently: Associate professor at the Metropolitan Autonomous University Cuajimalpa Campus (UAM-C).

**Milan ERDELJ**, financed by Inria Lille - Nord Europe (September 2010 - October 2013): *Mobile wireless sensor network architecture: Applications to mobile sensor deployment*. Cosupervision with Tahiry RAZAFINDRALAMBO and David SIMPLOT (both Inria Lille - Nord Europe).



Supervision quota: 33%. Enrolled at: Inria Lille - Nord Europe.

**Publications:** [J15, B2, C28].

Currently: Postdoc researcher at UTC-Heudiasyc.

**Carmelo COSTANZO**, Italian Ministry of Education grant (October 2008 - November 2011): *Algorithms and techniques towards the Self-Organization of Mobile Wireless Sensor, Robot and UAV Networks*. Codirection with Valeria Loscrì (Università della Calabria).

Supervision quota: 50%. Enrolled at: Università della Calabria, Italia.

**Publications:** [J18, J19, J21, C32, C33].

Currently: Project manager at Altran technologies.

## Visiting Ph.D. students

**Oscar ALVEAR**, *Optimizing environmental monitoring using UAV*, from Universitat Politècnica de Valencia, Spain. Cosupervision with Nicola ZEMA (UTC-Heudiasyc), July - October 2016.

**Angelo TROTTA**, *CUSCUS: Design and development of a simulation tool for the implementation of control systems and wireless mobile networking*, from Università di Bologna. Cosupervision with Nicola ZEMA (UTC-Heudiasyc), October 2015 - March 2016.

**Antonio GRANO**, *Sensor Fusion and Surrounding Environment Mapping for a Mobile Robot*, from Università della Calabria. Cosupervision with Vincent FREMONT and Ahmet SEKERCIOGLU (both UTC-Heudiasyc), February - July 2014.

## 2.3. Master students supervision

### Master in progress

**Nithin MANUEL**, *UAV-smart phone communications*, codirection with Milan ERDELJ (UTC-Heudiasyc). 2017.

### Master completed

**Nesrine MAHDoui**, *Study of multi-robots communications protocols for distributed visual simultaneous localization and mapping using bio-inspired mechanisms*, codirection with Vincent FREMONT (UTC-Heudiasyc), January - July 2016.

**Narjes ALAYA**, *Multi-media protocols in a network of unmanned aerial vehicles*, codirection with Milan ERDELJ (UTC-Heudiasyc), January - July 2016.

**Claudio PASCARIELLO**, *Control of wireless networked System: exploring the interactions between networking and control within a context of Multi-Robot system*, codirection with Nicola ZEMA (UTC-Heudiasyc). December 2015 - June 2016.

**Arselle SAIZONOU**, *Robot network for river monitoring and emergency management*, codirection with Milan ERDELJ (UTC-Heudiasyc), January - July 2015.

**Rosario SURACE**, *Design and simulation of optimal positioning techniques for UAV in sport event filming*, July - December 2011.

**Davide FABIO**, *Reactive coverage technique for wireless mobile sensors in presence of dynamic events*, July - December 2011.

**Carmelo COSTANZO**, *Reactive coverage technique for wireless mobile sensors in presence of dynamic events*, June - November 2008.

**Daniela MAURO**, *New methodologies for mobile terminal localization and road congestion measurement*, January - June 2008.

**Sabrina NICOSIA**, *New coverage techniques for mobile wireless sensors based on swarm intelligence*, December 2007 - May 2008.

## 3. Teaching activities and pedagogic responsibilities

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### 3.1. Teaching

I started my teaching experience at the Università della Calabria in 2003, as a teaching assistant while I was a Ph.D. student and I continued as a contract professor since 2006. At the Université de Technologie de Compiègne, I fulfill all my teaching duties. As a professor of the département de Génie Informatique (GI), I give courses related to two main disciplines: web development and wireless networks. The level of students who follow my classes is varied: it goes from the first year post-bac to the last year of the engineering degree curriculum, but I also intervene in the M1 and M2 levels of the TIS<sup>1</sup> master and in the apprenticeship. The courses of which I have been or I am responsible are detailed in the following.

From 2015    **Internet applications architecture** - (UTC code: SR03) - I give lectures (CM) and tutorials (TD) for the engineering degree curriculum (4<sup>th</sup> year) of the Université de Technologie de Compiègne - total volume (eq. TD): 90 hours.

This course introduces architectures (software and hardware) used in the information systems, such as the Internet, and the communication techniques (sockets, RPC) for distributed objects and application servers. More specifically, this course deals with the application layer programming, especially the server side. It also deals with the language for web programming: JavaScript, PHP, Ajax, JEE and the most recent frameworks. The course is complemented by a project to develop during the TD in JEE, which consists in programming both server and client sides of a web application.

From 2015    **JEE Architecture and web services** - (AI15) - I give lectures and tutorials for the apprentice engineering curriculum (3<sup>rd</sup> year) of the Université de Technologie de Compiègne - total volume (eq. TD): 50 hours.

This course is meant to give a practical experience to the apprentices on the usage of Java Enterprise Edition for developing web applications, interfaces and services. The students learn how to use JEE components, such as Servlets and JSP, as well as they develop their own tags library and Java Persistence API for database connection.

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<sup>1</sup>Technologies de l'Information et des Systèmes

- From 2015 **Web programming and security** - (AI16) - I give lectures and tutorials for the apprentice engineering curriculum (3<sup>rd</sup> year) of the Université de Technologie de Compiègne - total volume (eq. TD): 30 hours.  
This course presents the software architectures for distributed information systems, such as the Internet. It gives to the students the basics of web programming by introducing some programming languages for the web, such as JavaScript, PHP and JEE. Furthermore, an important part of the course is destined to the web application security: form control, injection tests, vulnerability definition.
- From 2015 **Advanced networking** - (TIS07) - I give lectures and tutorials for the master in Information and Systems Technology (2<sup>nd</sup> year) of the Université de Technologie de Compiègne - total volume (eq. TD): 28 hours.  
In this course, the algorithms, protocols and communication technologies used in the systems of systems design are presented. The course introduces some advanced networking systems, such as: mobile sensor, robot and UAV networks and proposes the state of the art of the technology concerning controlled mobility techniques for improving the network performance. Furthermore, the “homemade” simulators Fl-Air and CUSCUS are introduced and used to design and test algorithms for coverage and connectivity, in the framework of a student project.
- 2012-2015 **Systems, Networks and Security** - (SR06) - I gave lectures, tutorials and practical works for the engineering degree curriculum (5<sup>th</sup> year) of the Université de Technologie de Compiègne - total volume (eq. TD): 90 hours.  
The objective of this course is to provide a specialized training in the area of Information Systems Architecture, by addressing the subject from a theoretical as well as a practical point of view. All along the semester, people from companies give lectures to provide insights on real-world applications of the subjects studied in class. Three main topics are addressed: Information Systems Architecture and Management; Computer Network: WiFi, mobile networks, network management; Computer System Security: notions and stakes, methodology and legislation, flaw detection and attack analysis, cryptography.
- From 2012 **Supervision of students** during their “**stage assistant ingénieur**” (TN09) and their “**projet industriel de fin d’études**” (TN10) - total volume (eq. TD): 180 hours.  
The TN09 lasts 6 months and takes place in a professional context of public or private companies. It is scheduled at the 3<sup>rd</sup> semester of the “branche” (engineering students are Bac+3), and it consists, ususally, in supporting production services or similar services (design, control, development, maintenance, etc.). The work performed during the TN09 is summarized in a written report and presented with an oral presentation.

The TN10 lasts 6 months and takes place in a professional context of public or private companies. It is scheduled at the last semester of the engineering cursus ( Bac+4,5). It is meant to test the skills and capabilities learned by the students in a professional context, in order to practise their future jobs. Usually, the tasks assigned to the students are those normally assigned to a newly graduated. An oral presentation and a written report are needed to validate the final project.

Besides the mentioned courses, I also regularly intervene in two master courses **Networking Basics** (TIS01) and **Command of Cooperative Autonomous Robots** (TIS05) as well as in a course of the “Tronc Commun” of the engineering curriculum, **Information Processing** (NF92) and in a course of the first year of “branche” for the computer engineering students **Sensors for Intelligent Systems** (SY31).

**Total volume (eq. TD)** from 2012 until 2017: 2617 hours, which is an average of 520 hours TD/year.

## 3.2. Responsibilities

From 2017 **Coordinator** of the international activities of the Génie Informatique - Université de Technologie de Compiègne. This task consists in supporting the responsible of the bachelor’s degree program in supervising the studies and the sojourn of the foreign students. Therefore, the task implies the welcome and supervision of foreign students during their exchange semester, the continuous maintenance of the university network for the Génie Informatique and the creation of new partnerships with foreign institutions. Furthermore, every semester I support the responsible of the bachelor’s degree program in selecting the students from UTC who will spend a semester abroad.

## 4. Collective interest and administrative responsibilities

---

### 4.1. Proposal refereeing

- 2017      **Referee** of a project proposal submitted to the Consolidator Grant call of the **European Research Council (ERC)**.
- 2017      **Referee** of a project proposal submitted to the **FWF** Austrian Science Fund.
- 2016      **Referee** of a project proposal submitted to the “ASTRID programme” of the French **ANR** (Agence Nationale de la Recherche).
- 2016      **Recruitment Committee** for the position 4074, Maître de conférences, section 27, Université de Technologie de Compiègne.
- 2016      **Referee** of a project proposal submitted to the “Lead Agency project with Austria program” of the **FWO** Research Foundation - Flanders (Fonds Wetenschappelijk Onderzoek - Vlaanderen).
- 2015      **Referee** of a project proposal submitted to the French **ANR** (Agence Nationale de la Recherche).
- 2014      **Referee** of a project proposal submitted to the **STIC-AmSud** program for France-South America research collaboration.
- 2013      **Referee** of a project proposal submitted to the “Scholarships & Fellowships Programme” of the South African **NRF** (National Research Foundation).
- From 2013      **Responsible** of “Cellule Europe” for the Heudiasyc Laboratory. The Cellule Europe analyzes, sorts, filters and presents the Horizon 2020 calls for project in order for the members of the laboratory to have, year by year, a clear pictures of the open calls. Furthermore, to facilitate the creation and the consolidation of international partnerships, the Cellule Europe participates in the national and international networking meetings organised to diffuse the H2020 workprogramme.

## 4.2. Participation in Doctoral dissertation committee

- 03/07/2017 **Member of the dissertation committee** of Antonino ORSINO, Towards Native Device-to-Device Integration into Emerging 5G Cellular Systems @ Università Mediterranea di Reggio Calabria, Italy. Members of the committee: Gaetano PALUMBO, Francesco SCARCELLO, Enrico NATALIZIO.
- 27/02/2017 **Member of the dissertation committee** of Raul Armando FUENTES SAMANIEGO, Wireless Sensors Networks Monitoring - Application to secure interoperability @ Telecom SudParis, Paris, France. Members of the committee: Ana CAVALLI, Joaquin GARCIA ALFARO, Edgardo MONTES DEOCA, Emmanuel LOCHIN, Mercedes MERAYO, Enrico NATALIZIO.
- 02/12/2016 **Member of the dissertation committee** of Thouraya TOUKABRI, CVS: a Framework architecture for D2D-based Cellular Vehicular Services in 4G networks and beyond @ Telecom SudParis, Paris, France. Members of the committee: Pascal LORENZ, Ken CHEN, Houda LABIOD, Hossam AFIFI, Nabil CHARKANI, Lionel MORAND, Enrico NATALIZIO.
- 01/12/2016 **Referee** of the Ph.D. thesis of Raheeb MUZAFFAR, Routing and Video Streaming in Drone Networks @ Lakeside Laboratory, Klagenfurt, Austria for the Erasmus-Mundus joint doctorate program ICE.
- 01/02/2016 **Member of the dissertation committee** of Alvaro TORRES CORTES, Efficient real-time video delivery in vehicular networks @ Universitat Politècnica de València, Valencia, Spain. Members of the committee: Juan Pedro RODRIGUEZ LOPEZ, Antonella MOLINARO, Enrico NATALIZIO.
- 15/12/2015 **Member of the dissertation committee** of Natale GUZZO, Facing the real challenges in wireless sensor network-based applications: An adaptive cross-layer self-organization WSN protocol @ Inria Lille - Nord Europe, Lille, France. Members of the committee: David SYMPLOT-RYL, Andre-Luc BEYLOT, Fabrice VALOIS, Pascal DARAGON, Enrico NATALIZIO.
- 15/05/2015 **Member of the dissertation committee** of Nicola Roberto ZEMA, Spontaneous mobility and autonomous (re)configuration techniques to support next generation networks @ Università Mediterranea di Reggio Calabria, Italy. Members of the committee: Bruno NERI, Gilda SCHIRINZI, Gianfranco AMENDOLA, Enrico NATALIZIO.
- 26/02/2015 **Member of the dissertation committee** of Rosario SURACE, Design and Performance Evaluation of Algorithms for Wireless Self-Organizing Systems @ Università della Calabria, Cosenza, Italy. Members of the committee: Lalo MAGNI, Giuseppe MAZZARELLA, Enrico NATALIZIO.

## 5. Research activities

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My research activities focus on networking protocols and mobility schemes for wireless sensor, robot and UAV networks. More specifically, the main objective of my research is to demonstrate theoretically and empirically that the usage of controlled mobility in the context of intelligent devices (sensor, robot, and UAV) communications can improve the performance of the network, while providing the devices with the required level of connectivity to accomplishing their mission.

My research work can be split into **two main groups and a more recent third one**:

- Network management for unconstrained mobility (35%);
- Usage of controlled mobility for improving network performance (60%);
- Privacy preservation (5%).

The methodological approaches, developed in my career, are based on:

- Mathematical definition of the problems;
- Design of distributed algorithms for the network devices;
- Development of tools for network simulation;
- Implementation of the simulated communication schemes into a testbed.

**Keywords:** Sensor network, robot network, UAV network, controlled mobility, Internet of Things, privacy preservation.

The complete list of my publications is given on page 97, and the important numbers of my scientific production are as follows:

24 journals;

44 conference publications, of which 43 international;

5 paper invited to conferences;

3 book chapters;

66 different coauthors;

16 h-factor.



## 5.1. Software and simulator

2017      **Simulator-Emulator CUSCUS**: CommUnicationS-Control distribUted Simulator. CUSCUS is the first control-communication joint simulator. By using CUSCUS is possible to simulate a fleet of UAVs and take into consideration, at the same time, the aspects and features related to the navigation, formation control and physical control as well as the communication technology and networking protocols needed to make them communicate. **Related publications**: [S1, C8].

## 5.2. National and International cooperations

Inria Lille - Nord Europe (France): Until January 2014 I have been co-supervisor of two Ph.D. students (Milan ERDELJ and Karen MIRANDA) of the FUN team at Inria Lille. I collaborate with Nathalie MITTON (team leader) and Valeria LOSCRI, and I have collaborated with Tahiry RAZAFINDRALAMBO ([J7, J15, J17, J18, B2, C12, C14, C17, C18, C24, C27, C29, C30] in the publication list) on controlled mobility in wireless networks.

BWN Lab @ Georgia Tech (USA): In July 2014 and 2015, I invited, through the Labex MS2T, Ian AKYILDIZ, director of the BWN Lab at the Georgia Tech (USA), who gave two seminars on nanocommunications and 5G. I published a paper with Professor AKYILDIZ and Kaushik CHOWDHURY (next item) on monitoring river floods by using robot and sensor networks ([J8] in the publication list).

GENESYS Lab @ Northeastern University, Boston (USA): In June 2015, I invited, through the Labex MS2T, Kaushik CHOWDHURY, director of the GENESYS Lab at the Northeastern University of Boston (USA), who gave a seminar on cognitive networks. In 2017, Kaushik and I have submitted a project proposal to the Thomas Jefferson USA-France program, which has not been accepted for funding.

Grupo de Redes de Computadores @ Technical University of Valencia (Spain): in 2017, I hosted for 6 months at the Heudiasyc Lab a Ph.D. student supervised by my colleague Carlos TAVARES CALAFATE. We are collaborating on defining realistic scenarios for using fleet of UAVs in civil applications ([J6, C3] in the publication list).

ARTS Lab @ Università Mediterranea of Reggio Calabria (Italy): I collaborate with Antonio IERA (team leader), Antonella MOLINARO and Giuseppe RUGGERI on sensor and actuators networks and on the Internet of Things ([J9, C13, C24, I3] in the publication list).

DIMEG Department @ Università della Calabria (Italy): I collaborate with Francesca GUERRIERO and Luigi DI PUGLIA on modelling and optimizing communication and mobility in robot networks ([J14, J19, J22, C2, C12, C16, C23, C32] in the publication list).

Computer Science Department @ Università degli studi di Bologna (Italy): I collaborate with Marco DI FELICE and Luciano BONONI on the definition of new mobility algorithms for mobile devices ([J13, C8] in the publication list) and in 2016, I hosted for 6 months at the Heudiasyc Lab a Ph.D. student supervised by my Italian colleagues.

Electrical Engineering and Information Technology Department @ Università Federico II di Napoli (Italy): I collaborate with Sabato MANFREDI on finding control theory and communications aspects on which leverage in order to define a common background between the two research communities ([J3] in the publication list).

Lakeside Lab @ Alpen-Adria-Universität Klagenfurt (Austria): I collaborate with Evsen YANMAZ on robot networks topic, and with whom I submitted a project proposal to the ANR-FWF joint calls ([C4, F1] in the publication list).

VRIT Lab @ Military Academy of Tunisia: I collaborate with Zied CHTOUROU in supervising the work of Arbia RIAHI as a candidate to the Ph.D. in cotutelle, working on privacy preservation schemes in the Internet of Things ([J5, C19, I3, S2, S4] in the publication list).

Radiolab @ Università di Roma Tre (Italy): I collaborate with Anna Maria VEGNI on vehicular networks ([J11, J12, C21, C25] in the publication list).

LMAC Lab @ Sorbonne Universités in Compiègne (France): I collaborate with Pascal MOYAL for defining a mathematical framework for privacy preservation in Internet of Things communication algorithms ([S2] in the publication list).

### 5.3. Invited talk

29/09/2016 *Advantages and limitations of controlled mobility in UAV networks.* Northeastern University, Boston, USA.

04/06/2015 *Robot and Sensor networks for environmental monitoring.* CeSMMA Laboratory - Università della Calabria, Italy.

28/05/2015 *Advantages and limitations of controlled mobility in robot networks.* CITI Lab - Insa de Lyon, France.

03/11/2014 *Advantages and limitations of controlled mobility in flying robot networks.* **Invited speaker** at the Workshop “Flynet: Micro and Nano Aerial Vehicle Networks for Civilian Use”, organized by ETH Zurich, Switzerland (<http://www.swarmix.ch/flynet/>).

18/06/2014 *On the usage of controlled mobility in wireless sensor and robot networks.* **Invited speaker** at the “International conference on advanced Networking, Distributed Systems and applications (INDS 2014)”, which was held in Bèjaia, Algeria (<https://inds-2014.hds.utc.fr/>).

- 11/04/2014 *On the usage of controlled mobility in wireless sensor and robot networks*. **Invited speaker** at the “International workshop on the future of wireless networking”, organized by the BWN Laboratory of Georgia Tech, which was held in Atlanta, USA.
- 19/02/2014 *On the usage of controlled mobility in wireless sensor and robot networks*. Lakeside Laboratory, Klagenfurt, Austria.
- 30/09/2013 *Controlled mobility in Wireless Sensor, Actuator and Robot Networks*. **Invited speaker** at the Workshop “Crossed Seasons”, organized by the FUN research team at Inria Lille - Nord Europe, France (<https://www.inria.fr/en/centre/lille/calendar/france-south-africa-crossed-seasons>).
- 11/07/2013 *Controlled mobility in Wireless Sensor, Actuator and Robot Networks*. **Invited speaker** at the Workshop “Research days”, organized by the Lakeside Laboratory, Klagenfurt, Austria (<https://www.lakeside-labs.com/research-days-2013/>).
- 19/04/2012 *Controlled mobility in Wireless Sensor, Actuator and Robot Networks*. **Invited speaker** at the Workshop “PalmaRES”, organized by the Università Mediterranea of Reggio Calabria, Italy.

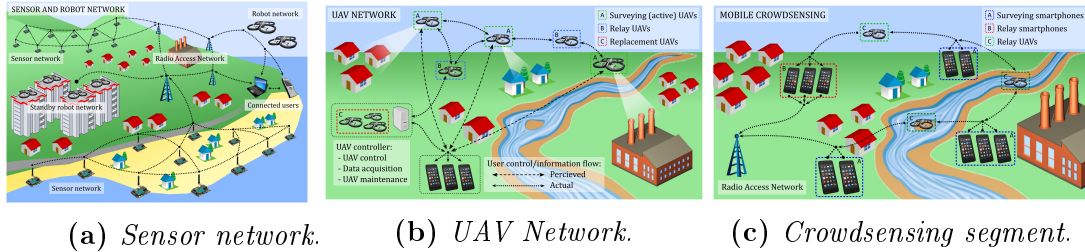
## 5.4. Science diffusion talk

- 23/02/2017 *We are such stuff. As dreams are made on*. **Invited speaker** at the first TEDx talk in Cosenza, Italy (<http://tedxcosenza.com/>).

## 6. Projects

### 6.1. Funded projects: coordinator

2014-2017 **Coordinator of the Project “IMATISSE: Inundation Monitoring and Alarm Technology In a System of Systems”** funded by the Region Picardie in the framework of the “Welcome of high quality researcher in Picardie’s laboratories” support. The idea that underlies this project is the design and implementation of a system of systems, which combines the possibilities opened by sensor and robot networks along with the human participation through the utilization of mobile crowdsensing. The proposed system of systems has the objective of constantly monitoring rivers and creeks in order to: evaluate potential dangerous situations, and, in case of disaster, give the alarm and facilitate the first aid personnel by providing them with real time multimedia communications from the areas hit with the disaster.



**Figure 6.1.:** *Components of IMATISSE system of systems.*

The three components of the system of systems are: (i) A static Wireless Sensor Network (WSN) deployed along the river (6.1a). The WSN has the role of monitoring the river and provide relevant statistics to forecast potential dangers. (ii) A Unmanned Aerial Vehicles (UAV) network (6.1b), which supports sensors communications by collecting the captured data when the situation is not critical, and provide communications with hit areas when a disaster occurred. (iii) Mobile Crowdsensing component that consists in an application suit to be installed on the smartphones of people who want to contribute their perspective, through sharing short videos or pictures, on the dangers and the happening events. The project is currently in its last year of development, and a complete proof of concept will be deployed in the Heudiasyc facilities before the end of 2017.

The support of the region Picardie for this project is **390 keuros**.

**Publications:** [J1, J8, C8, C10].

- 2013 **Coordinator of the Project “Robot and Sensor Networks”** funded by the Italian Ministry for Territorial Cohesion, in the framework of the “Messaggeri della Conoscenza” support. This project, which addressed Italian researchers working abroad, had the aim of spreading the research activities of the proposers throughout the students of Italian universities, in the form of Master and Ph.D. classes as well as practical research activities, e.g. the study and presentation of a survey paper, the discussion about some recent research papers, and the implementation of a small project consisting in using the Arduino platform to extend some terrestrial robots and UAVs capability. The content of the course consisted in the design, the functioning and the integration in a larger network of smart devices equipped with controlled mobility and other controlled features. The proposal was prepared with the Chairman of the telecommunications degree course of Università della Calabria (Italy) and the classes were given to the students of the same University in May and June 2013. The three best students were selected to spend 3 months at the Laboratory Heudiasyc setting up the communications among UAV.
- The support of the Italian Ministry for this project was **35 keuros**.

## 6.2. Funded projects: participant

- 2016-2018 **Scientific co-responsible of the Communications sub-unit for the project AIRMES (Fleet of heterogeneous cooperating UAVs)** in the framework of the National French FUI (Fonds Unique Interministériel) support.

The objective of the project is to develop a framework capable to let a fleet of heterogeneous UAVs to cooperate towards the achievement of a specific monitoring mission. I share the responsibility of the Communications sub-unit at the Heudiasyc Laboratory with Bertrand DUCOURTHIAL. The objective of the sub-unit is to provide the other partners with network protocols and communication mechanisms for UAVs that possess different capabilities. I supervise, along with Bertrand DUCOURTHIAL, a postdoc on this project.

The support of the FUI for the five partners of this project is **1.2 Meuros**.

**Publications:** [S3].

- 2015-2018 **Scientific co-responsible of the DIVINA (DIstributed cooperative VISual Navigation for multi-uAv systems)** research team of the Labex MS2T (Maitrise de Systems de Systems Technologiques).

The scientific objective of DIVINA is the navigation and exploration of unknown regions by using perception, control and communication capabilities of a fleet of UAVs. I share the scientific responsibility of

this interdisciplinary research team with Vincent FREMONT. I take care of the communications among the UAVs, and with the help of a Ph.D. student and a Postdoc, whose work I have supervised, I design, test and implement networking protocols for the UAV fleet while taking into consideration and using their mobility to improve the performance of the network towards a more efficient exploration and navigation. The support of the Labex MS2T for the three partners of this project is **300 keuros**.

**Publications:** [J3, J6, S1, C1, C2, C3, C4, C8, C9, C11, F1].

2010-2013 **Member of the POPS** research team of Inria Lille - Nord Europe for the project “RESCUE: RESeau Coordonné de sUBstitution mobile” funded by the French “Agence Nationale de la Recherche” (ANR).

The RESCUE project investigates both the underlying mechanisms and the deployment of a substitution network composed of a fleet of dirigible wireless mobile routers. Unlike many projects and other scientific works that consider mobility as a drawback, RESCUE uses controlled mobility of the substitution network to help the base network to reduce contention or to create an alternative network in case of failure.

As a postdoc in the POPS team, I participated in the project by supervising the work of the Ph.D. student Karen MIRANDA. The support of the ANR for the five partners of this project was **796 keuros**.

**Publications:** [J15, J17, C25, C28, C31].

2010-2011 **Member of the POPS** research team of Inria Lille - Nord Europe for the project “MISSION: MobIle SubStItution Networks” funded by the Inria in the framework of the Action de Recherche Collaborative (ARC) program. The project MISSION proposes to study and implement the deployment of a substitution network composed of mobile routers, able to reach the positions needed to replace broken links. MISSION focuses on the deployment and re-deployment for routers depending on the connectivity, but also on the bandwidth and delay requirements. I was hired as a postdoc on this project.

**Publications:** [C30].

2011-2013 **Proposal writer** for the project “STEM-NET: STEM devices for self-organizing wireless Networks”, funded by Italian Ministry of Education and Research in the framework of National research project (PRIN). The project STEM-NET proposes the introduction of the concept of stem unit among the wireless network devices. As its biological counterpart, a network stem unit will be able to self-(re)configure depending on the service requirements and on the context where it is working, and to self-organize through the interactions with other units. I was the person in charge to write the proposal, which was prepared over

the period of December 2009-April 2010, and accepted after my departure to France. The support of the Italian Ministry for the three partners of this project was **203 keuros**.

**Publications:** [J13].

## 7. Editorial activities and Technical Committees

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### 7.1. Technical Committees

2017      **Founding member and Vice-Chairman** of the **IEEE TCCN SIG** (Technical Committee on Cognitive Networks - Special Interest Group) on Cognitive Cyber-Physical Systems (CCPS). This SIG aims at providing a platform for international researchers and practitioners to share ideas, findings and innovations in related areas of cognitive radio technologies for CPS and more broadly cognitive communication and networking in CPS.

2015-2016      **Vice-Chairman** of the **IEEE TCSIM** (Technical Committee on Simulation). The TC on Simulation (TCSIM) is an IEEE Computer Society Technical Committee that promotes simulation-related research including, simulation design, development, methodologies, modeling and applications of simulation.

My role as a Vice-Chairman of the IEEE TCSIM was to promote international conferences and workshops with focus on simulation and applications of simulation to other research areas.

### 7.2. Editorship

From 2012      Associate Editor of Elsevier Ad Hoc Networks (impact factor 3,047, <http://www.journals.elsevier.com/ad-hoc-networks/>).

From 2014      Associate Editor of Elsevier Digital and Communication Networks (<https://www.journals.elsevier.com/digital-communications-and-networks/>) .

From 2016      Associate Editor of Wiley&Hindawi Wireless Communications and Mobile Computing (impact factor 1,899, <https://www.hindawi.com/journals/wcmc/>).

2013-2015      Associate Editor of Ad Hoc & Sensor Wireless Networks (impact factor 1,034, <http://www.oldcitypublishing.com/journals/ahsw-n-home/>).



### 7.3. Guest Editor of Special Issues

- 2017      Guest Editor of the Special Issue of the Elsevier Ad Hoc Networks on Advances in Wireless Communication and Networking for Cooperating Autonomous Systems (Submission Deadline, April 14th, 2017).
- 2016      Guest Editor of the Special Issue of the Elsevier Digital Communication and Networks on Theory and Applications of UAV Networks (Submission Deadline, October 15th, 2016).
- 2016      Guest Editor of the Special Issue of the Asian Journal of Control on Advances in Control and Optimization over Wireless Sensor and Actuator Networks (Submission Deadline, January 31st, 2016).
- 2016      Guest Editor of the Special Issue of the Hindawi Mobile Information Systems Journal on Crowdsensing and vehicle based sensing (Submission Deadline, May 20th, 2016).
- 2014      Guest Editor of the Special Issue of Elsevier Computer Communications on Mobile Ubiquitous Sensing: from Social Network Viewpoint (Submission Deadline, March 31st, 2014).
- 2014      Guest Editor of the Special Issue of Elsevier Ad Hoc Networks on Internet of Things security and privacy: design methods, detection, prevention and countermeasures (Submission Deadline, May 15th, 2014).
- 2012      Guest Editor of the Special Issue of Springer MONET on Wireless Technology for Pervasive Healthcare (Submission Deadline, September 15th, 2012).
- 2011      Guest Editor of the Special Issue of Elsevier Ad Hoc Networks on Theory, Algorithms and Applications of Wireless Networked Robotics (Submission Deadline, October 31st, 2011).

### 7.4. Conference and workshop organizer

Publicity Chair for the First International Balkan Conference on Communications and Networking (Balkancom) 2017;

Publicity Chair for the Sixth International Conference on Selected Topics in Mobile & Wireless Networking (MoWNet'17);

Track Chair for the Smart Spaces and IoT Networking Track of the 12th IEEE Consumer Communications and Networking Conference (IEEE CCNC) 2016, 2015;

TPC Chair of the International Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN) 2017, 2016, 2014;

Track Chair for the Vehicular Communications and Applications in Water, Land, and Sky Track of the 13th IEEE Consumer Communications and Networking Conference (IEEE CCNC) 2016;

Track Chair for the Cellular Networks Track of the 80th IEEE Vehicular Technology Conference (IEEE VTC Fall 2015);

Track Co-Chair for the IoT Services and Applications Track of the IEEE TENSYP Symposium (IEEE TENSYP) 2015;

Workshop Chair of the 6th International Conference on Ad Hoc Networks (AdHocNets) 2014;

Organizer and Chairman of the International workshop on Internet of Things - Ideas and Perspectives (IoTIP) at the IEEE International Conference on Distributed Computing in Sensor Systems (IEEE DCOSS) 2015, 2014, 2013;

Organizer and Chairman of the Special Track Unconventional Intra-body Communications (UnIC) at the 9th International Conference on Body Area Networks (BodyNets) 2014;

Publicity Chair of the 9th International Conference on Body Area Networks (BodyNets) 2014;

Proceedings & Journals publication Chair of the International Conference on Advanced Networking, Distributed Systems and Applications (INDS) 2014;

Organizer and Chairman of the 2nd Int'l Workshop: Mobility and Communication for Coordination and Cooperation workshop at the International Conference on Advanced Robotics (ICAR) 2013;

Track Chair of Distributed Systems, Protocols, Optimization and Applications at the 8th International Conference on P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC) 2013;

Organizer and Chairman of the MC3: Mobility and Communication for Coordination and Cooperation workshop at the International Conference on Computing, Networking and Communications (ICNC) 2012;

Publicity Chair of the 2012 IEEE International Conference on Internet of Things (iThings 2012);

Publicity Co-Chair of the 5th International Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN 2012-Spring), 2012;

Publicity Chair of The 7th International Conference on Bio-Inspired Models of Network, Information, and Computing Systems (BIONET-ICS 2012), 2012;

## 7.5. Technical Program Committee member

(Only 2017-2018)

The IEEE International Conference on Computer Communications (INFOCOM 2018) 2018;

The Annual Conference on Wireless On-demand Network Systems and Services (WONS) 2018;

IEEE 5G Forum 2018;

International Conference on Ad-Hoc Networks and Wireless (AdHoc-Now) 2017;

The IFIP Networking Conference (NETWORKING 2017) 2017;

The IEEE International Conference on Communications (ICC) 2017;

DroNet 2017;

International Conference on Computing, Networking and Communications (ICNC) 2017;

IEEE Global Communication Conference (GLOBECOM) 2017;

IEEE Personal, Indoor and Mobile Radio Communications (PIMRC) 2017;

The IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob) 2017.

## Part II.

### Scientific activities

# 1. Introduction

## Contents

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## 1.1. Context

All my research work, since my Master thesis, has been addressed at studying the impact of the mobility of communication devices (2G-3G-4G mobile devices, sensors, terrestrial and aerial robots<sup>1</sup>) on the wireless network formed by the same devices. Basically, there are two perspectives to take into consideration when studying mobility in wireless networks. Mobility can be considered as:

- A challenge for the network that has to cope with the movements of the devices in order to keep them connected and offer them the required services [22]. This kind of mobility will be called *impact-unaware mobility* in the rest of this manuscript, in order to characterize the fact that the node moves without taking into consideration the impact of their movements on the network (for example users of a cellular system who walk and use their cellular phones);
- A facility to exploit when the devices, in a distributed or a centralized fashion, can change position within the network in order to accomplish a task and improve the performance of the network [74]. In opposition to the previous type of mobility, and to characterize the fact that nodes “know” that their mobility may affect the network performance and may make movements to improve it, this mobility will be called *impact-aware mobility* or more simply *controlled mobility*.

The two perspectives imply different methodologies of analysis and investigation as well as different kinds of wireless networks. As the mobility of a node affects the most basic characteristic of the network, which is its topology, and as the classical ISO/OSI protocol stack model [109] was originally designed for static topologies, when mobility is *impact-unaware*, the designer of the network must define, at each protocol layer, mechanisms and techniques to face the risk of losing the connectivity of a node with the rest of the network. Furthermore, as each

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<sup>1</sup>the terms node, device, terminal will be used interchangeably in the rest of this manuscript

type of wireless network - cellular (2G-3G-4G), sensor (WSN), ad hoc (MANET), vehicular (VANET), mesh - has its own specificity, impact-unaware mobility must be managed accordingly. For this reason, there exist, in literature, a lot of schemes for managing mobility and surveys for each type of network [15] [19] [44] [9] [87]. In order to face the “problems” caused by the nodes mobility, it is necessary to find an accurate mobility model, which is often related to the context where the nodes move (e.g.: pedestrian, vehicular, in a city center or in a rural area, etc.). The definition of a mobility model allows the designer to determine mathematical bounds on certain communication parameters, such as delay, throughput, jitter, etc. in order to limit, or at least foresee, the degradation that the mobility can cause to the network. The mobility of the users in these networks is related to the type of network, hence the literature proposes several surveys of mobility models specific to the different types of networks [18] [54] [61] [53].

The devices’ “awareness”, in the second perspective, comes from the assumption that the devices possess, individually or as a group, the intelligence to sense, reason and act on the environment where they are located. Mobility is not anymore the mobility of the users who carry their devices, but is an inherent characteristic of the device itself. Necessarily, this assumption shrinks the set of candidate networks that can be considered, which are mobile wireless sensor networks (MWSN) [83], wireless sensor and robot networks (WSRN) [25], mobile ad hoc network (MANET) [48] and flying ad hoc network (FANET) [13]. In this case, mathematical models need to be defined in order to determine the best placement of the nodes to accomplish a specific mission while improving, or at least not degrading, the quality of the communications, as well as mobility algorithms must be designed to obtain the best movement sequences that minimize the risks and the costs of controlled mobility. Furthermore, the protocols used at each layer of the protocol stack, may be modified in order to foster the awareness of the devices and be able to specify the actions to perform to exploit the mobility. A very challenging issue for these networks is the management of cooperation and coordination among the nodes [68], which may also be heterogeneous and able to perform very different tasks. This issue brings up the need of considering systems which comprise different segments, such as mobile or static sensors for capturing information about the surrounding environment and terrestrial or aerial robots to perform actions over the environment. In this case, these systems fall into the classification of **Cyber-physical systems** or also **Systems of systems (SoS)**, to which a Chapter of this manuscript is devoted.

## 1.2. Career path

I started doing research during the final project of my Master, that I obtained from Università della Calabria, Italy, in 2001 under the supervision of Antonio IERA and Antonella MOLINARO. The first research project on which I worked dealt with the definition of handover algorithms for vehicular users of a cellular system, who moved within a city centre [50]. The project and my supervisors sparked my interest in the research world and, after one year of grant to study “Cellular Techniques for a Multitier Urban Scenario”, funded by the Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT) and a short experience in a

consulting firm, I accepted to continue my work towards the obtention of a Ph.D. in telecommunication engineering from the same university. My Ph.D. started in December 2002, it was devoted to the definition of resource allocation architectures, schemes and algorithms for handling mobility in 2G, IP and Satellite networks, and ended in March 2006 with the defense of my Ph.D. thesis on “New Algorithms of Mobility and Resource Management for Wireless Networks”.

During my last year of Ph.D. and the first of postdoc at the Università della Calabria, I had the chance to spend 13 months at the Broadband Wireless Networking Laboratory of the Georgia Institute of Technology in Atlanta, USA. This period was the most important for my career, as, under the supervision of Ian AKYILDIZ and thanks to very intellectually stimulating conversations I had with him and with two of the Ph.D. students of his lab (Tommaso MELODIA and Dario POMPILI), I started collecting papers and ideas to switch my perspective on mobility in wireless networks. It seemed to me that, the current literature on wireless networks, in 2006, missed completely the possibility of using mobility of nodes to improve the performance of a network. Therefore, I spent the first six months of my stay at the BWN Lab without producing any publishable work but reading all the works I could find, even from other disciplines such as Robotics, Artificial Intelligence, Swarm Intelligence, Animal and Biological Systems, to create the base of my knowledge needed for me to push the idea in the research community that mobility can be beneficial.

Some works had already demonstrated that mobility could improve the performance of the network [40], but these works still focused on random movements of nodes, typical of an *impact-unaware mobility* network. In 2006, the only work I had found concerning the possibility to use mobility was “Towards Mobility as a Network Control Primitive” [39], by David Goldenberg et al., which became my main inspiration and the source of my first work on controlled mobility. At that time, the main criticism to the idea of moving devices to improve the network performance, was that the devices are usually battery-powered (sensors or laptops), and that making them move towards a new position may actually be more expensive, in terms of energy, than letting them stay still in their original position. The main competitor of *controlled mobility* in WSN and MANET was, at that time, the *topology control* [88] of Paolo Santi, based on modifying the transmitter power of nodes in order to modify the topology of the network. “Why make a node move to a new position and consume a lot of energy, when you can change the topology of the wireless network by simply making the nodes change their transmitter power, and therefore their transmitting range?” was a typical question asked in professional meetings and conferences. The easiest answer was that the drawbacks of controlled mobility in terms of energy were actually counterbalanced by the advantages introduced into all the layers of the protocol stack, which could not be achieved by simply tuning the transmitter power. However, I preferred to go for the longer and harder road. Thanks also to the help of Valeria LOSCRI, and by extending Goldenberg’s work to a more general case, first I showed that a better placement can actually extend incredibly the lifetime of mobile sensor networks [73] [72] and later that, if we choose wisely the way of moving nodes [24], we can actually make the whole network save more energy compared to the case of static nodes.

Still, it was very difficult to get credit in the research community as very few re-

search groups around the world were actively working on *controlled mobility*. One of them was the FUN (former POPS) team at Inria Lille - Nord Europe, where I was recruited in 2010 as a postdoc researcher. It was a pleasure to discover that the project “MISSION: Mobile Substitution Networks” of Tahiry RAZAFINDRALAMBO, on which I was recruited, was explicitly based on the concept of *controlled mobility* and that another member of the team, Nathalie MITTON, was working on her “Energy Efficient Mobile Routing in Actuator and Sensor Networks with Connectivity Preservation” [45], which shared with my works the same perspective on exploiting mobility. In the FUN research group, thanks to their facilities, it was finally possible for me to implement and test in reality some of the algorithms that I had proposed in previous research works.

In 2012, I joined the “Réseaux et optimisation” (RO) research group at the Heudiasyc Lab of the Université de Technologie de Compiègne. In the previous years, I had worked often with colleagues from Operational Research and Optimization groups on the formulation of the mathematical models for determining the optimal placements of nodes in MWSN and WSRN, and at Heudiasyc I had the possibility to continue collaborating with colleagues from the same research area (Dritan NACE and Fabio D’ANDREAGIOVANNI). Moreover, Heudiasyc is a well known laboratory for its research on mobile robotics and the coordinator laboratory of the Labex MS2T (Maitrise de Systems de Systems Technologiques). The former allowed me, through the support of excellent postdoc fellows such as Milan ERDELJ and Nicola ZEMA, to keep implementing, my communication-based coordination and cooperation schemes within the fleets of Unmanned Aerial Vehicle (UAV) used in the laboratory; the latter has given me the opportunity to share my research activities with experts and researchers of other disciplines, such as Robotics and Automatic Control (Isabelle FANTONI), Perception and Vision (Vincent FREMONT and Ahmet SEKERCIOGLU), with whom we created an interdisciplinary research team, DIVINA of which I am scientific co-responsible. In DIVINA, we define architectures and algorithms for the simultaneous localization and mapping of fleets of UAVs within an unknown GPS-denied environment.

As the RO team is well known in France for its works on security, I have also started recently a new research activity on privacy preservation in the Internet of Things (IoT) in collaboration with Yacine CHALLAL and Abdelmadjid BOUABDALLAH.

I am currently spending 6 months of Délégation CNRS at the Heudiasyc Lab to reinforce the collaborations with my colleagues in the laboratory and prepare a proposal for a collaborative project within the H2020 calls.

### 1.3. Contribution

My contribution spans over a range of 10 years of research activities and more than 70 publications. Thus, it is difficult to decide the strategy to select a very limited set of works to present in this manuscript. The decision I made, concerning the selection strategy, is to present the works that I consider as milestones in my professional growth, even if they may not be those with the highest impact or those that I consider the best written.

My oldest group of works, object of study in Chapter 2, concerns the resource



management of wireless networks (cellular, IP, satellite) in presence of *impact-unaware mobility*. From this first group, I decided to present a **handover management scheme** for vehicular users of a 2-tier (micro- and macro-cells) 2<sup>nd</sup> generation cellular system [50]. Even if the context of this work is an outdated 2<sup>nd</sup> generation cellular system, the basic idea of classifying vehicular users according to their actual velocity in an urban scenario and assign them to micro- or macro-cell accordingly, could be applied to any wireless system that presents a multi-tier architecture. Basically, in this work, we found a way to make use of the information about the vehicles' speed and used it to split users into "slow users" and "fast users", and consequently assign them to micro-cells and to the macro-cell, respectively. Our method, based on the maximum velocity achieved by a vehicular user during its journey within each micro-cell showed to be more accurate in classifying users than the existing methods [105] [49], and made the system guarantee a better Grade of Service (GoS) to its users. This work, besides being the first research work I participated in, allowed me to have some intuitions that anticipated the *controlled mobility* concepts.

The second group of works, in Chapter 3, represent the main core of my research. Therefore, I decided to split my contribution into two categories: (i) works concerning the **definition of optimal placements and the mobility algorithms** for nodes to reach the optimal placements; (ii) works dealing with the **Point of Interests (PoI) discovery, coverage and tracking**. Concerning the former, at the time of my study, some works on ad hoc placements of nodes for improving energy efficiency already existed [81, 91, 100]. However, these works were tailored for very specific cases. Therefore, my colleagues and I decided to extend and modify the more general mathematical analysis proposed in [39] for mobile wireless sensor networks, with the objective of including nodes possessing different residual energies. Our contribution showed interesting properties, such as the equalization of the life-time of the nodes in the path between source and destination. As this work only dealt with finding the optimal placement for relaying a data flow of infinite duration, we introduced also a mobility algorithm to guide the nodes in the optimal positions. First, we demonstrated that, by using a distributed approach and local information, nodes may end up wasting, for the movement, more energy than that they can save by placing themselves in the optimal positions. Then, we proposed a scheme that, by making nodes virtualizing their movements to reach the optimal placement, possesses all the features required for working well in a mobile wireless sensor network: distributed, quickly convergent, adaptative [24] and we added also energy efficient, which was our main objective. Our work was one of the first in showing that, by using mobility, a mobile sensor and robot network can last longer than a static one. However, we were sure that the topic would soon become hot, and we kept working on the definition of mobility schemes for improving network performance. This research direction took me, among the other things, to the definition of the first mobility scheme for PoI discovery and coverage as well as for the Sport Event Filming (SEF) problem. For both these works, my contribution spanned from the mathematical analysis and formulation, respectively, to the definition of a distributed scheme for nodes mobility that uses only local information. In particular, the Sport Event Filming problem presents some very interesting features from the mathematical point of view, as it can be considered as a Dynamic Vehicle Routing Problem [79], which is very hard class

of optimization problems, whose solutions could be very useful for many applications from different domains. We found a suboptimal distributed solution for the SEF problem, without and with communication and connectivity constraints (SEF-C<sup>3</sup>).

The third group of works, in Chapter 4, addresses the integration of the algorithms of the previous Chapter into architectures composed of several, heterogeneous segments, such as sensor networks, terrestrial robot networks and UAV networks. For this group of works, which belongs to the System of Systems research area, my contribution is oriented to describing architectural choices, open issues and possible solutions of networking within an SoS, as well as, from a practical point of view, presenting integrated communication and control simulation and implementation tools for one or more segments of the SoS. The first contribution **identifies the role of Wireless Sensor Networks (WSN) and Unmanned Aerial Vehicles (UAV) in the context of natural disaster management**. Main applications of systems involving WSN and UAV are classified according to the disaster management phases, and a review of relevant research activities is provided along with the research and development challenges that still remain unsolved. The second work reflects the current merging of networking and control research fields within the scope of robotic applications, which is creating fascinating research and development opportunities. As the tools for a proper and easy management of experiments still lag behind, my contribution tries filling such gap by presenting **a simulation architecture for networked control systems** which is based on two well-known solutions in both the fields of networking simulation (the NS-3 tool) and UAV control simulation (the FL-AIR tool).

Finally, my contribution in the security field concerns the design of **privacy preservation schemes** in the Internet of Things. The evolution of the IoT invokes massive possibilities for exchanging private data enabling new business models across heterogeneous networks. Then, making IoT technologies secure and reliable becomes the basis to carry out this concept development. Intelligent Transportation Systems (ITS) noticed a fast development in communication technologies as one of the key founders of IoT. Indeed, vehicles are able to exchange various information types (safety, efficiency, security, etc.) with other vehicles and infrastructures. IoT devices for ITS are known for their limited memory space and computational capabilities. Conventional privacy solutions as encryption methods are inadequate to solve the above mentioned privacy concerns [55]. Also, other security systems as firewall, intrusion detection and intrusion prevention systems are not efficient in dynamic environments such as ITS contexts. One promising solution is the use of game theory to model the interactions of actors and decision making that balance valuable vehicular social information for personal and private information. My contribution, in this field concerns the proposal of a game theory-based privacy preservation model between data holder (driver, intelligent devices) and data requester (employer, supplier, etc). The main goal of the proposed game is to find the optimal protection strategy for a data holder to preserve private data over a series of interactions with a data requester.

## 1.4. Manuscript organization

This manuscript will be mainly focused on the two ways of looking at mobility in wireless networks, specifically in Chapter 2 and Chapter 3. Additionally, as the exploitation of controlled mobility by using heterogeneous devices brings up Systems of Systems issues, Chapter 4 will be devoted to my contribution in the design of communications for SoS. Finally, Chapter 5 describes a new research line on security in the Internet of Things that I started upon my arrival at the Université de Technologie de Compiègne. For each of the 4 chapters devoted to my research activities, I will present selected contributions that, for some reason, represented important milestones in my career. Chapter 6 concludes this manuscript with a summary of my research contribution as well as a presentation of research directions for my future work. As my main contribution spans over two opposite perspectives, it would not be possible to give a single state of the art. Therefore, customized ones will be given in the introduction of each chapter.

## 2. Facing mobility as a problem

### Contents

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### 2.1. Introduction

A basic design feature of the next-generation cellular systems will surely be the exploitation of an overlapping coverage composed of a picocell tier for indoor environments, a microcell tier for densely populated urban outdoor areas, a macrocell tier serving low-traffic sub-urban areas, and satellite coverage providing the user with worldwide accessibility [37, 6, 8]. From the literature, it clearly emerges that the focus of the multi-tier system-design activity has to be on three main topics [58]: 1) Detection of hotspot areas in an operational network and the consequent determination of both the best cell-area size and the position of the low-level base stations within the higher layer cells; 2) Resource allocation and management: how many channels must be allocated to a given coverage layer? Is it possible to use the same frequencies in every layer? 3) Call admission and handover control: is it advantageous to transfer a terminal call from one layer to another? Which policy allows the best grade of service (GoS)?

In this contribution, I will focus only on the third topic, by proposing an improvement to the methodologies employed to perform the user-mobility classification. My study refers to a two-tier coverage cellular system consisting of overlapping micro and macro cells in a realistic urban context. The two-tier solution allows the network to tolerate a higher traffic load. Nevertheless, it is actually effective only when the network algorithms are carefully designed to make the two layers be complementary. To this purpose, the horizontal and vertical handover mechanism plays a leading role. Through the handover mechanism it is, in fact, possible to transfer a call from cell to cell. This process is necessary during roaming to keep the user connected to the network and to optimize the channel-resource usage. It appears immediately clear how important the knowledge of the user-mobility profile is in such a context. In fact, it would ease the system task of optimizing the resource management while minimizing the control-traffic load. Following a first rough analysis, users can be classified into two categories: pedestrian (slow) and vehicle (fast). The former can then be assigned to the lowest

layer (microcells) and the latter to the macrocells, thereby avoiding too-frequent handovers. Logically, each proposed admission and handover-control algorithm has to keep other important parameters under control: the system capacity, new call-blocking probability, and handover call-dropping probability. Most studies in the literature [30, 95, 60] base their analysis on the main assumption that user-mobility classification can be performed by estimating the user dwell time in a cell. The system estimates the time a mobile terminal sojourns within a microcell. If it is lower than a fixed threshold, then the user is classified as fast and, usually, the call is switched to the upper layer; otherwise, it remains in the lower layer. What, in my opinion, seems to be an excessively optimistic hypothesis in the “classical” works is the assumption of constant user speed during the call. This assumption is too simplistic in areas characterized by high traffic fluctuation. For example, urban areas are characterized by the presence of traffic lights, crossroads, pedestrian crossing points, etc., which inevitably cause oscillations in the speed of the user engaging a call. A different assumption is considered in two research works [105, 49]. In both, the authors remove the classic, unrealistic assumption of a constant user speed during a call.

As a result of the analysis of these proposals, the idle-bonus algorithm in [49], according to the authors’ main objective, is very effective in maintaining the per call handover rate at a low value, while the algorithm proposed in [105], called the Y&N algorithm in the following, is the best choice in terms of system capacity and call-blocking/dropping probability. My contribution is the development of an algorithm whose objective is the achievement of a performance comparable with Y&N (in terms of blocking probability) and idle-bonus (in terms of handoff rate) algorithms. It uses an approach similar to the Y&N scheme and confirms its strong points, but exploits a different quantity for the user classification. The basic feature consists of avoiding basing the user-speed classification on the computation of the dwell time through the average-user mobility, but in exploiting the knowledge of the experienced peak velocity of the user within a cell. It will be shown how, during the speed-classification process, this permits the actual high variability of the user-speed profile to be taken into consideration.

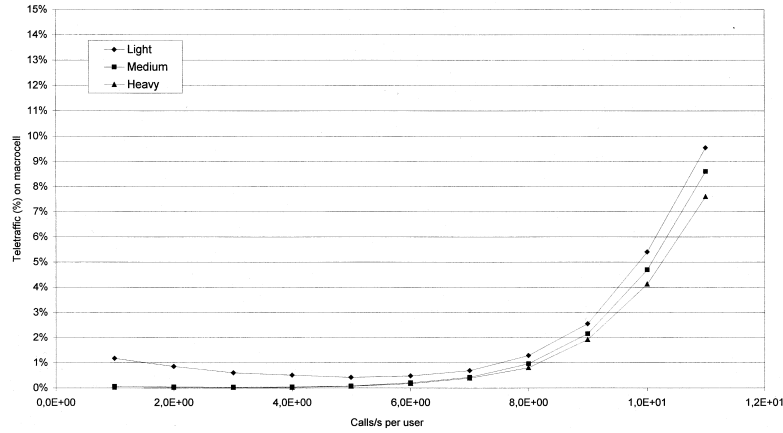
## 2.2. Using the peak velocity for user mobility classification

*A. Iera, A. Molinaro, S. Marano, E. Natalizio, Call Management Based on the Mobile Terminal-Peak Velocity: Virtues and Limitations in a Two-Tier Cellular System, IEEE Transactions on Vehicular Technology, Volume 52, Issue 4, Pages 794-813, July 2003.*

The Y&N method for user-mobility classification, although very effective in ideal conditions, does not work as in the intentions of the authors in an actual urban scenario. The authors consider that the mean speed of a user (and, thus, the sojourn time in a microcell) is “slowly varying” and that the layer selection is made by exponentially averaging the sequence of the sojourn times and then comparing the result with a threshold. We believe that the assumption of a slowly varying mean microcell sojourn time used by Y&N for the user classification is not accept-

**Table 2.1.:** *Example of user speed classification for the Y&N algorithm (Light vehicular traffic, 30- Erlang teletraffic, 20 m/s threshold velocity)*

Car Id	Intentional velocity (m/s)	Cell	Threshold time (s)	Last sojourn time (s)	Estimated mean time (s)	Class
55	22.762	6	19.918	18.0	22.4	Slow
55	22.762	7	19.918	64.0	36.2	Slow
55	22.762	8	19.918	31.5	34.7	Slow
55	22.762	9	19.918	56.0	41.8	Slow
151	22.620	6	19.918	29.5	25.1	Slow
151	22.620	7	19.918	15.0	21.7	Slow
151	22.620	8	19.918	14.0	19.2	Fast
151	22.620	9	19.918	43.5	27.3	Slow
12	24.651	6	19.918	26.0	30.4	Slow
12	24.651	7	19.918	52.5	37.8	Slow
12	24.651	8	19.918	21.5	32.3	Slow
12	24.651	9	19.918	26.0	30.2	Slow
170	22.273	6	19.918	27.0	23.8	Slow
170	22.273	7	19.918	52.0	33.2	Slow
170	22.273	8	19.918	15.0	27.1	Slow
170	22.273	9	19.918	32.0	28.8	Slow



**Figure 2.1.:** *Macrocell occupancy for different traffic conditions in the Y&N algorithm.*

able in the reference environment for our study (a urban context). Therefore, the Y&N algorithm has been tested in a more realistic scenario, through simulation campaigns, in which the mean user microcell sojourn time does not vary slowly, as assumed by the authors.

In Figure 2.1, the behavior of four randomly chosen vehicles (with an intentional velocity greater than the threshold value) is tracked during the crossing of the last four cells. Their identifying number, intentional velocity, last sojourn time, estimated mean microcell sojourn time, and algorithm-classification outputs are reported. The example considers light vehicular traffic and a teletraffic of 30 Erlang. The corresponding threshold velocity is 20 m/s. It is clear from the observation of the figures in the fifth column that a quantity whose value doubles or halves in one step should not be considered “slowly varying.” The release of the conditions of slowly varying average user speed, which follows the implementation of Y&N into a realistic urban scenario, affects the algorithm performance. The actual macrocell usage is different from what is expected. The objective of the Y&N algorithm was the assignment of a fixed load (3.6271 Erlang for a network configuration with eight channels in the macrocell) to the macrocell and the distribution of the remaining load to the microcells. Actually, the macrocell usage does not meet these expectations, as clearly shown in Figure 2.1. This is the result of an erroneous user-speed classification. It is evident that the macrocell layer is un-

derutilized. Should the macro-cellular load be actually equal to 3.6271 Erlang, the expected behavior when the number of calls per second per user increases would be characterized by a decreasing percentage of traffic in the macrocell layer with a minimum value of this percentage equal to 5%, for an offered traffic load equal to the maximum system capacity. This does not happen, as shown in Figure 2.1. Nevertheless, it presents excellent performance in terms of system capacity and blocking/dropping probabilities, mainly thanks to its rigorous approach. On the other hand, the idle-bonus algorithm in [49] is successful in keeping the handoff rate per call very low. Thus, in our analysis, we tried to find a way of trading off the handoff rate per call and the system GoS by exploiting the virtues of both approaches. The first point that clearly emerged from our analysis is that the microcell sojourn time in an urban context is not a suitable quantity to be smoothed through an exponential averaging because it does not have a slowly varying mean. Thus, a different, more reliable quantity to be used jointly with an exponential approach had to be found. A straightforward idea is to implement an algorithm that does not use, as does the Y&N algorithm, the sequence of real measured microcell sojourn times for the user-mobility classification. Differently, it considers the sequence of virtual sojourn times computed by assuming that the user crossed the whole last microcell at the peak velocity it was able to reach (even for a short time interval) in that microcell. Due to the use of the concept of maximum velocity, the algorithm will be called the Max\_vel algorithm. The average value of this quantity should not present aberrations or excessive deviations from the mean value because, in the simulated as well as in the real system, vehicles have the innate inclination to approach their own maximum velocity. If traffic conditions do not allow users to reach their “intentional velocity” for 2-3 consecutive microcells, when using the assumption of uniform vehicular traffic distribution, it is rather improbable that they will be able to reach it in successive cells. The maximum experienced velocity is defined within the range  $(0, \text{intentional\_vel})$ , where  $\text{intentional\_vel}$  is the intentional velocity of the user; for light traffic conditions, its value approaches the upper limit. For heavy traffic, the range is reduced to  $(0, \text{traffic\_vel})$ , where  $\text{traffic\_vel}$  represents the maximum velocity imposed by the traffic conditions to all the cars in the system. In Table 2.2, the observations on four randomly chosen vehicles (with an intentional velocity larger than the threshold value) performed for the Y&N algorithm are repeated when Max\_vel is exploited, for the same traffic and teletraffic parameters.

As we can see, we do not have large oscillations in the estimated values anymore; in some cases, estimated and measured values match. Moreover, cars with an intentional velocity slightly greater than the threshold are classified as fast, whereas cars with an intentional velocity slightly smaller than the threshold are considered to be slow. Future studies could be conducted to investigate the relationship between  $\text{traffic\_vel}$  and traffic conditions and between  $\text{traffic\_vel}$  and threshold velocity, so that it would be possible to find a more precise relationship between user mobility and teletraffic load.

In summary, we maintain the original idea of the idle-bonus algorithm, that if a terminal is classified as fast at least once during a call, this means that it has the natural inclination to gain the fast status again as soon as the traffic conditions allow it to do so. While idle-bonus took into account this assumption by giving the user a bonus to be spent in two successive micro-cells, let us say in a “discrete”

**Table 2.2.:** *Example of user speed classification for the Max\_vel algorithm (Light vehicular traffic, 30- Erlang teletraffic, 20 m/s threshold velocity).*

Car Id	Intentional velocity (m/s)	Cell	Threshold time (s)	Max sojourn time (s)	Estimated time (s)	Class
37	20.879	6	19.918	18.3	18.3	Fast
37	20.879	7	19.918	17.6	18.0	Fast
37	20.879	8	19.918	15.8	17.3	Fast
37	20.879	9	19.918	17.2	17.3	Fast
158	19.035	6	19.918	28.0	25.3	Slow
158	19.035	7	19.918	27.3	26.0	Slow
158	19.035	8	19.918	25.9	25.9	Slow
158	19.035	9	19.918	20.5	24.1	Slow
165	20.729	6	19.918	18.0	23.2	Slow
165	20.729	7	19.918	15.1	21.5	Slow
165	20.729	8	19.918	14.3	19.4	Fast
165	20.729	9	19.918	14.5	17.7	Fast
142	20.397	6	19.918	14.9	16.8	Fast
142	20.397	7	19.918	15.8	16.5	Fast
142	20.397	8	19.918	17.3	16.7	Fast
142	20.397	9	19.918	19.3	17.6	Fast

way, Max\_vel does the same in a “continuous” way by using exponential averaging based on the peak velocity, according to (2.1).

$$\begin{aligned}
 est'd\_mean\_sojourn\_time &= \alpha \times last\_sojourn\_time + \\
 &+ (1 - \alpha) \times est'd\_last\_sojourn\_time \quad (2.1)
 \end{aligned}$$

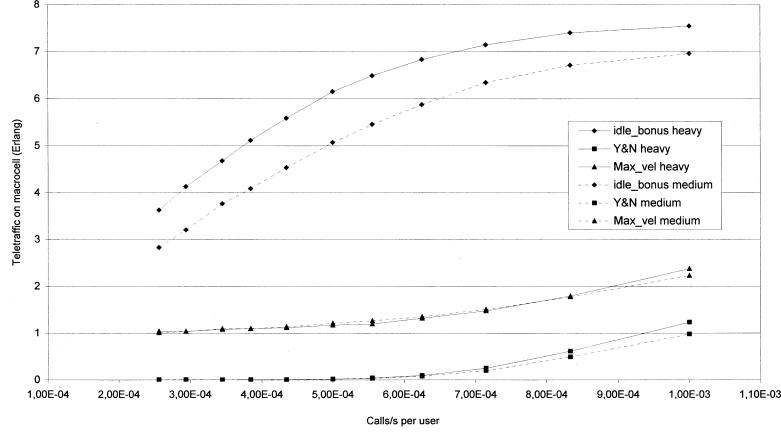
Furthermore, in this way, Max\_vel monitors the user velocity during the entire microcell crossing rather than only at the cell-border crossing, as idle-bonus does. On the other hand, Y&N, by using the exponential averaging based on the mean cell-sojourn time, classifies as fast only the users able to cross each microcell in a time shorter than the threshold time, which is almost inconceivable in an urban context.

### 2.2.1. Results

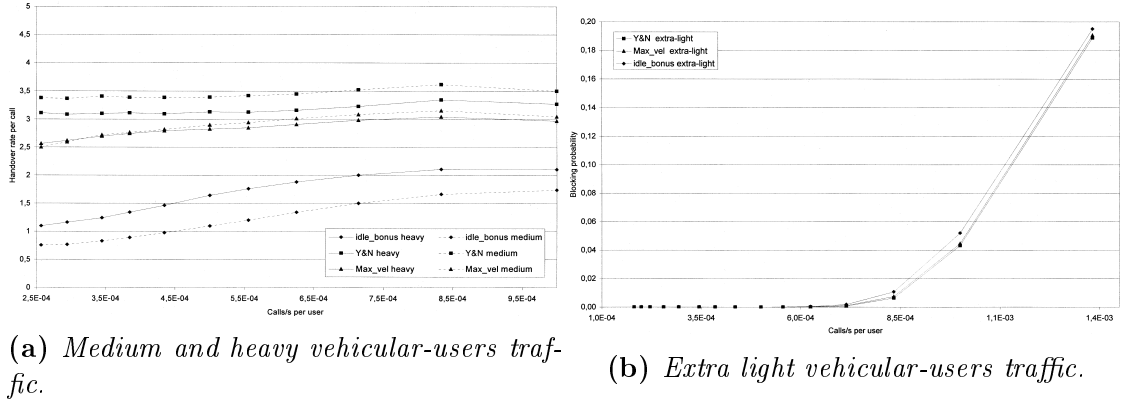
In Figure 2.2, the macrocell usage is shown versus the offered traffic load (call rate per user). As expected, Max\_vel loads the macrocell layer more than Y&N for any vehicular traffic conditions. In Figure 2.2, only the curves at heavy and medium vehicular traffic loads are shown, arrival rates of 0.7 vehicles/s and 0.5 vehicles/s respectively. This is due to the different approach of the two algorithms. In fact, by averaging the mean velocity of the traveling users, Y&N tends to consider as fast only a user who is fast “on average”; this means that it is not enough for a user to instantaneously reach a velocity higher than the threshold to be classified as fast, but it is necessary that its “average” speed remains higher than the threshold. On the contrary, Max\_vel classifies most of the users, which have intentional velocity higher than the threshold, as fast users because it considers the maximum velocity reached by a user crossing a cell in the computation of formula 2.1.

In Figure 2.3, we can observe the behavior of the algorithms with respect to the handover rate per call, for a variable vehicular traffic load. We can see that the Max\_vel algorithm performs 1 to 2 handovers less than the Y&N algorithm. The difference between the two algorithms is even more evident when the vehicular traffic load is lighter (less than 0.3 vehicles/s); in fact, in these situations, vehicles more easily reach their intentional velocity because the traffic jam is low. Thus, the system is stressed by fast users, which is the situation where Y&N seems to be





**Figure 2.2.:** Macrocell usage for *Max\_vel*, *idle-bonus*, and *Y&N* algorithms (medium and heavy traffic).



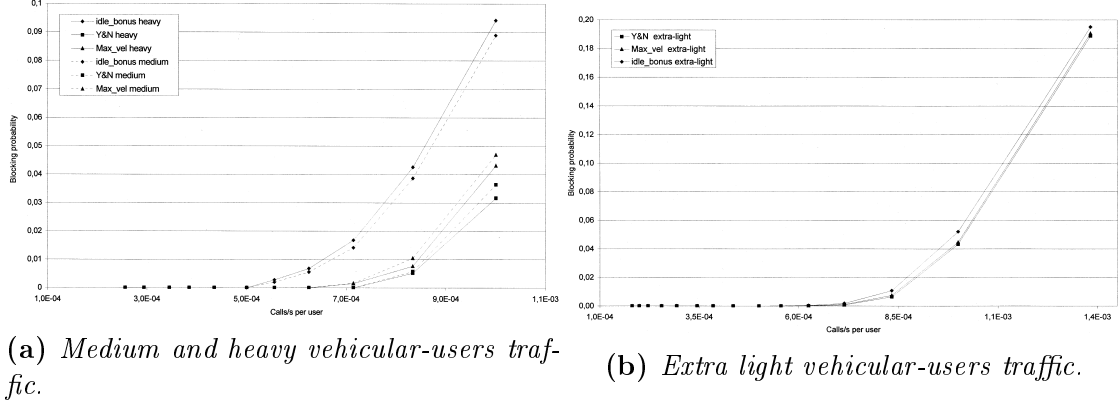
(a) Medium and heavy vehicular-users traffic.

(b) Extra light vehicular-users traffic.

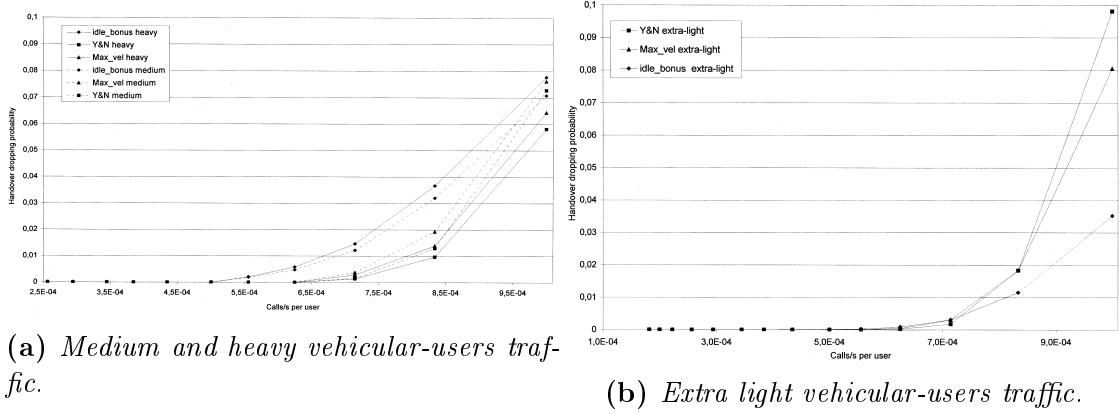
**Figure 2.3.:** Handover rate for the *Max\_vel*, *idle-bonus*, and *Y&N* algorithms.

less effective in successfully classifying the users. In fact, Y&N is more reluctant than *Max\_vel* in classifying users as fast; for this reason, most users remain in the microcells and perform more handovers. Figure 2.3b shows the number of handoffs per call when the vehicular traffic is extra light (0.1 vehicles/s). In this case, the gap between the two algorithms is more than two handovers per call at low load and decreases at higher loads due to the fact that the microcells become congested and traffic is switched over the macrocell, thus reducing the number of handoffs. Idle-bonus is always the one guaranteeing the lowest number of handoffs per call.

In Figures 2.4a and 2.5a, it is shown that the performances of *Max\_vel* in terms of other parameters are the same as those achieved by the Y&N algorithm, while idle-bonus shows the worst behavior, as expected. These curves have been computed when the vehicular traffic is heavy and medium, so most vehicles are prevented from reaching their intentional speed. In Figures 2.4b and 2.5b, blocking and dropping probabilities are shown when the vehicular traffic is extra-light (0.1 vehicles/s); in this case, the differences between the two algorithms are negligible. Furthermore *Max\_vel* outperforms Y&N at high traffic load. Once again, this is the consequence of the way of classifying user speeds used by the two algorithms. In fact, Y&N tends to saturate the microcell layer, hardly classifying users as fast, while *Max\_vel* distributes users between macro- and microcell layers. Therefore,



**Figure 2.4.:** Blocking probability for the *Max\_vel*, *idle-bonus*, and *Y&N* algorithms.



**Figure 2.5.:** Handover dropping probability for the *Max\_vel*, *idle-bonus*, and *Y&N* algorithms.

when the vehicular traffic is lighter (so vehicles are enabled to more easily reach their intentional velocity) and the teletraffic load is higher, the GoS performance of Y&N degrades, mostly due to the unavailability of microcell channels.

### 2.2.2. Discussion

In this work, we designed an effective algorithm for the admission and handoff control of mobile user connections in a realistic urban scenario with multi-tier cellular coverage. It exploits the knowledge of the instantaneous peak velocity of a user in the cells to overcome the weaknesses shown by other algorithms in the literature when operating in a realistic urban scenario. Experimental results proved that the proposed method is effective to guarantee the achievement of good performance in terms of handoff rate, blocking, and handoff-dropping probability. The positive behavior has been assessed under different vehicular traffic and teletraffic loads.

## 2.3. Conclusion and discussion

I wanted to include this work in the manuscript, even if it is my oldest one from 2003 (I could not even find the source files of the paper!) and it was done when the acronym *VANET* did not exist in the research community yet, because it actually

contains some intuitions that matured in the time and led me to switch perspective on mobility in wireless networks. Some of my comments, on the last page of the block notes that I used for it, say: “The main problem for the network seems to be the extreme variability of users speed, which degrades the quality of the services provided by the network. Users speed should be regulated in order to have a smaller range of variability and allow the system to cope with their mobility. Cars should move, as we can see in some futuristic movie, in a line, following each other all at the same maximum speed allowed on that road.” The concept imagined in the last sentence is now called *platooning* and it has become a widely investigated research topic by VANET researchers and car manufacturers, whereas the rest of the sentence anticipate the idea of controlling mobility in order to improve the network performance. During the years, until 2006, I kept working on “facing mobility as a problem for the network” in different contexts: cellular networks, IP networks, satellite networks. After 2006, my research switched to *controlled mobility*. However, recently, from 2014, I started collaborating with Anna Maria VEGNI and Barbara MASINI to define algorithms of resource management, handover management and Vehicle-to-Vehicle (V2V) for heterogeneous networks in 5G systems, and with Fabio D’ANDREAGIOVANNI and Dritan NACE to characterize the uncertainties, caused also by mobility, of data generation in body wireless sensor networks, and move towards a robust placement of bio-sensors.

**Publications:** [J11, J12, J20, J24, C5, C7, C22, C23, C26, C27, C34, C35, C36, C37, C38, C39, C40, C41, C42, C43, I1, I4, I5].

# 3. Exploiting mobility as a facility

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## 3.1. Introduction

In this chapter, I will present the main ideas that are at the core of my research activities and that concern the utilization of nodes' mobility to simultaneously achieve a specific target and improve the network performance.

As already anticipated in Section 1.2 and 1.3, the main criticism concerning the usage of *controlled mobility* is that the movement of nodes implies a high energy consumption, and that more convenient ways of changing topology should be rather taken into consideration. Therefore, the first part of my work in this area was devoted to the demonstration that moving nodes to change their placement can seem a waste of resources in the short term, but by using wise mobility algorithms, it is actually possible to save energy in the medium-long term. Thus, the first Section of this Chapter will present a summary of works on finding the placement of mobile wireless sensors that optimizes the energy consumption and extends the lifetime of the network, as well as it presents an effective mobility algorithm for energy saving.

Once the question of “why should we move nodes?” is answered, even only partially as the advantages of *controlled mobility* are not actually limited only to the energy savings, and a first example of mobility algorithm is presented, it is possible to go deeper into the “how should we move nodes?” question. In the second part of this chapter, I will give a couple of examples of *controlled mobility* algorithms for robot networks, in which the two objectives of achieving a specific target (such as discovering or monitoring a Point of Interest) and preserving the connectivity of the network and the quality of its services can be actually formulated in the same theoretical and empirical frameworks. Therefore, two works will be presented: the first concerning the Point of Interest (PoI) discovery and coverage, and the second concerning the application of a fleet of robots for filming a sport event. While the

first work could be now considered “classic” in the sense of the proposed application and study methodology, the second is more innovative, as it puts together control theory and communications, and represents a great exemplary case for targets that change dynamically during the mission time.

### 3.2. Why move nodes around?

*E. Natalizio, V. Loscrì, Controlled Mobility in Mobile Sensor Networks: Advantages, Issues and Challenges, Springer Telecommunication Systems, Special Issue on Recent Advance in Mobile Sensor Networks, Volume 52, Issue 4, Page 2411-2418, 2013. DOI: 10.1007/s11235-011-9561-x.*

Self-organization is a great concept for building scalable systems consisting of a large number of subsystems. Key factors in similar environments are coordination and collaboration of the subsystems for achieving a shared goal. This collaborative work may be realized through a central or distributed control and the primary objectives of similar networks are scalability, reliability and sustainability [52]. Moreover, with the miniaturization of computing elements, we have seen the appearance in the market of many mobile devices that can collaborate in an ad hoc fashion, without requiring any previous infrastructure control. This latter consideration allows us to consider the mobility as a fundamental aspect of the self-organizing networks. We can identify three macro-categories of mobility: random, predictable and controlled. In the first category, mobile devices are supposed to move according to a random mobility pattern. Many probabilistic models have been proposed in order to foresee devices’ movements. Unfortunately, random mobility represents a problem to solve more than an advantage to exploit. A network access point mounted on a means of public transportation that moves with a periodic schedule represents a case of predictable mobility. A predictable schedule permits an easier, programmable accomplishment of some desired target, but mobility is not considered as a network primitive yet. Finally, *controlled mobility* has been a hot research topic of the robotics community for many years. It concerns the motion coordination of a group of robots for a common objective, typically the coverage of a geographical area. But, the number of applications where controlled mobility is beneficial is enormous, and it spreads from underwater monitoring of seismic movements to planet exploration, from environmental sensing to site surveillance and localization of intruders. The coordination requires communication, computation and control among the robots. All these aspects are covered by the vast literature of theoretical and practical results in the control theory. Instead, in the networking research world, mobility has always been seen as an issue to face more than as a facility to exploit. Only recently, has controlled mobility gained an important role also for communications matters. As witnessed by the recent contributions in the wireless sensor, multihop, mesh and mobile ad hoc networking, controlled mobility offers several advantages to all those kinds of wireless networks which aim to an autonomous self-organization.

The first class of parameters which can be optimized by introducing controlled mobility in wireless networks is related with **power efficiency**. In [39], the authors present a distributed, self-adaptive scheme of mobility control for improving power

efficiency while maintaining connectivity in a wireless sensor network. What is more important is that they introduce mobility as a network control primitive. Power consumption is also investigated in [91] and [81]. In [91] the authors discuss the usage of controllable mobile elements in a network infrastructure in order to reduce the energy consumption. They show that for increasing nodes densities, the presence of a mobile base station reduces the energy usage with respect to a network of static nodes. The mobility pattern of the mobile node is designed so that the path is fixed, but the speed profile followed along the path is flexible. In [81], the authors split the nodes of a Mobile Ad-Hoc Network (MANET) in two categories: relay nodes, which are considered all mobile, and tracking nodes, which are static and used for getting information on a possible intruder of the network. They incrementally find the relays positions that minimize the total required transmission power for all the active flows in the MANET. A distributed annealing algorithm has been used for governing the motion of nodes. A different approach is considered in [100], where only one node is considered mobile. It can be the sink or a relay node. For the case where the sink is mobile, the upper bound on the network lifetime is analytically determined to be four times that of the static network. The authors claim that a mobile sink is not feasible, because the sink is expected to be static since it acts as gateway to a backbone network. For this reason, they assume that the mobile node is a relay and they construct a joint mobility and routing algorithm in order to make the network lifetime come close to the upper bound.

An even more intuitive benefit comes from the ability to control the **coverage** of the network, by modifying the positions of the nodes. A static network suffers from several disadvantages in covering a geographical area. First, even when the initial deployment did not leave regions uncovered, a static network can not cope with the dynamics of the environment and with the local disconnections. Second, the fixed positions of the nodes represent an easy target for a malicious attacker. Furthermore, if a specific **nodes displacement** is shown to be optimal for some objective, controlled mobility is the way to achieve it.

In [23], the authors design adaptive and distributed algorithms, based on Voronoi diagrams, in order to coordinate a multi-vehicle network to meet on an event point following a predefined distribution.

Butler and Rus in [16] obtain the same objective making nodes cover a given area and converge on specific points of interest in a distributed fashion. The novelty is in the absence of placements defined a priori, and in the presence of new constraints, added so as not to leave any portion of the environment uncovered.

A more theoretical study is presented in [14], where the authors consider two metrics of quality of coverage (QoC) in mobile sensor networks: the fractions of events captured and the probability that an event is captured. They provide analytical results on how these two performance metrics scale with the number of mobile sensors, their velocity patterns, and event dynamics. They also develop an algorithm for planning sensor motion such that the probability that an event is lost is bounded from above. In our opinion, an algorithm based on this work, would need each sensor to be programmed accordingly with the mobility pattern computed by a centralized unit.

Controlled mobility can be effectively used during the network **deployment** phase, when an optimal placement of the nodes is too expensive or impossible

due to environmental impedimenta. Reference [110] exploits the virtual force field concept for enhancing coverage. Sensors start from an initial random configuration, and, by using a combination of attractive and repulsive forces, they move to a final placement, where the area covered by each of them is maximized. The authors of [101] design two sets of distributed protocols, based on Voronoi diagrams, for controlling the movement of sensors to achieve target coverage. One set minimizes communications among the sensors, while the other minimizes movements. Coverage, deployment time, energy consumption and moving distances are the performance evaluation parameters used to show the effectiveness of their algorithms.

Controlled mobile sensors can also be used for **exploration and localization**, as in [89]. The cited work defines a hybrid architecture, made of a certain number of mobile actuators and a larger number of static sensors. The actuators move in the sensor-field and get information from the static sensors in order to perform site exploration, coverage repair and target localization. The algorithms which drive the actuators in their tasks are based on potential field and swarm intelligence.

**Load balancing** in wireless sensor networks is studied in [63]. The closest nodes to the base station are the bottleneck in the forwarding of data. A base station, which moves according to an arbitrary trajectory, continuously changes the closest nodes and solves the problem. The authors find the best mobility pattern for the base station in order to ensure an even balancement of the network load on the nodes.

It is well known that, in a wireless network, the **throughput** degrades with the number of hops. A node, which can act as a mobile relay, would limit the number of hops and increase network performance. In literature, we can find many works on data mules, whose predictable mobility is also used for improving the **delivery ratio** of data. In delay-tolerant networks, Message Ferrying exploits controlled mobility in order to achieve the same task of transporting data with a high delivery ratio and also where end-to-end paths do not exist between nodes. In [108], the authors propose a scheme which manages with multiple ferries and is able to meet the traffic demands while minimizing the average data delivery delay.

A sensed phenomenon may require different rates of sampling by the sensor nodes. This leads to a non-uniform distribution of sensed data on the network and, without an accurate scheduling strategy of data collection, to a possible buffers' overflow. In [92], the authors use mobile nodes for data gathering. First, they show that the scheduling of multiple mobile elements with **no data loss** is a NP-complete problem; then, they compare the performance of some computationally practical algorithms for single and multiple mobiles in terms of amount of overflow and latency in the data collection.

In [12], the authors deform the topology of a multi-hop wireless network by moving the nodes to create new links. They show a reduction in the mean **end-to-end delay** of the network, even more effective than the alternative approach of increasing the capacities of the most congested network links. The algorithm is centralized and it takes as inputs: the network topology, the coordinates of the wireless nodes and the network load. Then, it tries changing the network connectivity by moving the non-static network nodes in small steps. This is done such that, at each step, the network remains connected and its characteristic timescale goes down.

**Table 3.1.: Controlled mobility advantages**

Algorithm	Type of Network	Objective	# of Mobile Devices	Scheme	Type of Controlled Mobility
Mobility Control [39]	Multihop WN	Connectivity	All	Distributed	Adaptive
Adaptive Motion [91]	WSN	Energy Consumption	Sink	-	Programmed
Distributed Annealing [81]	MANET	Energy Consumption	All	Distributed	Adaptive
ARALN [100]	WSN	Network Lifetime	Single node	-	Programmed
Coverage Behavior [23]	WSN	Coverage	All	Distributed	Adaptive
Local Voronoi [16]	WSN	Coverage	All	Distributed	Adaptive
BELP [14]	WSN	Quality of Coverage	To be computed	Centralized	Programmed
VFA [110]	WSN	Deployment	All	Distributed	Adaptive
VEC, VOR, Minimax [101]	WSN	Deployment	All	Distributed	Adaptive
TARANTULAS [89]	WSAN	Localization	Some	Distributed	Adaptive
Joint Mobility and Routing [63]	WSN	Load Balancing	Sink	-	Programmed
MURA [108]	DTN	Delivery Ratio	Some	Centralized	Programmed
MES [92]	WSN	No Data Loss	Some	Distributed	Adaptive
CD [12]	Multihop WN	End-to-end delay	All	Centralized	Adaptive
Kansal [52]	WSN	Sustainability	All	-	-

In Table 3.1 all the cited works are shown along with the type of wireless network under investigation and the objective of the research<sup>1</sup>. In order to offer a better categorization, in the three following columns, we put the number of devices which are considered mobile, the scheme and the type of controlled mobility used in the algorithm.

Even though a few works had already aimed at using mobility in order to reduce the **energy consumption** [39, 91, 81, 100], still the main criticism about *controlled mobility* was that the movement of nodes implies a high energy consumption that may not be compatible with the limited resources of the battery-powered devices considered in these works. Therefore, we focused our attention on improving the **energy efficiency** as described in the next Section.

### 3.2.1. Improving Energy Efficiency

- E. Natalizio, V. Loscrì, E. Viterbo, *Optimal Placement of Wireless Nodes for Maximizing Path Lifetime*, *IEEE Communications Letters*, Volume 12, Issue 5, Pages 362-364, May 2008.
- E. Natalizio, V. Loscrì, A. Violi, F. Guerriero, *Energy Spaced Placement for Bidirectional Data Flows in Wireless Sensor Network*, *IEEE Communications Letters*, Volume 13, Issue 1, Pages 22-24, January 2009.
- Costanzo C., V. Loscrì, and E. Natalizio, *Distributed Virtual-Movement Scheme for Improving Energy Efficiency in Wireless Sensor Networks*, *The 12th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, 2009.

The placement of nodes in a wireless network is an important research field since the energy consumption and the lifetime of a network rest on the power used in the transmission and reception. This power usage, in turn, depends on the mutual position of the pair of communicating nodes. We know from [93] that a straight path of multi-hop communications, between source and destination, is

<sup>1</sup>The Table 3.1 reflects the state of the art at the time of the work, literature greatly expanded since then.



most energy efficient and there is also a unique hop count for any distance that minimizes the cost of communications. Goldenberg *et al.* show that the optimal positions of the relay nodes must lie entirely on the line between the source and the destination, and these nodes must be evenly spaced along the line [39]. Therefore, from now on, we shall refer to this approach as “evenly spaced”. We proposed a mathematical model, which focuses on the maximization of the lifetime of the path of nodes involved in a data flow. This model allows us to find the best placement of the devices when they have different levels of residual energies, for this reason we called our approach “energy spaced”. From the model, we find out that the optimal placement is on the straight line between source and destination as in [39], but the nodes must be spaced according to their residual energies, according to the following formula:

$$\begin{aligned}\mathbf{v}_i &= \mathbf{v}_{i-1} + \sqrt{\frac{E_{i-1}}{P_{rec}T_{PL}}} \mathbf{u} = \\ &= \mathbf{v}_1 + \sum_{k=1}^{i-1} \sqrt{\frac{E_k}{P_{rec}T_{PL}}} \mathbf{u}, i = 2, \dots, n-1,\end{aligned}\quad (3.1)$$

where

$$\mathbf{u} = \frac{\mathbf{v}_n - \mathbf{v}_1}{\|\mathbf{v}_n - \mathbf{v}_1\|}$$

and the path-lifetime  $T_{PL} = T_1 = T_2 = \dots = T_{n-1}$  can be found from

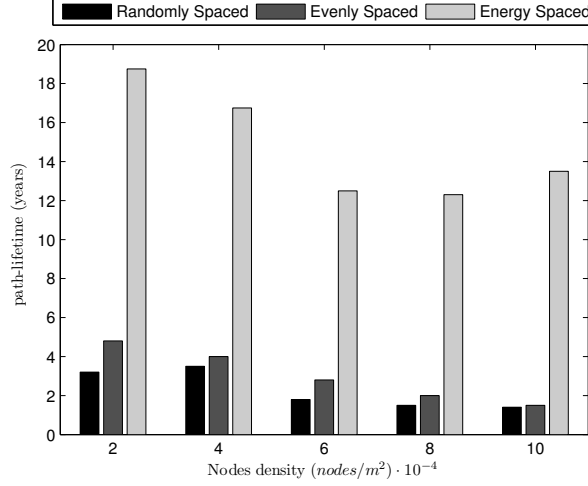
$$\mathbf{v}_n = \mathbf{v}_1 + \sum_{i=1}^{n-1} \sqrt{\frac{E_i}{P_{rec}T_{PL}}} \mathbf{u}, \quad (3.2)$$

i.e.,

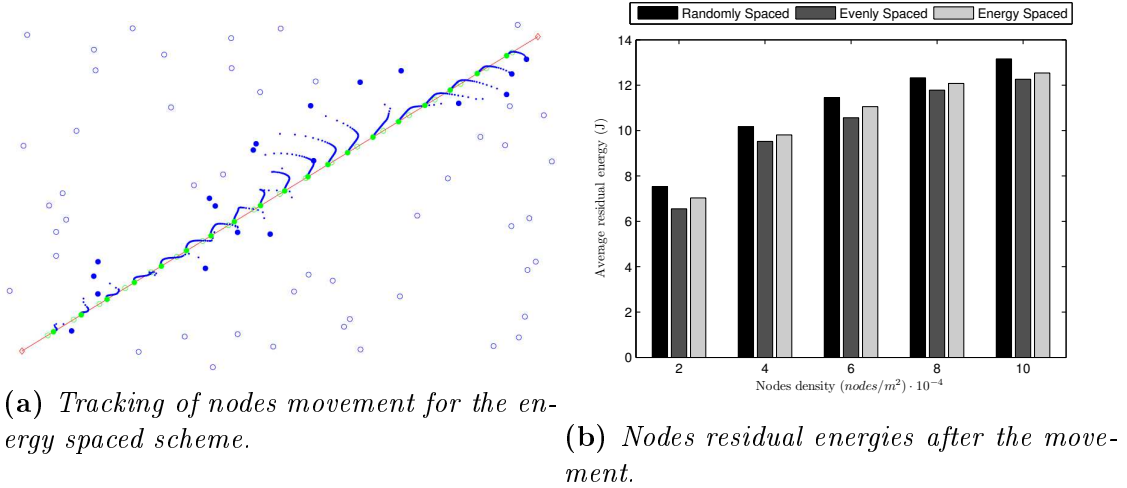
$$T_{PL} = \frac{1}{P_{rec} \|\mathbf{v}_n - \mathbf{v}_1\|^2} \left( \sum_{i=1}^{n-1} \sqrt{E_i} \right)^2. \quad (3.3)$$

Where  $\mathbf{v}_1$  and  $\mathbf{v}_n$  denote the known source and destination positions, respectively,  $\{\mathbf{v}_i\}_{i=2}^{n-1}$  are the positions of the  $n-2$  relay nodes,  $\{T_i\}_{i=1}^{n-1}$  and  $\{E_i\}_{i=1}^{n-1}$  are the life times and the residual energies of the nodes, respectively, and  $P_{rec}$  denotes the minimum required power in order for a bit to be correctly received. The obtained positions  $\mathbf{v}_i$  guarantee that the energy consumption is the minimum for each node in the data flow. Thus, nodes are closer or further from the following neighbour depending on their residual energies. In this way, mutual distances  $d_i$  are determined and transmission powers will be consequently adapted. In Figure 3.1, the “evenly spaced” and our “energy spaced” placement schemes are compared with the random one, when nodes density increases. In order to calculate the lifetime of the path of nodes involved in a bidirectional data flow, we assume that the data flow has an infinite duration and when nodes start the relay, they have different residual energies. The results show that a better placement means a longer lifetime.

In fact, both of the schemes improve the lifetime of the network, and the energy spaced one, by considering different residual energy levels, outperforms the other. Our first results show that an optimal placement in terms of lifetime of the network



**Figure 3.1.:** Comparison of the lifetime for the random, “evenly spaced” and “energy spaced” placement schemes.



**Figure 3.2.:** Uncontrolled movements of the nodes waste more energy than the nodes would save by reaching their optimal positions.

exists. However, continuous or uncontrolled movements of the nodes to reach the optimal positions introduce the side effect of wasting more energy than the nodes would save by reaching different positions. Our concern is to show that, also when the movement is controlled, the trajectories followed by the nodes for arriving at the best positions can be energy inefficient. In Figure 3.2a, the full blue circles represent the nodes chosen by the routing algorithm, the full green circles indicate the energy spaced positions, while the empty green circles are the evenly spaced ones. In the same figure, we have an example of a winding path travelled along by the nodes, in order to reach the energy spaced positions, on the straight line between the terminal nodes of a bidirectional data flow. The same figure could be plotted also for the evenly spaced algorithm, which moves each node, iteration by iteration, to the central position between its two most adjacent nodes in the path. In Figure 3.2b, the residual energies of the nodes, after they completed the movement and the transmission phase, are shown.

We compare the two schemes of placement and movement with the case where nodes did not move at all from their initial random positions, in terms of residual energy. It is possible to see that the movement makes the nodes have a lower level of residual energy. Apparently, this suggests us not to move the nodes, in order to react better to any change in the network.

For this reason, we design a **Virtual Movement Scheme** to use a distributed approach for calculating the nodes final positions. By using the usual distributed approach, nodes reach their final positions after several iterations, which include movements and exchange of messages among the nodes. With the “virtualization of the movements”, after a sequence of iterations, which do not include any movement, the nodes will know their final positions, as if they were calculated by a central computational unit, and only then, will they move toward those positions.

The implementation of the algorithm for the Energy Spaced Virtual Movement scheme in pseudo-code follows.

---

**Algorithm 1** Energy Spaced Virtual Movement

---

```

1:  $x_i$ : current position of node  $i$ ;
2:  $x_{i-1}$ : current position of node  $i - 1$ ;
3:  $x_{i+1}$ : current position of node  $i + 1$ ;
4:  $E_i$ : residual energy of node  $i$ ;
5:  $E_{i-1}$ : residual energy of node  $i - 1$ ;
6:  $E_{i+1}$ : residual energy of node  $i + 1$ ;
7: repeat
7:   send  $x_i$  and  $E_i$  to neighbours  $i - 1$  and  $i + 1$ ;
7:   receive  $x_{i-1}$ ,  $x_{i+1}$ ,  $E_{i-1}$  and  $E_{i+1}$ ;
7:   set  $\lambda(i)_{fw} = \frac{\sqrt{E_i}}{\sqrt{E_i} + \sqrt{E_{i-1}}}$ ;
7:   set  $position(i)_{fw} = (\lambda(i)_{fw}x_{i-1} + (1 - \lambda(i)_{fw})x_{i+1})$ ;
7:   set  $\lambda(i)_{bw} = \frac{\sqrt{E_i}}{\sqrt{E_i} + \sqrt{E_{i+1}}}$ ;
7:   set  $position(i)_{bw} = (\lambda(i)_{bw}x_{i+1} + (1 - \lambda(i)_{bw})x_{i-1})$ ;
7:   set  $x'_i = (position(i)_{fw} + position(i)_{bw})/2$ ;
7:   set  $x_i = x'_i$ ;
8: until (convergence)
8: move to  $x_i$ ;
```

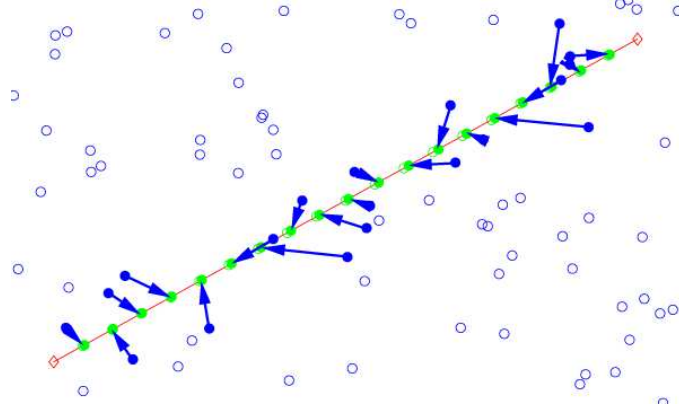
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### 3.2.1.1. Results

In Figure 3.3 we can see a simulation of the algorithm Energy Spaced Virtual Movement. This plot uses the same symbology of Figure 3.2a, with which it must be compared in order to see the different trajectories. With the Energy Spaced Virtual Movement, the movements are not performed at each iteration, but once for all as a last step of the algorithm. Thus, in the Figure 3.3. it is shown in blue the straight and shortest path performed by the nodes.

In what follows, we summarize the advantages introduced by the virtualization of movements:

- *Travelled distances*: when nodes move all at once, and not iteration by iteration, they can select the most advantageous path to travel in order to



**Figure 3.3.:** *Tracking of nodes movement for the energy spaced virtual movement scheme.*

reach the final placement. This can all be done with a distributed approach by using local information.

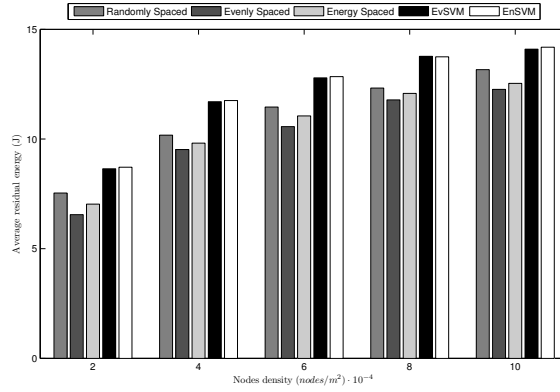
- *Movement's time cost:* we have not designed yet a model that takes into account accelerations and velocities of the nodes, when they move towards their new positions, but it is evident that many intermediate movements are more time consuming than one single movement. Thus, not only does our proposal converge to the algorithmic solution in a smaller number of iterations, but even the execution of the solution is faster than the other algorithm in literature.
- *Movement's energy cost:* the energy model used for the movement is a simple distance proportional cost model, valid for wheeled devices:  $E = k \cdot d$ , where  $k$  is a constant movement  $[J/m]$  and  $d$  is the travelled distance. This model considers the dynamic friction but it should be enriched by taking into account also the static friction, which represents the resistance to be overcome by a device, in order to start moving:  $E = k \cdot d + E_s$ , where  $E_s$  is the energy needed to overtake the static friction  $[J]$ . If the iterations' number increases, also the energy needed for overtaking the static friction will increase. With our scheme, the node moves only once and the term  $E_s$  will contribute only once to the total energy expenditure, and for this reason it can be neglected.
- *Protocol overhead:* for each iteration, nodes are called to compute their new position and communicate it to their neighbours. Thus, we require that the number of iterations is the minimum, in order not to increase the protocol overhead because of the messages' exchange.

Besides these additional advantages, we can conclude that our scheme is: distributed, adaptative, quickly convergent and suitable to be used in self-organizing systems. In the following, we will show that our scheme is also energy efficient, by showing the results of the Energy Spaced Virtual Movements (EnSVM) and the Evenly Spaced Virtual Movement (EvSVM) schemes, in comparison with the schemes with real movements, in terms of residual energy and travelled distances.

In Table 3.2, we give the details concerning the evaluation parameters. We study the performance of the proposed mechanisms by investigating scenarios with

**Table 3.2.: Evaluation Parameters**

Field Area ( $L \times L$ )	1000m x 1000m
Nodes Density ( $\rho$ )	$[2 \div 10] \cdot 10^{-4} \frac{\text{nodes}}{m^2}$
Flow Time Length ( $T_F$ )	$87.6 \cdot 10^3 h$
Flow Length ( $l$ )	$[200 \div 1000] \sqrt{2} m$
Maximum Transmission Radius ( $r$ )	$1/(2\sqrt{\rho}) m$
Relay Nodes Number ( $N$ )	$l/r$
Initial Residual Energy Range ( $E_i$ )	$15 \div 20 J$
Minimum Required Power ( $P_{rec}$ )	$3.16 \cdot 10^{-12} W/m^2$
Transmission Rate ( $r_T$ )	$1 kb/s$
Movement Constant ( $k$ )	$0.1 J/m$
Number of runs for each scenario	100
Statistical confidence interval	95%

**Figure 3.4.: Average residual energy for increasing nodes density**

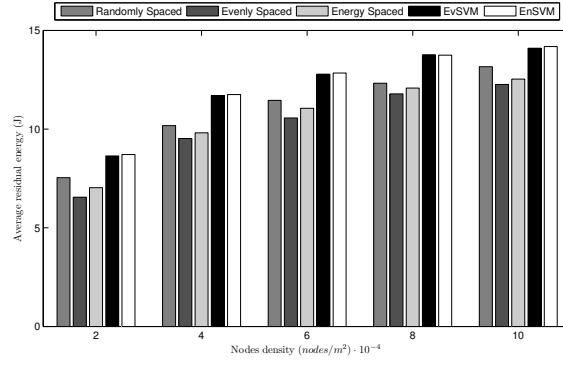
variable nodes density,  $\rho$ , and flow length,  $l$ . For all the scenarios, the simulations have been statistically validated by averaging the results over 100 runs, which allows us to reach the wanted interval of confidence (95%).

The energy required to send one bit at the distance  $d$  is  $E = \beta d^\alpha$ , where  $\alpha$  is the exponent of the path loss ( $2 \leq \alpha \leq 6$ ),  $\beta$  is a constant [ $J/(\text{bits} \cdot m^\alpha)$ ]. For  $\alpha$  and  $\beta$  we used values typical of the free space model [47].

In Figure 3.4, the nodes density is considered variable and the schemes performance has been evaluated for 5 different number of nodes: 200, 400, 600, 800 and 1000 in the 1000m x 1000m sensor field. The flow length is set to  $600\sqrt{2}m$ .

As we can see, the level of energy of the virtual schemes is always larger than the schemes with real movements. In respect of the Evenly Spaced scheme, it improves the performance by about 15-32%, while for the Energy Spaced that is able to take better advantage of higher densities, we have a decreasing improvement that varies between 23% and 13%.

In the second simulation campaign, we want to show the algorithms' performance when the physical distance between the two static terminal nodes varies between  $200\sqrt{2}m$  and  $1000\sqrt{2}m$ , with an increase step of  $200\sqrt{2}m$ , while the nodes density is set to  $6 \cdot 10^{-4} \frac{\text{nodes}}{m^2}$ . The upper limit is given by the size of the sensor field and it represents the case that the fixed terminals are placed at the two furthest corners of the field. This campaign is useful to understand if longer



**Figure 3.5.:** *Average residual energy for increasing flow length*

flows make nodes use more energy for travelling longer distances, as it was for the schemes with real movement. As we can see in Figure 3.5, when the movement is virtual, residual energy is not affected by the length of the flow, in fact they are quite constant for all the values of flow length. In Figure 3.5 we can see that, for this scenario, the improvement reported by the virtual movement schemes is  $10\% \div 20\%$  and  $9\% \div 18\%$  in respect of evenly spaced and energy spaced with real movement, respectively.

### 3.2.1.2. Discussion

In this Section I tried to summarize three of my initial works with controlled mobility, which aimed at (i) finding out the best placement of mobile nodes for relaying a flow of data while minimizing the energy consumption; (ii) designing a distributed algorithm for letting nodes move to the optimal positions. In these works, first we formulated an analytical model for the nodes placement in a mobile wireless sensors network, based on the residual energy of the nodes. The model allowed us to find the most energy efficient positions in order to prolong the path lifetime of the nodes of a mono-directional or bi-directional data flow. The same idea can be applied for a real sensor network when the positions of the terminal nodes of a larger number of simultaneous flows are fixed and known from the deployment phase, thus improving the overall energy performance and increasing the lifetime of the whole network. Successively, we developed a distributed algorithm based on virtual movement of nodes. The movement virtualization is a smart and very simple approach for exploiting the advantages of better nodes placement, without wasting energy because of the mobility. This new mechanism exhibits all the important features that a mobile wireless sensor networks placement and movement algorithm should possess: it is distributed, adaptive, quickly convergent and suitable to be used in self-organizing systems. Furthermore, it has been deeply analyzed through simulations, and it has been compared with other existing schemes that use real movement. In all the simulation scenarios, our mechanism outperformed the existing mechanisms in terms of energy consumption.

**Publications:** [J2, J4, J14, J16, J19, J22, J23, C21, C29, C32, C33].

### 3.3. How to move nodes around?

As we saw in the previous subsection, even if *controlled mobility* can be very beneficial for wireless networks, the nodes must move wisely in order not to waste energy that should be destined to collecting or relaying data. Basically, a *controlled mobility* algorithm for mobile sensor, robot and UAV networks should display the following features [24]:

- **distributed:** as most of the applications for which a mobile sensor, robot or UAV network is used, do not allow the devices to gather together or to share the collected information in one centralized point, all the mechanisms used in the network should be distributed, including the mobility algorithms;
- **quickly convergent:** as the basic feature for mobility in mobile sensor, robot and UAV networks is to be distributed, it may occur that the possibility to have only local information create some wasteful oscillations in the group behaviour. Furthermore, as often the missions for which the networks are deployed are time dependent, it is necessary that the final placement is attained as soon as possible;
- **adaptative:** the network can be called to respond to several different tasks and missions, often switching from one to another. Therefore, in order for the devices to easily adapt to the new task, the mobility mechanisms should also be flexible enough to perform well when a change in the objective occurs;
- **energy efficient:** as all the devices of these kinds of networks are battery-powered, all the mechanisms, especially those related to the mobility of the devices, should consider to limit the energy consumption as much as possible.

In the following two Sections, I will describe two works for **Points of Interest discovery and coverage** and for **filming sport events** that possess the mentioned features and that make explicit usage of *controlled mobility* to accomplish the mission. These two works are selected according to the fact that they both present a mathematical formulation of the problem, a simulation study of the performance, and the possibility of immediate implementation in a real scenario.

#### 3.3.1. Pol discovery and coverage

*M. Erdelj, V. Loscrì, E. Natalizio, T. Razafindralambo, Multiple point of interest discovery and coverage with mobile wireless sensors, Elsevier Ad Hoc Networks, Volume 11, Issue 8, Page 2288-2300, 2013.*

A typical application of sensor and robot networks is environmental monitoring. The sensors have to be deployed and placed on strategic locations to monitor the area of interest. In many cases, monitoring the whole area might be unnecessary. Therefore, monitoring some points of interest increases the sensing performance and reduces the deployment cost. Controlled mobility of sensors adds a new design primitive that needs to be carefully exploited [74]. When sensors have motion capabilities, monitoring only some PolS instead of the whole area also permits time dependent coverage.



(a) Mobile sensors ( $S_i$ ) follow the concentric circular paths and cover the PoIs ( $P_i$ ). (b) The angle that allows communications between sensors.

**Figure 3.6.:** Mobile sensor network with concentric coverage circles.

Very often, environmental monitoring applications require the knowledge of both the position of the PoI to cover and the characteristics of the monitored area. Obtaining all the necessary information about the environment is not an easy task, especially if the dynamic nature of the observed processes is taken into account. Furthermore, combining PoI coverage with the connectivity of each mobile sensor with the data sink is a challenging problem in mobile sensor deployment. In this work, we address a mobile sensor deployment algorithm that combines environment and PoI *discovery* along with *coverage* and *connectivity preservation*. However, the PoI discovery and coverage are opposing demands if the same set of devices is used for both operations. In order to maximize the PoI coverage in the field of interest, mobile sensors have to self-deploy in a certain manner and to adjust their positions according to the placement of PoIs that need still to be discovered, which excludes the application of any standard environment exploration technique. Our approach is based on the continuous and variable speed movement of mobile sensors, which follow concentric circular paths to explore and cover the field of interest. By constantly moving, sensors execute the environment discovery task and, by adjusting the movement velocity, they satisfy the constraints on PoI coverage and connectivity with the data sink. The algorithm that runs on all the mobile sensors is distributed and introduces a new technique of velocity calculation based on the information available from the sensors in one-hop neighborhood.

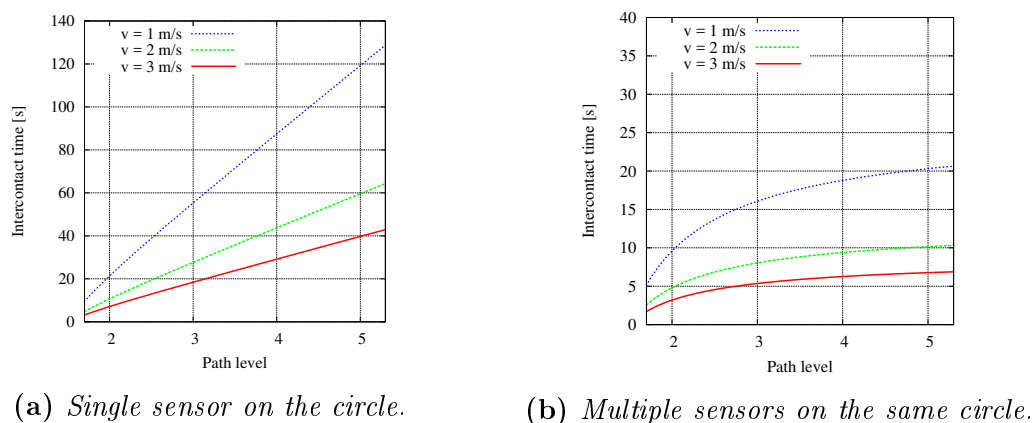
Recent works focused on multi-objective mathematical models to determine the best placement of mobile nodes for different tasks [42, 62]. In [14], authors analyze mobile sensor movement on a circular path with the goal to cover the set of predefined PoIs that lay on the same path. However, the position of the PoI is assumed to be known and the approach cannot be used for the multi-path problem (that introduces multiple movement paths and data sink). In [59], authors investigate the problem of collaborative area monitoring using both static and mobile sensors. They tackle the problem of unknown area exploration and coverage as well as introducing the connectivity issue. However, their focus is on a distributed algorithm for mobile sensors' path planning in order to improve the area monitoring in the way that these mobile sensors sample the areas that are least covered by the stationary sensors and move to the "suspicious" areas on stationary sensor demand in autonomous manner. A preliminary work aiming at three objectives together is [33].

In Figure 3.6a, we can see the mobile sensor network considered in this work.  $S$  is a base station, at the center, and the sensor  $S_i$  moves in circle around  $S$  at a different distance from it (in green in the figure) in order to discover the



Point of Interest,  $P_i$  in the figure. We assume that the communication range of each sensor allows communications with the sensor on the neighboring circle, the communication range is at least two times larger than the sensing range. In Figure 3.6b, we show the condition to satisfy for two neighboring nodes to be able to communicate. The angle  $\theta_{comm}$  is the minimum angle that allows the sensor to communicate. By using the cosine law, this angle is  $\theta_{comm} = \frac{2r_s^2(4n^2-8n+5)-r_c^2}{2r_s^2(4n^2-8n+3)}$  where  $n$  is the considered circle, which is distant  $r_s(2n-1)$  from the base station. We must notice here that for  $r_c = 2r_s$ ,  $\theta_{comm} = 0$ . If we consider that two sensors,  $S_i$  and  $S_j$ , must stay in the communication range of each other for a duration of  $T_{comm}$  to communicate, then, if  $\theta_{comm} = 0$ , then  $S_i$  and  $S_j$  must be static during  $T_{comm}$  to communicate. Instead, if  $2r_s \leq r_c < 4r_s$ , the velocity of  $S_j$  being on the  $n^{th}$  circle is  $v_j \leq \frac{2\theta_{comm}r_s(2n-1)}{T_{comm}}$  and the velocity of  $S_j$  being on the  $(n-1)^{th}$  circle is  $v_i \leq \frac{2\theta_{comm}r_s(2n-3)}{T_{comm}}$ . All the velocities smaller than those indicated in the previous two formulas would allow a communication lasting at least  $T_{comm}$ . However, in order to increase the encounter frequency, it would better to have the conditions satisfied with the equality. If we want to minimize the inter-contact time, i.e. the time needed for two sensors to get back in touch with each other, we assume that after they exit from the communication range of each other, they accelerate to their  $v_{max}$ . In this case, the inter-contact time for  $S_i$  and  $S_j$  is  $T_{int} = 2(\pi - \theta_{comm}) \frac{r_s(2n-3)(2n-1)}{4(n-1)v_{max}}$ . If more than one sensor is available for each circle, and the sensors on the same circle are evenly spaced on the circle, then the inter-contact time becomes:  $T_{int} = 2(\frac{\pi}{n} - \theta_{comm}) \frac{r_s(2n-3)(2n-1)}{4(n-1)v_{max}}$ . The same reasoning can be applied to the coverage of a PoI that requires  $T_{sens}$  to be considered covered.

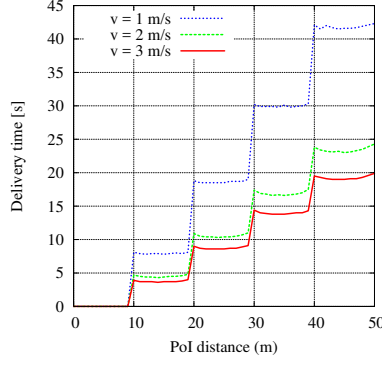
### 3.3.1.1. Results



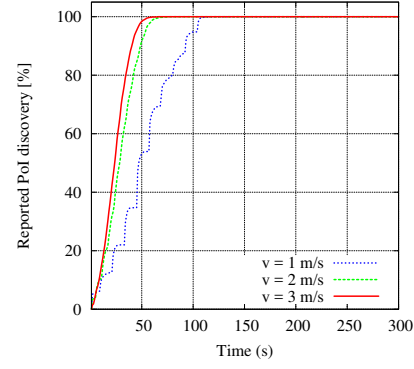
**Figure 3.7.:** Inter-contact time for sensors on neighboring circles.

Figures 3.7a and 3.7b show the inter-contact time according to the circle. Switching from a single sensor to multiple sensors per circle changes the relation from linear to logarithmic.

Figures 3.8a and 3.8b show some simulation results on the time needed to carry the information from a PoI to the base station according to its distance from the base station, and the fraction of PoIs discovered and known by the base station. In Figure 3.8b, we can see that the time for the base station to know all the PoI



(a) *PoI information delivery time.*



(b) *Percent of reported PoIs.*

**Figure 3.8.:** *PoI information delivery time and the percent of reported PoIs to the sink node for circular path approach.*

is 118s for a  $v_{max} = 1 \frac{m}{s}$  with 50 PoIs randomly distributed on a surface of  $8000m^2$ .

For all the diagrams, the parameters used are:  $r_s = 5m$ ,  $r_c = 11m$ ,  $T_{comm} = 2s$ .

### 3.3.1.2. Discussion

In this work we proposed a novel approach to integrate PoI discovery, multiple PoI coverage and data report to the sink. Our motivation for this work is the application of flying mobile sensors for the environmental monitoring, where there is a need to gather as much information as possible while covering the events that occur in the field of interest. By constantly moving, sensors execute the environment discovery task, and by adjusting the movement velocity, they satisfy the constraints regarding the PoI coverage and  $T_{data}$  connectivity with the data sink in order to report the PoI data. We have analyzed the effectiveness of the proposed approach analytically and have provided extensive simulation results to prove the feasibility of our concept.

**Publications:** [J6, J7, J9, J15, J18, J21, C3, C13, C14, C15, C18, C19, C24, C28, C30, I2].

### 3.3.2. Filming sport events

- E. Natalizio, R. Surace, V. Loscrì, F. Guerriero, T. Melodia, *Two Families of Algorithms to Film Sport Events with Flying Robots*, *The 10th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS)*, Hangzhou, China, October 2013.

- N. Zema, E. Natalizio, E. Yanmaz, *An Unmanned Aerial Vehicle Network for Sport Event Filming with Communication Constraints*, *First International Balkan Conference on Communications and Networking 2017 (BALKANCOM)*, Tirana, Albania, May 2017.

- E. Natalizio, N. Zema, E. Yanmaz, *Take the Field from Your Sofa: Leveraging UAVs for Sport Event Filming*, *in progress*.

Commercial drone technology market, currently around \$2 billion, is predicted rocket to as much as \$127 billion by 2020 [66]. According to another study that

surveyed managers and employees at Unmanned Aircraft Systems (UAS) companies, aerial photography and cinema will dominate the vertical markets in the next years [90]. In this work, we envision the usage of Unmanned Aerial Vehicles (UAV) for filming a sporting event and streaming videos to the spectators within the stadium.

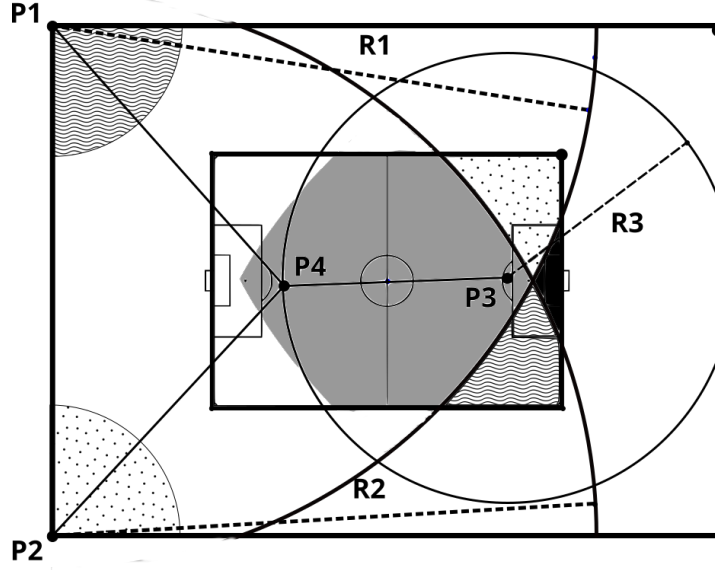
The most popular sport events are played by two teams that confront each other over a field of limited size. The game objective is usually to achieve a certain goal via a sequence of actions, where usually one team attacks and the other defends. This objective can be accomplished by carrying, kicking, shooting or dropping a single object (the *ball* in the rest of the text), such as a ball, a football, a disk etc., in a specific area that is defended by the opposite team. The main actors of the game are the two teams, the ball and the referees; i.e., one or more people that look after players' safety and enforce the rules of the game.

The *Sport Event Filming* (SEF) problem, which I recently introduced in [75], consists of finding the best sequence of positions to reach for a fleet of UAVs in order to maximize the satisfaction of the event's spectators and minimize the UAVs' traveled distance. The UAVs must move timely over the current position of the ball and film the action. In the original formulation of the SEF problem, no attention has been paid to the communication and connectivity constraints required to deliver a High Definition (HD) stream to the spectators. In this work, we extended the formulation of the SEF problem by including communications and connectivity constraints for a scenario with two UAVs, which are used as filming node and supporting node, respectively. We will refer to this new problem as *Sport Event Filming with Communications and Connectivity Constraints* (SEF-C<sup>3</sup>). As for the original SEF problem, the objective is to develop strategies to coordinate the movement of a group of mobile robots in the presence of highly varying time-space constraints. A solution to this problem is of interest for several application domains, and would pave the way for the design of mission-oriented devices and the definition of their coordination/cooperation schemes. From a modeling viewpoint, the problem belongs to the Dynamic Vehicle Routing (DVR) family, which aims at routing vehicles between depots and customers that can appear dynamically during the execution time. To the best of our knowledge, no solutions have been proposed for solving the dynamic SEF-C<sup>3</sup> problem, whose even the static variants are NP-Hard. Some solutions with static cameras exist [27, 80] but they cannot provide the same level of accuracy and entertainment given by mobile devices flying over the game field.

In this paper, we present some new mobility schemes for the UAVs of a SEF-C<sup>3</sup> problem in order to maximize viewer's satisfaction and to minimize the distance traveled by the drones, while taking into consideration the main communications and connectivity requirements for a HD multimedia data flow.

Specifically, the contribution of this work is the following:

- We introduce communications and connectivity requirements into the SEF problem formulation;
- We propose three dynamic movement techniques, based on control theory methods, to solve the problem in a distributed way and without any *a priori* knowledge of the sequence of actions, excluded for the general area they happen.



**Figure 3.9.:** *Model of stadium and game field as a set of two concentric rectangles: the soccer pitch  $110 \times 80[m]$ , and the spectators space  $210 \times 160[m]$ . In the shaded regions of the field the spectators cannot receive a HD video without using a supporting UAV.*

For the mathematical formulation of the problem, please refer to [75, 106].

The objective of this work is to provide a solution for filming a sport event and deliver the video streaming to all the spectators within the stadium, preferably in HD quality. Therefore, we consider the data to transfer as a standard MPEG-4 Part 14 stream, whose transmission requirements can be upper-bounded by published specifications to  $500 \sim 600$  Mbps [57]. The *ac* [76] and *ad* [77, 99] standards of IEEE 802.11 are advertised as capable to support an effective bandwidth of more than 600 Mbps even when not used with MIMO configurations. Thus, we devise the filming UAV as continuously broadcasting its video stream using a dedicated IEEE 802.11ac-capable wireless interface.

Broadcasting on a dedicated channel permits data to be correctly decoded by all the devices (spectators and other UAVs), which are close enough to the transmission source to receive the stream with a Bit-Error-Rate below the 802.11ac higher-bandwidth modes threshold. We define as  $R_{HD,i}$  the communication range associated with this transmission threshold for the receiving node  $i$ . It is also worth considering that, when using a broadcast strategy, there is no medium contention and thus it is feasible to approach the 802.11ac theoretical bandwidth limits.

According to previous studies [103] and the stadium geometry and dimensions in Figure 3.9, it is possible to distribute an HD stream to all the stadium spectators using only two UAVs assigned to the two roles. The two UAVs are dedicated to a side of the playing field and are each responsible for: (i-filming role) capturing the events in their area and diffusing it and (ii-supporting role) relaying the data if no events are detected. Therefore, the filming UAV: (i) always follows the actions (i.e. the ball) and (ii) broadcasts the video stream to both the spectators in his half-field and the other UAV. The supporting UAV, in turn, has to: (i) re-broadcast the data as received by the filming UAV and (ii) use a movement strategy that keeps it always inside the  $R_{HD}$  of all the spectators of its half-field and keep the filming UAV inside its own  $R_{HD}$ .

We propose a system that is capable of continuously satisfying the network constraints presented above. The requirements for HD broadcast directly translate to a set of distance constraints that the supporting node has to satisfy. The positions of the farthest spectators are identified in Figure 3.9 with  $P_1$  and  $P_2$ , whereas  $P_3$  and  $P_4$  are the positions of the filming UAV and the supporting UAV. Furthermore,  $R_1$  and  $R_2$  are the minimum distances the supporting UAV has to keep from  $P_1$  and  $P_2$ , respectively, to effectively broadcast the HD stream to the farthest spectators. Segment  $R_3$  (not on scale in the figure for display reasons) represents the range the supporting UAV has to stay within the filming UAV to receive an HD video stream.

Considering that the filming UAV tries to follow the actions, we describe a control system capable of dynamically driving the supporting node by applying virtual attractive and repulsive forces on the UAVs' control model:

$$\begin{aligned}\dot{x}(t) &= v(t) \\ \dot{v}(t) &= \begin{cases} u(t, x_4, v_4, x_3, v_3) \\ f(t) \end{cases}\end{aligned}$$

where  $x(t), v(t) \in \mathbb{R}^2$ ,  $u(t, x_4, v_4, x_3, v_3) : [0, +\infty[ \times \mathbb{R}^{2(n+1)} \rightarrow \mathbb{R}^2$  are, respectively, the position, velocity and control input associated with the supporting UAV, and  $f(t) : [0, +\infty[ \rightarrow \mathbb{R}^2$  is a signal describing the filming UAV velocity. Exploiting the Artificial Potentials, we can set:

$$u = -\nabla V_{x,y} + \gamma(v_i - v_4)$$

where  $\gamma(v_i - v_4)$  represents a velocity coupling. This function can be further specified by using the desired Potential Function.

### 3.3.2.1. Results

We use simulations to demonstrate the feasibility of our proposal and the improvements introduced into networking. Specifically, we compare different movement techniques and analyze their performance from two different perspectives. The first perspective deals with the quality of the events coverage. To this end, we consider the *average viewer satisfaction* to quantify the user experience and the *total traveled distance* by the UAVs to quantify the cost of physical resource consumption. The second perspective relates to networking, where we measure the *cumulative packet loss* of the filming transmissions. Using Network Simulator 3 [36], we have implemented the control model for the movement techniques and a selected set of techniques from [75].

The simulated UAVs are equipped with a single wireless interface and an Ad-Hoc MAC protocol to simulate a IEEE 802.11ac stack. As the UAVs are always within line of sight of each other, we consider a Ricean fading model, where the signal components coming from secondary paths are disregarded. The Artificial Potential method of this proposal is driven by the following set of functions, as

**Table 3.3.: Simulation Parameters**

Parameter	Value
Speed of Drones	15 [m/s]
Action Min Duration ( $t_{birth} \rightarrow t_{stop}$ )	0.2 [s]
Ball Min and Max Speed	$\{1 \div 40\}$ [m/s]
Number of runs for each scenario	20

described in the previous Section.

$$\text{HPF} = \frac{1}{R_{HD,i}^2 - \|d_{i,j}\|^2}$$

$$\text{HCPF} = \cosh\left(R_{HD,i}^2 - \|d_{i,j}\|^2\right)$$

$$\text{Binomial HCPF} = \cosh\left((R_{HD,i} - \|d_{i,j}\|)^2\right)$$

The HPF (Hyperbolic Potential Function) is characterized by a repulsive stimulus when a UAV approaches the  $R_{HD}$  boundary. The other two functions (Hyperbolic Cosine Potential Function and Binomial HCPF), instead, try to keep the UAV in the proximity of that value, albeit with different intensities. All the results come from the values upon 20 runs, statistically averaged over a confidence interval of 95%, not shown for figure readability. For each simulation scenario, we created a set of 20 actions whose positions and durations are uniformly and non-overlapping distributed (in space and time). The space is represented by the game field and the time is varied in order to have an action duration between a minimum of 2 [s] and a maximum variable between 6, 8, 10 and 12 [s]. The other used parameters are in Table 3.3.

Figure 3.10 shows the viewer satisfaction over maximum action duration. When the maximum action duration increases, all techniques improve the system performance as, in general, they all have more time to let the UAVs move. For the longest reaction times, the performance of HPF is the best. For the shortest, it is the Binomial HCPF that has the edge. In any case, the proposed solutions represent an improvement over the previous literature as they leverage a more dynamic movement scheme.

In respect to previous approaches, the movements followed by the UAVs, using the proposed approach, are smoother and tend to maintain the same distances between them. This behavior is visible in Figure 3.11. For this set of measurements, the proposed solutions are designed to maximize the networking performance and thus, keeping the UAVs at the correct distances all the time makes it possible to minimize the packet loss and increase the transmission quality. In the same situation, the results coming from BMI techniques show that they were not designed to consider telecommunications features. For instance, as the BMI-SR approach completely disregards the communications constraints, the performance of the packet loss is the lowest.

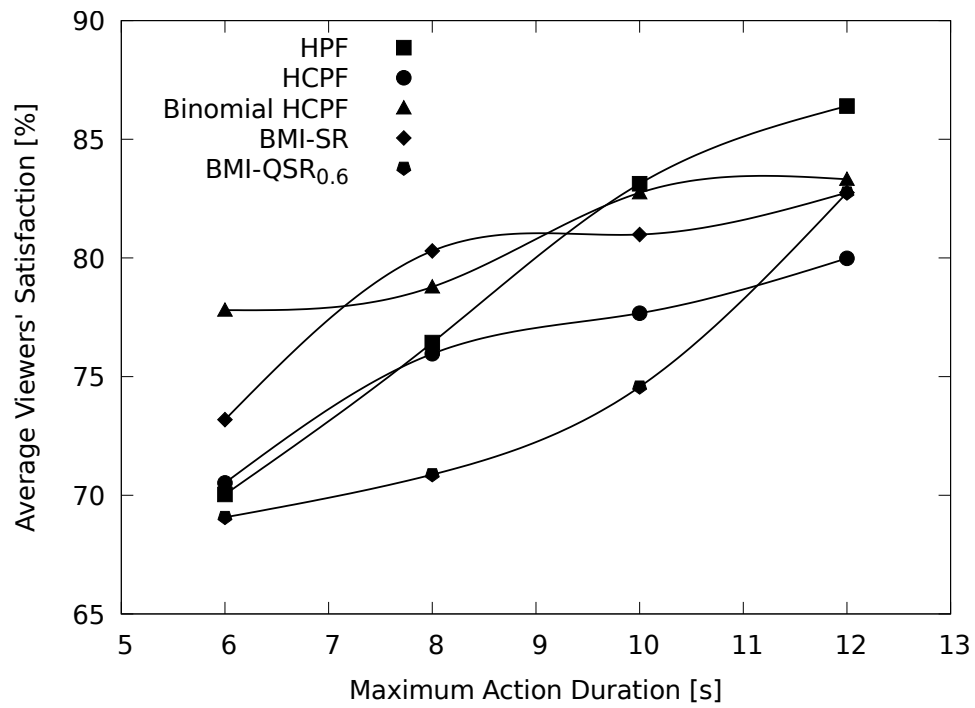


Figure 3.10.: Average Viewer Satisfaction over varying Maximum Action Duration.

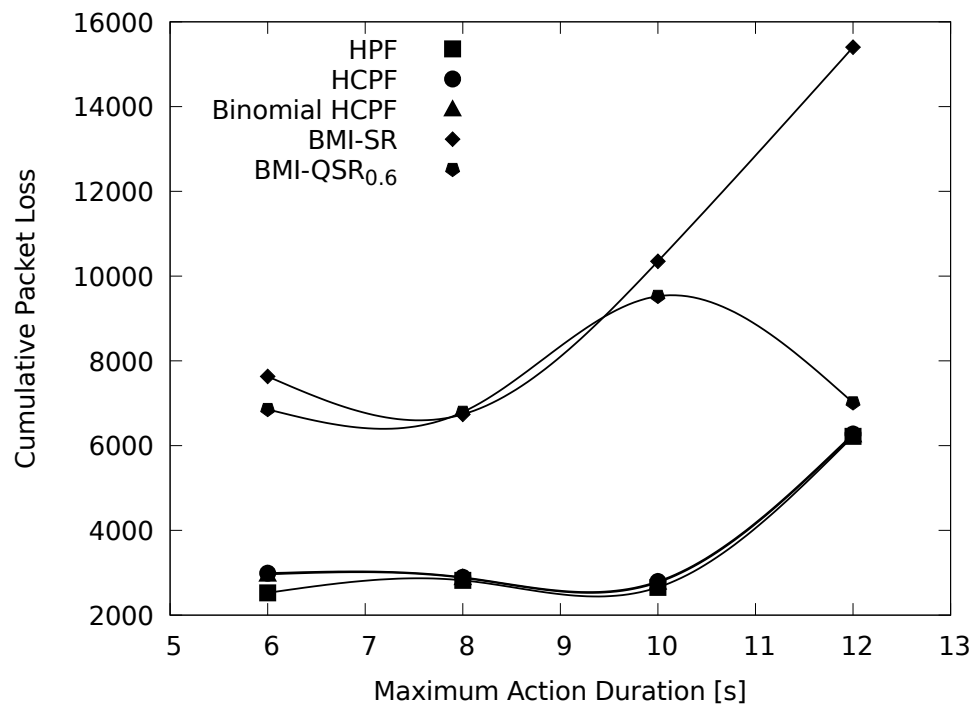


Figure 3.11.: Cumulative Packet Loss over varying Maximum Action Duration.

### 3.3.2.2. Discussion

In the context of coordination schemes for UAV networks, we have introduced the *Sport Event Filming* problem with communication and connectivity constraints (SEF-C<sup>3</sup>), where the spectators of a sport event within a stadium receive on their personal devices a video stream, taken from two UAVs that fly over the sport field. To coordinate the movements of the two UAVs, we have introduced the set of three distributed techniques inspired by control theory models. These schemes have no knowledge of the sequence of actions and use Artificial Potential methods to keep the connectivity of the two UAVs with the farthest spectators within the stadium. Through simulations, we have compared the performance of the proposed schemes with existing movement techniques in terms of packet loss as well as events coverage. Future works will consider the extension of the proposed schemes to unbounded fields (e.g.: as for bicycle races).

**Publications:** [J17, C2, C4, C17, C25, C31, F1].

## 3.4. Conclusion and discussion

I consider this Chapter as the most important of my manuscript as it contains a large part of my research efforts. Therefore, it was complicated to choose only some of the works I produced with my colleagues in the last years. Especially, I was sad not to have the space to include all the studies that use mobility by mimicking some animal behaviour, as *Swarm Intelligence*, which is one of my favourite research topics and on which I participated in writing several project proposals. The sequence of works presented in this Chapter should lead the reader to getting aware that controlled mobility can be very beneficial in networks where devices are intelligent and can control their own functioning; then, to consider that also energy efficiency, even though it may seem counter-intuitive, can be improved through nodes movements; and finally to show that mobility, as a powerful tool in mobile sensor, robot and UAV networks, must be used wisely. Actually, the last work of this Chapter is useful to introduce the following Chapter, as it shows the way how, according to my ideas and my research activities, this “wisdom” should be developed. In fact, I strongly believe that opening to different research fields and exchanging with researchers of other disciplines, can highly improve the originality, novelty and quality of my research work. This is the reason why I started discussing with researchers from robotic, control theory, and artificial intelligence communities. I was also lucky to have the opportunity to spend almost two years at Inria Lille - Nord Europe, where I was finally able to exploit the experience I had matured in Italy and in the United States. I started being known in the community, and I finally landed at the Heudiasyc Lab, which is a well known laboratory with a strong background in robotics and artificial intelligence. The richness in facilities of the Heudiasyc lab and the knowledge of the members of the lab offered me a unique possibility to finally implement and test my novel algorithms in real scenarios, as well as mix my experience with theirs. This mix of competencies brought me and two of my colleagues to create the interdisciplinary research team DIVINA (DIstributed cooperative VIsual Navigation for multi-uAv systems) in the framework of the Labex MS2T that works on Systems of Systems. Next Chapter will be devoted to the communications within Systems of Systems.



# 4. Systems of Systems perspective

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## 4.1. Introduction

Systems comprising intelligent devices, capable of self-organizing and cooperating towards a common goal, are interesting for many application domains. When these systems are, in turn, composed of other systems, we call them *Systems of Systems* (SoS). The interesting peculiarity of SoS, from the scientific point of view, is that, by definition, they require interdisciplinary studies and competencies and force practitioners to work together and define a common ground. As the natural context for *controlled mobility* to be fully exploited is mobile sensors, robot and UAV networks, it becomes straightforward to consider these networks as subsystems of a larger SoS and collaborate with colleagues of other discipline in order to define completely the role of communications and mobility for the accomplishment of a common mission. This is what happened in the DIVINA (DIstributed cooperative VISual Navigation for multi-uAv systems) research team, of which I am scientific co-responsible and that is born with the scientific objective of designing the functioning and interaction of a fleet of UAVs for the navigation and exploration of unknown regions by using perception, control and communication capabilities.

The works presented in this Chapter fall in the SoS perspective as they are based on the interactions of different subsystems or they propose integrated tools for simulation and testbed of specific segments of the SoS. More specifically, the first couple of works, written in the framework of the projet IMATISSE of which I am responsible, show the interactions between a sensor network and a UAV network in an environmental monitoring application. We define the role that each subsystem can play in the overall application as well as the support that

each segment can give when the other is not usable anymore. We look into the issues raised by natural disasters to the wireless communications, and the solutions that such a SoS can give to support the operation of preparedness, assessment, response and recovery. The second work presents instead a new simulation and fast prototyping tool for networks of UAVs. In fact, although different solutions have been proposed to simulate and emulate control systems and, more specifically, fleets of Unmanned Aerial Vehicles (UAVs), still they do not include an efficient and detailed network-side simulation, which is usually available only on dedicated software. On the other hand, current advancements in network simulations suites often do not include the possibility to include an accurate description of controlled systems. Therefore, this contribution aims at filling this gap.

## 4.2. Sensor and UAV network for disaster management

- M. Erdelj, M. Krol, E. Natalizio, *Wireless Sensor Networks and Multi-UAV Systems for Natural Disaster Management*, Elsevier Computer Networks, vol. 124, pp. 72-86, 2017. doi: 10.1016/j.comnet.2017.05.021.
- M. Erdelj, E. Natalizio, K. R. Chowdhury, I. F. Akyildiz, *Help from the Sky: Leveraging UAVs for Disaster Management*, IEEE Pervasive Computing, IEEE Pervasive Computing, vol. 16, no. 1, pp. 24-32, Jan.-Mar. 2017.

The occurrence of natural disasters is a recurrent important problem in all the areas of the world (Table 4.1). The physical extent of the disaster makes it very hard and in some cases completely impossible for humans to timely react to and face the problem. Currently, efforts have been made in order to: recognize and forecast the possibility that a disaster will happen, react in an efficient manner to the disaster in course of happening, quickly assess the damage, fix and restore normal state. It is expected that, due to the climate change effects, natural disasters will occur with increasing frequency [96]. Consequently, significant research and development efforts are devoted to create systems to predict, prevent, and efficiently respond to natural disasters.

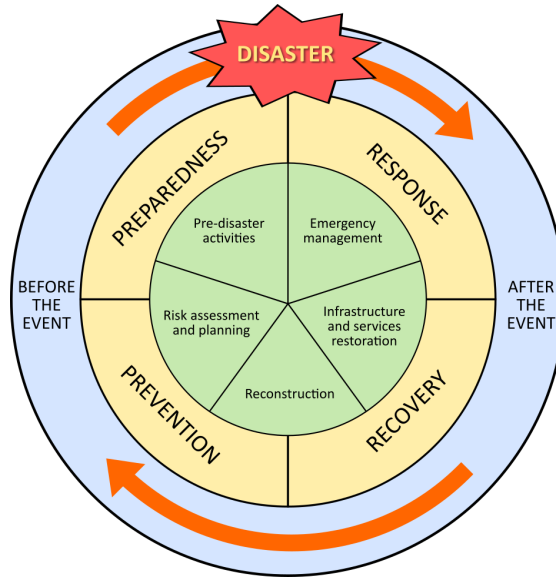
The ongoing process of planning the countermeasures before a disaster happens, responding to it during the disaster, and recovering after the disaster, is usually illustrated by the disaster management cycle. Its earliest example can be found in [11], while the most common four-phase disaster management cycle (Figure 4.1), presented by [10], can be summed up in the following:

- *Prevention/mitigation*. Where the goal is to minimize the effects of disaster (building warning codes and risk zones, risk analysis, public education).
- *Preparedness*. The main focus of this phase is on planning how to respond to a disaster. It includes preparedness plans, emergency exercises and training, but also the Early Warning System (EWS) development and implementation.
- *Response*. In this phase the goal is to minimize the hazards created by a disaster. It includes Search and Rescue (SAR) missions and emergency relief.

**Table 4.1.:** *Overview of the major events in Europe 1998-2009 [29].*

Hazard type	Recorded events	Number of fatalities	Overall Losses (EUR Billion)
Storm	155	728	44.338
Extreme temperature	101	77 551	9.962
Forest fires	35	191	6.917
Drought	8	0	4.94
Flood	213	1 126	52.173
Snow avalanche	8	130	0.724
Landslide	9	212	0.551
Earthquake	46	18 864	29.205
Volcano	1	0	0.004
Oil spills	9	n/a	n/a
Industrial accidents	339	169	n/a
Toxic spills	4	n/a	n/a
<b>Total</b>	<b>928</b>	<b>98 972</b>	<b>148.831</b>

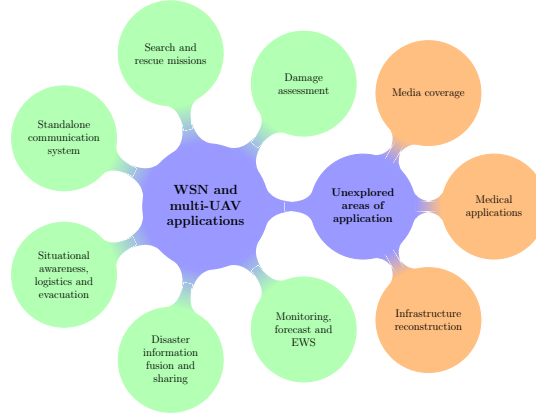
- *Recovery.* The damage has been assessed in this phase, and the knowledge acquired during the disaster will be used to evaluate the prediction models for the disaster.



**Figure 4.1.:** *Disaster management cycle.*

Recent developments in wireless communication technologies, energy storage, computing power and Unmanned Aerial Vehicles (UAV) make a system composed of Wireless Sensor Networks (WSN) and multi-UAV the perfect candidate to play an important role in the disaster management.

In [21] the applications of WSN and multi-UAV systems are classified in different application domains that fall into 3 main groups: *monitoring*, *response* and *forecast*. This classification is done roughly following the disaster management phases, where the *forecast* group of applications refers to the prevention and preparedness, the *response* group refers to the disaster response and recovery, while



**Figure 4.2.:** *Applications of WSN and multi-UAVs in disaster management.*

**Table 4.2.:** *WSN-related work applied to various natural disaster management scenarios. Here, a full circle represents the application of higher importance in the appropriate disaster phase, while a hollow circle represents the application of lower importance.*

Application domains	Prev	Prep	Resp	Recov	References
Monitoring, forecast, EWS	●	●	○		[12, 17, 28, 67]
Disaster information fusion and sharing	○	○	●	○	[9, 39, 49]
Situational awareness, logistics, evacuation			●	○	[21, 22, 30, 32, 50, 64, 66]
Standalone communication systems			●	○	[6, 15, 27, 29, 36, 46, 69]
Search and rescue missions			●	○	[18, 40, 52, 53, 55, 70]
Damage assessment			○	●	[23, 38, 59]

the *monitoring* covers the whole disaster cycle, as these applications provide disaster information during all the phases.

The groups of WSN and multi-UAV applications in disaster management considered in this work are the following (Figure 4.2):

- Monitoring, forecast and early warning systems,
- Disaster information fusion and sharing,
- Situational awareness, logistics and evacuation,
- Standalone communication system,
- Search and rescue missions,
- Damage assessment.

A review of the related works that deal with the WSN and Multi-UAV applications in disaster management is presented in Table 4.2.

In the following subsection we will present the roles of UAVs and WSN in the mentioned phases and scenarios.

### 4.2.1. Results

In this article, we envision a three-stage operational lifecycle, as shown in Fig. 4.3, where UAVs participate in natural disaster management: (i) *pre-disaster preparedness* – concerning surveying-related events that precede the disaster, static WSN-based threshold sensing and setting up early warning systems (EWS), (ii) *disaster assessment* – providing situational awareness during the disaster in *real time* and completing damage studies for logistical planning, and (iii) *disaster response and recovery* – including SAR missions, forming the communications back-bone, insurance-related field surveys. Each stage imposes a set of task demands on the UAVs, lasts different lengths of time, and has varying priority levels.

We argue that a single optimized but static network for all three stages is no longer sustainable; rather the network must continuously evolve in topology and capability. As the disaster stages progress, and as is evident from the typical functions involved in them in Fig. 4.3, static WSN deployments become progressively less effective. A classification of these disaster stages and possible related activities are summarized in Table 4.3.

- **Type A:** The type A disasters render the existing WSN infrastructure for monitoring not operational. The assessment and response and recovery phases are performed mainly using UAVs. The disasters that can be classified as type A disasters are mainly geophysical (earthquake, tsunami, volcano, landslide, avalanche) and hydrological (flash-floods and debris flow).
- **Type B:** The disaster partially impacts the existing WSN infrastructure. In this case, the role of UAVs is twofold, to reconnect the operational parts of WSN, and to perform other dedicated tasks. These are mainly climatological (extreme temperature, drought, wildfire), hydrological (floods) and human-induced (industrial hazard, structural collapse, power outage, fire, hazardous material contamination).
- **Type C:** This type mainly focuses on meteorological events, where the UAV cannot operate reliably during the assessment phase, and has limited

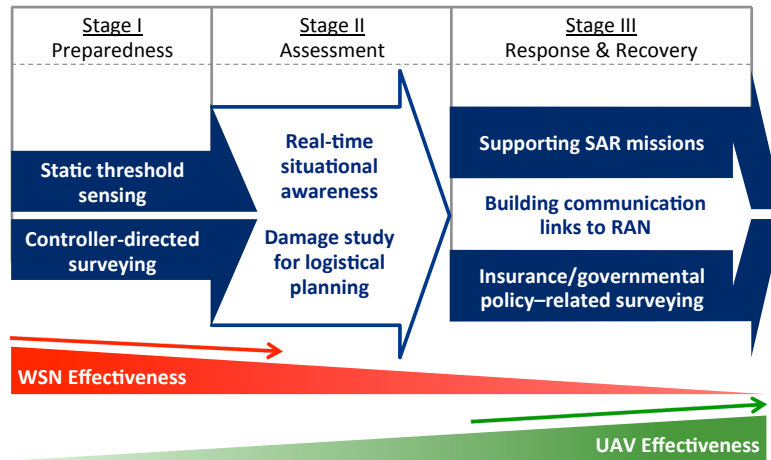
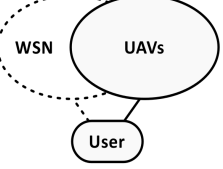
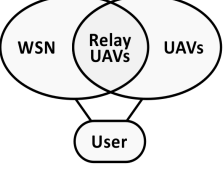
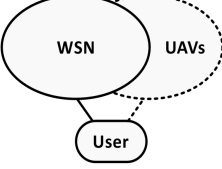


Figure 4.3.: Disaster stages and UAV-assisted operations.

**Table 4.3.:** *Disaster types, their impact on technology and system classification.*

Disaster types:		Type A	Type B	Type C
		Geophysical: earthquake, landslide Hydrological: flash-flood, debris flow	Climatological: wildfire Hydrological: flood Human-induced: industrial hazard, power outage	Meteorological: tropical storm, sandstorm, hurricane
Disaster impact on used technology:		WSN not operational UAVs fully operational	WSN partially operational UAVs fully operational	WSN fully operational UAVs partially operational
Conceptual system architectures:				
Disaster stages:	<u>Preparedness:</u> Monitoring and surveying Early Warning Systems (EWS)	WSN with limited UAV roles Different types of wireless sensors are statically deployed in the potential disaster area. An occurrence of a disaster triggers WSN reporting with optional UAV support.		
	<u>Assessment:</u> Situational awareness Damage assessment Structural inspection	No WSN      UAV Damage assessment and structural inspection is being done by UAVs.	Partial WSN      UAV Damage assessment is done by UAVs, backed up by the operational part of WSN.	WSN      No UAV WSN information fusion for situational awareness.
	<u>Response &amp; Recovery:</u> Rescue missions Supply delivery Communication system	No WSN      UAV Sensing, monitoring, SAR and communication restoration is being done by UAVs.	Partial WSN      UAV UAVs restore the broken connectivity and SAR by WSN&UAVs combination.	WSN      Partial UAV Integration of aerial surveys and ground observations for efficient decision support system.

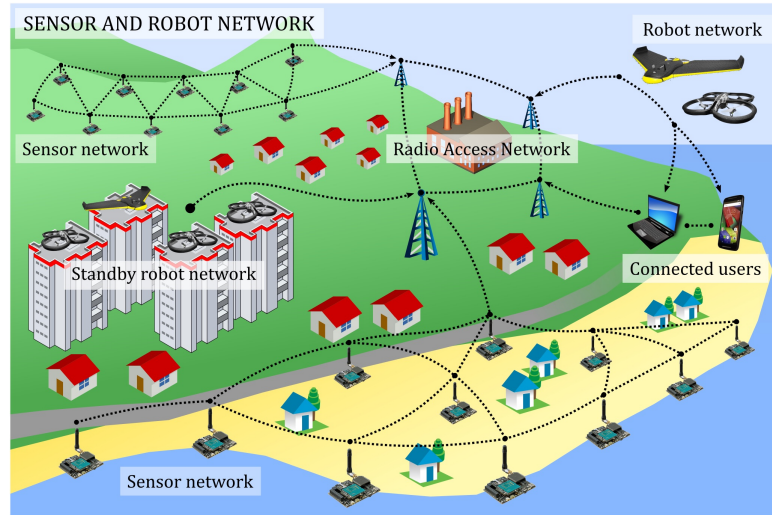
operational use in the disaster response & recovery phase due to the constraints of unstable weather conditions. In this case, the WSN must play a dominant role, with partial support made available through UAVs. Type C disasters are mainly meteorological in nature (tropical storm, hurricane, sandstorm, heavy rainfall).

## Disaster Preparedness – Stage I

Preparedness phase does not have a pre-defined duration, and may typically start from several years ahead of the anticipated disaster event, culminating with its actual occurrence. The lead role played by the WSN with limited support from the UAV is common for type A, B and C disasters. It is shown in Fig. 4.4, for a specific case study of flooding and landslide monitoring for clarity of explanation.

In the example scenario, multiple deployed sensors collect physical information (here, water level at the monitored bank and vibration/displacement on the mountain side) and forward this for logging at a centralized location. The simplest option is to use commercial, off-the-shelf cellular modem technology in the sensors, though this increases the weight and cost per sensors. A deployment scenario of landslide monitoring in the Italian Alps is presented in [35], where the WSN integrates different sensors with the monitoring displacements of landslides and triggering alarm in the case of debris flow.

Aerial surveillance via UAVs finds limited use in such types of disasters that requires ground-based measurements, given that the operational time of the UAVs may not be sufficient to capture the differential trends in the natural parameters being sensed. Instead of sensing, UAVs can play a role by assuming the load of data delivery from the resource-constrained sensors. For example, as shown in Fig. 4.4, stand-by UAVs can be called into active operational service to perform



**Figure 4.4.:** *Example mixed WSN-UAV deployment scenario for disaster preparedness for a case study of flooding and landslide monitoring.*

the function of so called *data mules*.

**Recommendation:** The focus in this stage should be on optimizing the WSN data acquisition, and data analysis in order to assess the probability of future disaster occurrences. In this stage, the UAVs will play the role of data mules.

## Disaster Assessment – Stage II

In this stage, a disaster is in progress, which has rendered parts of the topographical region unusable for vehicular traffic or for human habitation. The focus of the wireless network shifts (from monitoring) to providing an accurate assessment of the situation. The main task here is surveying the land area for available resources, and relaying this data back to the control center, all in real time.

### Type A Disaster

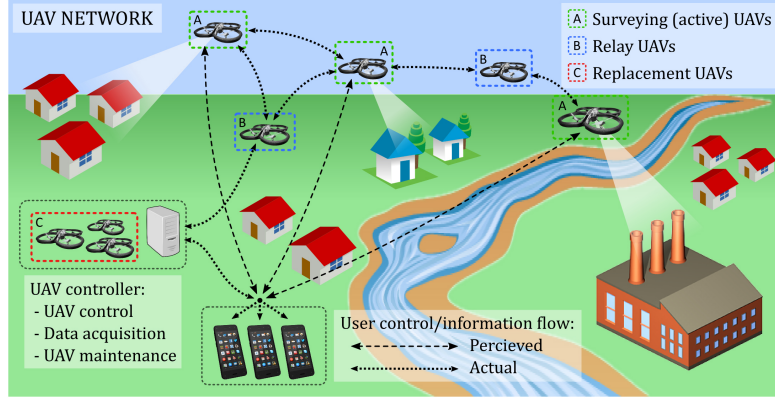
For type A disasters, the UAVs must form an independent network, without support from the ground sensors. When the task assignment is completely centralized, it is possible to partition the physical space into known regions, and assign one or more UAV per-region.

When the task assignment is de-centralized, the UAVs must first establish an aerial mesh that allows a fully connected network through local coordination. An example of such an aerial mesh is given in Fig. 4.5. Multiple UAV stations that are strategically deployed over a wide geographical area can provide at least certain guarantees that some parts of the UAV infrastructure would be operational even after the disaster occurred.

**Recommendation:** The use of heterogeneous UAV networks comprising fixed-wing UAVs for area scanning and identifying the important points to be covered and surveyed by rotary-wing UAVs.

### Type B Disaster

In the case of type B disasters, the WSN infrastructure is partially operational,



**Figure 4.5.:** *Network architecture for aerial connectivity plane.*

therefore it may still be used in conjunction with deployed UAV network, that can serve as bridging nodes and sustain the overall WSN topology.

Sensor-actor network architectures that have been studied extensively in [67] can be adopted in this scenario. Mobile actors, here UAVs, may move closer to regions of network partitions caused by loss of multiple sensors and act as forwarding relays for the WSN. While type B disasters bring about interesting joint roles of UAVs and sensors, there are additional considerations. For example, the UAV can only serve as the relay node to bridge the network partition for a short duration, and thus, the comparatively long-lived WSN must buffer and distribute packets along the end-to-end chain.

An interesting network paradigm is presented in context of mobile robots (which can also be substituted with UAVs) in [97]. Here, as the WSN is still operational and able to route packets to the remote sink, the mobile units perform more of the exploratory tasks but then leverage the WSN as the data forwarding backhaul.

**Recommendation:** Take advantage of the existing WSN infrastructure and dedicate a part of UAV network for WSN infrastructure reconnection. Besides environmental data acquisition, in this case WSN is useful for reconnecting disjunct parts of the UAV network.

### Type C Disaster

Given the particular nature of such types of disasters, there are instances of violent turbulence, strong winds and other weather-related artifacts that do not allow safe airborne operation of the UAVs during the assessment phase.

When situational awareness must be delegated to the WSN alone, deployments like *DistressNet*, an ad hoc wireless architecture that supports disaster response with distributed collaborative sensing, topology-aware routing using a multichannel protocol, and accurate resource localization [38] appears as a viable approach. *DistressNet* is implemented on a set of available sensors, mobile and static gateways, and a set of servers providing network services, data analysis and decision support.

**Recommendation:** Focus on the data provided by the WSN as well as other information sources available (e.g. social networks).



## Disaster Response & Recovery – Stage III

The UAV network will play a critical task in this phase by first establishing short-distance cellular connectivity to the affected users and then transferring data to the backbone cellular infrastructure via a relay network (Fig. 4.5). The network may also give feedback to the users about safe areas and evacuation routes based on the information gathered following the disaster assessment phase.

### Type A Disaster

The aerial connection plane involves creating a multi-hop relay network of UAVs that extends from isolated blocks of users to the nearest functional radio access network (RAN). This results in a multi-objective optimization problem of maintaining the intermediate forwarding capability, as well as the last-mile connectivity to the end-users [34].

An interesting new paradigm will emerge at the cross-roads of wireless software defined networking (WSDN) and the needs for establishing the aerial connectivity plane, especially in large scale disasters with thousands of affected users. This scenario can be envisaged as a set of open-flow switches embedded inside the UAVs, whose routing functions can be dynamically altered through commands issued by a remote controller [7].

**Recommendation:** Focus on the use of different camera types and specialized sensors and actuators mounted on UAVs, dedicated for rescue missions and supply delivery.

### Type B Disaster

When a supporting WSN is fully operational, it may be used to assist the UAV operation by offloading some of the non-time critical tasks. For example, when two major earthquakes occurred in Emilia-Romagna region in Northern Italy, UAV operators experienced the problem of being overwhelmed with information retrieval tasks [56]. Here, closely monitoring the information that flows back and forth from the disaster area to the end controller caused human errors in the operation of the UAV, and negatively impacted its performance in the rescue mission. An existing WSN may also contribute to on-the-fly establishment of multi-hop wireless access networks. The architecture proposed in [69] extends Internet connectivity from surviving access points to disaster victims through individual mobile devices. Similar concepts can be extended for the mixed WSN-UAV architecture, where UAVs form the virtual access points, and the WSN connects to this UAV network.

**Recommendation:** Maximize the data provided by the WSN in order to improve the efficiency of the search and rescue missions executed by UAVs.

### Type C Disaster

In this scenario, UAVs are limited in their ability to gather useful information from the disaster site, but they may operate from the periphery. We assume that the disaster involves major destruction to communications infrastructure, where cellular towers or fixed base stations are rendered ineffective. The only solution here is for sensors to forward their data using low power, forming multi-hop relay chains to the edge of the affected region. The advantage of using UAVs is that the pick up point at this edge can be dynamically decided based on the surviving

elements of the initial architecture. The use of mobile UAV stations proposed in our work can ensure the rapid UAV deployment and prompt UAV network setup, thus lowering the response time and increasing the disaster recovery rate.

**Recommendation:** Use the fully functional WSN in order to reconnect the impaired UAV networks.

#### 4.2.2. Discussion

With the summary of these two recent work, I wanted to present a new perspective for classifying disasters, and I introduced the vision of suitable network architectures that can be effective in each of these cases for disaster management. I believe that UAVs will play an increasing role in such scenarios, especially in the assessment of damage and performing recovery and rescue operations. Many new network paradigms such as aerial Wireless Software Defined Networking (WSDN) will need to be created, and enhancements to established theoretical frameworks, such as wireless sensor-actor networks, will be required for the next generation architectures proposed in these works. Finally, affected victims of the disasters will still, and perhaps increasingly, look to the sky for relief, but the challenge lies in designing reliable and effective networks of UAVs to ensure losses of lives and properties are minimized to the best possible extent.

**Publications:** [J1, J8, J13, B1, B2, B3, C8, C10].

### 4.3. CUSCUS: CommUnicationS-Control distribUted Simulator

*N. Zema, A. Trotta, E. Natalizio, M. Di Felice, L. Bononi, The CUSCUS simulator for Distributed Networked Control Systems: Architecture and Use-cases, submitted for publication to Elsevier Ad Hoc Networks.*

Aerial networks composed by Unmanned Aerial Vehicles (UAVs) constitute emerging cooperative systems characterized by unique features such as distributed coordination, autonomous 3D mobility, and context-awareness through the sensing capabilities [43]. In the next few years, the pervasive diffusion of UAVs is expected to pave the way to novel scenarios integrating IoT devices, aerial communications and mobile/multimedia applications. At the same time, the state of art of UAVs already includes a wide range of real-case deployments, from disaster recovery to surveillance and precision agriculture [31][46][32].

A key issue in most of the mentioned scenarios is the management of flying nodes' autonomous mobility in order to meet the Quality of Service (QoS) requirements of the applications [43]. In absence of a centralized controller, the fleet mobility is determined by decisions performed at each UAV, hence *consensus-based* or *distributed coordination* protocols are needed to avoid collisions [65], keep the network connected and achieve the mission-specific goals [82]. At the same time, the communication among nodes is strongly affected by the *propagation conditions* of the environment, so far that the effect of packet loss must be taken into account in networked robotic architecture design [102][107]. Finally, since the micro-mobility

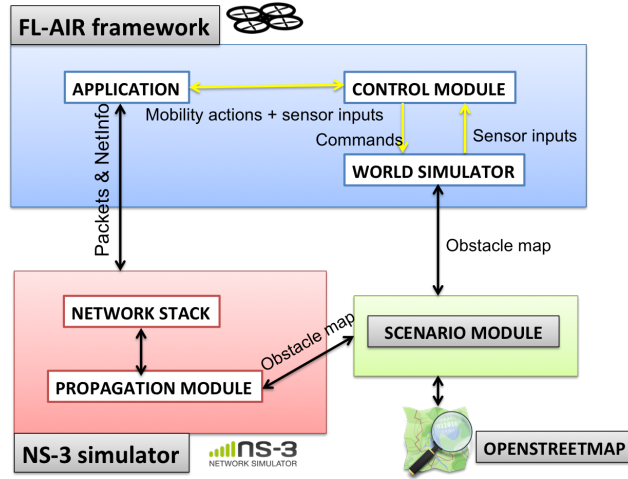
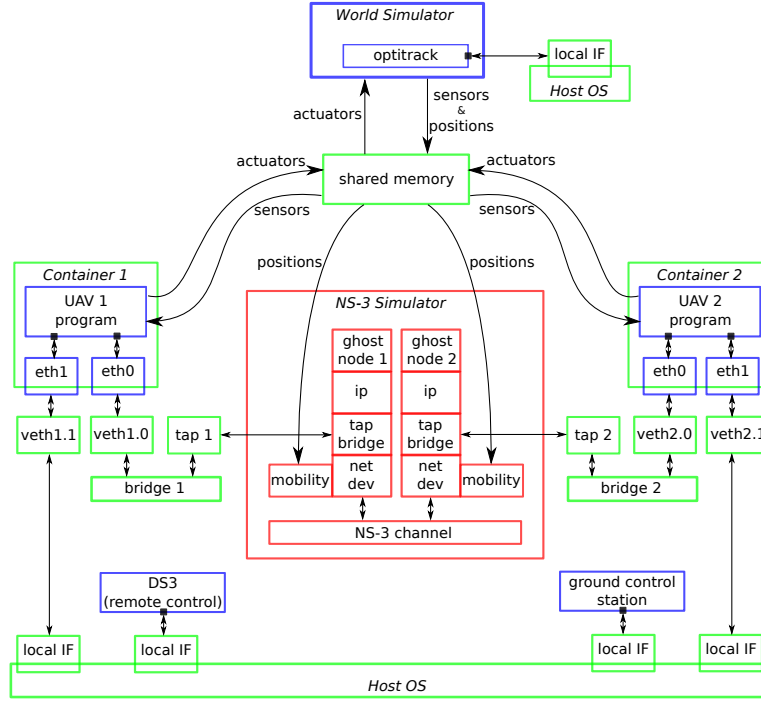


Figure 4.6.: Overview of the CUSCUS logical architecture.

of each UAV involves complex electromechanical dynamics, *robust controllers* are required for tuning the parameters governing the position and orientation of the flying node (e.g. the Proportional, Integrative and Derivative terms of the controller) [64]. The merging of networking and control fields is a natural consequence of the above mentioned issues: several communication-aware mobility schemes have been proposed for fleet creation and management [26][70]. Similarly, there exists plenty of communication protocols at the MAC, network and transport layers, which are specifically tailored to the UAVs scenarios, in order to cope with the dynamic topology and, at the same time, take maximum benefit from the self-placement capabilities of the nodes [86][17]. The growth of research in this area poses a fundamental question: which methodology to adopt in order to evaluate the performance of distributed networked control systems, producing reliable and accurate results? Several studies rely on small-case test-beds, e.g. [104]. However, experimental studies, in order to be meaningful, should consider many UAVs at the same time, and this might easily introduce excessive costs or present safety problems. Similarly, analytical models might likely become infeasible due to the large number of parameters to take into account, and the unknown correlations among them. Vice versa, simulation tools can provide a cost-effective solution in order to model the UAV applications before their effective deployment on a real scenario. However, although there are several tools enabling to model flight control [3][4] or network protocols [98][2], no software addresses the issues of both the fields at the same time.

In this work, we fill such gap by proposing a novel simulation framework for networked control system, called CommUnicationS-Control distribUted Simulator (CUSCUS). Differently from the state of the art, CUSCUS allows simulating both the UAV networking and formation phases, via the integration of two existing tools: the Framework Libre AIR (FL-AIR) simulator [1] and the mainstream network simulator NS-3 [36]. Using FL-AIR, a real-time and fine-grained simulation of the micro-mobility of each UAV can be achieved, including the modeling of virtual sensors/actuators, the PID regulations and the drone stability. Moreover, it is possible to create UAV applications and test them on a simulated control environment before the actual deployment, since the same code can also be plugged



**Figure 4.7.:** *Overview of CUSCUS architecture*

into real UAVs.

Figure 4.6 shows the logical architecture of the CUSCUS framework, composed by two simulators: the FL-AIR framework, the NS-3 simulator as well as by the Scenario Module. This latter is in charge of loading the real scenario map, and works inbetween the other two components. In FL-AIR, the user can write the C++ code of the UAV Application (e.g. video-surveillance); mobility actions are sent to the Control component, which is in charge of implementing and translating them into proper commands to send to each motor of the UAV. Based on them, the position of the UAV within the virtual scenario is updated by the World Simulator, which is a component of FL-AIR. Moreover, both FL-AIR applications and the Control component can have access to sensors (cameras, ultrasonic sensors, etc), whose input is provided by the World Simulator, based on the characteristics of the scenario, indicated by the Scenario Module. All the network packets produced by FL-AIR application are routed through the network stack in NS-3, and then transmitted on the simulated wireless channel. To this aim, we developed a novel propagation module which takes into account the signal attenuation caused by obstacles, again based on the information provided by the Scenario Module. The main architecture of the CUSCUS framework is depicted in Figure 4.7.

### 4.3.1. Results

To demonstrate the validity and the effectiveness of CUSCUS, we performed a three-folded simulation campaign in order to display the features of CUSCUS and evaluate the feasibility of its deployment. The first campaign aims at showing the impact of CUSCUS on its host system. The second campaign aims at evaluating the simulator's ability in integrating accurate control models. The capability to

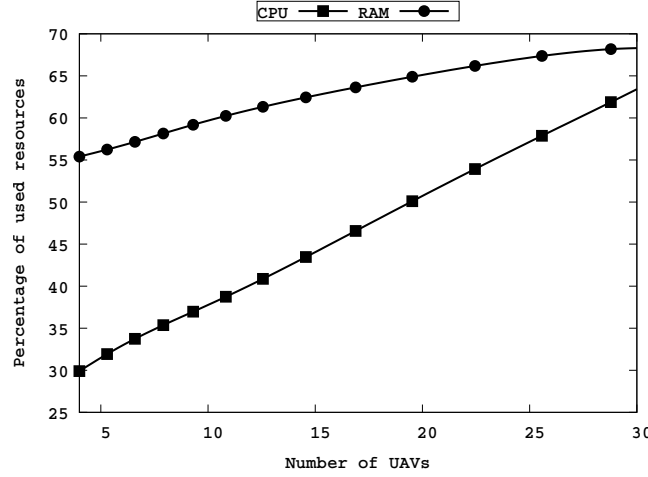


Figure 4.8.: *Resource Usage at the host varying the number of UAVs.*

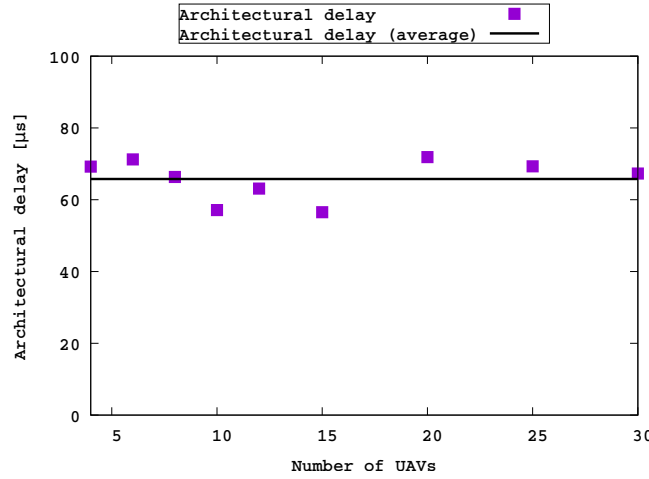
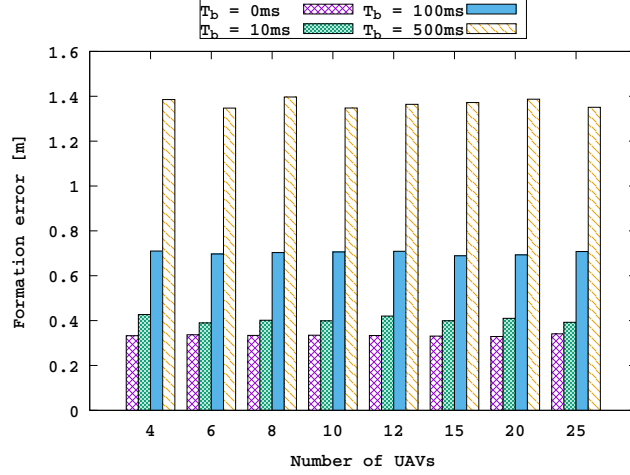


Figure 4.9.: *Architectural delay of CUSCUS varying the number of UAVs.*

incorporate real-world UAV parameters into network-oriented simulations is the object of the third simulation campaign.

A first index that can be used to evaluate the performances of CUSCUS is represented by the physical resource used by the host during the simulation. Figure 4.8 shows the percentages of CPU and RAM usage, when the number of UAVs increases. We can notice that the CPU utilization increases linearly with the number of simulated entities, and sub-linearly when considering the memory allocation; this constitutes an interesting property for a simulation tool. Hence, this result shows the *scalability* of CUSCUS, which is able to efficiently exploit the available resources. Although no bottleneck could be observed in the Figure, it is worth remarking that the system performance is bound by the hardware characteristics of the host machine. A straightforward approach in order to achieve scalability regardless of the number of simulated nodes and of the complexity of the scenario is to increase the number of available hosts, balancing the simulation load within the cluster (vertical scalability).

The second test that we have done in order to characterize our architecture is



**Figure 4.10.:** Formation Error varying the number of simulated UAVs and  $T_b$ .

the analysis of the *architectural* delay introduced by CUSCUS. This measure is important as it can estimate the fixed time delays introduced by the CUSCUS framework. The extension and stability of these overheads assume a high importance when CUSCUS is used to simulate control systems for UAVs. In Figure 4.9, we see the delay  $[\mu s]$  the packets experience in the path from FL-AIR to NS-3. The broadcast time  $T_b$  is set to  $50ms$  for this experiment. We can notice from the Figure 4.9 that the *architectural* delay introduced is constant and it stands around  $70\mu s$ . This result shows that the delay introduced solely by CUSCUS is negligible and stable with respect to the UAVs number, i.e. the traffic generated by the simulation scenario does not influence the variation of the *architectural* delay.

With the last experiment, we want to show the proposed architecture *suitability* for the study and analysis of distributed networked control system. We executed a series of tests, modifying the number of UAVs and the  $T_b$  value, in order to study the impact of using a simulated communication network for the exchange of control system messages. By using a modified version of the scenario used in the previous experiments, we measure the error introduced in the formation control inside FL-AIR due to *network* delays. In this case, the nodes will not retrieve the information about the position of the other UAVs from the Optitrack localization system; instead, they will use the positions their neighbors have broadcasted through the simulated NS-3 channel. This *error*  $[m]$  is defined as the distance between the *actual position* for the simulated UAVs and their *reference position* in the formation. The *reference position* is the position that nodes should be at, when their control system does not use the network for exchanging position data, but only the *Optitrack* system. In this last case ( $T_b = 0ms$  in the figures), the *error* is reduced to a minimum and it is due only to the control system itself. Instead, when the simulated UAVs receive the information concerning the position from their neighbors, there is a *delay* introduced by the network.

Figure 4.10 shows this *error*, as the result of these tests. From these experiments, we can infer the following conclusions: (i) an increase of the  $T_b$  value strongly impacts the formation error, whereas (ii) the number of UAVs does not affect this error. The former conclusion comes from the fact that we are running a distributed control system that has to work with outdated information about the neighboring

nodes' positions. The latter comes from the fact that, in this particular case, communications issues such as packets collisions and, hence, packet retransmissions, have a negligible impact on the wireless communication network. It is to remark that the collision probability is very small since the exchanged packets are also very small. They are composed by only the sender node's position and orientation.

In conclusion we can state that the CUSCUS framework is able to execute reliable distributed networked control system simulations by keeping time overheads constant when the number of simulated UAVs varies. Hence, it enables the user to study and analyze practical instances of this kind of control systems.

### 4.3.2. Discussion

In this work, we have presented CUSCUS, a novel framework for modeling and simulation distributed Networked Control Systems, and more specifically fleets of Unmanned Aerial Vehicles (UAVs). Differently from the existing tools, our software is able to take into account both realistic UAV micro-mobility, drone dynamics and wireless communications, via the integration of the FL-AIR suite with the mainstream network simulator NS-3. Furthermore, CUSCUS enables realistic 3D simulations by importing the scenario description from the OpenStreetMaps, and by modeling the impact of obstacles on the wireless propagation as well as on the UAV mobility and path planning. The CUSCUS framework supports two usage modes: (i) as a benchmarking tool, it allows analyzing the performance of cross-layer algorithms (i.e. mobility-aware network protocols, or network-aware mobility algorithms), which constitute the main approaches in the literature of UAV systems; (ii) as a pre-deployment tool, it allows testing the operations of UAV applications in highly realistic simulated scenarios before their utilization in the real world, by using the same code.

**Publications:** [J3, J10, S1, S3, C1, C9, C11, C12].

## 4.4. Conclusion and discussion

With these two works, I wanted to give a proper application context to the algorithms that have been presented in the previous Chapter, and I wanted to show a simulation and fast prototyping tool that integrates control models and networking protocols for fleets of UAVs. My objective in showing these two works was to give a Systems of Systems perspective of my work, especially the most recent one, which slowly moves along two research directions: (i) the study and definition of architectures for coordination and cooperation in mobile sensor, robot and UAV networks and (ii) the “translation” of my new and old algorithmic proposals into fleets of UAVs. More specifically, the first work showed the advantages of using sensor networks and UAV networks for facing a natural disasters, defined the roles of the two subsystems when work separately or as two segment of a larger system. The second work presented a new tool that allows modeling the impact of networking dynamics as well as of network protocol operations on the fleet mobility and the UAV formation control, and vice-versa. These works are in the set of my most recent contributions and surely represent the direction I will keep working in the next years.

# 5. Security in the Internet of Things

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## 5.1. Introduction

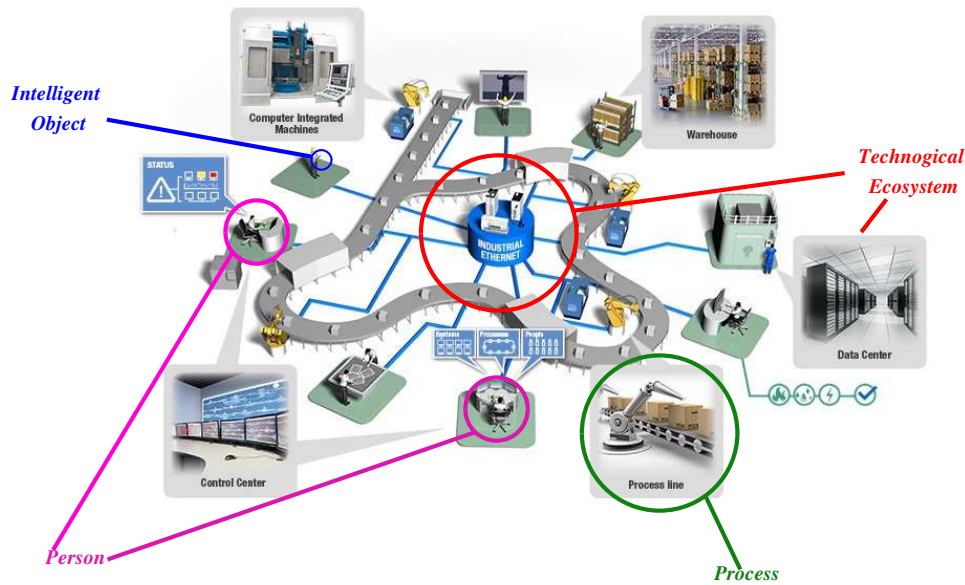
In 2012, upon my arrival at the Heudiasyc Laboratory, I joined the “Réseaux et Optimisation” research group, which is well known for its work on computer and network security. Therefore, as I had the chance to learn from and work with experienced researchers of this domain, I decided to study the issues raised by the connection of billions of smart objects around the world, in what it is called the Internet of Things. As my experience with security mechanisms and algorithms was close to zero, first I worked with some colleagues and a Ph.D. student on a survey on the open issues of security in the IoT, and then, we selected together one topic - the privacy of IoT users - to investigate it more deeply and propose some novel solutions. This last Chapter is devoted to show this new effort by presenting the work on *privacy preservation* in the specific context of transportation systems.

## 5.2. Privacy preservation

- A. Riahi, E. Natalizio, Y. Challal, Z. Chtourou, *A roadmap for security challenges in Internet of Things*, Elsevier Digital Communications and Networks, 2017. doi: 10.1016/j.dcan.2017.04.003.
- A. Riahi, E. Natalizio, P. Moyal, Y. Challal, Z. Chtourou, *A game theoretic approach for privacy preserving model in IoT-based commercial transportation*, submitted for publication to Elsevier Computer Networks.

The concept of the Internet of Things (IoT) was introduced in 1999 [41], after the explosion of the wireless devices market, and the introduction of the Radio Frequency Identification (RFID) and the Wireless Sensor Networks (WSN) technologies. IoT concept aims at connecting anything, anyone, at anytime in anyplace. It involves things or objects such as sensors, actuators, RFID tags and





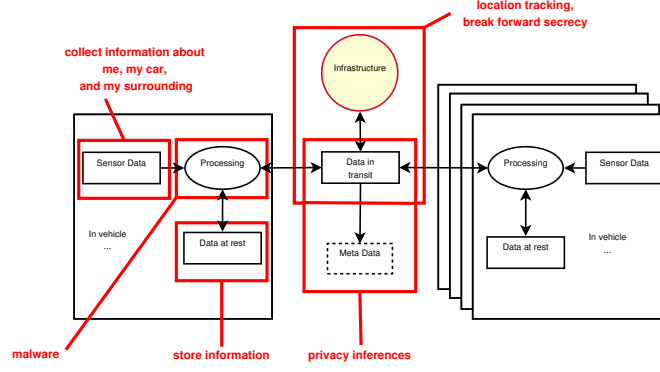
**Figure 5.1.:** *A smart factory environment composed of person, smart object, process and technological ecosystem as the main elements of our systemic and cognitive approach for security in the Internet of Things. (@<http://www.moxa.com>.)*

readers, to permit interaction between the physical and virtual worlds. An illustrative example of IoT application in a smart factory is shown in figure 5.1. In this system, we can distinguish four main components: person, process, technological ecosystem and intelligent objects.

In 2011, the number of interconnected systems exceeded the number of human beings. In 2012, 9 billion of devices were interconnected; this number is expected to reach 24 billion devices in 2020. The financial market size is around the amount of 1.3 trillion dollars for mobile network operators in various domains and applications like healthcare, transportation, public services and electronics [41].

As an extension of the classical Internet framework and technology, previous security models should be applicable to the IoT to guarantee basic security services including authentication, confidentiality, integrity, non-repudiation, access control and availability. However, IoT is constrained by many new factors. First, numerous *things* may interact together in a complex manner, through many security techniques and according to different policy requirements [94]. Second, IoT devices can have different operation environments and, usually, limited computational power. Third, some IoT applications can foresee the participation of a huge number of nodes leading to serious security problems. As a consequence, security challenges became more difficult to fulfill as it is hard to develop a generic "one fits all" security strategy or model. Consequently, "Security Shield for Internet of Things" has been identified in 2014 by DARPA (Defense Advanced Research Projects Agency) as one of the four projects with a potential broader impact larger than the Internet itself.

The evolution of the IoT invokes massive possibilities for exchanging private data enabling new business models across heterogeneous networks. Then, making



**Figure 5.2.:** *Privacy violation in connected cars [78].*

IoT technologies secure and reliable becomes the basis to carry out this concept development. Intelligent Transportation Systems (ITS) noticed a fast development in communication technologies as one of the key founders of IoT. Indeed, vehicles are able to exchange various information types (safety, efficiency, security, etc.) with other vehicles and infrastructures. ITS involves open platform for a mobility ecosystem to share information and intelligence through a full chain involving sensors, data storage, dynamic processing, format transformation, horizontal platform-to-platform export, open APIs, etc. ITS core technologies include reliable and real-time platforms managing mixed vehicle services, efficient navigation, improved decision-making algorithms, communication and network technologies, and open service platform.

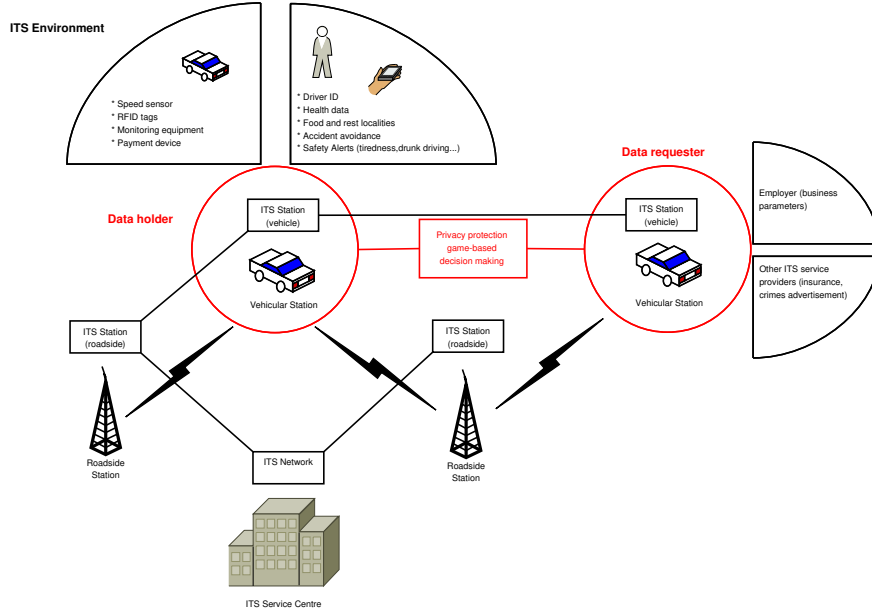
ITS enables interactions among sensors, vehicles, drivers and supervisors. It integrates features of both vehicular networks and social networks, which raise considerable privacy issues as shown in figure 5.2. For example, location privacy issues may be caused by unencrypted messages (identifier, location, speed and heading) exchanged over the network. These data may be linked to driver's identity and lead to identity theft, tracking and users linkage. Consequently, the system can be abused by third parties (employers, insurance companies, criminal organizations) to track individuals, and re-identify anonymous users in a social network graph [28].

From security point of view, these systems are exposed to many risks as attacking autonomous vehicle sensors including wheel encoder, on-board unit, e-maps, ultrasonic sensors, radar, camera, GPS, 802.11p, etc. Many security attacks may take place such as replay, relay, jamming, spoofing, tracking, and blinding. To avoid these threats, countermeasures such as detect jamming attacks on cameras via spectral analysis, increase redundancy by adding cameras, etc. may be taken [78]. To highlight the seriousness of privacy concerns, we list the most important attacks of connected cars in the last few years in table 5.1.

In Figure 5.3, we illustrate, over the architecture proposed in [51], the actors of our game theory model and interactions of ITS system. Private data are hold by sensors, intelligent vehicles and drivers (Data Holder, DH). They are connected to employer/supervisor to optimize the movement of people and products, improve financial profit, public safety, and the environment, etc. In this scenario, other ITS service providers (insurance companies, criminal organizations, advertisement companies) may attempt to access sensing data to improve their activities

**Table 5.1.:** *Recent attacks to connected cars.*

Year	Attack	Description
2010	Vehicles Disabled Remotely Via Web Application	A former employee of an Austin, Texas car dealership sought revenge against his former employer. The attacker used stolen credentials to log into a web application, and physically disabled vehicles without knowledge or consent of their owners.
2011	CAESS (Center for Automotive Embedded Systems Security) Experimental Analysis	A team of researchers conducted a range of lab experiments and road tests and found that it was possible to manipulate a vehicle's functions by injecting messages on the CAN (Controller Area Network) bus (disabling the brakes, brake individual wheels on demand, stop the engine, falsify information on the vehicle's speedometer) [20].
2013	Miller and Valasek Physical Hack	Hackers targeted the systems of a 2010 Ford Escape and a 2010 Toyota Prius and were able to reverse engineer the vehicles CAN bus communications.
2015	Miller and Valasek Remote Hack	Attackers successfully demonstrated that an unaltered passenger vehicle (a 2014 Jeep Cherokee) could be remotely exploited without the need for any physical access to gain remote access and execute code.
2015	Tesla was also affected	Hackers found a total of six vulnerabilities of the car software.
2015	Jeep Cherokee controlled over critical features through its "Uconnect" infotainment system	Hackers managed to send commands to the dashboard functions, transmission, brakes, and steering remotely. The company recalled 1.4 million vehicles to fix the security flaw.
2016	BMW, Audi and Toyota cars can be unlocked and started with hacked radios	24 different car models from 19 manufacturers can be remotely unlocked and started using a simple hack. The hack uses a simple radio amplifier, and involves cars with keyless-entry systems, which send a radio signal from the car to the key when the owner is a short distance away that opens the car door.
2016	Hack attack of the metro transport systems in San Francisco	Hackers forced the agency of mass transit system to shut down its light-rail ticketing machines and allowing passengers to ride for free. Microsoft Windows-based computers were attacked with outdated software, and ticket machines display the message "You hacked. ALL data encrypted".



**Figure 5.3.:** Overall architecture of IoT-based ITS application.

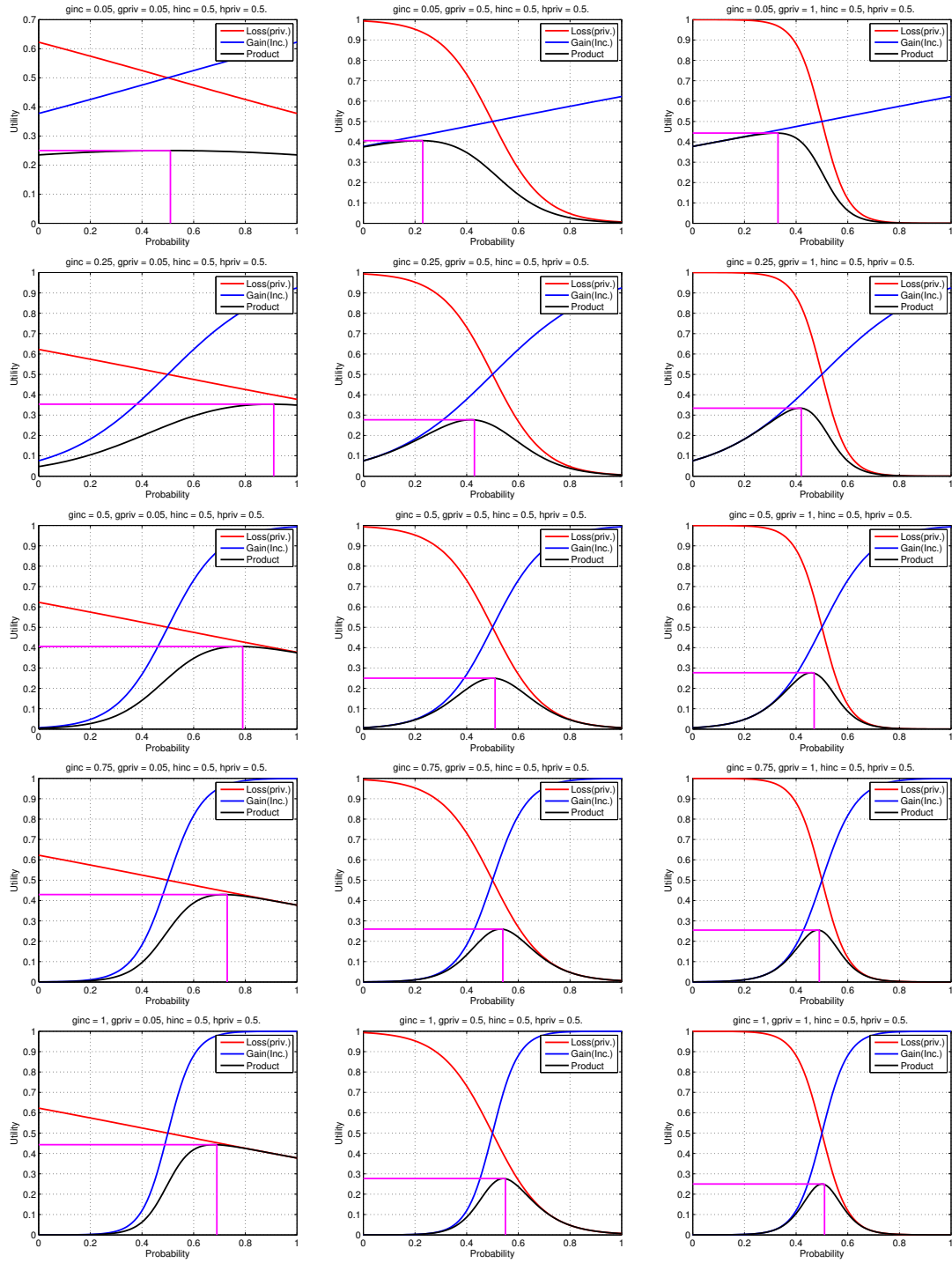
(Data Requester, DR). They may carry an attack (passive/active) or motivate data holder by proposing some incentive motivation.

By defining the utility functions and the possible strategies of the players, it is possible to define an optimization problem, whose solution is the equilibrium of the game (for more details, please refer to [85]).

### 5.2.1. Results

We solve the game equilibrium numerically for different situations in the game. Then, we show gain and loss functions, calculate their product, find its maximum point, and get the corresponding steady state. To distinguish between different situations, we analyze the player behaviour by modifying the normalized value of two parameters  $g_{inc}$  and  $g_{priv}$ , where  $g_{priv}$  depends on parameters defined by user preferences and realized privacy, and  $g_{inc}$  depends on motivation value proposed by DR, respectively.

In the first column of Figure 5.4, we choose a limited privacy concession ( $g_{priv} \approx 0$ ), and we search for the equilibrium point for different values of  $g_{inc}$ . We notice that the probability of disclosing data is high ( $p_{equilibrium} > 0.5$ ) in all situations. In the second column, we choose an intermediate privacy concession ( $g_{priv} = 0.5$ ). We found that equilibrium probability for small values of  $g_{inc}$  (non interesting incentive motivation) is small. That means, disclosing private data for the high values of  $g_{inc}$  is more probable due to the interesting incentive offer ( $p_{equilibrium} = 0.2 - 0.6$ ) in all situations. In the third column, we choose a high privacy concession ( $g_{priv} = 1$ ). We found that equilibrium probability for different values of  $g_{inc}$  (interesting and non interesting incentive motivation) is low. That means, players hesitate to disclose private data even for high values of  $g_{inc}$  ( $p_{equilibrium} < 0.5$ ) in almost all situations.



**Figure 5.4.:** Game equilibrium and corresponding steady states for normalized values of incentive motivations ( $h_{inc}$ ) and privacy concession ( $h_{priv}$ ).

### 5.2.2. Discussion

In this work, we proposed a game-based solution to protect private data exchanged in the ITS context where each player aims to maximize his/her payoff. We used a Markovian process to highlight interactions between game players and to show the context changing features in IoT context. Our model takes into consideration two different scenarios where DR may be curious or malicious, which is very close to reality. We also showed that our model is applicable in particular cases of ITS by adapting its parameters. And, we proved that numerical results matches the theoretical findings.

With this aim in mind, we defined some different states for each player, solved the Markovian system numerically, and illustrated the steady state. We come up to integrate parameters related to an IoT context and those related to privacy preservation in a global system. Then, we sketched the DH behavior in different situations by adapting the corresponding parameters of the system such as energy costs, privacy concession and incentive motivation.

Finally, we illustrated the utility function to analyze the equilibrium solution of the system, which reflects the disclosure probability of DH,  $p_D$ . This parameter is calculated to illustrate the DH ability to disclose private data in each situation by adapting energy, incentive and privacy parameters. Then, we showed that DH behavior depends to its current situation and acts accordingly.

**Publications:** [J5, S2, S4, C6, C16, C20, I3].

## 5.3. Conclusion and discussion

In this last Chapter I presented two of my recent works in the domain of computer and system security. This is a new research line that I started pursuing upon my arrival at the Heudiasyc Lab. In order to get into this topic, I worked on the preparation of a survey that presents related works, issues and solutions for security preservation in the Internet of Things. Thanks to this survey, which was organized following a systemic approach [84], it has been possible for me to have a clear idea of the state of the art and decide to pursue a specific objective while supervising a Ph.D. student who works on this subject. The specific topic addressed in our work deals with privacy preservation of IoT objects' owners. We developed a game theory model and a Markov chain that can actually be used in very different contexts, and that are useful to find out the probability that Data Holders would disclose their personal information to Data Requesters. In the presented work, these models have been applied to an Intelligent Transportation System, but they can be easily extended to other domains.

## 6. Conclusions and future work

In this last Chapter, I will offer a brief summary of the presented research lines in order to define the roadmap that involves my next research directions.

Basically, the largest part of my research activities since my Master final project is related to analyzing, defining and using mobility algorithms in wireless networks. The first contributions of my work, from my Master graduation until the obtention of my Ph.D., were all oriented at finding a way to face the harmful impact of users' mobility in a wireless system. In this field, I mainly contributed with novel **resource and handover management schemes** that take into account the unconstrained or *impact-unaware mobility* of the users and optimize the resources usage of the system to accommodate as many users as possible and offer them the best available quality of service. Usually, the methodology used, in this first part of my career, was to dissect the existing mobility management schemes in order to determine their advantages and drawbacks, propose new schemes based on improving existing schemes' drawbacks and assess the quality of the new solutions by simulation. In this phase, the devices I considered are not aware of their mobility and of the impact it would have on the network performance. Therefore devices (or users) followed predefined mobility models, which were selected according to the simulated scenario. Then, the mobility model and the network protocols were put together in the simulation in order to interact with each other and find out if the new scheme was, somehow, able to outperform the previous ones in terms of network performance. The deeper I went in the analysis of existing schemes and the proposal of new solutions, the better I saw that when the network has the possibility to make some realistic *a-priori* assumption on the users' mobility, or is able to "measure" it at run-time, probabilities for the network designer to provide schemes that allows a good performance increase. In one of my first works, not presented in this manuscript, I proposed that the network could keep track of the *recurrent paths* of users [71] in order to allocate resources in advance. In the current technical specifications of the 3GPP initiative for 5G systems, they introduce the concept of **Mobility Pattern**: "The Mobility Pattern is a concept that may be used by the 5G system core network to characterise and optimise the UE mobility. The 5G system core network determines and updates Mobility Pattern of the UE based on subscription of the UE, statistics of the UE mobility, network local policy, and the UE assisted information, or any combination of them. The statistics of the UE mobility can be historical or expected UE moving trajectory. UE mobility pattern can be used by the AMF to optimize mobility support provided to the UE, for example, Registration area Allocation." [5].

**Lesson learned:** The network must "understand" users' mobility.

By learning the mentioned lesson from these first works, I moved towards the

second phase of my career, which is still ongoing and is characterized by the effort of demonstrating that mobility, when used wisely, is not detrimental for the network performance and can actually improve the quality of the services provided to the users. Therefore, the focus of my research switched to networks comprising intelligent devices that are aware of their mobility, and that actively use it to accomplish a mission or simply to improve the communications, such as mobile sensors, robots and UAVs. My contributions on this topic are numerous, and span from the **definition of mathematical frameworks** to assess the quality of nodes placement schemes, to the proposal, simulation and test of new **mobility schemes** that improve the network performance. The research methodology of this second part of my career, without abandoning the simulation, got enriched with the mathematical modeling of the problems and the implementation of the solutions in real environments. The former made me open a couple of collaborations with operational researchers and learn a lot about optimization problems, the latter gave me the possibility to put my hands on the physical devices and mature some practical experiences. By classifying my contributions in this domain, one can see that the biggest part of my efforts have gone to mobility algorithms for improving the coverage of the network, which is useful for both monitoring&surveillance and filming&tracking applications. For the algorithms that I proposed, I had the possibility to learn and apply several different techniques of swarm intelligence (e.g.: particle swarm optimization) and artificial intelligence (e.g.: neural networks and reinforcement learning), control theory (e.g.: potential field and PID control models) and robotics (e.g.: formation control and simultaneous localization and mapping schemes). More and more I realized that, to propose complete solutions, I needed on one side to integrate my competencies in networking and communications with those of other disciplines and, on the other side, that I should consider several interacting systems.

**Lesson learned:** Robot and UAV systems are at the intersection of networking, AI, robotics, and optimization.

Consequently, the next phase of my career, still ongoing since my arrival at the Heudiasyc Lab, has been characterized by the design of the communication schemes needed in systems composed of several subsystems, such as sensor networks, terrestrial robot networks and UAV networks. In this context, I received a grant (IMATISSE project from Region Picardie) for a system composed of a sensor network, a UAV network and a crowdsensing system that work together for the monitoring and management of natural disasters. My contributions consists in: the **definition of the networking architectures** for coordination and cooperation intra- and inter-segment, the **integration of controlled mobility algorithms** within systems of systems, the **development of simulation&emulation tools** for control and communications. More specifically, in the IMATISSE project, as it is the first proposal that puts together the three mentioned components, it has been necessary to describe possible architectural choices, and identifies the roles of the three components, as well as to classify issues and possible solutions of networking. The preparation of these works gave me the possibility to focus on some specific aspects, such as the perennial continuity of service with a fleet of UAV, on which I have deepened my interest. A second



main contribution, in this area, reflects the current merging of networking and control research fields within the scope of robotic applications. As the tools for a proper and easy management of experiments is still missing, my contribution aimed at filling such gap by presenting a simulation architecture for networked control systems based on the integration of two existing solutions. For both these contributions that also led to the systematic examination of Cyber-physical systems, the research methodology involved: a deep analysis of existing architectures and proposals of new ones in the scope of 4G and 5G heterogeneous systems, an extended investigation into current interface technologies and simulation tools, and the creative effort of finding the research and development challenges in future applications and scenarios for integrated systems. Once involved in this research activity, it has appeared clearly to me that, in the future, autonomous collaborative high-end systems, capable of performing specialized missions as well as flexible enough to switch tasks and roles at run-time, would take more and more space in the market, and that this kind of system will be part of the future 5G systems.

**Lesson learned:** Aiming at the integration of heterogeneous systems, we will get to the virtualization of devices and their functions.

Finally, my contribution in the security field concerns the design of **privacy preservation schemes** in the Internet of Things. The evolution of the IoT invokes massive possibilities for exchanging private data enabling new business models across heterogeneous networks. Then, making IoT technologies secure and reliable becomes the basis to carry out this concept development. Due to the limited capabilities of the IoT devices, conventional privacy solutions as encryption methods are inadequate to solve privacy concerns [55]. Therefore, a new trend of solutions, based on game theory, is gaining momentum. I applied this methodology to model the data exchange between a Data Holder and a Data Requester in an Intelligent Transportation Systems (ITS). This first contribution on this topic made me realize, in an extremely broad market, such as that of the IoT, which spans from fitness trackers and healthcare devices to consumer electronics and connected cars, how important it is to define privacy preservation schemes to “defend” users from data theft.

**Lesson learned:** Security for the IoT has a potential larger impact than the Internet itself.

The main objective of my research, since my visit at the BWN Lab of the Georgia Tech in 2005-2006, became the inclusion of *mobility* among the control primitives of a network. I believe that, with my research, I contributed to the enormous steps that the research community has made in this direction in the recent years, but the objective has not been completely attained yet. Therefore, my most important direction which will lead my research in the next years, is still to find out, demonstrate and exploit the usage of *controlled mobility* as a primitive of wireless sensor, robot and UAV networks. Several more concrete research directions derive from this general objective, especially when we consider the fact that the specifications of the future 5G systems aim at taking into account extreme latency and reliability of data delivery at very high-speed mobility.

In the following, I will list the research directions in which I am interested, by splitting them according to the type of expected contribution: theoretical or practical.

### Theoretical:

- *Problem formulation*: Autonomous collaborative systems, made up of several subsystems, have a potential huge impact on the market, as they can provide customizable solutions to any problem that requires quick and efficient operations, such as disaster management, monitoring, surveillance, filming, tracking, goods delivery, and the list could go on. Each application implies a certain number of specific tasks to accomplish, which can be considered stand-alone problems that need a solution for the devices to achieve. In this sense, tasks formulation becomes, at the beginning a mathematical formulation effort. Basically, as we have seen in Section 3.3.2, the mathematical formulation of the specific problem, such as “follow a sport action in order to film it”, helps finding a first sub-optimal (as usually these problems are NP-Hard) solution to the problem, and may represent an upper bound on the potential performance even when the solution is unfeasible (due to unrealistic assumptions). Only in a few of my works, and only for some specific objective, the mathematical formulation of the problem has been completely developed. Therefore, I count on taking into consideration other applications, such as goods delivery, UAV-assisted Internet provision, multi-target tracking, etc., and formulate the mathematical model associate to the problem;
- *Mathematical framework modeling*: My first works on finding the optimal placement of nodes involved in a data flow, presented in Section 3.2.1 proposed a mathematical framework for assessing the quality of the proposed solution, by extracting some relevant information from the problem formulation. For those works, the only objective was to maximize the lifetime of the network. Hence, the proposed mathematical framework allows us to only assess the performance of a placement and data relaying protocol in terms of the energy expenditure. I would like to explore the possibility to establish different mathematical frameworks, which can take into consideration other important parameters, such as the delay of the data flow, the throughput end-to-end and hop-by-hop of the relaying chain, the jitter and the perceived quality in case of multimedia transmission. Several of these parameters have been the object of study for *unconstrained mobility*, but no one of them has been used for creating a mathematical framework in case of *controlled mobility*.

### Practical:

- *Usage of Network Virtualisation and Network Slicing*: 5G systems, to respond to the need to see Anything as a Service, foresee a massive usage of Network Virtualisation (NV) and Network Slicing (NS), which are concepts based on Software Defined Networking (SDN) and Network Functions Virtualisation (NFV). Thanks to NV, it would be possible to deliver greater

network flexibility by allowing traditional network architectures to be partitioned into virtual elements that can be linked through software. On the other hand, NS allows multiple virtual networks to be created on top of a common shared physical infrastructure. The virtual networks are then customised to meet the specific needs of applications, services, devices, customers or operators. In this sense, the robot or UAV network, can become a Virtual Network slice and specific tasks can be seen as slice instances with different configurations, which can be quickly reprogrammed when the mission changes. I am very interested in pursuing this research direction in the years to come, in order to establish a solid research record in robot and UAV networks for 5G systems;

- *SoS integration*: By continuing the work of Chapter 4, where the different cooperating networks have been considered as different subsystems of a System of Systems, I would like to get a broader knowledge of software and hardware devices, used to interface different subsystems as well as to sense and capture useful data. Basically, I find that, the process started in the DIVINA research group, which “obliged” researchers belonging to different communities to speak the same language in order to reach a shared objective, is very beneficial for the implementation of a system, able to cope with realistic assumptions in a real-life scenario. Hence, I would like to pursue these interdisciplinary collaborations in order to enrich the theoretical studies (see the *Problem formulation* item in the previous list of research directions) with realistic implementations that would raise the Technology Readiness Level (TRL) of the systems, towards their industrialization.
- *UAV fleet management*: I would like to specialize my interest in UAV networks by focusing on the fleet management. After having set up the CUS-CUS simulator/emulator presented in Section 4.3, I would like to propose a complete reconfigurable software/hardware suite for the management of a fleet of UAVs in pursuit of a set of missions. This means, for the communication side of the research activity, the usage of Software Defined Radio, such as in [7], and Network Slicing (see the first item of this list) to provide a scalable, flexible and resilient network architecture; from the control theory perspective, the definition of new control models that make explicit use of communications among the UAV for improving their individual performance as well as the group behaviour [65].

## 7. Publications

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### Journals

- [J1] M. Erdelj, M. Krol, E. Natalizio, *Wireless Sensor Networks and Multi-UAV Systems for Natural Disaster Management*, Elsevier Computer Networks, vol. 124, pp. 72-86, 2017. doi: 10.1016/j.comnet.2017.05.021.
- [J2] S. Yahiaoui, M. Omar, A. Bouabdallah, E. Natalizio, Y. Challal, *An energy efficient and QoS aware routing protocol for wireless sensor and actuator networks*, AEU - International Journal of Electronics and Communications, Available online 1 September 2017, ISSN 1434-8411, <https://doi.org/10.1016/j.aeue.2017.08.045>.
- [J3] S. Manfredi, E. Natalizio, C. Pascariello, N. Zema, *A Packet Loss Tolerant Rendezvous Algorithm for Wireless Networked Robot Systems*, Asian Journal of Control, vol. 19, no. 5, pp. 1-11, September 2017. doi: 10.1002/asjc.1470.
- [J4] A. Gogu, D. Nace, E. Natalizio, Y. Challal, *Using dynamic programming to solve the Wireless Sensor Network Configuration Problem*, Elsevier Journal of Network and Computer Applications, vol. 83, pp. 140-154, April 2017.
- [J5] A. Riahi, E. Natalizio, Y. Challal, Z. Chtourou, *A roadmap for security challenges in Internet of Things*, Elsevier Digital Communications and Networks, 2017. doi: 10.1016/j.dcan.2017.04.003
- [J6] O. Alvear, N. Zema, E. Natalizio, C. Calafate, *Using UAV-Based Systems to Monitor Air Pollution in Areas with Poor Accessibility*, Journal of Advanced Transportation, vol. 2017, Article ID 8204353, 14 pages, 2017. doi: 10.1155/2017/8204353.
- [J7] T. Razafindralambo, M. Erdelj, D. Zorbas, E. Natalizio, *Spread and Shrink: Point of Interest Discovery and Coverage with Mobile Wireless Sensors*, Elsevier Journal of Parallel and Distributed Computing, vol. 102, pp. 16-27, April 2017. doi: 10.1016/j.jpdc.2016.09.003.
- [J8] M. Erdelj, E. Natalizio, K. R. Chowdhury, I. F. Akyildiz, *Help from the Sky: Leveraging UAVs for Disaster Management*, IEEE Pervasive Computing, IEEE Pervasive Computing, vol. 16, no. 1, pp. 24-32, Jan.-Mar. 2017.
- [J9] N. Zema, E. Natalizio, G. Ruggeri, M. Poss, and A. Molinaro, *MeDrone: On the use of a medical drone to heal a sensor network infected by a malicious epi-*

*demic*, Elsevier Ad Hoc Networks, Volume 50, Page 115-127, November 2016.

[J10] X. Wang, Y. A. Sekercioglu, T. Drummond, E. Natalizio, I. Fantoni, V. Fremont, *Fast Depth Video Compression for Mobile RGB-D Sensors*, IEEE Transactions on Circuits and Systems for Video Technology, vol. 26, no. 4, pp. 673-686, April 2016. doi: 10.1109/TCSVT.2015.2416571.

[J11] A. Vegni, E. Natalizio, *Forwarder Smart Selection Protocol for Limitation of Broadcast Storm Problem*, Elsevier Journal of Network and Computer Applications, 10.1016/j.jnca.2014.08.009.

[J12] A. Vegni, E. Natalizio, *A hybrid (N/M)CHO soft/hard vertical handover technique for heterogeneous wireless networks*, Elsevier Ad Hoc Networks, Volume 14, Page 51-70, March 2014.

[J13] G. Aloï, L. Bedogni, M. Di Felice, V. Loscrì, A. Molinaro, E. Natalizio, P. Pace, G. Ruggeri, A. Trotta, N. R. Zema, *STEM-Net: an evolutionary network architecture for smart and sustainable cities*, Transactions on Emerging Telecommunications Technologies, Volume 25, Page 21-40, 2014.

[J14] F. Guerriero, R. Surace, V. Loscrì, E. Natalizio, *A Multi-objective Approach for Unmanned Aerial Vehicle Routing Problem with Soft Time Windows Constraints*, Elsevier Applied Mathematical Modelling, Volume 38, Issue 3, Page 839-852, 2014.

[J15] M. Erdelj, V. Loscrì, E. Natalizio, T. Razafindralambo, *Multiple point of interest discovery and coverage with mobile wireless sensors*, Elsevier Ad Hoc Networks, Volume 11, Issue 8, Page 2288-2300, 2013.

[J16] E. Natalizio, V. Loscrì, *Controlled Mobility in Mobile Sensor Networks: Advantages, Issues and Challenges*, Springer Telecommunication Systems, Special Issue on Recent Advance in Mobile Sensor Networks, Volume 52, Issue 4, Page 2411-2418, 2013. DOI: 10.1007/s11235-011-9561-x.

[J17] K. Miranda, E. Natalizio, T. Razafindralambo, *Adaptive Deployment Scheme for Mobile Relays in Substitution Networks*, International Journal of Distributed Sensor Networks, 2012.

[J18] C. Costanzo, V. Loscrì, E. Natalizio, T. Razafindralambo, *Nodes self-deployment for coverage maximization in mobile robot networks using an evolving neural network*, Elsevier Computer Communications, Special Issue on Wireless Sensor and Robot Networks: Algorithms and Experiments, Volume 35 Issue 9, May 2012, Pages 1047-1055. DOI: <http://dx.doi.org/10.1016/j.comcom.2011.09.004>.

[J19] F. Guerriero, A. Violi, E. Natalizio, V. Loscrì, C. Costanzo, *Modelling and Solving Optimal Placement problems in Wireless Sensor Networks*, Elsevier Applied Mathematical Modelling, Volume 35, Issue 1, January 2011, Pages 230-241.

[J20] E. Natalizio, P. Pace, A. Violi, F. Guerriero, *A reactive and dependable transport protocol for wireless mesh networks*, Elsevier Journal of Parallel and Distributed Computing, vol.70, no. 5, pp. 431-442, May 2010.

[J21] V. Loscrì, E. Natalizio, C. Costanzo, *Simulations of the impact of Controlled Mobility for Routing Protocols*, EURASIP Journal on Wireless Communications and Networking, Special Issue on Simulators and Experimental Testbeds Design and Development for Wireless Networks, vol. April 2010, doi:10.1155/2010/315381.

[J22] E. Natalizio, V. Loscrì, A. Violi, F. Guerriero, *Energy Spaced Placement for Bidirectional Data Flows in Wireless Sensor Network*, IEEE Communications Letters, vol. 13, no. 1, pp. 22-24, January 2009.

[J23] E. Natalizio, V. Loscrì, E. Viterbo, *Optimal Placement of Wireless Nodes for Maximizing Path Lifetime*, IEEE Communications Letters, vol. 12, no. 5, pp. 362-364, May 2008.

[J24] A. Iera, A. Molinaro, S. Marano, E. Natalizio, *Call Management Based on the Mobile Terminal-Peak Velocity: Virtues and Limitations in a Two-Tier Cellular System*, IEEE Transactions on Vehicular Technology, vol. 52, no.4, July 2003.

## Under review

[S1] N. Zema, A. Trotta, E. Natalizio, M. Di Felice, L. Bononi, *The CUSCUS simulator for Distributed Networked Control Systems: Architecture and Use-cases*, submitted for publication to Elsevier Ad Hoc Networks.

[S2] A. Riahi, E. Natalizio, P. Moyal, Y. Challal, Z. Chtourou, *A game theoretic approach for privacy preserving model in IoT-based commercial transportation*, submitted for publication to Elsevier Computer Networks.

[S3] M. Erdelj, O. Saif, E. Natalizio, I. Fantoni-Coichot, *MAVLink-based Automatic Replacement Algorithm for Continuous UAV Operation*, submitted for publication to Elsevier Ad Hoc Networks.

[S4] A. Riahi, E. Natalizio, S. Mazlout, Y. Challal, Z. Chtourou, *Privacy preservation using game theory in e-health application*, submitted for publication to Springer Wireless Personal Communications.

## Contribution to book

[B1] N. El Zoghby, V. Loscrì, E. Natalizio, V. Cherfaoui, *Robot Cooperation and Swarm Intelligence*, in *Wireless Sensor and Robot Networks: From Topology Control to Communication Aspects*, World Scientific Publishing Company, Chapter 8, Pages 168-201, 2014.

[B2] M. Erdelj, N. Mitton, E. Natalizio, *Applications of Industrial Wireless Sensor Networks*, Chapter 1 in *Industrial Wireless Sensor Networks*, CRC Press 2012.

[B3] V. C. Gungor, E. Natalizio, P. Pace, and S. Avallone, *Challenges and Issues in Designing Architectures and Protocols for Wireless Mesh Networks*, Chapter 1 in *Wireless Mesh Networks: Architectures, Protocols, and Applications*, Springer-Verlag, 2007.

## Conferences

### International conferences

[C1] N. Mahdoui, V. Frémont, E. Natalizio, *Cooperative Navigation Strategy for Micro-Aerial Vehicles Fleet Authors*, IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI), Daegu, Korea, November 2017.

[C2] L. Di Puglia Pugliese, F. Guerriero, E. Natalizio, N. Zema, *A biobjective formulation for filming sport events problem using drones*, The 9th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems (IEEE IDAACS): Technology and Applications, Bucharest, Romania, September 2017.

[C3] O. P. Alvear, N. Zema, E. Natalizio, C. Tavares Calafate, *A chemotactic pollution-homing UAV guidance system*, Advanced Industrial Nets & Intelligent Systems-AINIS Symposium at IEEE Wireless Communications and Mobile Computing (IWCMC), Valencia, Spain, June 2017.

[C4] N. Zema, E. Natalizio, E. Yanmaz, *An Unmanned Aerial Vehicle Network for Sport Event Filming with Communication Constraints*, First International Balkan Conference on Communications and Networking 2017 (BALKANCOM), Tirana, Albania, May 2017.

[C5] F. D'Andreagiovanni, D. Nace, A. Nardin, E. Natalizio, *Robust relay node placement in body area networks by heuristic min-max regret*, First International Balkan Conference on Communications and Networking 2017 (BALKANCOM), Tirana, Albania, May 2017.

[C6] A. Riahi, E. Natalizio, Y. Challal, Z. Chtourou, *A Markov game privacy preserving model in retail applications*, International conference on selected topics in Mobile and Wireless Networking (MoWNet), Avignon, France, May 2017.

[C7] F. D'Andreagiovanni, A. Nardin, E. Natalizio, *A Fast ILP-Based Heuristic for the Robust Design of Body Wireless Sensor Networks*, In: G. Squillero and K. Sim (Eds.): *EvoApplications 2017, Part I*, LNCS 10199, pp. 1-17, 2017.

- [C8] M. Krol, E. Natalizio, N. Zema, *Tag-based Data Exchange in Disaster Relief Scenarios*, The 10th International Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN) @ International Conference on Computing, Networking and Communications (ICNC 2017), Silicon Valley, United States, January 2017.
- [C9] N. Zema, A. Trotta, G. Sanahuja, E. Natalizio, M. Di Felice, L. Bononi, *CUSCUS: An integrated simulation architecture for Distributed Networked Control Systems*, The 14th Annual IEEE Consumer Communications & Networking Conference (CCNC), Las Vegas, United States, January 2017.
- [C10] M. Erdelj, E. Natalizio, *UAV-assisted disaster management: Applications and open issues*, The 9th International Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN) @ International Conference on Computing, Networking and Communications (ICNC 2016), Kauai, United States, February 2016.
- [C11] N. Mahdoui, E. Natalizio, V. Frémont, *MultiUAVs Network Communication Study for Distributed Visual Simultaneous Localization and Mapping*, The 9th International Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN) @ International Conference on Computing, Networking and Communications (ICNC 2016), Kauai, United States, February 2016.
- [C12] X. Wang, A. Sekercioglu, T. Drummond, E. Natalizio, I. Fantoni, V. Frémont, *Collaborative Multi-Sensor Image Transmission and Data Fusion in Mobile Visual Sensor Networks Equipped with RGB-D Cameras*, IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI), Baden-Baden, Germany, September 2016.
- [C13] V. Loscrì, E. Natalizio, F. Guerriero, N. Mitton, *Efficient Coverage for Grid-Based Mobile Wireless Sensor Networks*, The 17th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2014.
- [C14] N. Zema, E. Natalizio, M. Poss, G. Ruggeri, A. Molinaro, *Healing Wireless Sensor Networks from Malicious Epidemic Diffusion*, The 11th IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS), Marina del Rey, United States, May 2014.
- [C15] V. Loscrì, E. Natalizio, N. Mitton, *Performance Evaluation of Novel Distributed Coverage Techniques for Swarms of Flying Robots*, The 12th IEEE Wireless Communications and Networking Conference (WCNC), Istanbul, Turkey, March 2014.
- [C16] L. Zaouche, S. Aitarab, A. Khireddine, M. Omar, E. Natalizio, M. Bouabdallah, *A reputation-based approach using collaborative indictment\exculpation for detecting and isolating selfish nodes in MANETs*, International conference on advanced Networking, Distributed Systems and applications (INDS), Béjaia, Algeria, June 2014.



- [C17] E. Natalizio, R. Surace, V. Loscrì, F. Guerriero, T. Melodia, *Two Families of Algorithms to Film Sport Events with Flying Robots*, The 10th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS), Hangzhou, China, October 2013.
- [C18] N. Mitton, E. Natalizio, R. Wolhuter, *Beacon-less mobility assisted energy efficient georouting in energy harvesting actuator and sensor networks*, The 12th International Conference on Ad Hoc Networks and Wireless (ADHOC-NOW), Wroclaw, Poland, July 2013.
- [C19] V. Loscrì, E. Natalizio, T. Razafindralambo, N. Mitton, *Distributed Algorithm to Improve Coverage for Mobile Swarms of Sensors*, IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS), Boston, United States, May 2013.
- [C20] A. Riahi, Y. Challal, E. Natalizio, Z. Chtourou, A. Bouabdallah, *A Systemic Approach for IoT Security*, 1st International workshop on Internet of Things - Ideas and Perspectives @ IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS), Boston, United States, May 2013.
- [C21] N. Maalel, E. Natalizio, A. Bouabdallah, P. Roux, M.E. Kellil, *Reliability for Emergency Applications in Internet of Things*, 1st International workshop on Internet of Things - Ideas and Perspectives @ IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS), Boston (USA), 20-23 May 2013.
- [C22] A.M. Vegni, E. Natalizio, A. Stramacci, *Opportunistic Clusters Selection in a Reliable Enhanced Broadcast Protocol for Vehicular Ad hoc Network*, Poster session, IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS), 2013.
- [C23] V. Loscrì, E. Natalizio, G. Aloï, *A novel Communication Technique for Nanobots based on acoustic signals*, 7th International Conference on Bio-Inspired Models of Network, Information, and Computing Systems (BIONETICS), Lugano, Switzerland, 2012.
- [C24] V. Loscrì, E. Natalizio, F. Guerriero, G. Aloï, *Particle Swarm Optimization Schemes Based on Consensus for Wireless Sensor Networks*, The 15th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2012.
- [C25] K. Miranda, E. Natalizio, T. Razafindralambo, A. Molinaro, *Adaptive Router Deployment for Multimedia Services in Mobile Pervasive Environments*, Work in Progress session, The 10th IEEE Pervasive Computing and Communication conference (PerCom), 2012.
- [C26] A.M. Vegni, A. Stramacci, E. Natalizio, *SRB: A Selective Reliable Broadcast*

*Protocol for Safety Applications in VANET*, International Conference on Selected Topics in Mobile & Wireless Networking (iCost), 2012.

[C27] V. Loscrì, E. Natalizio, V. Mannara, G. Aloï, *Acoustic Communication Techniques for Nanobots*, 7th International Conference on Body Area Networks, BodyNets 2012.

[C28] M. Erdelj, E. Natalizio, T. Razafindralambo, *Multiple Point of Interest Discovery and Coverage with Mobile Wireless Sensors*, International Workshop on Mobility and Communication for Cooperation and Coordination (MC3) @ International Conference on Computing, Networking and Communications (ICNC), 2012.

[C29] R. Surace, V. Loscrì, E. Natalizio, *On the Impact of the Propagation Environment on Controlled Mobility Algorithms*, International Workshop on Mobility and Communication for Cooperation and Coordination (MC3) @ International Conference on Computing, Networking and Communications (ICNC), 2012.

[C30] P. Pace, V. Loscrì, E. Natalizio, T. Razafindralambo, *Nodes Placement for reducing Energy Consumption in Multimedia Transmissions*, in IEEE Personal Indoor Mobile and Radio Communications (PIMRC), 2011.

[C31] K. Miranda, E. Natalizio, T. Razafindralambo, *On the impact of router's mobility on substitution networks*, Poster presentation in the Twelfth ACM International Symposium on Mobile Ad Hoc Networking and Computing, Paris, France, May 2011.

[C32] C. Costanzo, V. Loscrì, and E. Natalizio, *Distributed Virtual-Movement Scheme for Improving Energy Efficiency in Wireless Sensor Networks*, The 12th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), pp. 297-304, Tenerife, Spain, October 2009.

[C33] V. Loscrì, E. Natalizio, C. Costanzo, F. Guerriero, A. Violi, *Optimization Models for Determining Performance Benchmarks in Wireless Sensor Networks*, in Proceedings of IARIA SENSORCOMM, pp. 333-338, Athens, Greece, June 2009.

[C34] V. Loscrì, E. Natalizio, E. Viterbo, D. Mauro, *Carrier Independent Localization Techniques for GSM Terminals*, in IEEE Personal Indoor Mobile and Radio Communications (PIMRC), pp 1-5, 2008.

[C35] V.C. Gungor, P. Pace, E. Natalizio, *AR-TP: An Adaptive and Responsive Transport Protocol for Wireless Mesh Networks*, Proceeding of IEEE International Conference on Communications (ICC), pp. 3740-3745, Glasgow, Scotland, June 2007.

[C36] P. Pace, E. Natalizio, *Wireless Communication Networks via Aerial Platforms: Dynamic Fair Power Sharing Admission Control for UMTS real time traffic sources*, Proceedings of the 14th IEEE International Conference On Telecommunications (ICT), Penang, Malaysia, May 2007.

[C37] E. Natalizio, G. Aloï, *Exploiting Recurrent Paths of Vehicular Users in a Third Generation Cellular System Urban Scenario*, IEEE Personal Indoor Mobile and Radio Communications (PIMRC), 2006.

[C38] E. Natalizio, A. Molinaro, S. Marano, *Packet Scheduling Algorithms for Providing QoS on UMTS Downlink Shared Channels*, Vehicular Technology Conference (VTC-Fall), 2005.

[C39] P. Pace, E. Natalizio, *Dynamic Fair Power Sharing Admission Control for HAP-UMTS communication system*, Proceedings of IST Mobile and Wireless Communications Summit, Budapest, July 1-5, 2007.

[C40] E. Natalizio, A. Scicchitano, S. Marano, *Mobility Anchor Point Selection Based on User Mobility in HMIPv6 Integrated with Fast Handover Mechanism*, IEEE Wireless Communications and Networking Conference (WCNC), Vol.3, pp. 1434-1439, March 2005.

[C41] P. Pace, G. Aloï, F. De Rango, E. Natalizio, A. Molinaro, S. Marano, *An integrated Satellite-HAP-Terrestrial system architecture: resources allocation and traffic management issues*, Proceedings of the IEEE Vehicular Technology Conference (VTC Spring), Milano, Italy, May 2004.

[C42] E. Natalizio, A. Molinaro, S. Marano, *Reducing packet loss in hierarchical mobile IPv6*, IEEE Personal, Indoor and Mobile Radio Communications (PIMRC), Vol. 3, pp. 1876-1880, September 2004.

[C43] E. Natalizio, A. Molinaro, S. Marano, *The Effect of a Realistic Urban Scenario on the Performance of Algorithms for Handover and Call Management in Hierarchical Cellular Systems*, 11th IEEE International Conference on Telecommunications (ICT), pp. 1143-1150, August 2004.

## **French conferences**

[F1] N. Zema, E. Natalizio, E. Yanmaz, *Enregistrement d'événements sportifs par un réseau de drones avec des contraintes de communication*, 9ème Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications (AlgoTel 2017), Quiberon, France.

## **Invited conferences**

[I1] B. M. Masini, A. Bazzi, E. Natalizio, *Radio Access for Future 5G Vehicular Networks*, Proceedings of the IEEE Vehicular Technology Conference (VTC Fall), Toronto, Canada, September 2017.

- [I2] L. Zaouche, E. Natalizio, A. Bouabdallah, *ETTAF: Efficient Target Tracking and Filming with a Flying Ad Hoc Networks*, The 1st International Workshop on Experiences with the Design and Implementation of Smart Objects (SMART-OBJECT) @ The 21st ACM Conference on Mobile Computing and Networking (Mobicom), Paris, France, 2015.
- [I3] A. Riahi, E. Natalizio, Y. Challal, N. Mitton, A. Iera, *A systemic and cognitive approach for IoT security*, International Conference on Computing, Networking and Communications (ICNC), Honolulu, United States, 2014.
- [I4] G. Aloï, A. Borgia, S. Costanzo, G. Di Massa, V. Loscrì, E. Natalizio, P. Pace, F. Spadafora, *Software Defined Radar: synchronization issues and practical implementation*, ISABEL, Barcelona, Spain, October 2011.
- [I5] E. Natalizio, V. Loscrì, G. Aloï, N. Paoli, *The practical experience of implementing a GSM BTS through Open Software/Hardware*, ISABEL, Rome, Italy, November 2010.

# Bibliography

- [1] FL-AIR: Framework libre air. available from <https://uav.hds.utc.fr/software-flair/>.
- [2] Network Simulator- ns (version 2). available from <http://www.isi.edu/nsnam/ns/>.
- [3] Phoenix rc. <http://www.phoenix-sim.com>.
- [4] Simdrone from h-sim. <http://www.h-sim.com>.
- [5] 3rd Generation Partnership Project. Technical specification group services and system aspects; system architecture for the 5g system; stage 2 (release 15). Technical report, September 2017.
- [6] I. F. Akyildiz, J. McNair, J. S. M. Ho, H. Uzunalioglu, and Wenye Wang. Mobility management in next-generation wireless systems. *Proceedings of the IEEE*, 87(8):1347–1384, Aug 1999.
- [7] I. F. Akyildiz, P. Wang, and S.-C. Lin. Softair: A software defined networking architecture for 5g wireless systems. *Computer Networks*, 85(Supplement C):1 – 18, 2015.
- [8] I. F. Akyildiz and W. Wang. A dynamic location management scheme for next-generation multitier pcs systems. *IEEE Transactions on Wireless Communications*, 1(1):178–189, Jan 2002.
- [9] I. F. Akyildiz, Jiang Xie, and S. Mohanty. A survey of mobility management in next-generation all-ip-based wireless systems. *IEEE Wireless Communications*, 11(4):16–28, Aug 2004.
- [10] D. E. Alexander. *Principles of Emergency Planning and Management*. Terra and Oxford University Press, 2002.
- [11] A. Baird, P. O’Keefe, K. Westgate, and B. Wisner. *Towards an explanation and reduction of disaster proneness*. Bradford University, Disaster Research Unit, 1975.
- [12] A. Basu, B. Boshes, S. Mukherjee, and S. Ramanathan. Network deformation: Traffic-aware algorithms for dynamically reducing end-to-end delay in multi-hop wireless networks. In *In Proceedings of ACM MobiCom*, pages 100–113, 2004.
- [13] I. Bekmezci, O. Koray Sahingoz, and S. Temel. Flying ad-hoc networks (fanets): A survey. *Ad Hoc Networks*, 11(3):1254 – 1270, 2013.

- [14] N. Bisnik, A. A. Abouzeid, and V. Isler. Stochastic event capture using mobile sensors subject to a quality metric. *IEEE Transactions on Robotics*, 23(4):676–692, Aug 2007.
- [15] M. Bouaziz and A. Rachedi. A survey on mobility management protocols in wireless sensor networks based on 6lowpan technology. *Computer Communications*, 74(Supplement C):3 – 15, 2016. Current and Future Architectures, Protocols, and Services for the Internet of Things.
- [16] Z. Butler and D. Rus. Controlling mobile sensors for monitoring events with coverage constraints. In *In Proceedings of IEEE ICRA*, pages 1568–1573, May 2004.
- [17] Y. Cai, F. R. Yu, J. Li, Y. Zhou, and L. Lamont. Medium access control for unmanned aerial vehicle (uav) ad-hoc networks with full-duplex radios and multipacket reception capability. *IEEE Transactions on Vehicular Technology*, 62(1):390–394, Jan 2013.
- [18] T. Camp, J. Boleng, and V. Davies. A survey of mobility models for ad hoc network research. *Wireless Communications and Mobile Computing*, 2(5):483–502, 2002.
- [19] B.R. Chandavarkar and G. Ram Mohan Reddy. Survey paper: Mobility management in heterogeneous wireless networks. *Procedia Engineering*, 30(Supplement C):113 – 123, 2012. International Conference on Communication Technology and System Design 2011.
- [20] S. Checkoway, D. McCoy, B. Kantor, D. Anderson, H. Shacham, S. Savage, K. Koscher, A. Czeskis, F. Roesner, and T. Kohno. Comprehensive experimental analyses of automotive attack surfaces. In *Proceedings of the 20th USENIX Conference on Security, SEC’11*, pages 6–6, Berkeley, CA, USA, 2011. USENIX Association.
- [21] D. Chen, Z. Liu, L. Wang, M. Dou, , J. Chen, and H. Li. Natural disaster monitoring with wireless sensor networks: A case study of data-intensive applications upon low-cost scalable systems. *Mob. Netw. Appl.*, 18(5):651–663, October 2013.
- [22] S. Corson and J. Macker. Mobile ad hoc networking (manet): Routing protocol performance issues and evaluation considerations, 1999.
- [23] J. Cortes, S. Martinez, T. Karatas, and F. Bullo. Coverage control for mobile sensing networks. *IEEE Transactions on Robotics and Automation*, 20(2):243–255, May 2004.
- [24] C. Costanzo, V. Loscrí, and E. Natalizio. Distributed virtual-movement scheme for improving energy efficiency in wireless sensor networks. In *In Proceedings of ACM MSWIM*, pages 297–304, 2009.
- [25] D.-I. Curiac. Towards wireless sensor, actuator and robot networks. *J. Netw. Comput. Appl.*, 63(C):14–23, March 2016.

- [26] K. Daniel, S. Rohde, N. Goddemeier, and C. Wietfeld. Cognitive agent mobility for aerial sensor networks. *IEEE Sensors Journal*, 11(11):2671–2682, Nov 2011.
- [27] F. Daniyal and A. Cavallaro. Multi-camera scheduling for video production. In *European Conference on Visual Media Production (CVMP)*, London, UK, Nov. 2011.
- [28] A. Devare, A. Hande, A. Jha, S. Sanap, and S. Gawade. A survey on internet of things for smart vehicles. *International Journal of Innovative Research in Science, Engineering and Technology*, 5(2):1212–1217, 2 2016.
- [29] EEA. Mapping the impacts of natural hazards and technological accidents in europe. Technical Report 13, European Environment Agency, 2010.
- [30] E. Ekici and C. Ersoy. Multi-tier cellular network dimensioning. *Wireless Networks*, 7(4):401–411, Jul 2001.
- [31] M. Erdelj and E. Natalizio. Uav-assisted disaster management: Applications and open issues. In *2016 International Conference on Computing, Networking and Communications (ICNC)*, pages 1–5, Feb 2016.
- [32] M. Erdelj, E. Natalizio, K. R. Chowdhury, and I. F. Akyildiz. Help from the sky: Leveraging uavs for disaster management. *IEEE Pervasive Computing*, 16(1):24–32, Jan 2017.
- [33] M. Erdelj, E. Natalizio, and T. Razafindralambo. Multiple point of interest discovery and coverage with mobile wireless sensors. In *2012 International Conference on Computing, Networking and Communications (ICNC)*, pages 121–125, Jan 2012.
- [34] M. Di Felice, A. Trotta, L. Bedogni, K. R. Chowdhury, and L. Bononi. Self-organizing aerial mesh networks for emergency communication. In *2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, pages 1631–1636, Sept 2014.
- [35] S. Frigerio, L. Schenato, G. Bossi, M. Cavalli, M. Mantovani, G. Marcato, and A. Pasuto. A web-based platform for automatic and continuous landslide monitoring: The rotolon (eastern italian alps) case study. *Computers & Geosciences*, 63(Supplement C):96 – 105, 2014.
- [36] P. Fuxjaeger and S. Ruehrup. Validation of the ns-3 interference model for ieee802.11 networks. In *Wireless and Mobile Networking Conference (WMNC), 2015 8th IFIP*, October 2015.
- [37] A. Ganz, C. M. Krishna, D. Tang, and Z. J. Haas. On optimal design of multi-tier wireless cellular systems. *IEEE Communications Magazine*, 35(2):88–93, Feb 1997.
- [38] S. M. George, W. Zhou, H. Chenji, M. Won, Y. O. Lee, A. Pazarloglou, R. Stoleru, and P. Barooah. Distressnet: a wireless ad hoc and sensor network architecture for situation management in disaster response. *IEEE Communications Magazine*, 48(3):128–136, March 2010.

- [39] D. K. Goldenberg, J. Lin, A. S. Morse, B. E. Rosen, and Y. R. Yang. Towards mobility as a network control primitive. In *Proc. ACM international symposium on Mobile ad hoc networking and computing (MobiHoc 2004)*, pages 163–174, 2004.
- [40] M. Grossglauser and D. Tse. Mobility increases the capacity of ad-hoc wireless networks. *IEEE/ACM Transactions on Networking*, 10:477–486, 2001.
- [41] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami. Internet of things (iot): A vision, architectural elements, and future directions. *Future Gener. Comput. Syst.*, 29(7):1645–1660, 2013.
- [42] F. Guerriero, A. Violi, E. Natalizio, V. Loscri, and C. Costanzo. Modelling and solving optimal placement problems in wireless sensor networks. *Applied Mathematical Modelling*, 35(1):230 – 241, 2011.
- [43] L. Gupta, R. Jain, and G. Vaszkun. Survey of important issues in uav communication networks. *IEEE Communications Surveys Tutorials*, 18(2):1123–1152, Secondquarter 2016.
- [44] B. Haider, S. Henna, A. Gul, and F. Aadil. A survey on mobility management techniques in vanets. In *2016 IEEE International Conference on Computer and Information Technology (CIT)*, pages 125–133, Dec 2016.
- [45] E. Hamouda, N. Mitton, and D. Simplot-Ryl. *Energy Efficient Mobile Routing in Actuator and Sensor Networks with Connectivity Preservation*, pages 15–28. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011.
- [46] S. Hayat, E. Yanmaz, and R. Muzaffar. Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint. *IEEE Communications Surveys Tutorials*, 18(4):2624–2661, Fourthquarter 2016.
- [47] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. An application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications*, 1(4):660–670, October 2002.
- [48] J. Hoebeker, I. Moerman, B. Dhoedt, and P. Demeester. An overview of mobile ad hoc networks: applications and challenges. *Journal of the Communications Network*, 3(3):60–66, 2004.
- [49] A. Iera, A. Molinaro, and S. Marano. Handoff management with mobility estimation in hierarchical systems. *IEEE Transactions on Vehicular Technology*, 51(5):915–934, Sep 2002.
- [50] A. Iera, A. Molinaro, E. Natalizio, and S. Marano. Call management based on the mobile terminal-peak velocity: virtues and limitations in a two-tier cellular system. *Vehicular Technology, IEEE Transactions on*, 52(4):794–813, 2003.
- [51] European Telecommunications Standards Institute. Intelligent transport systems (its); vehicular communications; basic set of applications; definitions. Technical Report ETSI TR 102 638 V1.1.1, ETSI, June 2009.



- [52] A. Kansal, M. Rahimi, D. Estrin, W. J. Kaiser, G. J. Pottie, and M. B. Srivastava. Controlled mobility for sustainable wireless sensor networks. In *2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004.*, pages 1–6, Oct 2004.
- [53] D. Karamshuk, C. Boldrini, M. Conti, and A. Passarella. Human mobility models for opportunistic networks. *IEEE Communications Magazine*, 49(12):157–165, December 2011.
- [54] F. K. Karnadi, Z. H. Mo, and K. c. Lan. Rapid generation of realistic mobility models for vanet. In *2007 IEEE Wireless Communications and Networking Conference*, pages 2506–2511, March 2007.
- [55] T. Kasper, D. Oswald, and C. Paar. *Sweet Dreams and Nightmares: Security in the Internet of Things*, pages 1–9. Springer Berlin Heidelberg, Berlin, Heidelberg, 2014.
- [56] G. J. M. Kruijff, F. Pirri, M. Gianni, P. Papadakis, M. Pizzoli, A. Sinha, V. Tretyakov, T. Linder, E. Pianese, S. Corrao, F. Priori, S. Febrini, and S. Angeletti. Rescue robots at earthquake-hit mirandola, italy: A field report. In *2012 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 1–8, Nov 2012.
- [57] S. Kwon, A. Tamhankar, and K.R. Rao. Overview of h. 264/mpeg-4 part 10. *Journal of Visual Communication and Image Representation*, 17(2):186–216, 2006.
- [58] X. Lagrange. Multitier cell design. *IEEE Communications Magazine*, 35(8):60–64, Aug 1997.
- [59] T. Lambrou and C. G. Panayiotou. Collaborative area monitoring using wireless sensor networks with stationary and mobile nodes. *EURASIP J. Adv. Signal Process*, 2009:7:1–7:16, January 2009.
- [60] B. Li, C.K. Wu, and A. Fukuda. Performance analysis of flexible hierarchical cellular systems with a bandwidth-efficient handoff scheme. *IEEE Transactions on Vehicular Technology*, 50(4):971–980, Jul 2001.
- [61] G. Lin, G. Noubir, and R. Rajaraman. Mobility models for ad hoc network simulation. In *IEEE INFOCOM 2004*, volume 1, page 463, March 2004.
- [62] V. Loscri, E. Natalizio, C. Costanzo, F. Guerriero, and A. Violi. Optimization models for determining performance benchmarks in wireless sensor networks. In *2009 Third International Conference on Sensor Technologies and Applications*, pages 333–338, June 2009.
- [63] J. Luo and J. P. Hubaux. Joint mobility and routing for lifetime elongation in wireless sensor networks. In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, volume 3, pages 1735–1746 vol. 3, March 2005.

- [64] T. T. Mac, C. Copot, T. T. Duc, and R. De Keyser. AR.Drone uav control parameters tuning based on particle swarm optimization algorithm. In *2016 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR)*, pages 1–6, May 2016.
- [65] S. Manfredi, E. Natalizio, C. Pascariello, and N. Zema. A packet loss tolerant rendezvous algorithm for wireless networked robot systems. *Asian Journal of Control*, 19(4):1413–1423, 2017. asjc.1470.
- [66] M. Mazur. Global market for commercial applications of drone technology valued at over \$127 bn. Technical report, PricewaterhouseCoopers, 05 2016.
- [67] T. Melodia, D. Pompili, V. C. Gungor, and I. F. Akyildiz. Communication and coordination in wireless sensor and actor networks. *IEEE Transactions on Mobile Computing*, 6(10):1116–1129, Oct 2007.
- [68] Ivan Mezei, Veljko Malbasa, and Ivan Stojmenovic. Robot to robot: Communication aspects of coordination in robot wireless networks, December 2010.
- [69] Q. T. Minh, K. Nguyen, C. Borcea, and S. Yamada. On-the-fly establishment of multihop wireless access networks for disaster recovery. *IEEE Communications Magazine*, 52(10):60–66, October 2014.
- [70] S. Morgenthaler, T. Braun, Z. Zhao, T. Staub, and M. Anwander. UAVNet: A mobile wireless mesh network using unmanned aerial vehicles. In *2012 IEEE Globecom Workshops*, pages 1603–1608, Dec 2012.
- [71] E. Natalizio and G. Aloï. Exploiting recurrent paths of vehicular users in a third generation cellular system urban scenario. In *Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on*, pages 1–5, 2006.
- [72] E. Natalizio, V. Loscr , F. Guerriero, and A. Violi. Energy spaced placement for bidirectional data flows in wireless sensor network. *IEEE Communications Letters*, 13(1):22–24, 2009.
- [73] E. Natalizio, V. Loscr , and E. Viterbo. Optimal placement of wireless nodes for maximizing network lifetime. *IEEE Comm. Letters*, 12(5):1–3, 2008.
- [74] Enrico Natalizio and Valeria Loscr . Controlled mobility in mobile sensor networks: advantages, issues and challenges. *Telecommunication Systems*, 52:2411–2418, 2013.
- [75] Enrico Natalizio, Rosario Surace, Valeria Loscr , Francesca Guerriero, and Tommaso Melodia. Two families of algorithms to film sport events with flying robots. In *The 10th IEEE International Conference on Mobile Ad-hoc and Sensor Systems and Networks and Wireless (MASS)*, pages 319–323, Hangzhou, China, October 2013.
- [76] R. Van Nee. Breaking the gigabit-per-second barrier with 802.11 ac. *IEEE Wireless Communications*, 18(2):4–4, 2011.

- [77] E. Perahia and M. X. Gong. Gigabit wireless lans: an overview of ieee 802.11 ac and 802.11 ad. *ACM SIGMOBILE Mobile Computing and Communications Review*, 15(3):23–33, 2011.
- [78] J. Petit, M. Feiri, and F. Kargl. Revisiting attacker model for smart vehicles. In *IEEE 6th International Symposium on Wireless Vehicular Communications, WiVeC 2014*, pages 1–5, Piscataway, NJ, USA, September 2014. IEEE.
- [79] V. Pillac, M. Gendreau, C. Gueret, and A. L. Medaglia. A review of dynamic vehicle routing problems. *European Journal of Operational Research*, 225(1):1 – 11, 2013.
- [80] F. Z. Qureshi and D. Terzopoulos. Surveillance in virtual reality: system design and multi-camera control. *Proc. of IEEE Int. Conf. on Computer Vision and Pattern Recognition, CVRP 07*, pages 1–8, June 2007.
- [81] R. Rao and G. Kesidis. Purposeful mobility for relaying and surveillance in mobile ad hoc sensor networks. *IEEE Transaction on Mobile Computing*, 3(3):225–232, 2004.
- [82] S. Rao and D. Ghose. Sliding mode control-based autopilots for leaderless consensus of unmanned aerial vehicles. *IEEE Transactions on Control Systems Technology*, 22(5):1964–1972, Sept 2014.
- [83] J. Rezazadeh, M. Moradi, and A. S. Ismail. Mobile wireless sensor networks overview. *International Journal of Computer Communications and Networks (IJCCN)*, 2, 03 2012.
- [84] A. Riahi, E. Natalizio, Y. Challal, N. Mitton, and A. Iera. A systemic and cognitive approach for iot security. In *International Conference on Computing, Networking and Communications (ICNC)*, Hawaii, USA, January 2014.
- [85] A. Riahi, E. Natalizio, P. Moyal, Y. Challal, and Z. Chtourou. A game theoretic approach for privacy preserving model in iot-based commercial transportation. *Submitted for publication to Elsevier Computer Networks*, 2017.
- [86] S. Rosati, K. KruÅEelecki, G. Heitz, D. Floreano, and B. Rimoldi. Dynamic routing for flying ad hoc networks. *IEEE Transactions on Vehicular Technology*, 65(3):1690–1700, March 2016.
- [87] D. Saha, A. Mukherjee, I. S. Misra, and M. Chakraborty. Mobility support in ip: a survey of related protocols. *IEEE Network*, 18(6):34–40, Nov 2004.
- [88] P. Santi. Topology control in wireless ad hoc and sensor networks. *ACM Comput. Surv.*, 37(2):164–194, June 2005.
- [89] W. K. G. Seah, K. Z. Liu, M. H. Jr. Ang, J. G. Lim, and S. V. Rao. Tarantulas: Mobility-enhanced wireless sensor-actuator networks. In *In Proceedings of IEEE Sensor Networks, Ubiquitous, and Trustworthy Computing*, volume 1, pages 548–551, 2006.

- [90] C. Snow. Film or Farm: Which is the Bigger Drone Market? Technical report, Skylogic Research, 06 2014.
- [91] A. A. Somasundara, A. Kansal, D. D. Jea, D. Estrin, and M. B. Srivastava. Controllably mobile infrastructure for low energy embedded networks. *IEEE Transactions on Mobile Computing*, 5(8):958–973, August 2006.
- [92] A. A. Somasundara, A. Ramamoorthy, and M. B. Srivastava. Mobile element scheduling with dynamic deadlines. *IEEE Transactions on Mobile Computing*, 6(4):395–410, April 2007.
- [93] I. Stojmenovic and X. Lin. Power-aware localized routing in wireless networks. *IEEE Transactions on Parallel and Distributed Systems*, 12(11):1122–1133, November 2001.
- [94] H. Sundmaeker, P. Guillemin, P. Friess, and S. Woelffle, editors. *Vision and Challenges for Realising the Internet of Things*. European Commission, 2010.
- [95] C. W. Sung and W. S. Wong. User speed estimation and dynamic channel allocation in hierarchical cellular system. In *Proceedings of IEEE Vehicular Technology Conference (VTC)*, pages 91–95 vol.1, Jun 1994.
- [96] K. Than. Scientists: Natural disasters becoming more common. *Live Science*, October 2005.
- [97] G. Tuna, V. Cagri Gungor, and K. Gulez. An autonomous wireless sensor network deployment system using mobile robots for human existence detection in case of disasters. *Ad Hoc Networks*, 13(Part A):54 – 68, 2014. (1)Special Issue : Wireless Technologies for Humanitarian Relief and (2)Special Issue: Models And Algorithms For Wireless Mesh Networks.
- [98] A. Varga. Omnet++. In *Modeling and Tools for Network Simulation*, pages 35–59. Springer, 2010.
- [99] L. Verma, M. Fakharzadeh, and S. Choi. Wifi on steroids: 802.11 ac and 802.11 ad. *IEEE Wireless Communications*, 20(6):30–35, 2013.
- [100] W. Wang, V. Srinivasan, and K.C. Chua. Using mobile relays to prolong the lifetime of wireless sensor networks. In *In Proceedings of ACM MOBICOM*, pages 270–283, August 2005.
- [101] X. Wang, S. Wang, and J. Ma. Dynamic deployment optimization in wireless sensor networks. *Lecture Notes in Control and Information Sciences*, 344:182–187, October 2006.
- [102] M. Yajnik, Sue Moon, J. Kurose, and D. Towsley. Measurement and modelling of the temporal dependence in packet loss. In *INFOCOM '99. Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, volume 1, pages 345–352 vol.1, Mar 1999.

- [103] E. Yanmaz, S. Hayat, J. Scherer, and C. Bettstetter. Experimental performance analysis of two-hop aerial 802.11 networks. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 3118–3123. IEEE, 2014.
- [104] E. Yanmaz, R. Kuschnig, and C. Bettstetter. Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility. In *2013 Proceedings IEEE INFOCOM*, pages 120–124, April 2013.
- [105] K. L. Yeung and S. Nanda. Channel management in microcell/macrocell cellular radio systems. *IEEE Transactions on Vehicular Technology*, 45(4):601–612, Nov 1996.
- [106] N. Zema, E. Natalizio, and E. Yanmaz. An unmanned aerial vehicle network for sport event filming with communication constraints. In *First International Balkan Conference on Communications and Networking 2017 (BALKANCOM)*, May 2017.
- [107] Y. Zeng, R. Zhang, and T. J. Lim. Wireless communications with unmanned aerial vehicles: opportunities and challenges. *IEEE Communications Magazine*, 54(5):36–42, May 2016.
- [108] W. Zhao, M. Ammar, and E. Zegura. Controlling the mobility of multiple data transport ferries in a delay-tolerant network. In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, volume 2, pages 1407–1418 vol. 2, March 2005.
- [109] H. Zimmermann. Osi reference model - the iso model of architecture for open systems interconnection. *IEEE Transactions on Communications*, 28(4):425–432, April 1980.
- [110] Y. Zou and K. Chakrabarty. Sensor deployment and target localization in distributed sensor networks. *ACM Transactions on Embedded Computing Systems*, 3:61–91, 2004.

## Part III.

### Five main publications



- [1] M. Erdelj, E. Natalizio, K. R. Chowdhury, I. F. Akyildiz, *Help from the Sky: Leveraging UAVs for Disaster Management*, IEEE Pervasive Computing, vol. 16, no. 1, pp. 24-32, Jan.-Mar. 2017. doi: 10.1109/MPRV.2017.11 (IF: 3,250). Summary: This survey of advances in unmanned aerial vehicles (UAVs) for network-assisted first response to disaster management covers disaster prediction, assessment, and response, presenting network architectures for geophysical, climate-induced, and meteorological disasters based on interaction between the UAV and wireless sensor network. My contribution (30% of the work): This paper is relevant as it is the first survey that proposes a classification of the communication problems into a system composed by UAVs and sensors that aims at supporting first aid operators before, during and after a natural disaster. My contribution concerns the analysis of the existing protocols and the definition of the open issues.
- [2] N. Zema, E. Natalizio, G. Ruggeri, M. Poss, and A. Molinaro, *MeDrone: On the use of a medical drone to heal a sensor network infected by a malicious epidemic*, Elsevier Ad Hoc Networks, vol. 50, pp. 115-127, November 2016. doi: 10.1016/j.adhoc.2016.06.008 (IF: 3,047). Summary: In this paper we devise a system for a mobile node to locate, track, access and cure the infected nodes of a WSN threatened by a proximity malware infection. For this purpose we first devise a curing operation scheme for a dedicated mobile node and then we provide an implementation for it in form of a multiprocess network and movement protocol. My contribution (30% of the work): For this work I proposed the problem and the mobility algorithm for the UAV that is in charge of curing the infected nodes.
- [3] F. Guerriero, R. Surace, V. Loscrì, E. Natalizio, *A Multi-objective Approach for Unmanned Aerial Vehicle Routing Problem with Soft Time Windows Constraints*, Elsevier Applied Mathematical Modelling, vol. 38, no. 3, pp. 839-852, 2014. doi: 10.1002/ett.2785 (IF: 2,350). Summary: In this work, we propose a distributed system composed of autonomous Unmanned Aerial Vehicles (UAVs), able to self-coordinate and cooperate in order to ensure both spatial and temporal coverage of specific time and spatial varying Points of Interest. My contribution (20% of the work): I proposed the problem, and I contributed defining the context to perform the simulation study. Once we have gotten the results I proposed new research directions to improve the mathematical model.
- [4] E. Natalizio, R. Surace, V. Loscrì, F. Guerriero, T. Melodia, *Two Families of Algorithms to Film Sport Events with Flying Robots*, In the proceedings of the 10th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS), Hangzhou (China), October 2013 (Acceptance rate 2013: 29%). Summary: In this paper, we introduce two families of distributed algorithms to control the movement of groups of flying robots that are monitoring an event by moving over the field where the event takes place, while optimizing some specific objective. My contribution (50% of the work): This paper is very relevant in my research activities as it presents the first practical application for a fleet of UAVs, where the communication capabilities are actively used. I proposed the problem, its mathematical formulation and a first solution that has been extended later.



[5] E. Natalizio, V. Loscrì, *Controlled Mobility in Mobile Sensor Networks: Advantages, Issues and Challenges*, Springer Telecommunication Systems, Special Issue on Recent Advance in Mobile Sensor Networks, Volume 52, Issue 4, Page 2411-2418, 2013. DOI: 10.1007/s11235-011-9561-x (IF: 1,542). Summary: This survey is the first, and still currently the only one, that sketches a macro-classification of the different objectives which can be pursued by controlled mobility within mobile sensor networks. In this survey, we identify and highlight the interactions between this specific type of mobility and the layers of the control stack. My contribution (60% of the work): This work is the result of several months of studies on problems and existing solutions in using mobility to improve network performance. I proposed the first classification of existing solutions and I defined advantages and drawbacks of mobility at each protocol stack layer.