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Overcoming the Technical Hurdles of IoT Adoption: the FITNESS Project Vision and Insights

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ABSTRACT The Internet of Things (IoT) has emerged as a transformative force, enabling seamless connectivity and data exchange between diverse devices and networks. However, the realization of a truly interoperable, secure, and energy-efficient IoT ecosystem remains a significant challenge. In this paper, we present the vision and the first key findings of the FITNESS project, a comprehensive research initiative funded by the French Research Agency (ANR) as part of the France 2030 program. Our work aims to develop solutions that enable the IoT's full potential, emphasizing scalability, interoperability, security, and sustainability, and enabling seamless connectivity and efficient data transmission between diverse IoT devices and networks. We focus in this paper on three critical areas: IoT architecture and interoperability, the place of Artificial Intelligence in IoT, and energy efficiency. Additionally, we identify and analyze key use cases that demonstrate the practical applications of our research, highlighting the importance of real-world implementation to validate and refine our solutions. Through our dedicated research efforts, we have made significant advances across several key areas, while also laying the groundwork for further development in others. These contributions support the emergence of a more secure, efficient, and interoperable IoT ecosystem, and provide a foundation for adoption by stakeholders seeking to harness its transformative potential.

INDEX TERMS Artificial Intelligence; Energy Efficiency; Future Networks; Industry 4.0; Internet of Things; IoT Architecture; Interoperability; Use Cases

Acronyms

AGV Automated Guided Vehicle.

AI Artificial Intelligence.

AIaaS AI-as-a-Service.

AIoT AI-of-Things.

API Application Programming Interface.

AR Augmented Reality.

CNN Convolutional Neural Network.

Cobot Collaborative Robot.

DRL Deep RL.

FSK Frequency Shift Keying.

IAKM Infrastructure Assisted Knowledge Management.

IIoT Industrial IoT.

IoT Internet of Things.

LEO Low Earth Orbit.

LoRa Long Range.

LoRaWAN LoRa Wide Area Network.

LPWAN Low-Power Wide-Area Network.

MAB Multi-Armed Bandit.

MAC Medium Access Control.

MEC Multi-access Edge Computing.

ML Machine Learning.

- NB-IoT** Narrowband-IoT.
- NN** Neural Network.
- NOMA** Non Orthogonal Multiple Access.
- NS** Network Slicing.
- NWDAF** NetWork Data Analytics Application Function.
- O-RAN** Open-Radio Access Network.
- OS** Operating System.
- PAPR** Peak to Average Power Ratio.
- PHY** Physical Layer.
- QoS** Quality of Service.
- RIC** RAN Intelligent Controller.
- RL** Reinforcement Learning.
- SCHC** Static Context Header Compression.
- SDN** Software Defined Network.
- TCA** Trust Convergence Accelerator.
- TSN** Time-Sensitive Networking.
- UE** User Equipment.
- UPF** User Plane Function.
- URLLC** Ultra Reliable Low Latency Communications.
- V2V** vehicle-to-vehicle.
- V2X** vehicle-to-everything.
- ViT** Vision Transformers.
- WPAN** Wireless Personal Area Network.

I. INTRODUCTION

THE Internet of Things (IoT) has evolved significantly over the past decade, transforming from a nascent concept to a tangible reality with growing adoption across various industries. This trajectory is anticipated to persist, with IoT poised to drive unprecedented innovation and integration in the years ahead, see Fig. 1. Today, IoT is already present in our daily lives, with a growing array of devices, sensors, and systems interconnected and exchanging data to create a more efficient, sustainable, and connected world. From smart home appliances and wearables to industrial automation and transportation systems, IoT has found concrete utilizations in numerous sectors. For instance, IoT-enabled sensors and devices are being used in industrial settings to optimize production processes, predict maintenance needs, and enhance overall efficiency. In the realm of transportation, IoT is facilitating the development of smart traffic management systems, autonomous vehicles, and connected mobility solutions. Additionally, IoT is playing a crucial role in the healthcare sector, enabling remote patient monitoring, personalized medicine, and improved disease diagnosis. Furthermore, IoT is also being leveraged in smart cities initiatives, where it is being used to optimize energy consumption, waste management, and public safety.

In recent years, a plethora of reviews and surveys, [1]–[6], have been published, providing a comprehensive overview of the challenges that the IoT must overcome in order to realize its full potential. They cover a wide range of topics, including technical challenges as well as economic and social challenges. By synthesizing the findings of these papers, researchers and practitioners can gain a deeper understanding of the complexities of IoT development and identify key areas

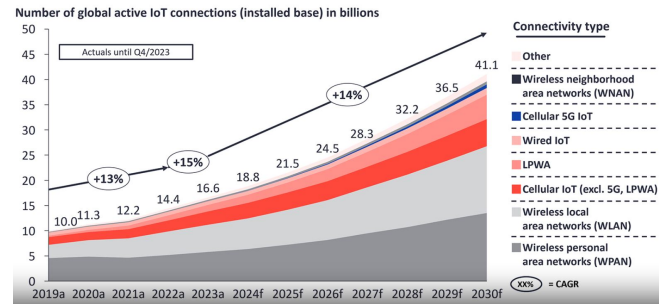


FIGURE 1. Global IoT market forecast, in billions of connected IoT devices [From IoT Analytics, May 2023]

that require further research and innovation.

The FITNESS project, launched in mid-2023, is a four-and-a-half-year research initiative funded by the French Research Agency (ANR) as part of the France 2030 program. With a strong commitment to advancing the state-of-the-art in IoT technologies it brings together a diverse team of over 60 researchers, including 16 dedicated Ph.D. students. This collaborative effort aims to address the key challenges and opportunities in IoT, fostering innovation and driving progress in this rapidly evolving field. The project is structured around three distinct pillars, each focusing on a specific aspect of IoT development.

The first pillar, Massive IoT aims to develop efficient and flexible IoT solutions that can coexist with both proprietary and standardized protocols, and seeks to ensure scalability, energy efficiency, security, latency, and heterogeneity. The project addresses these challenges through the design of ultra-low power connected objects and the study of Wireless access for massive access. Additionally, it studies end-to-end performance to ensure efficient data transmission, with the goal of creating IoT systems that are not only efficient and cost-effective but also flexible and adaptable to different application domains.

The second pillar, Industry 4.0, addresses the need for mission-critical connectivity in industrial settings. It also recognizes the importance of the digitalization and wireless connectivity for the manufacturing industry, and seeks to simplify the underlying technology to enable new services and applications, such as predictive maintenance and automated quality control. The goal is to create IoT systems that can provide reliable, secure, and high-performance connectivity, while also enabling new use cases such as digital twins, intelligent products, and connected workers (see Fig. 2).

The third pillar, Vehicular and Connected Transport, focuses on significantly improving the safety of connected mobility. As shown in Fig. 3, connected mobility is a rapidly evolving field, with autonomous cars being developed and tested through numerous field trials around the world. This pillar aims to ensure that connected mobility systems are not only efficient and convenient but also safe and reliable. A key challenge is ensuring reliable vehicle-to-everything (V2X) connectivity while driving, and maintaining accurate

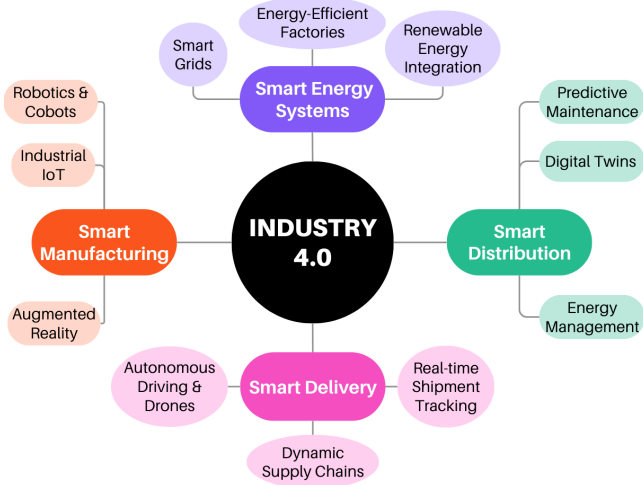


FIGURE 2. Examples of Industry 4.0 Applications

localization even in the face of potential resource shortages such as limited network bandwidth.

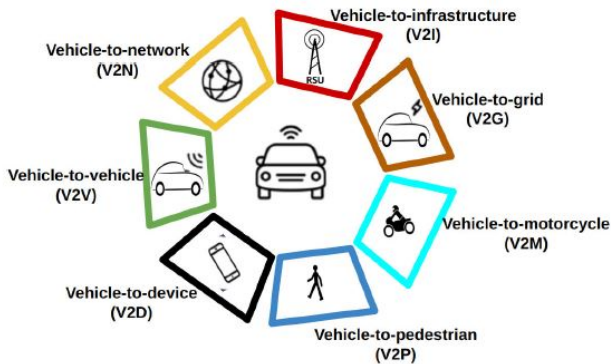


FIGURE 3. V2X communication modes

In this document, we delve into the core challenges tackled by the FITNESS project and present our vision and initial findings in addressing key areas that cut across the three above-mentioned pillars. The structure of the paper is illustrated in Fig. 4. We first explore the intricacies of designing efficient and interoperable IoT architectures (section II). We then investigate the role of Artificial Intelligence (AI) and Machine Learning (ML) in IoT (section III). In section IV, we examine the energy consumption patterns of IoT devices and networks, developing strategies to optimize power usage and promote sustainable IoT deployments. In section V, we provide a consolidated synthesis table that summarizes all technical contributions of the FITNESS project, highlighting their novelty and current maturity level. Lastly, we present in section VI several IoT use cases that demonstrate the practical applications of our research in the three pillars of the project, with a focus on a heterogeneous smart factory use case within the Industry 4.0 domain.

This paper positions itself as an academic white paper, designed to present the strategic vision and multidisciplinary advances of the FITNESS project. By highlighting major technical challenges in the IoT domain our objective is to showcase the research directions pursued and the solutions currently under development, while encouraging dialogue with both academic and industrial communities. In this context, the document covers a broad set of technological building blocks explored within the project. It is important to emphasize that not all studies presented are at the same level of maturity: some have already led to advanced implementations or simulations, while others are still in the exploratory phase. This diversity reflects the collaborative research dynamic at the heart of FITNESS, aimed at addressing cross-cutting and systemic challenges. The level of maturity of each study is indicated in Fig. 4 by a color code.

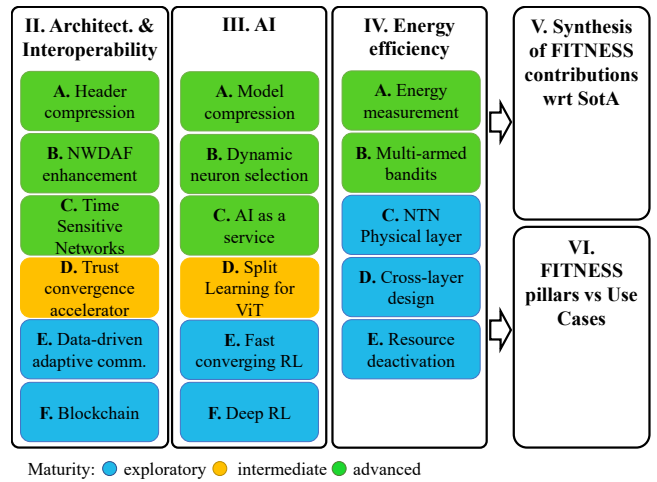


FIGURE 4. Structure of the paper and maturity of the studies

II. ARCHITECTURE & INTEROPERABILITY

This chapter outlines the comprehensive vision of the FITNESS project for advancing architecture and interoperability in IoT ecosystems, supported by key research initiatives that collectively aim to create a seamless, efficient, and secure IoT environment. Through our work on header compression, enhanced network analytics, time-sensitive networking, adaptive communication protocols, trust mechanisms, and blockchain-based solutions, we aim to establish a unified framework that ensures interoperability across diverse devices and networks while maintaining the highest standards of performance and security. This integrated approach reflects our commitment to building an IoT ecosystem that is not only highly functional but also resilient against emerging threats.

A. Header compression for Interoperable, Efficient and Secure IoT

Worldwide development and deployment of IoT is a long process, which includes both clean-slate approaches and evo-

lutions of multiple legacy systems, especially related to industrial and critical infrastructures. In certain situations, the requirements are so strict that the only way to move forward seems to be sacrificing interoperability, efficiency, or security to reach a particular objective. The main example for this is the approach taken by Low-Power Wide-Area Network (LPWAN) networks, such as LoRa Wide Area Network (LoRaWAN) or Sigfox. Their foundational differences, such as being standalone platforms that are not interoperable with IP, made them difficult to integrate with existing IoT/Information Technology/Operational Technology. systems. However, a major innovation has enabled the use of interoperable IoT stacks on these technologies—the Static Context Header Compression (Static Context Header Compression (SCHC)).

SCHC is an international standard developed by IETF [7], which enables the use of LPWAN — compatible with both 5G Standalone or Non-Standalone architectures — for the operation of historical protocols, which are found to be deployed in hundreds of millions of critical infrastructure devices, such as Smart Electricity, Water, and Gas meters — DLMS/COSEM/IEC 62056 (see IEC 62056-8-12). SCHC operates in a unique manner, which makes it uniquely positioned as a universal optimizer for IoT traffic — any pattern or regularly formatted traffic can be compressed to the absolute minimal useful information, a notion closely related to information entropy. The principle of operation is simple — the IoT device and the core network share a common context — a dictionary — that stores all stable information. The protocol SCHC removes that information and sends over the air only bits that carry useful information. In this regard, SCHC enables the most energy efficient operations of IoT devices, but also reduces the transmission latency for Ultra Reliable Low Latency Communications (URLLC) [8] communications. For example, SCHC is considered for inclusion for the future ambient IoT devices currently being discussed at the 3GPP and Wi-Fi Alliance.

The FITNESS project focuses on the fine integration of SCHC in the 5G data plane, introducing the necessary signaling elements to enable devices to natively use SCHC compression within the network. The architecture of the integration solution is explained in [9] and illustrated in Fig. 5. A new SCHC User Plane Function (UPF), named S-UPF, is introduced. It handles the compression and decompression processes while maintaining full IP compatibility between the device and the application server.

B. Enhancement of NWDAF

Native integration of AI is expected to revolutionize 5G network operations, optimization and management beyond what we know today (e.g. real-time, zero-touch, intend-based control and optimization). The success receipt might lie in a tight integration between Open-Radio Access Network (O-RAN) RAN Intelligent Controller (RIC) (notably *dApps*) and 3GPP NetWork Data Analytics Application Function (NWDAF). At first view, both might have competitive objectives with vendor specific solutions and network domain silos. Located

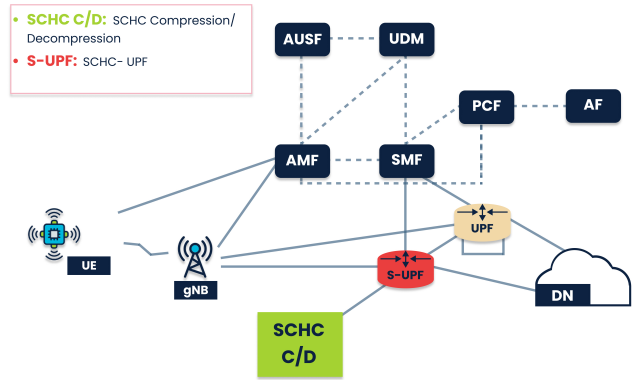


FIGURE 5. Integrating Static Context Header Compression (SCHC) into 5G Networks [9]

in the 5G Core Network System, the 3GPP NWDAF benefits from native quasi-real-time analytics. Yet, O-RAN RICs has Application Programming Interfaces (APIs) available for non-3GPP AI/ML usages. Accordingly 3GPP in recent releases is setting course for NWDAF not only to use AI for data analytics but to be the cogwheel of AI operations for O-RAN compliant network optimizations.

The FITNESS project focuses on extending the NWDAF with AI-as-a-Service (AIaaS) functionalities, introducing the required APIs for the NWDAF to identify, locate and retrieve the necessary AI/ML model for a specific network optimization. The architecture of the extended NWDAF is described in [10] and illustrated in Fig. 6, where the three main services provided by 3GPP for network data analytics are depicted. While [10] focused on AI/ML model provision services for AI-powered analytics required by other Network Functions, future work will extend it with open APIs to connect to O-RAN RICs and other Multi-access Edge Computing (MEC) functions for closed-loop network automation.

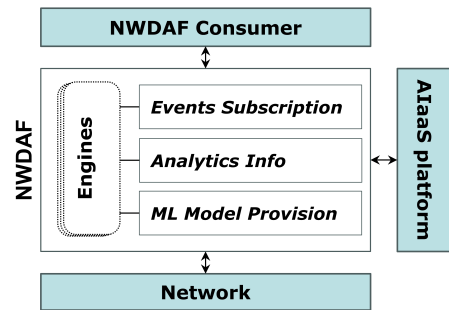


FIGURE 6. AIaaS-NWDAF architecture overview [10]

C. Time-sensitive Networking

A critical challenge arises from the increasing heterogeneity of industrial networks, encompassing legacy systems with varying communication protocols and modern wireless technologies like 5G, which presents significant integration challenges. These systems must now seamlessly integrate diverse

communication technologies, such as time-slotted Wireless Personal Area Networks (WPANs), Time-Sensitive Networking (TSN) Ethernet, and 5G cellular networks. Ensuring end-to-end latency management across these heterogeneous network segments is essential, particularly for mission-critical and time-sensitive industrial applications that require deterministic data flows. In fact, the increasing reliance on robotics for critical tasks in industrial settings, such as remote operations and real-time control, demands communication networks that can deliver high reliability and ultra-low latency. TSN, a set of standards designed to enhance real-time communication capabilities through time synchronization, traffic scheduling, and resource reservation, is essential for these applications.

The integration of TSN and 5G offers the potential to extend the benefits of TSN (such as its ability to achieve deterministic communication) over wireless links, enabling greater flexibility and mobility in industrial setting. This is a promising research direction, as highlighted by several standardization bodies such as the 3GPP [11] and the 5G Alliance for Connected Industries and Automation [12]. This integration addresses the need for low-latency and deterministic communication for wireless cellular networks, serving applications such as smart factories and autonomous vehicles. One of the main challenges remains ensuring that the deterministic communication of TSN is not degraded when TSN traffic traverses 5G wireless links.

The FITNESS project focuses on developing a Software Defined Network (SDN)-based reconfiguration tool to facilitate the configuration and management of end-to-end TSN mechanisms across the heterogeneous network. In particular, it considers the special case of 5G-TSN integration as specified in 3GPP release 17 (see Fig. 7). The project implements interfacing modules (also called TSN translators) between the 5G system and the TSN Ethernet networks, as well as the different APIs that need to be exposed to the SDN reconfiguration tool. These translators — Network-side and Device-side TSN Translators [11], [13], [14] — translate TSN control frames and data packets into the appropriate 5G formats, while preserving timing information and QoS parameters, enabling the entire 5G system (including the 5G modem (User Equipment (UE)), the access network (gNodeB) and the core network (5G control plane and UPF)) to operate as a transparent virtual TSN switch. This transparency ensures that the two TSN Ethernet domains separated by this 5G network are synchronized to the nanosecond and that the Quality of Service (QoS) and constraints of the critical flows coming from a TSN Ethernet domain are well respected.

D. Trust convergence Accelerator

The growing complexity of Industrial IoT (IIoT) systems — characterized by heterogeneous devices, fluctuating network conditions, and resource constraints — introduces significant challenges for achieving secure and interoperable architectures. One of the foundational components in addressing these challenges is trust management, which is based

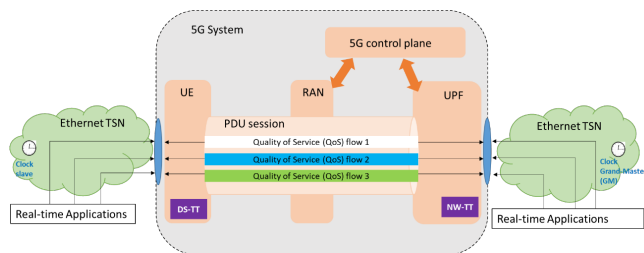


FIGURE 7. Target 5G-TSN integration architecture

on the continuous monitoring of nodes' behaviors and interactions to evaluate their trustworthiness over time. This process ensures seamless collaboration and secure interactions between devices, particularly in dynamic environments where traditional static approaches often fail [15]. A key issue in trust management is trust convergence, which refers to the time required for the system to accurately evaluate and stabilize the trust levels of network nodes in the presence of dynamic conditions. In IIoT environments, factors such as varying signal quality, interference, and latency can delay convergence and compromise the reliability of the system.

To address these challenges, the FITNESS project is developing the Trust Convergence Accelerator (TCA), a ML-based approach designed to predict and accelerate trust convergence under diverse network conditions. The TCA leverages a novel network condition parameter, *netC*, which aggregates real-time metrics such as the Signal to Noise Ratio, Signal to Interference plus Noise Ratio, packet loss, jitter, latency, and throughput. By dynamically adjusting the trust evaluation process, the TCA enhances trust accuracy and accelerates convergence even in challenging conditions. This approach integrates well with advanced wireless technologies such as Wi-Fi 6, which utilizes features such as Orthogonal Frequency Division Multiple Access and Multi-User Multiple Input Multiple Output to optimize performance in dense and heterogeneous networks [16], [17]. Preliminary simulations suggest that the TCA framework offers significant potential to improve trust management in IIoT systems, aligning directly with the FITNESS project's objectives of enhancing security, scalability, and reliability.

Efforts within the FITNESS project extend beyond trust management in IIoT environments. For instance our research on reputation-based trustworthiness degrees [18] highlights the complexities of maintaining trust in interference-variable vehicular networks and underscores the importance of adaptive solutions across diverse IoT scenarios.

E. Data-driven adaptive communication for dense IoT networks

In recent years, the field of IoT communications has focused primarily on optimizing traditional network performance metrics such as throughput, energy consumption, and packet delivery rates. However, the informativeness of the transmitted data, which remains the primary objective in many appli-

cations, has received relatively little attention. The emerging concept of goal-oriented communications aims to address this gap by designing communication protocols that prioritize the informativeness of received data over conventional network metrics [19]. In the context of dense sensor networks, where massive access and adaptive data transmission are critical, existing approaches tend to treat network challenges and data informativeness separately. While network research focuses on improving generic communication protocols, data-driven methodologies often overlook the transmission dynamics, packet losses, etc.

The FITNESS project develops adaptive communication solutions that are explicitly guided by application objectives, with a strong emphasis on maximizing data informativeness while operating under resource constraints and dynamic environmental conditions. This could be particularly relevant for various IoT applications where spatial, temporal, and spatio-temporal correlations may exist, such as mapping physical phenomena [20] and some industrial applications [21]. Our approach focuses on designing novel Medium Access Control (MAC) and routing protocols capable of dynamically adapting to environmental and network fluctuations. By leveraging recent advances in reinforcement learning, we aim to develop decentralized communication strategies that can learn and evolve in real-time, optimizing both network efficiency and data-driven decision-making. Moreover, integrating distributed learning mechanisms across the IoT-edge-cloud continuum is crucial to enhancing network scalability and adaptability.

F. Leveraging blockchain for authentication and audit in IoT architectures

Besides the aforementioned investigations in section II-D to enhance trust in IIoT, there is a need for fast and efficient authentication schemes that can be supported by the large variety of IoT devices. Major trends in the research works focus on introducing light certificate solution which better fits to the constrained capacities of IoT devices [22], on shifting the authentication efforts on the infrastructure side [23] or on combining light certificate and blockchain at the protocol level, in order to build a solution which is less dependent from the infrastructure management [24].

The FITNESS project aims to develop a solution that incorporates the above-mentioned features, with the advantage of operating at all levels — IoT application servers, communication protocols and IoT devices. Indeed, once a blockchain based approach is adopted for authentication, the underlying technology can be used for its other functionalities: (i) immutability, which allows to trace any event, verify every data, and therefore ensure a full auditability of the IoT application, (ii) intrinsic distributed nature of the blockchain, which guarantees both the management and the storage of the events and data soundly among the IoT application servers and the IoT devices.

The proposed approach should address the specific case of data exchanged through vehicle-to-vehicle (V2V) commu-

nications, outside the infrastructure coverage area, and the merging of these local data with the global infrastructure (Fig. 8). Moreover, the cryptographic functionalities offered by the blockchain allow the use of pseudonym-based certificate which only the issuer may provide the real identity of the owner. In this way, it is possible to authorize the anonymous participation of the IoT devices owned by users that value their privacy. In case of infringement, local legal rules should allow recovering the real identity from the certificate issuer. In developing such approaches, The FITNESS project aims to improve trust and favor the participation of more devices in various IoT cooperative applications.

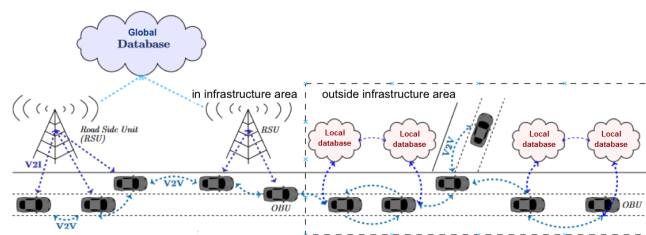


FIGURE 8. Blockchain based approach for authentication and audit in IoT/IoV infrastructure

III. THE PLACE OF AI

In the realm of the IoT, the integration of AI has emerged as a transformative force, unlocking new possibilities for real-time decision-making, predictive analytics, and autonomous systems. Recognizing the immense potential of AI in revolutionizing IoT, the FITNESS project has dedicated significant efforts to exploring the intersection of these two domains. Our vision is to empower IoT devices and networks with intelligent capabilities, enabling them to adapt, learn, and optimize their behavior in real-time. To achieve this, we focus on key research areas that address the unique challenges and constraints of IoT, such as limited computational resources, energy efficiency, and the need for robust and secure AI models. In this section, we present our findings and contributions in the realm of AI for IoT, showcasing the potential of AI as a driving force behind the next generation of intelligent, interconnected, and autonomous systems.

A. Model compression

Recent advances in model compression have demonstrated multiple paths toward efficient Neural Networks (NNs) for IoT deployment. In [25], we investigated whether unstructured pruning (i.e. parameters removal) could effectively reduce network depth (i.e. remove entire layers). Through entropy-guided pruning, this work demonstrated that it's possible to identify and remove entire layers while maintaining model performance. The proposed EGP algorithm showed particular promise on popular architectures like ResNet-18 and Swin-T, offering a new direction for model compression.

In [26], we proposed a novel approach for improving model efficiency by identifying and removing spurious correlations

(known as biases) from NN representations through Voronoi cell analysis. This method detects undesirable feature dependencies automatically, without requiring explicit bias labels, enabling more efficient and robust models. Building upon these insights about feature dependencies and bias, [27] made a significant discovery that goes beyond traditional pruning approaches: not only can we extract efficient subnetworks from pretrained models, but these subnetworks can simultaneously achieve both model compression and bias removal.

While conventional pruning methods focus solely on maintaining task performance, our approach revealed that unbiased subnetworks naturally exist within biased networks, requiring no additional training to extract them. This dual benefit—achieving model sparsification while eliminating unwanted biases—represents a significant advancement for IoT applications. The ability to deploy both smaller and more reliable models without retraining is particularly valuable in IoT contexts, where computational resources for model adaptation are limited and trustworthiness is crucial. Current work is aiming at improving the compression rates by applying similar methods during training to more efficiently guide more efficiently the network towards a sparser architecture while preventing specific information from being used.

B. Dynamic neuron selection

Developing efficient algorithms for resource-constrained systems requires addressing the significant computational and memory costs of training NNs. Two recent works from the FITNESS project have made important contributions in this direction by challenging static approaches to network updates. Both works share a core insight: not all neurons need to be updated at every training step, and the selection of which neurons to update can be dynamically determined during training. This idea manifests in complementary ways in the two approaches. In [28], SCoTTi introduces an adaptive framework that optimizes a threshold parameter to determine which neurons require updates based on their ‘velocity’—a measure of how quickly their output is changing. Meanwhile, [29] applies a similar velocity-based principle specifically under extreme memory constraints, demonstrating that dynamic selection can outperform static approaches even with severe resource limitations. Both works leverage the concept of neuron velocity, though with different objectives: SCoTTi aims to minimize overall computational cost while maintaining performance, while [29] focuses on maximizing performance within a fixed memory budget.

These approaches demonstrate that dynamic neuron selection is a powerful paradigm for efficient training in resource-constrained environments. By moving away from static update strategies and towards adaptive approaches that respond to the network’s learning dynamics, both works achieve significant efficiency gains while maintaining model performance. Their success suggests that dynamic selection strategies may be key to enabling efficient on-device learning for IoT applications, where both computational and memory resources are limited.

C. AI as a service

Whereas AI has been one of the most impacting innovation in the past decade, it has been developed in silos (network domain, operator, stakeholders). A total control of the overall AI development and usage allowed to rapidly propose tailored-designed AI functions, yet at the cost of significant energy consumption, slow model training due to lack of pertinent data, or AI duplications in different silos.

The next decade is expected to focus on AI ubiquity, enabling devices to be independent actors of a global AI ecosystem interconnected as an AI-of-Things (AIoT). A central entity toward this goal is an AIaaS architecture capable of IoT-powered smart agent discovery, on-boarding, orchestration, and model sharing in a fully heterogeneous *communication-sensing-computing* triptych critical to future *Composite AI* systems.

The FITNESS project introduces such AIaaS platform in [30], depicted in Fig. 9. In a nutshell, it consists of an AIaaS server orchestrating AI training and provisioning, as well as multiple AIaaS clients exposing AI capabilities of potential AI actors. The AIaaS platform remains transparent to AI actors through open Representational State Transfer APIs to register, train or use AI developed by other entities.

To validate the effectiveness of the approach, we conducted a real experiment using the CARLA driving simulator, specifically focusing on ML support in an AI-driven junction risk assessment scenario. The platform is provided as open-source, the full code and video for the Infrastructure Assisted Knowledge Management (IAKM) implementation and its integration with CARLA in a concrete junction management scenario is available on EURECOM gitlab.

In the next steps, this architecture will be extended to be decentralized.

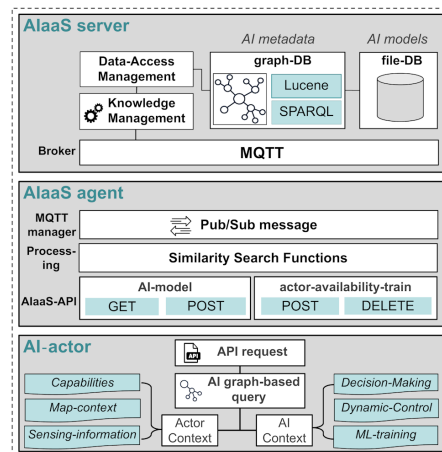


FIGURE 9. AIaaS architecture for future AIoT.

D. Split Computing for Vision Transformers

One standard method for running AI models that exploit data from IoT devices is to use Edge or Cloud Computing. This approach, known as AI edge/cloud offloading, reduces

the computational load on resource-constrained devices by shifting the workload to more powerful servers [31]. However, offloading data to remote servers increases the risks related to privacy and security [32]. A second approach is model compression, which seeks to reduce the complexity and size of learning models while preserving performance as closely as possible to the original model [33]–[35]. A final approach is related to distributed inference and learning. It consists of splitting the model into two distinct parts: a first part (referred to as the head) executed on the end-device and a second part (referred to as the tail) executed on a remote server (Edge or Cloud). This model division can be exploited for training (learning) and inference (computing) tasks. This flexible approach leverages the benefits of split learning for collaborative training and split computing for efficient inference.

Naturally, these approaches have been applied to various model architectures, particularly Convolutional Neural Network (CNN) variants for image and vision tasks. While transformer-based models such as Vision Transformers (ViT) [36] are gaining traction in these domains, most studies on Split Computing still focus on CNNs due to their efficiency in reducing inference delay and bandwidth consumption [37]–[40]. A common strategy in these works is compressing intermediate features before transmission, which effectively minimizes data transfer between the device and server.

Only a few studies in the literature have focused on applying Split Learning to ViT models [41], [42]. These works adopt a strategy where only the embedding layer and the classification layer are placed on the end device, which limits the capabilities of the model splitting. They do not address the full potential of Split Learning, where the key challenge is to find the optimal point that reduces the learning time. Both works are closer to data offloading than true Split Learning.

Research within the FITNESS project focuses on split computing specifically designed for ViTs and the development of adaptive compression methods. Our goal is to reduce inference time, optimize resource usage, and enhance the feasibility of deploying AI models in IoT environments, where bandwidth and computational power are often limited. An initial approach to latent space compression and split point selection has been proposed.

E. Fast converging reinforcement learning for latency-critical IoT

While a previous section explored efficient training of NNs on the resource constrained IoT devices, this section explores how Reinforcement Learning (RL) algorithms can be designed for quickly converging to optimal solutions for latency critical IoT services. The radio resource allocation problem for latency critical services has been addressed in the 5G literature from the lens of URLLC services. [43] proposed a queuing model that computes the delay outage probability for URLLC packets and determined the amount of resources that would be allocated for the system for reaching the reliability

target. In a more dynamic setting where resource allocation is updated on the fly, [44] proposed a heuristic that selects a resource allocation policy with low energy consumption that reaches the reliability target. However, there is a lack for a provably optimal solution with a low regret.

The FITNESS project developed on a generic framework for optimizing the service rate adaptation policy. We exploit the structure of the problem for restricting the search space of policies to a limited, threshold-based subset that includes the optimal policy, even when the distribution of traffic arrivals is unknown. The focus of the project is to adapt this generic framework to different IoT use cases, including delay-constrained and energy-constrained scenarios.

F. Deep RL in 5G NOMA-MEC-NS for IIoT

Future Generation Wireless Networks enable unprecedented opportunities for applications like predictive maintenance, real-time asset tracking, smart energy management, and industrial automation in IIoT as shown in Fig. 2. These advancements raise the need for diverse QoS [45] requirements. 5G networks leverage advanced technologies like Network Slicing (NS) [46], MEC [47], and dynamic resource allocation to ensure efficient and tailored service delivery for various use cases. The integration of MEC with NS is especially critical in IIoT, where heterogeneous tasks require highly efficient and flexible resource management.

As it is illustrated in Fig. 10 NS addresses this by creating multiple logical networks on a shared physical infrastructure, each tailored to specific QoS demands. MEC complements this by bringing computation closer to users, minimizing latency for delay-sensitive applications and reducing energy consumption through task offloading. Additionally, in the critical context of IIoT, efficient resource utilization is of paramount importance. This can be achieved by enabling multiple users to share the same resources (e.g. frequency and time). Non Orthogonal Multiple Access (NOMA) [48] plays a key role in enhancing spectral efficiency and optimizing resource allocation, making it an essential technology for addressing the high connectivity demands of IIoT applications. However, optimizing resource allocation in this MEC-NOMA-NS framework presents significant challenges, particularly in IIoT applications, where diverse tasks impose non-linear, heterogeneous constraints, resulting in complex, non-convex optimization problems. This necessitates the development of novel approaches to manage and optimize resource allocation effectively, ensuring heterogeneous QoS requirements are maintained while addressing the intricacies of this dynamic and complex environment.

The FITNESS project proposes a novel deep learning approach based on a new Deep RL (DRL) architecture that ensures low complexity and high reliability. This approach will be combined with an appropriate system model to address resource allocation optimization in 5G NOMA-MEC-NS, considering QoS heterogeneity, user mobility and the challenges of a complex, dynamic and realistic environment in the context of IIoT.

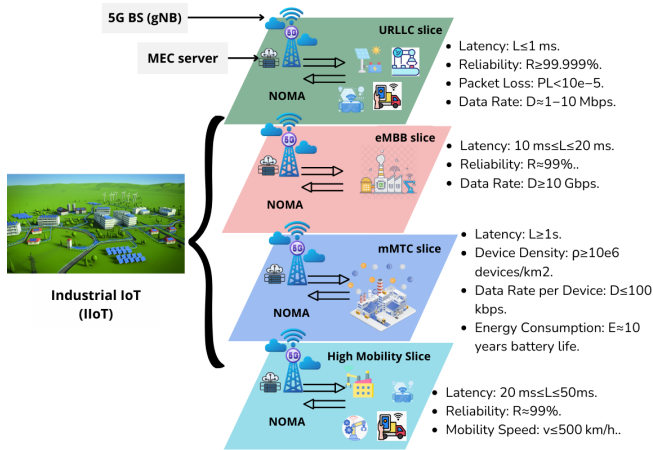


FIGURE 10. Enabling IIoT with NOMA-Enhanced MEC and Network Slicing

IV. ENERGY EFFICIENCY

As the IoT continues to grow in scale and complexity, ensuring the energy efficiency of IoT devices and networks has become a critical challenge. The FITNESS project aims at enabling IoT devices and networks to operate with minimal energy consumption, extending battery life, reducing environmental impact, and lowering operational costs. In this section, we present our findings and contributions, showcasing innovative approaches to optimize power usage, enhance resource allocation, and design low-power IoT systems. By focusing on these key research areas, we strive to pave the way for a more sustainable and eco-friendly IoT future.

A. Evaluation and Analysis of Energy Consumption

The deployment of IoT network implies numerous disseminated nodes for which energy supply and autonomy must be questioned. IoT objects, are often powered by limited and/or intermittent energy sources. To correctly estimate and optimize the lifetime of a sensor node, accurate energy consumption models derived from measurements must be established for various wireless transmission technologies [49], [50]. These models must take into account the circuit energy consumption but also propagation channels and network aspects. Refined energy consumption models, taking into account the environment of the sensor nodes through the network density and the geographical distribution of the nodes, have been proposed in the literature, particularly for LoRaWAN [50] and — in the context of the FITNESS project — Wi-Fi HaLow [51] technologies. By considering the error and collision probabilities and thus the number of retransmissions, these models allow us to estimate the lifetime of the nodes in realistic environments and applications.

The maturity of energy harvesting technologies and low-power microcontrollers opens the prospect of developing batteryless computing for IoT networks and applications. One of the critical challenge in IoT deployment is ensuring the ability to collect and transmit data over the Internet at low energy cost and using sustainable solutions. We thus expect

the advent of intermittently-powered, batteryless devices that operate entirely using energy extracted from their environment. Wireless Power Transmission is a promising solution for some applications. Its efficiency has been evaluated in realistic indoor environment in [52]. Intermittently operating devices present numerous technological challenges in various domains (electronics, Information Technology, etc.).

As part of the FITNESS project, we address these challenges through a multi-pronged approach that includes: predictive modeling of harvested energy, fine-grained estimation of consumption across all components of the IoT stack (sensor, microcontroller, radio), and protocol optimization tailored to energy intermittency. By combining these elements, FITNESS aims to enable energy-aware design and adaptive operation of IoT devices, particularly in scenarios where energy availability is scarce, variable, or unpredictable. This work contributes to the long-term goal of achieving self-sustaining, maintenance-free IoT deployments capable of making intelligent trade-offs between sensing fidelity, data freshness, and longevity.

B. Low power Multi-Armed Bandits

IoT has revolutionized modern industries by interconnecting devices that can sense, communicate, and process data to perform specific tasks autonomously or cooperatively. Achieving this requires a seamless integration of automatic control systems and communication technologies to support various application areas, such as intelligent traffic control and automatic warehouse management systems [53]. A key challenge in such systems is to efficiently control the remote devices in order to achieve desired objectives in dynamic and uncertain environments. This necessitates real-time decisions-making based on limited information (generated by the device itself or from the surrounding environment), while also considering the trade-offs between exploration and exploitation of different control strategies. Multi-Armed Bandit (MAB) algorithms offer a powerful framework for addressing control problems in such settings [54]. However, MAB algorithms are usually employed in cases in which the controller and the actuator are placed in the same entity, and not connected via wireless links.

In [55] the FITNESS project explores the application of MAB algorithms to control remote devices, which faces considerable challenges primarily represented by latency and reliability. Specifically, we analyze the performance of MABs operating in environments where the action feedback from controlled devices is transmitted over an unreliable communication channel and stored in a Geo/Geo/1 queue. We investigate the impact of different queue sampling strategies on MAB performance, showing how queueing delay can strongly affect the performance of MAB algorithms such as Upper Confidence Bound or Thompson Sampling. Motivated by this fact, we propose a novel stochastic approach. Its performance in terms of regret is evaluated against established algorithms in the literature. Furthermore, as the energy consumption naturally demands high attention in any sustainable

development effort, especially in the presence of resource poor devices [56], we study in [55] the trade-off between maximizing rewards and minimizing energy consumption.

The FITNESS project bridges the gap between decision-making algorithms, unreliable communication environments, and energy consumption, providing key contributions to the design of robust and energy-efficient control strategies. These findings can enhance the reliability and performance in IoT-based systems in diverse domains such as industrial automation, smart cities, and beyond.

C. NTN physical Layer

The potential of Low Earth Orbit (LEO) satellite constellations to extend the reach of IoT networks has generated significant attention, with Long Range (LoRa) and Narrowband-IoT (NB-IoT) emerging as the most widely studied candidates for such deployments. Existing works have demonstrated their feasibility under realistic Doppler and link budget conditions, making them strong contenders for early satellite-based IoT services.

However, these technologies exhibit inherent limitations when viewed through the lens of scalability, energy efficiency, and Physical Layer (PHY) interoperability. LoRa, while energy-efficient, suffers from low spectral efficiency and limited adaptability. NB-IoT offers better throughput but imposes higher energy and hardware complexity. Both rely on protocol and waveform designs originally optimized for terrestrial use, which may prove sub-optimal under the stringent constraints of satellite backhauls involving high round-trip times and massive device densities.

Rather than reiterating existing performance analyses, FITNESS aims to explore an alternative PHY-layer design tailored to future IoT scenarios in space. The project investigates a flexible, low-complexity waveform architecture based on orthogonal modulation schemes using Hadamard codes, combined with low-Peak to Average Power Ratio (PAPR) Frequency Shift Keying (FSK) variants and convolutional coding. This approach seeks to combine the best of two worlds: the resilience and simplicity of spread-spectrum techniques, and the higher spectral efficiency of structured orthogonal codes.

A key innovation lies in the design of a digital receiver with turbo-processing capabilities, intended to approach near-Shannon performance in highly constrained IoT settings. The envisioned architecture targets not only satellite uplinks, but also aims to provide a PHY unification layer that can bridge disparate terrestrial and non-terrestrial access schemes, including LoRa, Orthogonal Chirp Division Multiplexing, and custom spread-spectrum protocols.

These developments are currently in the conceptual and simulation design phase. Future work will focus on evaluating these waveform candidates in realistic LEO channel models and assessing their performance in terms of bit error rate, energy per bit, synchronization robustness, and receiver complexity.

D. Energy-Efficient Cross-Layer Design for LoRaWAN

LoRaWAN is a flagship technology in the LPWAN landscape, widely adopted for its low energy consumption and extended communication range. However, most current optimizations follow a layer-by-layer approach based on the traditional OSI model [57]. This compartmentalization limits overall efficiency, particularly in long-term deployments where nodes are difficult to access.

FITNESS explores an integrated approach that combines cross-layer design, [58], dynamic slicing, and intelligent local scheduling to optimize resource usage on IoT nodes. Dawaliby et al. [59] conducted a pioneering study on adaptive dynamic network slicing in LoRa networks, proposing a dynamic inter-slicing algorithm based on Maximum Likelihood Estimation and an intra-slicing strategy to optimize resource allocation. Their research demonstrated the effectiveness of network slicing in improving QoS and isolation between slices in LoRa networks. However, energy efficiency trade-offs and lack of real-world validation remain open challenges for practical deployment.

To achieve coordination of decision-making across the physical, MAC, and application layers, taking into account both traffic priorities and energy constraints, the FITNESS project builds upon RIOT Operating System (OS), an open-source, real-time OS that is lightweight and modular—ideal for constrained devices. RIOT already supports fine-grained scheduling, energy management, and integrated network protocols. FITNESS aims to extend it with an adaptive slicing layer that can isolate different traffic types (critical, periodic, best-effort) and dynamically schedule the radio module's activity and sleep periods.

Ultimately, this architecture will be tested in representative deployments such as smart agriculture or environmental monitoring. The objective is to maximize node longevity while ensuring stable and differentiated network performance according to application requirements.

E. Resource deactivation policy for energy efficiency

While the energy consumption of resource-constrained IoT devices is essential, as explained above, reducing the energy consumption on the network side is, on the other hand, also of high importance. The intermittent nature of IoT traffic which may also be latency-critical, puts a high pressure on the network for ensuring a high availability. This results in a high energy cost, as the network resources have to remain active to serve incoming traffic. On the flow level, when sleep mode is implemented on the scale of seconds or minutes, [60] considers activating/deactivating non-overlapping femtocells within a macro base station coverage, using complete, partial, or delayed information about user localization and traffic load. [61] investigates sleep mode levels with different power values and transition times. For sleep mode operating at smaller time scales (e.g. packet level), [62] proposed a resource activation/deactivation scheme in a virtualized 5G network setting. Here, the policy is optimized at a small tile scale to enable advanced sleep mode while taking into

account activation/deactivation delays of resources. However, these algorithms typically assume prior knowledge of the incoming traffic distribution to derive the optimal policy.

As part of the FITNESS project, we are designing a novel learning-based framework that addresses this challenge by enabling real-time, distributed control of energy-hungry infrastructure elements based on minimal observations and without requiring explicit knowledge of traffic dynamics. Our approach leverages a low-regret DRL strategy capable of autonomously identifying energy-saving opportunities while maintaining service quality. This work lays the foundation for a new class of intelligent, self-adaptive IoT infrastructures, where energy efficiency is not statically configured, but dynamically learned and enforced at runtime across heterogeneous network segments. Initial simulations are ongoing, with deployment in emulated edge environments planned in the next phase of the project.

V. SYNTHESIS

The FITNESS project addresses a wide range of research challenges related to the deployment of scalable, secure, and energy-efficient IoT systems. These challenges span multiple domains — from protocol design and AI for constrained devices to cross-layer architectures and energy-aware communications. To provide a consolidated view of the work conducted within the project, Table 1 summarizes the main contributions presented in this document.

Each row corresponds to a technical study or design effort described in the paper. For each, we highlight the addressed limitations in the state of the art, the specific innovation proposed within FITNESS and the current level of maturity (with the same color code than in Fig. 4). This table aims to offer a high-level perspective on how these efforts align with FITNESS’s overarching vision and where they currently stand in terms of development and validation.

VI. USE CASES

Defining IoT use cases is a critical step in the development and deployment of IoT systems, as it enables stakeholders to understand the specific requirements, constraints, and expected outcomes of IoT applications. By identifying and analyzing these use cases, we can ensure that IoT technologies developed within the FITNESS project are tailored to meet the unique needs of different industries, applications, and environments.

A. FITNESS, a large scope of addressed challenges

The FITNESS project addresses a wide range of challenges arising from real-world IoT deployments across multiple domains, including Industry 4.0, massive IoT and Vehicular IoT. Each use case highlights specific requirements in terms of network performance, energy efficiency, security, and system adaptability. Tables 2 to 4 summarize the key requirements identified for each use case, the FITNESS contributions that are designed to address them, and the expected impacts. While quantitative evaluation is still ongoing, the table out-

lines the technological directions and improvements that FITNESS aims to deliver, supporting more scalable, efficient, and trustworthy IoT infrastructures across diverse application scenarios.

B. Mapping Application Needs to IoT Solutions: An Industry 4.0 Focus

The use case “Upgrading an existing production system” has been selected within the “Industry 4.0” domain for its alignment with the FITNESS project’s objectives. It illustrates the complexity of integrating diverse technologies, systems, and protocols in heterogeneous industrial environments combining legacy machinery and modern IoT devices.

In this case, a heavy materials manufacturer faces several challenges. Its Ethernet-based infrastructure limits flexibility and scalability. The manual handling of heavier goods has become impractical as demand increases, while maintaining production speed now requires more operators for repetitive precision tasks. In parallel, training the workforce to adapt to new technologies has emerged as a significant obstacle. To address these issues, potential solutions include the introduction of Automated Guided Vehicles (AGVs) to streamline material transport, Collaborative Robots (Cobots) to assist in precision tasks and reduce physical strain, and Augmented Reality (AR) systems to accelerate operator training and minimize errors. These technologies, however, bring additional demands on the communication infrastructure.

The FITNESS project proposes a decision-support methodology, helping industrial stakeholders map application needs to technological options, and make sustainable, informed choices for their Industry 4.0 transformations: Table 5 summarizes the throughput and latency requirements associated with their deployment, underlining the critical role of robust and responsive networks for ensuring monitoring, predictive maintenance, and remote operation.

While existing technologies such as 5G, 4G, and Wi-Fi, can technically support these needs, FITNESS recognizes that network selection should not rely solely on performance metrics. Economic, social, and environmental factors must also be taken into account; our research continues in this direction.

VII. CONCLUSION AND NEXT STEPS

In this paper, we have explored the transformative potential of integrating the advanced technologies explored in the FITNESS project into IoT ecosystems. Our analysis demonstrates how these solutions can effectively map to diverse IoT use cases, addressing the multifaceted challenges inherent in modern IoT deployments.

By examining architectural innovations, the integration of AI, and strategies for energy efficiency, the FITNESS project has delivered a set of promising solutions — some already implemented, others currently under development — to address key constraints in IoT systems. This work enhances the scalability, sustainability, and adaptability of future IoT deployments in an increasingly dynamic technological land-

TABLE 1. Synthesis of FITNESS contributions, their novelty, and maturity

Section	State of the Art	FITNESS contribution	Maturity
II.A Header Compression for Interoperable, Efficient and Secure IoT	SCHC used in LPWAN; not integrated in cellular cores	Embedding SCHC in 5G UPF for URLLC traffic with minimal overhead	Architecture validated
II.B NWDAF Enhancement through AIaaS	NWDAF offers basic analytics; lacks integration with AI services	AIaaS provisioning model integrated with NWDAF for smart analytics	Architecture validated
II.C Time-Sensitive Networking and 5G Integration	No end-to-end TSN mechanisms across the heterogeneous 5G network	SDN-based orchestration + DS-TT/NW-TT translators across domains	Modular components prototyped
II.D Trust Convergence Accelerator	Static convergence; lacks responsiveness to network dynamics	ML-based “netC” indicator for fast trust adjustment in wireless links	Preliminary simulations
II.E Data-Driven Adaptive Communication	Static protocol selection; little integration of data semantics	Maximizing data informativeness under resource constraints and dynamic environmental conditions, relying on RL	Initial framework
II.F Leveraging Blockchain for Authentication and Audit	Need for fast and efficient authentication schemes that can be supported by the large variety of IoT devices	Blockchain for authentication, management, tracing and storage of events and data	Initial framework
III.A Model Compression for Edge AI	Pruning & quantization widely used; bias-aware pruning less explored	Dual-purpose pruning that compresses and removes representational bias	Research result
III.B Dynamic neuron selection	Static neuron updates; not adaptive	Neuron velocity-based update strategies (SCoTTi) for efficient learning	Published research
III.C AI as a Service for Edge IoT	Edge-cloud AI orchestration fragmented; lacks portability	IoT-powered smart agent discovery, onboarding, orchestration, and model sharing	Real experiment
III.D Split Learning for ViT	Split learning used mostly for CNNs; few ViT studies	Partitioning & compressing ViT for constrained IoT inference	Proof-of-concept
III.E Fast-Converging Reinforcement Learning for IoT	Convergence often slow; poor real-time behavior	DRL with fast regret bounds + reduced action spaces for IoT (delay and energy constrained scenarios)	Initial framework
III.F DRL in 5G NOMA-MEC for IIoT	Complex, non-convex resource allocation optimization problems	DRL for joint resource, user & QoS orchestration with MEC/NOMA	Initial framework
IV.A Evaluation and Analysis of Energy Consumption	Models often limited to PHY layer or protocol-level	Cross-layer consumption modeling + harvesting prediction	Measurement-based
IV.B Low-Power Multi-Armed Bandits	Bandits used in scheduling; rarely combined with energy models	MAB adapted for low-power devices + contextual inputs	Published research
IV.C Physical Layer Explorations for Satellite IoT	LoRa/NB-IoT studied in LEO; modulation innovation lacking	Hadamard/FSK waveform + turbo decoding in LEO context	Early modeling
IV.D Energy-Efficient Cross-Layer Design for LoRaWAN	OSI model dominates; few real-time cross-layer schedulers	Joint MAC/PHY/app coordination + slicing in RIOT OS	Under development
IV.E Resource Deactivation Policy for Energy Efficiency	Sleep control static or heuristic; no learning	DRL strategy for autonomous node deactivation decisions	Initial framework

TABLE 2. Selection of Industry 4.0 use cases and FITNESS studied solutions

Use Case	Key requirement	FITNESS contribution	Expected impact
Upgrading an existing production system	Selecting the appropriate network technologies	Decision-support grid based on application constraints*	Support informed, multi-criteria selection of network technologies for optimized Industry 4.0 deployments
Remote control of devices over wireless channels	Reliable and energy-efficient remote control over constrained wireless networks	Multi-Armed Bandits; Time-sensitive networking	Improved factory efficiency by reduced delays, minimized downtime and enabled seamless coordination between devices, leading to faster production and lower operational costs
Heterogeneous devices management	Maintaining secure and trustworthy communications across diverse devices and changing network conditions	Trust convergence accelerator	
AI-based managing system for factory devices	Reliable communication, fast response times, efficient resource management, ability to adapt to changes in device needs and movements	Novel Deep Reinforcement Learning approach	

*Details in section VI-B

TABLE 3. Selection of Massive IoT use cases and FITNESS studied solutions

Use Case	Key requirement	FITNESS contribution	Expected impact
Environment monitoring, smart agriculture	Constrained battery power, hard-to-access environments	Crosslayer design (including slicing) + RIOT OS-based edge devices	Reduced operational costs, faster data processing for real-time decision-making, and enhanced reliability in monitoring systems, which result in more sustainable and cost-effective agricultural practices
	Energy efficiency, latency	Integration of SCHC in the 5G data plane	
	Informativeness of transmitted data	Data-driven adaptive communication protocols	
Non-Terrestrial applications	Low device energy consumption, high Doppler resilience	New Physical Layer, advanced access mechanisms	More stable and reliable connections in areas with weak or no traditional network coverage
Smart city	Low network energy consumption	RL schemes that converge rapidly to the optimal sleep mode policy	More sustainable, eco-friendly urban environment with improved city services

TABLE 4. Selection of Vehicular IoT use cases and FITNESS studied solutions

Use Case	Key requirement	FITNESS contribution	Expected impact
Dynamic and Mobile IoT for Connected Vehicles	Autonomous mapping of communication capacity	Autonomous mobile robotics and SLAM [†] approach.	Seamless connectivity, better route optimization, and enhanced traffic management
	Deployment of IoT considering mobility and dynamic topologies	Modeling IoT networks as dynamic graphs for optimized decision-making	
	Low-latency reactions to traffic conditions	Fast-converging RL algorithms for quick adaptation	
Securing V2X Communications	Authentication and trust establishment both in and out of infrastructure coverage	Blockchain-based modeling of V2X communications with non-repudiable transaction management	Enhanced autonomous driving, reduced accidents, and increased public trust in connected transportation systems
	Safe and efficient navigation through complex intersections	AIaaS assisting automated driving for real-time decision-making	

[†]Simultaneous Localization And Mapping

scape. Our contributions also highlight the essential role of interdisciplinary collaboration in tackling these complex challenges.

Looking ahead, the FITNESS project will continue research and development in these areas to fully realize the potential of IoT. Future work focus on refining these technologies, exploring new applications, and addressing challenges such as security, hardware simplification, privacy, and interoperability.

By addressing key challenges and demonstrating practical applications, this work not only contributes to the academic discourse but also provides actionable insights for industry practitioners.

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TABLE 5. Example of FITNESS decision grid for the Industry 4.0

		Network requirement			Recommended Technologies for the Pack (AGV+Cobot+AR)	
		Exchanged data	Data rate	E2E latency		
Industry 4.0 technologies	AGV	Uplink	Location data	≤ 10 Mb/s	≤ 200 ms	5G Network Technology Enables mobility (for AGVs) Data rates: 1-10 Gbps Suitable latency: <1 ms High connection capacity 4G Network Technology Enables Mobility Data rates: 300-600 Mbps Suitable Latency: 20-50 ms Reliable connection Wi-Fi Enables Mobility Data rates: 11 Mbps-10 Gbps Latency :7-25ms Frequencies exposure (certain norms)
			Operational status	≤ 100 kb/s	≤ 1s	
		Downlink	Load, motor temperature and energy consumption	< 10 Mb/s	≤ seconds	
			Video stream	≤ 100 Mb/s	<500 ms	
	Cobot	Uplink	Navigation instructions	≤ 10 Mb/s	≤ seconds	
			Software reconfigurations/updates	≤ 100 Mb/s	Non-critical, high tolerance	
		Downlink	Joints location and speed	< 10 Mb/s	≤ 100 ms	
			Operational status	≤ 100 kb/s	≤ 1s	
	AR	Uplink	Load and Force data on end-effector	< 10 Mb/s	≤ 100 ms	
			Motor temperature, Energy consumption	< 10 Mb/s	≤ seconds	
		Downlink	Motion and security instructions	< 10 Mb/s	≤ 50ms	
			Software reconfigurations/updates	≤ 100 Mb/s	Non-critical, high tolerance	
AR	Uplink	User Position and Orientation	≤ 100 kb/s	< 20 ms		
		Operational status	≤ 100 kb/s	≤ 1 s		
	Downlink	Environmental Image flow	< 250 Mb/s	<150 ms		
		Image flow (Immersion)	< 250 Mb/s	<150 ms		
AR	Downlink	Software reconfigurations/updates	≤ 100 Mb/s	Non-critical, high tolerance		

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