

Received 2 November 2023, accepted 26 November 2023, date of publication 30 November 2023,
date of current version 5 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3338180

RESEARCH ARTICLE

Exploiting Multihoming Capabilities in 5G-Enabled IoT Nodes

RAFAEL FAYOS-JORDAN¹, SANTIAGO FELICI-CASTELL², JAUME SEGURA-GARCIA²,
JOSE M. ALCARAZ-CALERO¹, (Senior Member, IEEE), AND ANTONIO CERVELLO-DUATO³

¹School of Computing, Engineering and Physical Sciences, University of the West of Scotland, Paisley, PA1 2BE Scotland, U.K.

²Department of Computer Science, Escola Tècnica Superior d'Enginyeria, Universitat de València, Burjassot, 46100 Valencia, Spain

³Department of Electronic Engineering, Escola Tècnica Superior d'Enginyeria, Universitat de València, Burjassot, 46100 Valencia, Spain

Corresponding authors: Santiago Felici-Castell (santiago.felici@uv.es) and Jaume Segura-Garcia (jaume.segura@uv.es)

This work was supported in part by the MCIN/AEI/10.13039/501100011033 under Grant PID2021-126823OB-I00, in part by the European Regional Development Fund (ERDF)—A Way of Making Europe funded by MCIN/AEI/10.13039/501100011033 and the European Union NextGenerationEU/Plan de Recuperación, Transformación y Resiliencia (PRTR) under Grant TED2021-131040B-C33, in part by the European Commission Horizon 2020 5G-PPP Program “6G BRAINS: Bringing Reinforcement learning Into Radio Light Network for Massive Connections” under Grant H2020-ICT-2020-2/101017226, in part by the Horizon Europe “INCODE: Programming Platform for Intelligent Collaborative Deployments Over Heterogeneous Edge-Internet of Things (IoT) Environments” under Grant HORIZON-CL4-2022-DATA-01-03/101093069. Also, to the Generalitat Valenciana with grant references CIAICO/2022/179 and CIAEST/2022/64, as well as the Research Vice-rectorship of Universitat de València for funding the grant with reference UV-INV-EPDI-2647726 for a research stay and the Spanish Ministry of Education in the call for Senior Professors and Researchers to stay in foreign centers for the grant PRX22/00503.

ABSTRACT 5G communications allow the integration of different wireless technologies to exploit the added value of multihoming scenarios. Furthermore, in connection with the Internet of Things (IoT), multihomed nodes are very interesting, since it allows one to address new challenges and adapt the usage of communication technologies to new requirements imposed by the location of each deployment, the available energy resources on each node, and the IoT application itself. There are available commercial wireless nodes that embed and handle multiple interfaces. Terms such as seamless and transparent communications as well as technology integration fit well within the 5G standards. However, in practice, these wireless nodes are basically relayed in one of these wireless technologies when connected, and in the case of using other interfaces, their usage is not coordinated. In this context, we propose and implement a novel and efficient heterogeneous interface selection algorithm for multihoming and integrative communications using commercial products by performing local decisions on a per-packet basis, analysing different issues and approaches from a practical point of view, both hardware and software. We compare our proposal with other alternatives, highlighting the opportunities by exploiting these multihoming features in 5G-enabled IoT nodes.

INDEX TERMS 5G, heterogeneous networks, Internet of Things, multihoming, seamless/transparent communications.

I. INTRODUCTION

5G performance targets high data rate, reduced latency, energy savings, cost reduction, higher system capacity, and massive device connectivity [1]. These 5G communications allow the integration of different wireless technologies with the goal of supporting massive machine-type services, enhanced mobile broadband for multimedia distribution, and ultra-reliable low latency for emergency cases.

The associate editor coordinating the review of this manuscript and approving it for publication was Hosam El-Ocla¹.

5G is highly integrative, as one of its priorities is to provide a deep level of integration between cellular and short-range communications, tying any new 5G air interface and spectrum to provide universal high-rate coverage, seamless and transparent communications across radio access technologies. Thus, short- and long-range technologies would complement each other by using virtualization technologies and softwarization of the network and radio functions.

With regard to the Internet of Things (IoT), these multi-technology features provided by 5G technologies can add extremely new and interesting opportunities, since we

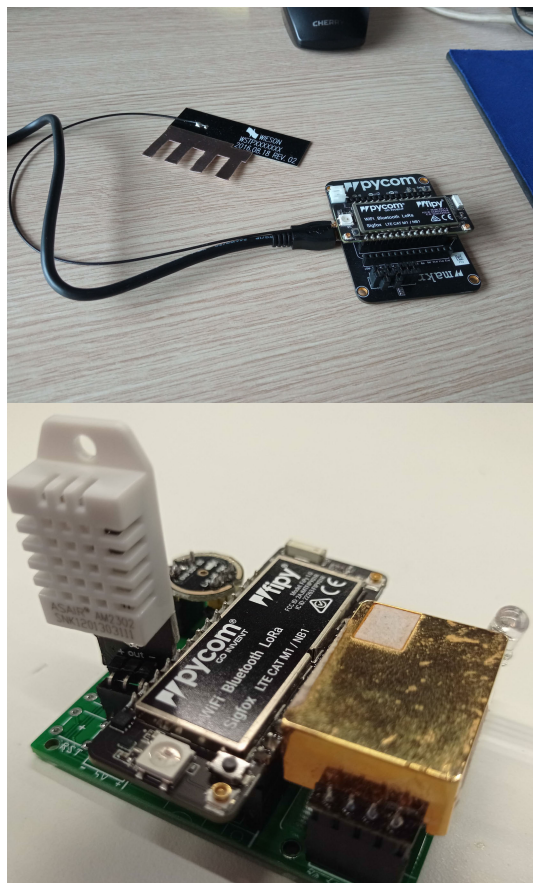


FIGURE 1. Above: a Pycom FiPy module. Below: an example of a 5G-enabled IoT node for air quality monitoring based on this module.

can address new challenges and adapt to new requirements imposed by the location of each deployment, the available energy resources on each node as well as the IoT application itself. Notice that the proliferation of wireless sensor networks requires a vast number of wireless nodes, where costs are a key factor, constraining drastically in general the performance of these deployed nodes, in terms of computation and communications capabilities. This limitation opens the doors to solutions based on fog and edge computing for smart distribution of computing load using 5G Mobile/Multi-access Edge Computing (MEC) architecture [2] to mitigate and overcome these issues. An overview of these challenges and enabling technologies for IoT within a 5G context are shown in [3], where it is discussed physically, MAC (medium access control), and network layers of wireless IoT networks, which all have significant impacts on latency and reliability.

In this context, several commercial products are embedding multiple wireless interfaces under the 5G paradigm within the same device. An example is the so-called FiPy module [4], [5] by Pycom Ltd,¹ that includes onboard

¹Pycom Ltd. went into administration on September 2022, but the newly created Pycom BV took over this company to prevent the products going end of life at the time of writing.

technologies such as Low-Power Wide-Area Network (LPWAN) with LoRa/Sigfox,² short-range communications with WiFi and Bluetooth, classified as Low-power Wireless Personal Area Networks (LoWPAN) and cellular communications-based technologies, such as Long Term Evolution (LTE) for machines (LTE-M) and Narrow Band IoT (NB-IoT). In Figure 1, above it is shown this module with LTE-M communication and below, our own prototype for air quality IoT monitoring node.

Although these wireless technologies are rather different, under an abstraction layer these technologies could cooperate and work together, building scenarios known as heterogeneous networks. Nevertheless, in practice in most cases, as shown in the state-of-the-art section, these wireless nodes only use one of these wireless technologies at a time, and in the case of using other interfaces, their use is not coordinated.

In this paper, we focus on heterogeneous networks and multihomed 5G-enabled IoT nodes to exploit these features by using commercial products (in particular the FiPy module) in real scenarios, by analyzing different issues from a practical point of view, both hardware and software. For the interface selection, we propose and implement a novel algorithm by performing local decisions on a per-packet basis. We will compare our proposal with other alternatives, highlighting the opportunities by exploiting the multi-homing features.

The rest of the paper is structured as follows. Section II introduces the related work, highlighting the opportunities of our proposal. Section III describes the main features of commercial nodes with support for 5G communications on IoT missions, exploring the potential for multi-homing applications and their requirements. In Section IV, we propose an optimization algorithm to handle these requirements. In Section V, we present the experimental evaluation and discuss the results. Finally, in Section VI, we conclude the paper and show the future work.

II. RELATED WORK

In the context of heterogeneous networks within the 5G paradigm, we can find interesting contributions. In [6], it is proposed in a theoretical way a self-optimizing technique based on vertical handover (among different wireless technologies) for load balancing in heterogeneous wireless networks (2G/3G/4G/5G/Wi-Fi) where User Equipment's (UE) collect several Quality of Service (QoS) metrics and send them to the core (big-data repository) for further processing. These metrics are extended by the network provider's information under the perspective of a global environment as a global heterogeneous mobile network. The authors formalize the problem of access network selection to improve the quality of mobile services through the efficient use of heterogeneous wireless network resources and optimal horizontal-vertical handover procedures, proposing

²In 2022, Sigfox went into bankruptcy proceedings and the firm Unabiz took its control at the time of writing.

a method for adaptive selection of wireless access based on big-data analysis over the centralized information gathered and shared. With their proposal, it is achieved a 16% increase in performance of the heterogeneous network using the statistical network resource reservation method, compared to homogeneous networks. In [7], the authors formulate the problem of distributed Radio Access Technologies (RAT) selection by considering multiple traffic classes over different heterogeneous technologies for serving the different applications running at the UEs, by applying a set of policies for ordering the preferences and the resource allocation of the network. Their framework is evaluated by simulation for a variety of traffic classes in terms of QoS requirements and provides results on capacity utilization and load distribution over available RATs.

With regard to seamless and transparent communications, we have found as well interesting initiatives. In [8], small cells are used to improve the performance in 5G networks. They increase the number of cell changes, handovers, and losses. Using distributed mobility-aware solutions in this scenario, as an alternative to a centralized mobility solution, scales better and is more efficient in terms of routing. However, there is a limitation in performance. Their results show 30% reduction in signaling, 53% in packet loss, and 90% reduced load on the core compared to the existing Locator and Identity Split Protocol (LISP) mobile node protocol. Other approaches based on device-to-device cooperation are shown in [9], [10], and [11]. In particular, in [9] it is shown, in a theoretical way, how a heterogeneous cellular network can provide traffic offloading that can be exploited to effectively improve network capacity by utilizing complementary network communication techniques (device-to-device) with a focus on massive connections for machine-type communications, determining network access, in order to improve overall network capacity and mitigate traffic congestion. In [10], in the same line, it is proposed theoretically an optimized caching strategy to share content distribution on top of device-to-device technology, based on information-centric networking principles in order to improve also network efficiency. In [11], we can find other alternatives to improve network performance in 5G, using overlay networks combined with device-to-device cooperation. In this case, it is proposed a smart base station-assisted partial-flow device-to-device offloading system that provides seamless video streaming services to clients by effectively offloading parts of the video traffic.

In [12], a novel paradigm for wireless network access is proposed in a 5G wireless Dynamic Network Architecture (5G-DNA), where certain classes of smart devices act as an Access Point (AP) temporarily, while connected to the Internet on 5G wireless DNA. Since these AP's are not stable, users need a seamless, efficient, and reliable schedule for switching between available AP's. The authors propose two different switching policies (taking into account preemptive issues) to improve network performance, concluding that in

the low mobility scenarios, preemptive switching is preferred because it has acceptable signaling overhead and provides higher capacity, and brings higher profit for AP's. In the high mobility scenarios, non-preemptive switching is a better option because it incurs fewer switching and higher profit for AP's.

Also, we can find different applications where communications in this context are a key point and where the simultaneous use of different interfaces is extremely important. In [13], a use case for an ambulance service with medical video streaming to the hospital based on 5G small cell-based is shown. Using small cell networks, it can enhance the medical QoS. Besides, it studied the impact of small-cell heterogeneous networks on medical video streaming along with the system modeling and technical requirements, including the performance analysis for medical video sequences affected by packet losses. The results of the proposed scenario show through a simulation that in a mobile small cell-based ambulance scenario, outperforms the traditional macrocell network scenario. In [14], this critical application is better shown with a real deployment and a specific network slicing for this video streaming prioritization.

About commercial 5G-enabled IoT platforms, in [15], using the mentioned FiPy module, it proposed a comparison between WiFi and LoRa technologies taking into account the constraints of each technology. The comparison done in a factory, includes transmission time, energy consumption, and coverage, highlighting that LoRa has better coverage but less Throughput. In a similar way, in [16] it was tested the same module for IoT monitoring using both LoRa and Sigfox technologies, but independently, achieving distances of 1.17 and 10 km respectively. It is worth mentioning other similar and interesting commercial products based on ESP32 system-on-chip [17] that could be used under certain 5G paradigms, such as LILYGO TTGO T-SIM7000G Module ESP32 [18], but their characteristics, functionality, and design do not fit in the same way as the FiPy module does.

The concept of multihoming is also linked to routing protocols. From this approach, different authors have proposed routing protocols for multi-homing nodes in an IoT context. In [19], the authors propose the Ant Colony Optimization On-demand Multi-path Distance Vector (ACO-MDV) routing algorithm to enhance power efficiency, considering multi-homing options on IoT. In [20], it is shown an energy-aware heuristic routing and resource allocation for a multi-hop network via smart edge device-to-device communications.

In terms of transport layer protocols, traditional Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) as well as Stream Control Transmission Protocol (SCTP) are still used in this context. In particular, SCTP manages several logic interfaces with the goal to use all of them to improve fault tolerance. Extensions to these established transport protocols are receiving considerable attention from

Internet Engineering Task Force (IETF). In [21] two main extensions for concurrent transmissions, the Multipath TCP (MP-TCP) extension for TCP and the Concurrent Multipath Transfer extension for SCTP (CMT-SCTP) are analyzed and compared. The authors highlight that the different path management strategies of both protocols have a significant impact on their performance in real scenarios. MP-TCP creates a full mesh of paths among the available interfaces that perform significantly better than CMT-SCTP, which only uses an alternative path for robustness. Nevertheless, the MP-TCP strategy suffers from scalability problems due to the full mesh among the multiple interfaces. Other solutions based on overlay networks, tunneling techniques, and Software Defined Networks (SDN) are also relevant. In [22], it is analyzed the switching time (handoff time) among heterogeneous interfaces (Ethernet, WiFi, Bluetooth) using an Open Virtual Switch (OvS) managed by an RYU SDN controller on a Raspberry Pi. In conclusion, the authors show that the handoff time varies greatly depending on the interface type and the switching direction. But notice that the switching decision is done manually for the experiments and benchmarking, not decided based on other external or internal requirements, such as application, battery status, etc.

Finally, in [23] are depicted the open challenges and a survey of the potentials of 5G technologies in terms of multihoming options considering QoS and Quality of Experience (QoE) issues. Besides, in [24], is done a review of the related work taking into account the utilization of 5G technologies in IoT applications, considering the limitations due to network optimization and interferences. In this line, in [25], it is proposed a multihomed network model for coexistence and diverse IoT applications in smart cities from a theoretical point of view. Also in [26], the use of machine learning techniques has been applied for traffic steering in scenarios with heterogeneous ultra dense 5G networks.

In summary, we see from this review that on one hand there are many theoretical approaches that can help us to analyze and to define different strategies, most of them based on offloading techniques based on device-to-device communications and using vertical handovers. However, although these scenarios are interesting for certain 5G applications, they do not fit well with our approach from a practical point of view. On the other hand, we have seen practical implementations using different wireless technologies on heterogeneous networks, but without a global vision of cooperation. Thus, based on this, we see that there is a need to coordinate and manage the different wireless technologies in the context of heterogeneous networks, focusing on 5G-enabled IoT nodes, in particular, based on FiPy modules. In this case, some constraints are internal to the nodes, given by the FiPy module itself and its implementation, the available energy resources on each node and other constraints are external to the nodes, given by the wireless technologies and the location of each deployment and of course by the IoT application. All these issues are discussed

TABLE 1. Comparison of the different wireless technologies embedded in a FiPy module.

Technology	Consumption	Coverage	Bit-rate
Sigfox	very low	medium	very low
LoRa	low	medium	low
NB-IoT	medium	high	low
LTE-M	medium++	high	medium –
WiFi	high	medium-	high
Bluetooth	medium+	low	medium++

and explained in the following sections. Notice that at the end, in Section V, we have introduced Table 4, where we compare our proposal with the references from the related work with higher similarity, analyzing the pros and cons of each, along with some comments.

III. A COMMERCIAL 5G-ENABLED IOT NODE

One of the most relevant low-cost commercial platforms for the 5G paradigm is the FiPy module. The design of this module consists of an integration of different elements on a board with the goal to build a generic 5G-enabled IoT node with a set of heterogeneous wireless interfaces.

A. HARDWARE ISSUES

The FiPy module includes different wireless communication technologies, such as WiFi, Bluetooth, LoRa, Sigfox and dual LTE-M (CAT M1) and NB-IoT on one single tiny board. The main features of these onboard technologies are detailed next. Sigfox (as a class 0 device) and LORA (both class A and C device types) use 800/900 MHz band ISM. WiFi (IEEE 802.11b/g/n 16 Mbps) and Bluetooth (low energy and classic) use 2.4 GHz band ISM. LTE-M/NB-IoT, based on 3GPP release 13 LTE Advanced Pro, supports narrow-band LTE UE categories M1/NB1 use 17 radio frequency bands supported from 699 MHz to 2170 MHz. In LTE-M/NB-IoT the transmission current is 420 mA peak at 1.5 W and a reception current of 330 mA peak at 1.2 W.

This module is based on the Tensilica LX6 CPU Xtensa® dual-core 32-bit LX6 microprocessor(s) (the same as the ESP32 system-on-chip [17]), that allows up to 600 Dhrystone Million Instructions per Second (DMIPS), with an extra ultra-low power coprocessor that can monitor General Purpose Input/Outputs (GPIO), the ADC channels and controls most of the internal peripherals during deep-sleep mode, consuming only 25uA. The module is equipped with 520KB and 4MB RAM and 8MB flash memory.

Table 1 summarizes the main features of the different interfaces and technologies embedded in the FiPy module, highlighting consumption, coverage, and bit rate. Among these technologies, we must stress that Sigfox, LoRa and Bluetooth technologies work in Layers 1 and 2 and the other ones in Layer 3 of the Open System Interconnection (OSI) model. For Layer 1 and 2 technologies, we should add externally a gateway to include Layer 3 connectivity through a gateway, in the same way as LoRa and LoRaWAN specification do [27].

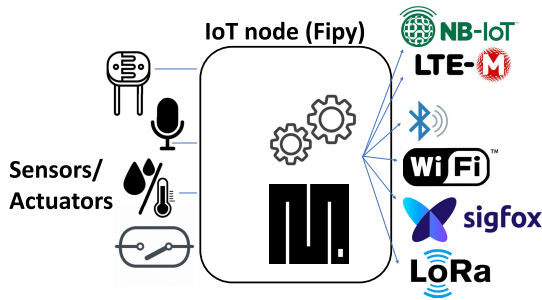


FIGURE 2. Scheme of a multi-homed IoT node based on the FiPy module with sensors and actuators.

B. SOFTWARE ISSUES

In our case, the main program is running the IoT application, reading from sensors and writing to actuators, as it is shown in Figure 2. When it is necessary to send or receive information, the module will run locally a decision algorithm, explained in the next section, to choose at the time of transmission the most appropriate wireless interface.

The FiPy module by default runs a MicroPython interpreter (multi-threading enabled). MicroPython is a programming language designed specifically for constrained environments such as microcontrollers and embedded systems. It is a subset of the Python 3 programming language that has been heavily optimized for these specific platforms. MicroPython does not support some of the advanced features found in Python 3 such as meta-classes (at least yet) and dynamic typing. Additionally, the libraries and functions available in MicroPython are limited due to the constrained environment and the need for minimal memory and processor utilization.

Thus, the access to the wireless interfaces must take into account a set of rules and policies given by each wireless technology and others imposed by the FiPy module itself. Notice that FiPy modules have some limitations given by the quality of the built-in modems, as we will show in Section V.

We conclude that based on these constraints, the FiPy module fits well in a scenario with heterogeneous networks. However, for the IoT application, it is challenging to optimize the communication process. The IoT application will send and receive packets and when this is done, the wireless technology should be selected according to local criteria. This decision should be based on the location of each deployment, the available energy resources on each node as well as the IoT application itself. With regard to the transport protocols to manage the communication process, we discard heavy and standardized multihoming and multipath transport protocols, such as MP-TCP and CMT-SCTP, since they exceed the resources on these modules. In addition, for simplicity and to provide verifiable results, our approach to the communication process is based on the analysis of independent packets.

IV. PROPOSED MULTIHOMING OPTIMIZATION ALGORITHM

In this section, we propose the multihoming optimization algorithm and its implementation to select the appropriate

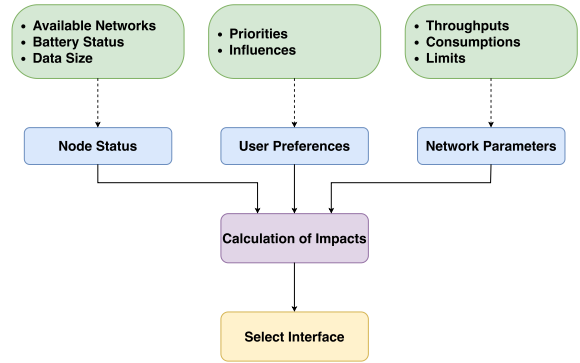


FIGURE 3. Flow chart of the proposed multihoming optimization algorithm to select the best wireless interface.

wireless interface, according to a set of policies and preferences given at the transmission time, on a per-packet basis as discussed before. It must be stressed that the proposed algorithm can be easily generalized and adapted to any other similar multihoming node.

A. ALGORITHM DESIGN

Figure 3 shows the flow chart of the proposed algorithm. This algorithm is running on each FiPy module, and it selects locally the best technology (or interface) by weighting different metrics and parameters as it is explained next, according heuristically to the performance benchmarking of this module. As depicted in this figure, the selection is based on the calculation of the different impacts, by analyzing the status of the node, the user preferences, and the network parameters per technology.

Thus, this selection is performed using an optimization logic by processing parameters, values, and their relation (by given equations), defined in Tables 2 and 3. In particular, Table 2 defines the different parameters, metrics, and impacts, given by the communication requirements and the IoT application’s needs. In this table, we distinguish three types of metrics: a) **measured metrics**, directly measured from the module, such as measured throughput, consumption in miliwatts per byte sent (mW/B), and price or monetary costs, b) **user-defined metrics**, that can be set as predefined user influences or imposed by the standards (for instance, in case of LoRa and Sigfox) for the selection criteria, determined by priority, time limit and impacts given by throughput, data limit, consumption, battery and price and c) **automatically detected metrics**, that depend on the hardware, such as the technology availability, battery levels, data to send or the required time for the transmission.

In Table 3, we define the proposed and underlying equations that determine the selection of the communication technology. To carry out the comparison, we normalize these values among the technologies, such as throughput, data limit, consumption, and price, denoted as NTp_x , NDI_x , $NCox$ and NPr_x . Additionally, users can influence the result through personal preferences by defining the impact of each parameter defined, setting influence indexes

TABLE 2. Parameters defined per technology $x = [wifi, bt, lora, lte, nb]$ used in the proposed algorithm.

Measured			User Defined			Automatically Detected		
Name	Abbreviation	Units	Name	Abbreviation	Units	Name	Abbreviation	Units
Throughput(x)	Tp_x	Kbps	Priority(x)	P_x	[0..1]	Available(x)	A_x	[0, 1]
Consumption(x)	Co_x	mW/B	Time Limit(x)	Tl_x	%	Battery Level	Bl	[0..1]
Price(x)	Pr_x	-	Throughput Influence	I_{tp}	[0..1]	Data to Send	Ds	Bytes
			Data Limit Influence	I_{dl}	[0..1]	Time Used(x)	Tu_x	%
			Consumption Influence	I_{co}	[0..1]			
			Battery Influence	I_{bl}	[0..1]			
			Price Influence	I_{pr}	[0..1]			

TABLE 3. Set of equations used by the proposed Algorithm per technology $x = [wifi, bt, lora, lte, nb]$.

Normalized Throughput(x): $NTp_x = \frac{Tp_x}{Tp_{max}}$		Throughput Impact(x): $ITp_x = NTp_x^{I_{tp}}$
Data Limit(x):	Remaining Data:	Normalized Data Limit(x): Data Limit Impact(x):
$Dl_x = Tp_x \cdot 60 \cdot 60 \cdot 24 \cdot \frac{Tl_x}{100}$	$Rd_x = Tp_x \cdot 60 \cdot 60 \cdot 24 \cdot \frac{Tl_x - Tu_x}{100}$	$NDl_x = \frac{Dl_x}{Dl_{max}}$ $IDl_x = NDl_x^{I_{dl}}$
Normalized Consumption(x):	Inverse NCO_x :	Consumption Impact(x):
$NCO_x = \frac{Co_x}{Co_{max}}$	$INCO_x = -NCO_x + NCO_{min} + 1$	$ICO_x = INCO_x^{I_{co}}$
Battery Level Impact: $IBl_x = (NCO_x^{-Bl+2})^{I_{bl}}$		
Normalized Price(x):	Inverse NPr_x :	Price Impact(x):
$NPr_x = \frac{Pr_x}{Pr_{max}}$	$INPr_x = (-NPr_x + NPr_{min}) \cdot 0.9 + 1$	$IPr_x = INPr_x^{I_{pr}}$
Time Limit Impact:	$ITl_x = \begin{cases} 1, & Rd_x \geq 8Ds \\ 0, & Rd_x < 8Ds \end{cases}$	

from 0 (no impact) to 1 (full impact) and are calculated automatically based on measures, user preferences and status of different parameters. The data limit and remaining data expressions are related to the measured throughput (Tp_x) and the time limit (Tl_x). As a consequence, data limit impact is related to the data limit influence (I_{dl}) and the normalized data limit (NDl_x). Notice that these expressions will allow us to fulfill the LoRa and Sigfox standards. In relation to energy consumption, the consumption impact is proportional to the inverse normalized consumption ($INCO_x$) and the consumption influence (I_{co}), together with the battery level impact (IBl_x) that depends on normalized consumption (NCO_x), the battery level (Bl) and the battery influence (I_{bl}). The price impact is related to the inverse normalized price ($INPr_x$) and the price influence (I_{pr}). Finally, the impact of the time limit (ITl_x) is a binary function that considers eight times the data to send (D_s) as a threshold for the remaining data (Rd_x).

Then, given these parameters, the algorithm calculates a Final Score (F_s) for each technology (x) as follows:

$$F_{S_x} = P_x \cdot A_x \cdot ITp_x \cdot IDl_x \cdot ICO_x \cdot IBl_x \cdot IPr_x \cdot ITl_x \quad (1)$$

Thus, from these scores, the selected interface to transmit the packet is given by the one with the highest F_{S_x} .

B. ALGORITHM IMPLEMENTATION

The implementation of the algorithm in the FiPy module is as follows. The file structure of the MicroPython application is led by the *main* and the *boot* files. Initially, the *boot* file disables all the interfaces, in order to avoid energy consumption. Then, in the same folder where these two files are located, we add a file containing a class with the implementation of the selection algorithm, as described before. Thus, we call this class from the *main* file every time we want to send a packet through the selected interface. Besides, the parameters in Tables 2 and 3 are automatically updated internally to the module every time a packet is sent, except A_x that it should be updated periodically (in our case, every day), as a kind of self-auto calibration, to check if there are changes in availability for the onboard wireless technologies.

V. EVALUATION AND RESULTS

As was explained in the previous section, the selection algorithm relies on the evaluation and estimation of the parameters and metrics depicted in Tables 2 and 3 for each technology. Due to the limitations of the FiPy module in each of its interfaces, a prior benchmarking and profiling process is necessary to adjust the selection algorithm. For example,

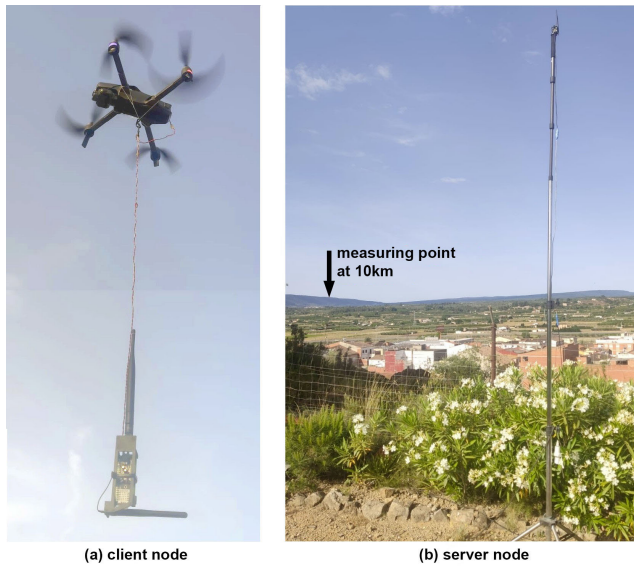


FIGURE 4. Example of pictures for the technology benchmarking and profiling process of the FiPy module for LoRa, using a drone as support: a) client node and b) server node.

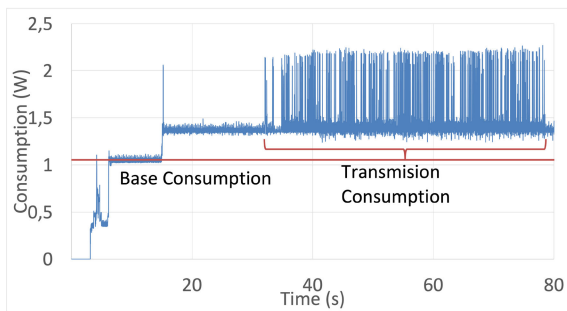


FIGURE 5. WiFi Consumption while transmitting a total of 10MB.

it is not the same case if it is transmitted from one module to another directly than to an access point, as the performance depends on the hardware used in each case, affecting the throughput and the transmission distance. Besides, to ensure reliable performance measurements in the communication process, for these tests in particular, Fresnel zones were taken into account according to the carrier frequency used in each technology, the line of sight, and avoiding external interference zones. Thus, tripods over 4 m high were used when the distance did not exceed 300 m, as in the case of WiFi and Bluetooth, and for longer distances, a drone was used instead. Figure 4 shows the testbed for LoRa technology using this drone (as a client) and the server.

The tests carried out to estimate the parameters shown in Table 2, were as follows. For throughput analysis two FiPy modules were used, one as a server and the other as a client, and the transmission was done at different distances, using different packet sizes to determine the optimal for each distance.

For consumption analysis, both voltage and current were monitored all the time. The nodes were programmed to

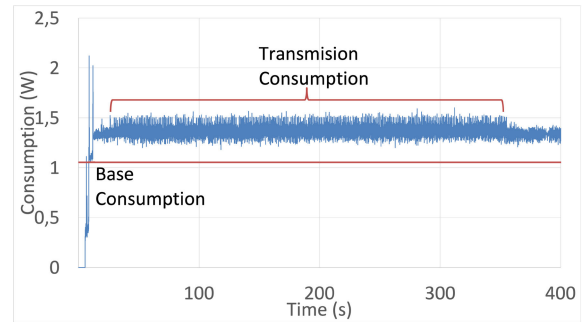


FIGURE 6. Bluetooth Consumption while transmitting a total of 1MB.

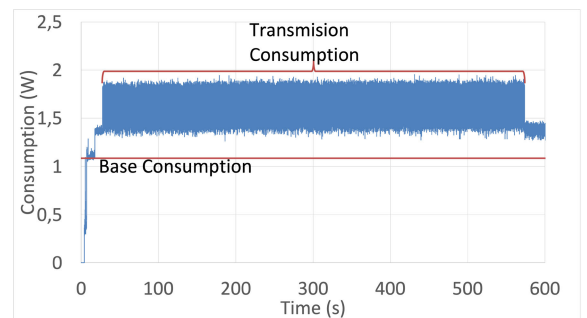


FIGURE 7. LoRa Consumption while transmitting a total of 1MB.

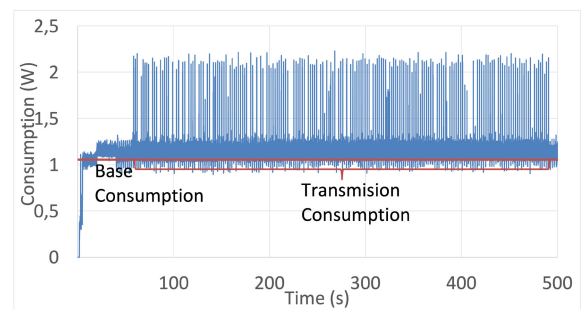


FIGURE 8. LTE-M Consumption while transmitting a total of 1MB.

deactivate all interfaces and only activate the one to be tested. Initially, to measure the base consumption the nodes were inactive (idle) for a few seconds, and after that, started transmitting a total of 10MB in the case of WiFi and 1MB otherwise, to measure the transmission consumption. Notice that since the heterogeneous interfaces in the same module have different nominal throughputs, and because we are also measuring power consumption, we have analysed each interface under a similar time window, that is the reason we use different data sizes. With these results, it was possible to determine the base consumption of the FiPy module, the consumption when the interface is active, and when the data is being transmitted. Figures 5-8 show the consumption for the interfaces tested at these three different steps: base (idle), active, and transmitting. With these results, we are able to calculate and estimate the consumption per byte, by taking as a reference the consumption while sending data, subtracting

	TP(x) [Kbps]	Co(x) [mw/B]	Pr(x)	TI(x) [%]	Tu(x) [%]
WiFi	1800	0,000176	0	100	20
Bluetooth	50	0,010522	0	100	50
LoRa	18	0,016693	0	1	0
LTE-M	18	0,004087	20	100	23

Ds	BI	Itp	Idl	Ico	Ibl	Ipr		
50	0,9	0,5	0,5	0,1	0,8	0,9	P(x)	A(x)
		ITP(x)	IDl(x)	ICo(x)	IBl(x)	IPr(x)	ITI(x)	Fs(x)
WiFi	1	0	1	1	1	1	1	0
Bluetooth	1	0	0,166666667	0,166666667	0,969001655	0,972670124	1	0
LoRa	1	1	0,1	0,01	0,945130747	0,951552741	1	0,000899342
LTE-M	1	1	0,1	0,1	0,989286488	0,990566025	0,125892541	0,001233688

FIGURE 9. Example of interface selection using the proposed algorithm on the FiPy module.

Ds	BI	Itp	Idl	Ico	Ibl	Ipr		
50	0,9	0,5	0,3	0,1	0,8	0,9	P(x)	A(x)
		ITP(x)	IDl(x)	ICo(x)	IBl(x)	IPr(x)	ITI(x)	Fs(x)
WiFi	1	0	1	1	1	1	1	0
Bluetooth	1	0	0,166666667	0,341278752	0,969001655	0,972670124	1	0
LoRa	1	1	0,1	0,063095734	0,945130747	0,951552741	1	0,005674463
LTE-M	1	1	0,1	0,251188643	0,989286488	0,990566025	0,125892541	0,003098885

FIGURE 10. Another example of interface selection changing data limit influence.

TABLE 4. Comparison of the multi-homing proposal with the state-of-the-art alternatives with pros and cons.

Reference	Pros	Cons	Comments
[9]	traffic offloading by device to device to reduce congestion	theoretical	heterogeneous cellular network
[10]	optimized caching strategy	theoretical	share content distribution on top of device to device
[6]	self-optimising technique based on vertical handover	theoretical	load balancing in heterogeneous wireless networks based on big data learning
[12]	seamless and efficient schedule for switching between AP	theoretical	5G-DNA where smart devices act temporarily as AP
[11]	overlay networks combined with device to device cooperation	theoretical	smart device-to-device offloading to provide seamless video streaming
[7]	dynamic heterogeneous network selection algorithm based on network UE requirements	theoretical	UEs allocate each traffic class through each technology given certain policies
[15]	performance evaluation	WiFi and LoRa independently	comparison between WiFi and LoRa technologies using FiPy modules
[16]	performance evaluation	Sigfox and LoRa independently	comparison between Sigfox and LoRa technologies using FiPy modules
ours	multi-home communications in 5G-enabled node	constraints imposed by MicroPython, extra 2 ms delay	context-aware technology selection in heterogeneous wireless network based on FiPy module

the base consumption, and dividing by the total number of bytes sent.

Finally, the results of this technology benchmarking and profiling process are shown in Figures 11-14. In this case, the Throughput vs. Received Signal Strength Indicator (RSSI) is shown for each technology. We must stress that due to the limitations of the modems embedded in the FiPy module, the throughput seems to be unaffected by RSSI (it does not depend on the distance) and only slightly when the connection is going to be lost. Thus, according to this, RSSI is

not relevant to this algorithm for these modules. It may seem that in the case of LTE-M the RSSI affects the throughput but in fact, measurements taken below -75dBm are very unstable and have continuous connection losses and are therefore not taken into account.

Figure 9 shows an example of these calculations and trade-off analysis based on Equation 1 to select the best interface. In this case, the parameters have been introduced as an example to simulate that the WiFi and Bluetooth interfaces were not available and only LoRa and LTE-M were available.

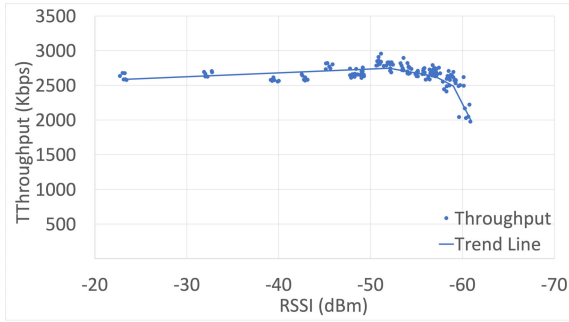


FIGURE 11. Throughput versus RSSI in WiFi transmission.

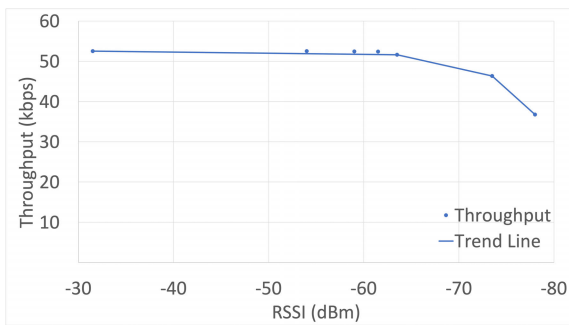


FIGURE 12. Throughput versus RSSI in bluetooth transmission.

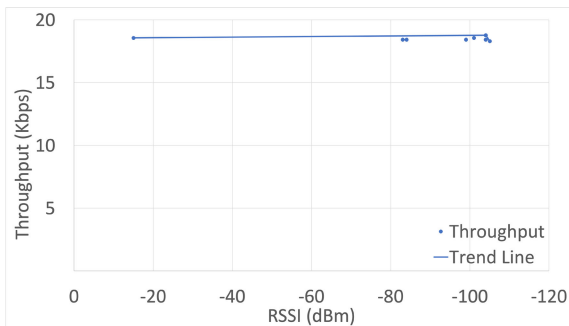


FIGURE 13. Throughput versus RSSI in LoRa transmission.

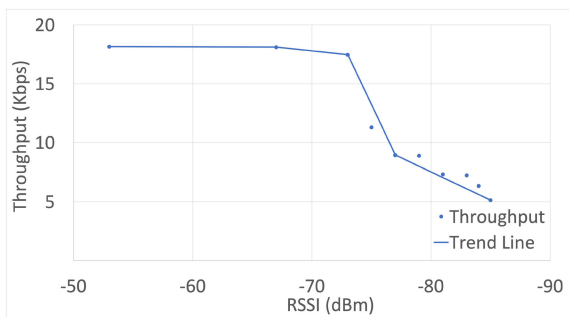


FIGURE 14. Throughput versus RSSI in LTE-M transmission.

In this example, LoRa was better in terms of price and had the same throughput score. However, LTE-M was better in consumption and data limit, and it was finally the interface selected by the algorithm. But, if we increase the price of

LTE-M, the result changes to LoRa, as well as if we make available WiFi and Bluetooth, then the algorithm would choose WiFi. Another example can be seen in Figure 10, but reducing the influence of the data limit, where in this case, we can see that the algorithm selects LoRa as the interface to send data.

As a conclusion of these exhaustive tests, it is clear that the WiFi interface outperforms the others in all terms analysed (throughput, consumption, price and time limits). Thus, if this interface is available, the algorithm always selects WiFi as the transmission interface, but this may change at other nodes, with the availability of new transmission technologies, or if the user sets the WiFi Priority very low.

In Table 4, we compare our proposal with the state-of-the-art. In particular, we analysed and showed similar alternatives considered in Section II, the pros and cons of each, along with some relevant comments. As we can see, most of them are theoretical, except two ([15] and [16]), that have a practical approach using the same FiPy module, although considering each wireless technology independently and not concurrently.

VI. CONCLUSION

In this work, we have focused on transparent and integrative communications in a 5G and IoT context. We have shown an implementation of a multi-homed 5G-enabled IoT node, based on a novel and efficient heterogeneous interface selection algorithm running in a commercial multi-homed product, the Fipy module, by performing local decisions on a per-packet basis at the transmission or reception time. The selection criteria depend on the location of the node and available technologies, the available energy resources as well as the IoT application itself.

On the one hand, with regard to the advantages of our proposal, we see the benefits of managing simultaneously several heterogeneous wireless interfaces, in terms of resilience and fault tolerance, efficient communication management, flexibility to adapt new scenarios in a proactive way, as well as to adapt easily to new application requirements. However, on the other hand, we add additional burden and processing, which is translated into an extra delay of 2 ms. Although this extra delay is very small and should have a nearly negligible impact on most IoT applications, it could have some impact on the performance in high-speed and real-time applications. But we must stress that these applications are not the most common in the context of IoT.

Also from our results and performance evaluation, we realize that there are some limitations on the Fipy module due to a combination of the hardware selection (mainly the ESP32 MCU selection) and the firmware implementation (we have used the latest published version: 1.20.2 release 6 of this firmware³).

³This firmware has a release date of 28/10/2021 but has no major modifications since August 2019 and is based on a branch of ESP-IDF which has no updates since 11/01/2019 and its last major modification dates from 2017.

As future work, we are currently working on a new design and enhanced version of this module to overcome these limitations, taking into account important factors such as energy and costs. Besides, we are porting the algorithm to other IoT devices and boards, such as Raspberry Pi or Nvidia Jetson. In addition, we are currently working on a new board that implements the same communication technologies as FiPy but without so many hardware and software limitations and we plan to test the algorithm on it and carry out specific tests to include parameters such as RSSI or packet size in order to improve the algorithm. Also, in order to increase the alternatives and communications paths, we will consider the option to forward packets using the cooperation of neighbouring nodes in a kind of fog collaboration process.

ACKNOWLEDGMENT

The authors would like to thank Mohamed Khadmaoui-Bichouna for his contributions to the work of this article.

REFERENCES

- [1] *5G; System Architecture for the 5G System*, document TS 23.501, ETSI, 3GPP, Version 15.3.0, Release 15, 2022, Accessed: Jun. 3, 2023. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/15.03.00_60/ts_123501v150300p.pdf
- [2] (2022). *ETSI GS MEC 003: Mobile Edge Computing (MEC); 003 V3.1.1 (2022-03)*. Accessed: Jul. 6, 2023. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/03.01.01_60/gsmec003v030101p.pdf
- [3] Z. Ma, M. Xiao, Y. Xiao, Z. Pang, H. V. Poor, and B. Vucetic, "High-reliability and low-latency wireless communication for Internet of Things: Challenges, fundamentals, and enabling technologies," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 7946–7970, Oct. 2019.
- [4] Pycom.io. (2022). *FiPy, Five Network Development Board for IoT*. [Online]. Available: Accessed: Dec. 28, 2022. [Online]. Available: <https://pycom.io/product/fipy/>
- [5] Pycom. (2018). *FiPy Specifications*. Accessed: Apr. 29, 2022. [Online]. Available: <https://docs.pycom.io/datasheets/development/fipy/>
- [6] M. Beshley, N. Kryvinska, O. Yaremko, and H. Beshley, "A self-optimizing technique based on vertical handover for load balancing in heterogeneous wireless networks using big data analytics," *Appl. Sci.*, vol. 11, no. 11, p. 4737, May 2021. [Online]. Available: <https://www.mdpi.com/2076-3417/11/11/4737>
- [7] V. Passas, V. Miliotis, N. Makris, and T. Korakis, "Dynamic RAT selection and pricing for efficient traffic allocation in 5G HetNets," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–6.
- [8] E. M. O. Fafolahan and S. Pierre, "A seamless mobility management protocol in 5G locator identifier split dense small cells," *IEEE Trans. Mobile Comput.*, vol. 19, no. 8, pp. 1745–1759, Aug. 2020.
- [9] W. Cao, G. Feng, S. Qin, and M. Yan, "Cellular offloading in heterogeneous mobile networks with D2D communication assistance," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4245–4255, May 2017.
- [10] C. Xu, M. Wang, X. Chen, L. Zhong, and L. A. Grieco, "Optimal information centric caching in 5G device-to-device communications," *IEEE Trans. Mobile Comput.*, vol. 17, no. 9, pp. 2114–2126, Sep. 2018.
- [11] G. S. Park, W. Kim, S. H. Jeong, and H. Song, "Smart base station-assisted partial-flow device-to-device offloading system for video streaming services," *IEEE Trans. Mobile Comput.*, vol. 16, no. 9, pp. 2639–2655, Sep. 2017.
- [12] X. Huang, F. Ke, R. Yu, Y. Liu, and Y. Wu, "Preemptive and non preemptive switching protocols for 5G wireless dynamic network architecture," *IEEE Trans. Veh. Technol.*, vol. 68, no. 12, pp. 12256–12270, Dec. 2019.
- [13] I. U. Rehman, M. M. Nasralla, A. Ali, and N. Philip, "Small cell-based ambulance scenario for medical video streaming: A 5G-health use case," in *Proc. 15th Int. Conf. Smart Cities, Improving Quality Life Using ICT IoT (HONET-ICT)*, Oct. 2018, pp. 29–32.
- [14] I. Martinez-Alpiste, J. M. Alcaraz-Calero, Q. Wang, G. Golcarenenji, E. Chirivella-Perez, and P. Salva-Garcia, "5G-based smart ambulance: The future of the emergency service in the global pandemic and beyond," *IEEE Commun. Soc. Technol. News*, pp. 1–7, Oct. 2020. [Online]. Available: <https://www.comsoc.org/publications/ctn/5g-can-shape-mission-critical-healthcare-services>
- [15] P. Ferreira, R. N. Miranda, P. M. Cruz, and H. S. Mendonça, "Multi-protocol LoRaWAN/Wi-Fi sensor node performance assessment for industry 4.0 energy monitoring," in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2019, pp. 403–407.
- [16] O. Elijah, S. K. A. Rahim, M. J. Musa, Y. O. Salihi, M. J. Bello, and M.-Y. Sani, "Development of LoRa-sigfox IoT device for long distance applications," in *Proc. IEEE Nigeria 4th Int. Conf. Disruptive Technol. Sustain. Develop. (NIGERCON)*, Apr. 2022, pp. 1–5.
- [17] Espressif Systems. (2023). *ESP32 System-On-Chip*. Accessed: Jul. 28, 2023. [Online]. Available: <https://www.espressif.com/en/products/socs/esp32>
- [18] LILYGO. (2023). *LILYGO TTGO T-SIM7000G Module ESP32-WROVER-B Chip WiFi Bluetooth 18560 Battery Holder Solar Charge Development Board*. Accessed: May 27, 2023. [Online]. Available: http://www.lilygo.cn/prod_view.aspx?TypeId=50033&Id=1246
- [19] N. Krishnaraj and S. Smys, "A multihoming ACO-MDV routing for maximum power efficiency in an IoT environment," *Wireless Pers. Commun.*, vol. 109, no. 1, pp. 243–256, Nov. 2019, doi: 10.1007/s11277-019-06562-0.
- [20] F. Al-Turjman, B. D. Deebak, and L. Mostarda, "Energy aware resource allocation in multi-hop multimedia routing via the smart edge device," *IEEE Access*, vol. 7, pp. 151203–151214, 2019.
- [21] M. Becke, H. Adhari, E. P. Rathgeb, F. Fa, X. Yang, and X. Zhou, "Comparison of multipath TCP and CMT-SCTP based on intercontinental measurements," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 1360–1366.
- [22] R. Nozaki, L. Guillen, S. Izumi, T. Abe, and T. Suganuma, "A study on heterogeneous network switching time in IoT environments using SDN," in *Proc. IEEE 10th Global Conf. Consum. Electron. (GCCE)*, Oct. 2021, pp. 859–860.
- [23] S. Ibnalfakih, E. Sabir, and M. Sadik, "Multi-homing as an enabler for 5G networks: Survey and open challenges," in *Advances in Ubiquitous Networking 2*, R. El-Azouzi, D. S. Menasche, E. Sabir, F. De Pellegrini, and M. Benjillali, Eds. Singapore: Springer, 2017, pp. 347–356.
- [24] M. Pons, E. Valenzuela, B. Rodríguez, J. A. Nolasco-Flores, and C. Del-Valle-Soto, "Utilization of 5G technologies in IoT applications: Current limitations by interference and network optimization difficulties—A review," *Sensors*, vol. 23, no. 8, p. 3876, Apr. 2023. [Online]. Available: <https://www.mdpi.com/1424-8220/23/8/3876>
- [25] E. U. Ogbodo, A. M. Abu-Mahfouz, and A. M. Kurien, "Enabling LPWANs for coexistence and diverse IoT applications in smart cities using lightweight heterogeneous multihomed network model," *J. Sensor Actuator Netw.*, vol. 11, no. 4, p. 87, Dec. 2022. [Online]. Available: <https://www.mdpi.com/2224-2708/11/4/87>
- [26] I. Chatzistefanidis, N. Makris, V. Passas, and T. Korakis, "ML-based traffic steering for heterogeneous ultra-dense beyond-5G networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2023, pp. 1–6.
- [27] LoRa Alliance. (2022). *LoRaWAN Specification*. Accessed: May 5, 2023. [Online]. Available: <https://tinyurl.com/lwspec11>



RAFAEL FAYOS-JORDAN received the B.S. degree in telematics engineering from the University of Valencia, in 2018, where he is currently pursuing the Ph.D. degree. He is also a Researcher with the School of Computing Engineering and Physical Sciences, University of the West of Scotland. His research interests include the IoT platforms and node management, cloud computing, and network management.



multiresolution techniques for data transmission with the quality of service.

SANTIAGO FELICI-CASTELL received the M.Sc. and Ph.D. degrees in telecommunication engineering from the Polytechnical University of Valencia, Valencia, Spain, in 1993 and 1998, respectively. He is currently an Associate Professor with the University of Valencia, Valencia. He is also a Cisco Systems Certificated Instructor and he has authored over 40 technical papers in international journals and conferences. His research interests include networking, communication systems, and



prestigious journal in the field, he has served as the chair in 20 international flagship conferences, and contributed as a technical program committee member in more than 100 international conferences. On the industrial side, he has more than 50 patents and intellectual property rights. From the leadership perspective, he has significant experience as a Principal Investigator or as Co-Investigator in more than 20 research projects at local, national, and especially at European and international levels. He is the Co-Technical Manager for EU Horizon 2020 projects SELFNET and SliceNet.

JOSE M. ALCARAZ-CALERO (Senior Member, IEEE) is currently a Professor in networks with the School of Engineering and Computing, University of the West of Scotland (UWS). He is an IEEE Senior Member with experience in 5G networks, network slicing, monitoring, automation, and management. On the academic side, he has more than 150 publications in SCI-indexed international journals, conferences, and books. He has been involved in 20 editorial activities in the most



a Visiting Researcher with multiple European research centers. He has coauthored over 90 publications in national and international journals, book chapters, and conferences. He was on the Organizing Committee of several national and international conferences, including the International Workshop on Virtual Acoustics, in 2011. He is a member of the Spanish Acoustics Society and the European Acoustics Association.

JAUME SEGURA-GARCIA received the M.Sc. and Ph.D. degrees in physics from the University of Valencia, Valencia, Spain, in 1998 and 2003, respectively. After completing his Ph.D. degree, he was with the Robotics Institute, University of Valencia, where he was involved in several projects related to intelligent transportation systems. Since 2008, he has been with the Department of Computer Science, University of Valencia, where he is currently an Associate Professor. He has been



involved in the development of wireless technologies for potential application in upcoming physics experiments. He possesses a specialized skill set in hardware and firmware design, which he leverages in his various academic and research endeavors.

ANTONIO CERVELLO-DUATO received the degree (Hons.) in telecommunication electronic engineering and the master's degree in electronic engineering from the University of Valencia, in 2016 and 2017, respectively, where he is currently pursuing the Ph.D. degree. His research interests include significant contributions to the data acquisition path for the tile calorimeter at the ATLAS experiment within the large hadron collider (LHC) with CERN. Moreover, he is

• • •