This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

5G Waveforms for IoT Applications

Ivo B. F. de Almeida[1], Luciano L. Mendes[2], Joel J. P. C. Rodrigues[2,3,4], Mauro A. A. da Cruz[2]
[1] Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Germany
[2] Instituto Nacional de Telecomunicações (Inatel), Santa Rita do Sapucaí-MG, Brazil
[3] Instituto de Telecomunicações, Lisboa, Portugal
[4] Federal University of Piauí (UFPI), Teresina-PI, Brazil
ivobizon@ifn.et.tu-dresden.de, luciano@inatel.br, joeljr@ieee.org, maurocruzter@gmail.com

***Abstract*— In the future, many objects will communicate with each other and with human beings, enabling a vast range of possible services and applications. However, this scenario comes with stringent network requirements. This paper studies and discusses recent technologies that were proposed to achieve the requirements of the Internet of Things (IoT) and massive machine type communications (mMTC). It focuses on their physical layer characteristics and identifies gaps that 5G networks need to address to achieve full connectivity in the IoT scenario. Hence, a detailed tutorial on the possible radio access technologies for 5G networks focusing on IoT use-cases is presented.**

The advanced 5G waveforms discussed are: *i*) orthogonal frequency division multiplexing (OFDM), *ii*) universal filtered multicarrier (UFMC), *iii*) filter bank multicarrier (FBMC), and *iv*) generalized frequency division multiplexing (GFDM). The features that each radio access technology should present to address the main IoT's requirements are emphasized.

***Index Terms*— 5G, PHY layer, Internet of Things, FBMC, GFDM, OFDM, UFMC, wireless communications.**

I. INTRODUCTION

THE deployment of the fifth generation (5G) mobile network is expected to start by 2020 [1]. This new and omnipresent network will represent a significant change in the industry, business, and people's life in general. Coverage, data throughput, latency, and energy efficiency will be enhanced compared to the current fourth generation (4G) system [2]. Therefore, a new range of novel services and applications is yet to emerge. For instance, the Internet of Things (IoT) [3] is a networking paradigm that is promising to change the way technology is experienced in daily life. IoT can be defined as an integration of wired and wireless communication technologies, sensors and actuators that allow users to control and monitor objects (*things*) through the Internet, which also cooperate among themselves [4]. IoT devices will be pervasive, i.e., they will be present in houses, hospitals, streets, parking lots, farms, and factory plants.

Consequently, the connectivity profile will change drastically from what is now experienced in 4G cellular networks, where most connected devices are smartphones that start new data transfers according to the owner's profile.

Forecasts regarding IoT devices state that, by 2020, the connection density will get up to 10^6 devices/km^2 [5]. Hence, the radio access technology must cope with a massive number of heterogeneous devices as well as a high volume of data consumed by smartphones. The 4G network is not prepared to accommodate the envisioned IoT services, although efforts are being made to introduce this type of service with Long Term Evolution (LTE) in most recent releases [6]. For instance, maintaining orthogonality and synchronization among users and radio base stations (RBS) demands a considerable amount of energy. Consequently, battery-powered devices cannot operate for long periods of time without constant battery replacement. This issue represents a significant shortcoming for the IoT scenario [7]. IoT applications are an important motivation for the development of a new mobile network, and it is also one of the major challenges faced by 5G networks.

Regarding 5G's physical layer (PHY) standardization, there is an exciting discussion about the best suited waveform for achieving the required performance among all the scenarios that 5G will address. Figure 1 illustrates the main scenarios and possible applications for 5G. The scenarios include *i*) ultra reliable low latency communications (URLLC), *ii*) enhanced mobile broadband (eMBB), *iii*) extreme remote area communications (eRAC), and *iv*) massive machine type communications (mMTC). URLLC will enable critical services over mobile networks. Hence, it will require overall latency less than 1 ms, ultra accurate device positioning, data rates in the order of 1 Gbps, and 99.999% reliability [8][9]. In general lines, eMBB shall provide very large bandwidth allocation by operating with frequencies in the range of 6–90 GHz, support to device-to-device (D2D) communication, massive multiple input multiple output (MIMO) and data rates up to 10 Gbps [10]. eRAC will play an important role, for example, in precision agriculture, forest fire prevention, environmental monitoring, and precise weather reports [3]. mMTC presents a great challenge for 5G design due to its contrasting requirements. However, IoT represents one of the major design stimuli for 5G networks. Support device density in the order of 1 million devices per km^2, very high energy efficiency for allowing battery-powered devices to remain active for at least 10 years without battery replacement are the primary challenges [11][12]. The 5G standardization is currently a work in progress that will continuously evolve to address all the requirements imposed on the future network. On December 2017, 3GPP approved the non-standalone 5G new radio specifications, where the 4G core is used to provide connectivity management, while the radio access is provided by the new PHY. This version will allow operators to launch 5G enhanced mobile broadband services faster and

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

with less investments [13]. On July 2018, 3GPP presented the standalone 5G new radio specifications, with a 5G core network capable of providing the new 5G services. With the 5G core, other 5G scenarios, such as mMTC and URLLC will become possible [13]. Currently, 3GPP Release 16 is under development, and it will bring new features for the 5G networks, including the TV and radio broadcast capabilities, networking slicing, full IoT support, vehicle-to-everything communication, integration with satellite networks and novel radio techniques. Release 16 will result in the IMT-2020, and is the major input for the complete 5G standardization. Release 16 is expected to be ready by December 2019 [14].

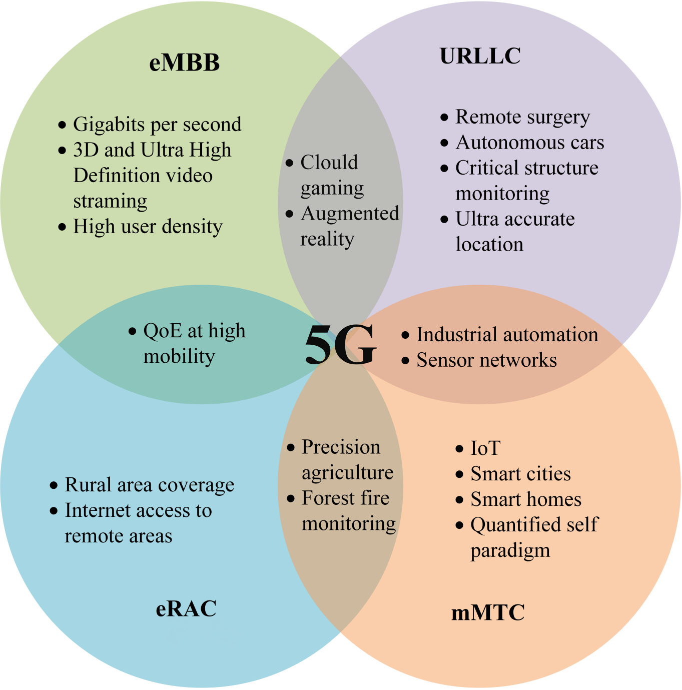

Fig. 1. Expected scenarios for 5G networks.

This tutorial aims to clarify the requirements that 5G PHY needs to fulfill so that connectivity and quality of service (QoS) are achieved in IoT use-cases, i.e., in the mMTC scenario. For further comprehension, this paper maps these requirements as PHY characteristics.

Since 5G and IoT are popular research areas, there are important tutorials about these technologies. In [15], the authors presents a tutorial about the main techniques that can trigger the 5G new services. Also, they present the main challenges for implementing these techniques and show that pre-commercial trials did not reach the 5G goals. However, [15] do not cover the details of the IoT applications and there is no comparison with other technologies regarding this specific use case. In [16], the authors bring an enlightening discussion about the applications of MTC, including its main challenges and promising solutions. In this tutorial, we list the main non-3GPP technologies that can provide IoT service, highlighting their advantages and disadvantages. Additionally, it describes the main waveforms proposed for 5G, discussing how each new modulation scheme can contribute with the IoT over 5G scenario. Therefore, this paper builds a bridge between the current IoT solutions and the future possibilities for the 5G networks.

The main contributions of the paper are the following:

i. Study the IoT scenarios to identify critical requirements, followed by a research on the current technologies that should provide connectivity for IoT;

ii. Presents a discussion on the gaps left by some IoT solutions that 5G networks must cover to unleash the full potential of the mMTC applications;

iii. A review of the state of the art regarding 5G PHY waveform candidates.

The remaining of the paper is organized as follows. Section II presents the main IoT use-cases and its requirements. Section III compares currently proposed techniques to identify the gaps that need to be filled by the 5G mobile networks. Section IV reviews the state of the art on multicarrier modulation techniques that are 5G PHY candidates. Section V discusses the most suitable technique for the IoT scenario based on the studies presented in this paper as well as simulation results. Finally, section VI concludes the paper and suggests further research works.

II. IoT Scenario and Requirements

IoT promises to be a revolution in the telecommunications market by providing Internet connectivity to everyday objects. The vast range of applications and services demand several requirements. In general, the requirements are the following: *(i)* low power consumption that allows battery-powered devices to remain in service for roughly 10 years; *(ii)* low cost devices, which allows a great number of *things* to be purchased without an excessive amount of investment; *(iii)* service availability, for devices to operate anywhere and anytime; *(iv)* low device maintenance, for allowing general users to operate; and *v*) scalability, i.e., the network should cope with the rapid growth in device population [4]. Besides the broad scope of requirements behind the IoT scenario, the 5G PHY will also deal with high data throughput and low latency applications. Since all these competing requirements will not be simultaneously required by a given application, adapting and tailoring the 5G PHY to support the demands from the user on the fly is a key feature of the future mobile network. For this reason, a flexible PHY becomes a vital part of the whole network [7].

Some standards today can partially address the IoT requirements, e.g., IEEE 802.15.4 focusing on the industrial perspective and Bluetooth focusing on the domestic use-cases [17]. More recent technologies, such as low power wide area (LPWA) networks, are becoming attractive due to their availability and low power consumption [17]. Main examples are SigFox and Long Range (LoRa) [18][19]. However, the *ubiquitous* status is still hard to reach with these techniques, since they are not so well established as cellular networks [20][21]. Nevertheless, cellular networks are experiencing a huge increase in the signaling traffic due to the large number of connected devices [22]. Under these circumstances, the possibility of connecting devices that are roughly synchronized by a non-orthogonal waveform decreases the signaling burden and becomes very attractive.

IoT devices are classified as controlling or monitoring devices [23][24]. IoT use-cases can be divided into domestic, industrial, and mission-critical. Domestic objects focus on general users and include commercial products. Even though commercial products are still scarce, they are generally associated with smart houses, enhanced learning, energy monitoring, personal applications, and e-health [4]. Its most relevant requirements are low cost, low maintenance, and battery life span. In addition, due to the *quantified self* paradigm, security and privacy are also a major concern [25]. Industrial IoT and mission-critical IoT present similar specific requirements. On one hand, industrial IoT is focused on providing automation solutions for industries and further increasing workers' security in hazardous factory plants. On the other hand, mission-critical IoT can be used for monitoring essential services or hazardous locations, e.g., nuclear power plants, offshore petroleum extraction platforms, and health-related applications such as inpatient monitoring. These applications demand a higher level of network reliability with packet loss in the order of 10^{-9}, latency in the order at 1 ms, and availability of 99.999% of the time [5].

III. NON 5G TECHNOLOGIES THAT ADDRESS IOT REQUIREMENTS

Several communication technologies have emerged for connecting IoT devices, some are novel and designed for IoT use-cases, and some are already well employed in other scenarios. Such technologies are, namely, Bluetooth 5.0 Low Energy [26], IEEE 802.15.4 [27], LoRa [20], Sigfox [28], WiFi HaLow [29], Narrow band IoT (NB-IoT) [30][31]. Regardless, these technologies are not mature enough or do not attend to all requirements to be used on a enormous scale [12][17].

The PHY of these technologies is discussed, emphasizing the advantages and drawbacks of each technology. Table I summarizes the main PHY characteristics of the aforementioned technologies. Such comparison can be constructive for identifying the technological gaps that 5G networks need to fulfill for the IoT paradigm to become a reality. 5G will not completely replace the technologies presented in this section. Instead, 5G should be an important component of the IoT connectivity scenario. In other words, 5G will complement these technologies in future applications and services.

A. Bluetooth Low Energy

The Bluetooth technology is commonly found in smartphones, cars, wireless mouses, keyboards and earphones. This communication protocol characterizes a personal area network (PAN), and it is designed to provide short distance (approximately 10m) connectivity among devices. However, to expand its territory into the IoT scenario, the standard needed to reduce energy consumption and, therefore, be able to operate with coin-sized batteries [32]. Hence, the Bluetooth Special Interest Group (SIG) added a low energy (BLE) configuration when they released Bluetooth version 4.0 for targeting this market segment [32][33]. Differently from the conventional Bluetooth, BLE is optimized for transmitting short packets of data sporadically.

One of the main differences between conventional Bluetooth and its low energy configuration lies in the PHY. While the conventional has 79 channels with 1 MHz bandwidth, BLE presents 40 channels with 2 MHz bandwidth. In both conventional Bluetooth and BLE these RF channels are divided in two types: advertising and data channels. The advertising channels are used for device discovery, broadcast, and connection establishment, whereas data channels are used for data transmission between the connected devices [26][33]. Also, both operate in the unlicensed industrial scientific medical (ISM) band (2.4 GHz). In the conventional Bluetooth, the modulation technique can vary from Gaussian frequency shift keying (GFSK) to four phase shift keying (4-PSK) and 8-PSK, whereas in BLE only GFSK is used. GFSK presents very low peak-to-average power ratio (PAPR), which translates to low energy consumption, since high efficiency power amplifiers operating close to the 1 dB compression point can be employed [34].

Conventional Bluetooth 4.0 operates in a master-slave configuration, and the network can be configured as a mesh, point-to-point, or broadcast topology. The network formed with a master device and one or more slaves is called a piconet. All the data transfer happens upon the establishment of the piconet. A scatternet is formed by conjunction of one or more piconets. As a result, network scalability can be achieved. However, latency might be in the order of a few seconds due to the mesh network configuration. In BLE 4.0, a slave node cannot connect with more than one master, so only star and point-to-point topologies are possible, which limits its ability to scale.

The latest version, called Bluetooth 5, was proposed by the Bluetooth SIG in 2016 [26]. The focus for improvements in this version was the BLE configuration, while conventional Bluetooth remains roughly the same as previous versions [35]. This newer BLE version presents a two-fold increase in transmission rate, from 1 Mbps to 2 Mbps, and the possibility to increase range with the introduced coded operation mode that operates at 500 kbps [35][36]. Despite the improvements, the BLE 5 still can only operate in star topology, which limits its ability to scale [26]. Nevertheless, efforts by either academia and industry have been made to enable a mesh topology in BLE and, therefore, increasing its changes to be largely employed in the IoT market [37].

B. IEEE 802.15.4

IEEE 802.15.4 defines the medium access control (MAC) and PHY layers [38]. The physical layer operates in different ISM bands according to the region where it is deployed. The 2.4 GHz band is universal, other frequency bands are, e.g., 868 MHz in Europe and 915 MHz in North America.

IEEE 802.15.4 is designed for PANs, and it is mostly employed in embedded systems for agricultural, environmental,

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

TABLE I
PHY CHARACTERISTICS OF THE MAIN TECHNOLOGIES THAT ADDRESS IOT REQUIREMENTS.

Characteristic	Bluetooth 5.0 Low Energy	IEEE 802.15.4	LoRa™	Sigfox®	WiFi HaLow IEEE 802.11ah	Narrow Band IoT
Modulation scheme	GFSK	OQPSK, DQPSK and BPSK	GFSK and a proprietary scheme based on CSS	UL: DBPSK DL: GFSK	M-QAM	GMSK
Coding type	Convolutional FEC	Reed-Solomon FEC	Block FEC	–	Convolutional FEC or LDPC	Turbo
Coding rate	1/2	3/4	4/5	–	1/2, 2/3, 3/4 and 5/6	2/3
Multiple access	FDMA and TDMA	CSMA-CA	Aloha	RFTDMA	RAW	UL: SC-FDMA DL: OFDMA
Maximum data rate	500 kbps (coded) 2 Mbps (uncoded)	1 Mbps	50 kbps	600 bps	78 Mbps	100 kbps
Operating frequency band	ISM	ISM	sub-GHz ISM	sub-GHz ISM	sub-GHz ISM	(i) GSM band (ii) LTE guard-band (iii) LTE in-band
RF channel bandwidth	2 MHz	5 MHz and 2 MHz	125 kHz	100 Hz	1, 2, 4, 8 or 16 MHz	(i) 200 kHz (ii) 180 kHz (iii) 180 kHz
Number of RF channels	40	16 of 5 MHz 10 of 2 MHz	16	1920	26, 13, 6, 3 or 1	1
Transmission technique	FHSS	DSSS and CSS	Single carrier	UNB	OFDM	(i) Single carrier (ii) OFDM (iii) OFDM
Maximum coverage range	18 m (indoor) 150 m (outdoor)	20 m (indoor) 500 m (outdoor)	5 km (urban) 15 km (rural)	10 km (urban) 50 km (rural)	1 km	20 km
Coverage extension	Available through Scatternet	Available through multi-cluster	Not available	Overlapping RBSs	Not available	Not available

Acronyms: RF (radio frequency), GFSK (Gaussian frequency shift keying), FEC (forward error correction), FDMA (frequency division multiple access), TDMA (time division multiple access), ISM (industrial scientific medical), FHSS (frequency hoping spread spectrum), OQPSK (offset quadrature phase shift keying), DQPSK (differential QPSK), BPSK (binary PSK), CSMA-CA (carrier sense multiple access with collision avoidance), DSSS (direct sequence SS), CSS (chirp SS), UL (uplink), DL (downlink), RFTDMA (random frequency time division multiple access), UNB (ultra-narrow band), M-QAM (m-ary quadrature amplitude modulation), LDPC (low-density parity-check), RAW (restricted window access), OFDM (orthogonal frequency division multiplexing), GMSK (Gaussian minimum frequency shift keying), SC-FDMA (single carrier frequency division multiple access), OFDMA (orthogonal frequency division multiple access).

and industrial monitoring [39]. Differently from the IEEE 802.11 family, IEEE 802.15.4 is not focused on high data rates, and differently from Bluetooth, it is not focused on connecting personal devices. It was proposed to be a low cost and energy efficient wireless protocol for resource-constrained sensor networks in large geographical areas.

For example, Zigbee employed IEEE 802.15.4 successfully. The major advantage over the others is that Zigbee is able to operate in a multi-hop configuration. Hence, allowing network scalability [40]. However, as aforementioned, latency may not achieve the desired values due to the network topology.

IEEE 802.15.4 has seven different operation modes defined. From IoT perspective, the modes that lead to low power consumption are offset quadrature phase shift keying with direct sequence spread spectrum (OQPSK-DSSS), differential QPSK with chirp spread spectrum (DQPSK-CSS), and Gaussian frequency shift keying (GFSK) with no spread spectrum technique employed. The maximum data rate for these modes are respectively 250 kbps, 1 Mbps, and 100 kbps [38]. Zigbee operates with low transmission power and duty cycle. However, to the best of authors’ knowledge, a practical estimation of battery consumption in these modes is not available in the literature.

IEEE 802.15.4 operates in the unlicensed ISM band and robustness to interference becomes a challenging issue. However, the spread spectrum techniques used cause low interference in other systems, and also are more immune to interference caused by others [41].

The addition of the Internet protocol (IP) to IEEE 802.15.4 networks can be accomplished by the 6LoWPAN protocol, which is a short term for IPv6 over low power wireless personal networks. 6LoWPAN is a mid-layer protocol placed between the network and MAC layer, i.e., under IPv6 protocol and the IEEE 802.15.4. The 6LoWPAN protocol compresses

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

the overhead necessary to transmit IP packets, thus allowing an efficient transmission and energy savings [39][42].

C. LoRa™

LoRa is classified as Low Power Wide Area Network (LPWAN) technology developed by the Semtech [18][43]. It was proposed in 2015, so it is more recent than Zigbee and Bluetooth. Similarly to them, it operates at a low rate and offers low power consumption. However, differently from the previously mentioned technologies, LoRa (and LPWANs in general) focuses on wide area coverage. LPWANs have coverage much larger than PANs but smaller than cellular networks. The LoRa coverage is around tens of kilometers [19][44]. This feature makes LoRa an interesting option for applications related to smart cities and precision agriculture. Applications that demand higher network throughput might be set aside, since LoRa provides, at maximum, only 50 kbps [19]. Furthermore, practical results have shown that a few million devices can be attended by a single base station [44]. However, the coverage area decreases exponentially as the number of devices increase.

At the physical layer, LoRa uses a proprietary modulation technique based on Chirp Spread Spectrum (CSS) in conjunction with GFSK. The CSS allows a simpler time and frequency synchronization, so less expensive components can be employed. In addition, the CSS based modulation presents inherent robustness to doubly dispersive channels [45]. Another strong point of LoRa’s PHY is that the modulation schemes used present constant envelope. Hence, high-efficiency power amplifiers can be used, and energy consumption is optimized. However, the 50 kbps rate can only be achieved with GFSK. The maximum data rate with the CSS modulation is 11 kbps [46].

D. Sigfox®

Sigfox is also classified as a LPWAN and it operates in an ultra narrow band configuration. In contrast with LoRa, Sigfox is a proprietary scheme and, therefore, with closed documentation. Consequently, very little information is available to the community. Nonetheless, some information about its PHY can be found in [28][47].

The operating frequency band is 868 MHz in Europe and 915 MHz in the United States. The multiple access technique is asynchronous, so there is no energy expenditure with synchronization between device and RBS. For establishing a connection, the device transmits three consecutive messages. Each message is transmitted over different time and frequency slots that are randomly chosen. This is an example of paradigm change in the multiple access technique, and it has made Sigfox an interesting solution for IoT connectivity. Another key point is that the reception is based on a cooperative scheme. Any RBS can receive messages from the transmitting devices. This reception diversity translates in to a better quality of service. Sigfox has created a communication protocol based entirely on IoT requirements, and it is the one that has given one step further to realize the envisioned IoT paradigm.

E. WiFi HaLow

WiFi HaLow is part of the WiFi family and it is specified by the standard IEEE 802.11ah. Similarly to the aforementioned technologies, it offers a long range, low power, and low rate solution to connect a huge number of devices. In contrast, IEEE 802.11ah presents a more complex PHY. It supports modulation indexes up to 256-QAM that are transmitted using orthogonal frequency division multiplexing (OFDM), and multiple input multiple output (MIMO) is present in both downlink and uplink [48][49]. Therefore, the maximum data rate is 78 Mbps when the channel bandwidth is set to 16 MHz and the modulation index is set to 256. Since it operates at unlicensed frequencies below 1 GHz, the coverage ranges from 100 m to 1 km [50].

F. Narrow Band IoT

Different from all mentioned techniques, Narrow Band IoT (NB-IoT) is the only solution based on cellular networks. For this reason, it presents a large coverage area and a higher level of reliability, due to the dedicated spectrum band. NB-IoT is one of the systems that are called pre-5G or 4.5G. For instance, it is totally dedicated to connect IoT devices on a large scale, and it represents a major step towards the conjunction between cellular technologies and IoT. It was proposed in LTE Release 13 by the 3rd Generation Partnership Project (3GPP) in 2015 [51]. NB-IoT can be employed in three different configurations: *(i) stand-alone*, where it can transmit data over one GSM channel with 200 kHz bandwidth, *(ii) guard-band*, where carriers are placed inwards the LTE guard band occupying the bandwidth of one Resource Block (RB) (180 kHz), and *(iii) in-band*, where one RB is assigned for the IoT device to operate within the LTE bandwidth [52]. As NB-IoT stand-alone mode will operate in the GSM bandwidth, an efficient re-farming of GSM’s band is possible, and this ensures coexistence with legacy and present systems [30].

NB-IoT proposes improved indoor coverage and supports up to 52547 devices per cell [53], and battery life span of approximately 10 years with a 5 Wh battery if the devices transmit every 2 hours a 200 bytes message with 33 dBm output power [51]. As an illustration, a 5 Wh battery means that a device should operate with approximately 6 CR2032 batteries [54]. The latency can get up to 10s [55]. Although 5G requirements are more strict, NB-IoT is also one step forward in providing connectivity for IoT devices.

G. Limitations of the Available IoT Connectivity Technologies

The 5G cellular network will not completely replace the technologies presented in this section. Instead, they should be an important part of the IoT connectivity scenario. In other words, 5G will supplement these technologies for making real the future applications and services.

Technologies that are already available present interesting solutions for IoT connectivity. However, they present drawbacks that hinder IoT full connectivity. In particular, Bluetooth and IEEE 802.15.4 employ modulation techniques that are known for the low energy consumption a fairly good data rate

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

for IoT standards, but they lack in coverage area. Wifi HaLow presents a complex PHY structure compared to its competitors, which enables 1 km coverage area and the highest data rate. However, the OFDM employment in the PHY demands high energy consumption due to the strict synchronism needed and the high PAPR. Likewise, NB-IoT suffers from the same OFDM shortcomings. LPWANs have presented an attractive approach, trading data rate for coverage comparable to cellular networks and low energy consumption. These technologies fall short in terms of reliability since they operate in the unlicensed ISM bands.

Given these points, one can notice that some 5G should provide enough coverage for addressing IoT smart farming use-cases while employing techniques that are energy efficient. In addition, the scalability and reliability of the licensed spectrum is necessary.

IV. WAVEFORM CANDIDATES FOR 5G PHY

This section presents an overview of the main candidates for 5G PHY, highlighting its drawbacks and improvements over the current 4G technique. Comparisons will be performed in terms of OOB emission, energy efficiency, complexity, efficiency considering short packet transmission, and latency. Equally, the study compares the PHY from the technologies presented in Section III with the 5G candidates. Table II summarizes the desired characteristics of the 5G PHY waveform and their relation with the IoT connectivity scenario.

TABLE II
WAVEFORM'S CHARACTERISTICS AND CORRESPONDENT IOT BENEFITS.

Waveform characteristic	IoT benefit
Low out-of-band (OOB) emission	· Spectrum holes occupancy · Efficient spectrum usage
Low PAPR	· Low power consumption · 10+ years battery life span
Efficiency in short packet transmission	· Low latency · High density of devices
Low complexity	· Low cost devices
Rough synchronization	· Low cost devices · Low power consumption · High density of devices

A. Orthogonal Frequency Division Multiplexing

OFDM is the current waveform employed in LTE PHY. It has been extensively studied and widely deployed in wired and wireless communication systems, e.g., IEEE 802.11n (WiFi) [56] and Asynchronous Digital Subscriber Line (ADSL) [57]. Indeed, OFDM is a robust multicarrier technique that has become attractive because of its low complexity. However, due to the wide range of requirements of 5G networks, some OFDM characteristics hinder the use of this waveform in future mobile networks [58]. Consequently, new multicarrier techniques, as well as improvements to OFDM, are being recently studied.

So far, CP-OFDM will remain active in 5G non-standalone systems, which will be operating in the current 4G frequency bands [59]. This part of the 5G will enable the EMBB case, giving users a glimpse of what is yet to come in the future standalone 5G. OFDM lacks performance to be deployed as the only 5G radio access technology that can address all the 5G scenarios. The research trend related to other scenarios is to leave behind the strict synchronism and find a trade-off between interference, complexity, and cost [1][7][60].

In the OFDM system, parallel streams of data are transmitted by orthogonal subcarriers, so no intercarrier interference (ICI) is observed. Therefore, if proper synchronism is achieved, a user remains orthogonal to others. The modulation procedure is carried out through an inverse fast Fourier transform (IFFT) at the transmitter side. Demodulation is then accomplished using the FFT. For this reason, zero forcing equalization can be easily done in the frequency domain since it will be a simple scalar inversion [61]. Hence, OFDM is a simple choice when compared to recently proposed waveforms for 5G. Figure 2 illustrates the OFDM transceiver diagram.

To protect the OFDM symbol against multipath propagation impairments, a copy of part of the end of the symbol is placed at its beginning. This copy is called a cyclic prefix (CP). By doing so, the channel does not ruin the orthogonality among subcarriers, and a simple equalization procedure can be accomplished. Even though CP protects the OFDM symbol, it also causes a reduction in the spectral efficiency since it does not contain useful user information. In the perspective of short packet transmission, i.e. low latency, the CP means low efficiency in resource utilization since the size of an OFDM symbol could be the same as the CP size [62]. Nonetheless, the CP size is proportional to the channel's delay profile, and in applications such as smart farming, where the distance between devices and base stations is tens of kilometers, the CP can become larger than the useful information. Figure 3 exemplifies a hypothetical scenario where the OFDM symbol is the same length as the CP.

Interference among users, i.e., ICI, is not observed if orthogonality is maintained through strict synchronism. Any user using different subcarriers remains orthogonal to others if proper synchronism is achieved. If synchronism is not satisfied, devices will suffer from self interference, as well as interference with other users. Thus, from IoT's perspective, lots of energy will be spent until the synchronization process is finished, and 10 years battery life span will be impracticable. In addition, OFDM shows high peak-to-average ratio (PAPR), which means that low-efficiency amplifiers must be used [63]. From IoT's perspective, this leads to high battery consumption. However, when the synchronization process is finished a simple zero-forcing frequency domain equalizer can be used for canceling the multipath channel effect [61].

Furthermore, data symbols are shaped with a rectangular filter in the time domain, so subcarriers will be *sinc* shaped in the frequency domain. As a result, undesired levels of out-of-band (OOB) emission are observed [64].

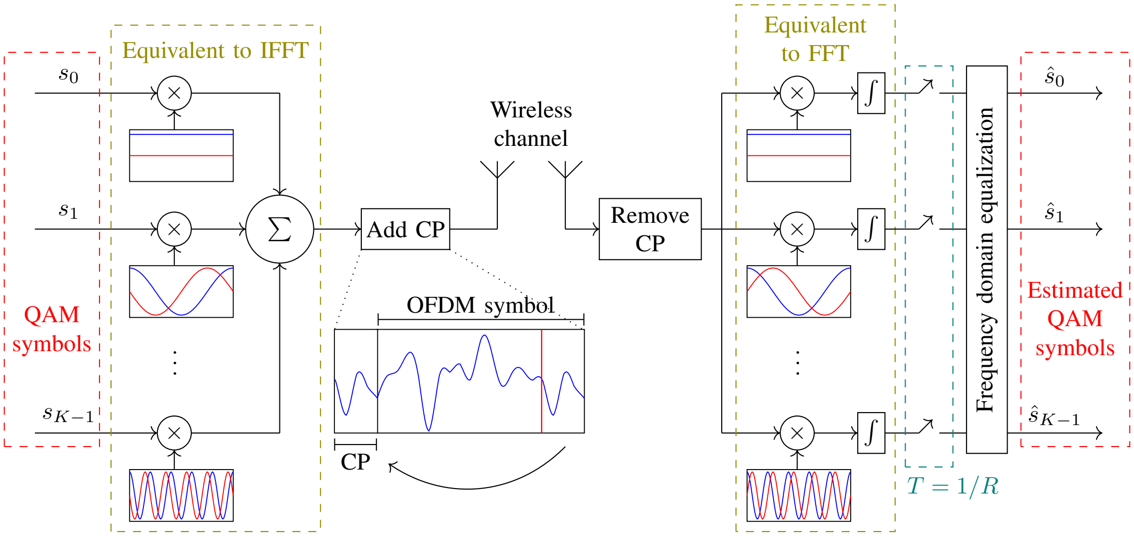

Fig. 2. Illustration of the OFDM transceiver diagram.

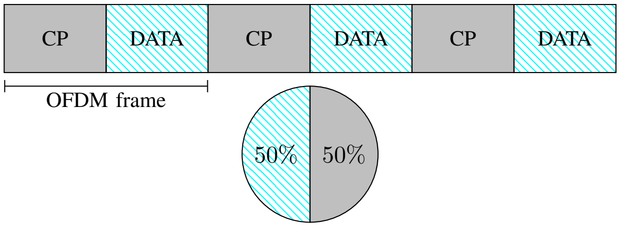

Fig. 3. Low efficiency in short packet transmission due to CP in the OFDM frame structure.

B. Filter Bank Multicarrier

FBMC was first proposed by Saltzberg [65] and Chang [66], in 1967, and it was rediscovered as an alternative PHY for future radio access by Bellanger [67]. It is a multicarrier modulation technique where orthogonality between all the subcarriers is not strictly maintained. There are different schemes to construct the pair modulator demodulator. In this paper, it is presented the FBMC-STM (Staggered Modulated Multi-tone) with the use of offset QAM (OQAM). This scheme uses a prototype digital FIR (Finite Impulse Response) filter to obtain the filter bank structure. Each filter is shifted in frequency, allowing subcarriers to occupy the available bandwidth. Half Nyquist prototype filters with good frequency localization are preferred since they do not cause ISI at the sampling instant and minimize the intrinsic ICI between subcarriers [68][69]. A pulse with good time-frequency localization means that it is well contained both in time and frequency domains.

Figure 5 shows a set of subcarriers in the frequency domain, and it is possible to see that ICI only happens between neighboring subcarriers due to good frequency localization of the prototype filter. Hence, orthogonality between neighboring subcarriers must be ensured. For the sake of comparison, OFDM must ensure orthogonality among all subcarriers. This is a key attribute of FBMC, since relaxing orthogonality constrains leads to better time-frequency localization and diminishes the interference caused by transmissions from asynchronous users [67].

In order to solve this neighboring ICI problem, OQAM comes into play. The imaginary and real parts of the data symbols are shifted by $T/2$, where T represents the data symbol time, and a $\pi/2$ phase rotation between adjacent subcarriers is also introduced. Thus, the subcarriers with even index carry the real part, and odd indexed subcarriers carry the imaginary part of the data symbol. No interference is observed in time or frequency domain, and the maximum spectral efficiency can be achieved. This arrangement is called FBMC-OQAM [69].

A possible implementation of the FBMC-OQAM transceiver structure is shown in Fig. 4. For the FBMC notation, let K represent the total number of subcarriers, $d_{k,m}$ the complex QAM data symbol that is transmitted over the kth subcarrier in the mth time-slot and $g_{k,m}[n]$ the synthesis/analysis filters. The discrete-time FBMC-OQAM transmit signal is obtained by

$$x[n] = \sum_{m=-\infty}^{+\infty} \sum_{k=0}^{K-1} \Re\left\{d_{k,m}\right\} g_{k,m}^{(\mathcal{I})}[n] + j \sum_{m=-\infty}^{+\infty} \sum_{k=0}^{K-1} \Im\left\{d_{k,m}\right\} g_{k,m}^{(\mathcal{Q})}[n], \quad (1)$$

where $g_{k,m}^{(\mathcal{I})}[n]$ and $g_{k,m}^{(\mathcal{Q})}[n]$ are respectively given by

$$g_{k,m}^{(\mathcal{I})}[n] = p\left[n - mK\right] \exp\left(j2\pi \frac{k}{K} n + j\frac{\pi}{2} k\right) \quad (2)$$

$$g_{k,m}^{(\mathcal{Q})}[n] = p\left[n - \left(m + \frac{1}{2}\right) K\right] \exp\left(j2\pi \frac{k}{K} n + j\frac{\pi}{2} k\right), \quad (3)$$

where $p[n]$ is the prototype filter impulse response. The received signal passes through the analysis filter bank, and

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

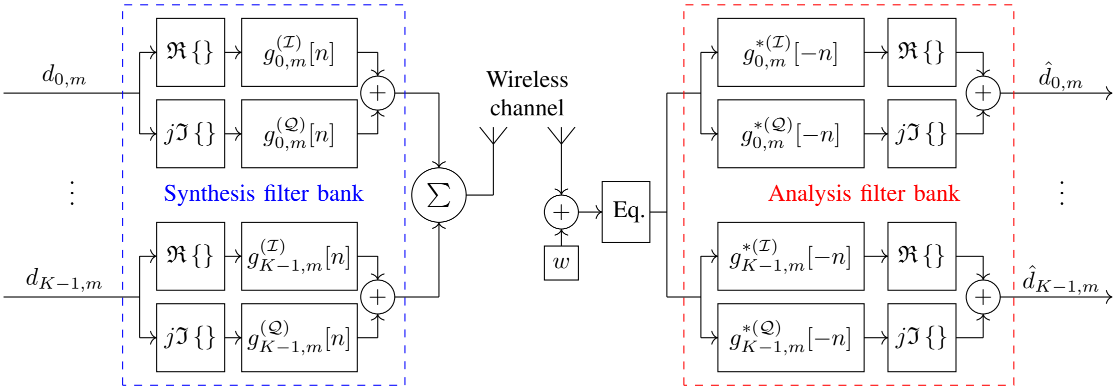

Fig. 4. Illustration of the FBMC-OQAM transceiver diagram.

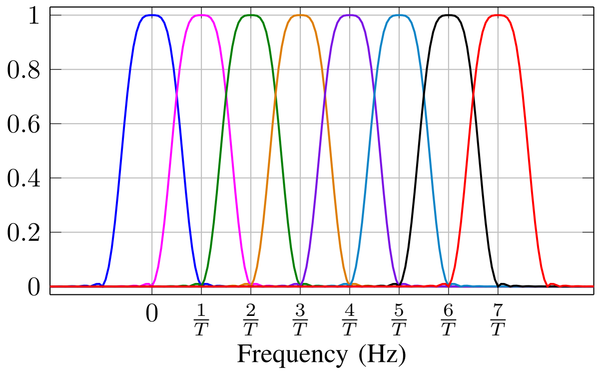

Fig. 5. Set of FBMC subcarriers in frequency domain emphasizing the interference between neighboring subcarriers.

the estimated data symbols $\hat{d}_{k,m}$ are obtained. The complex conjugate operation is represented by $(\cdot)^*$.

The main advantages of FBMC-OQAM schemes are spectral efficiency and low OOB emission. The spectral efficiency can be considered 1 if a long stream of data is to be transmitted. However, FBMC-OQAM employs a linear filtering procedure for shaping data symbols. Consequently, for short packet transmission, the ramp-up and ramp-down of the filters leads to lower spectral efficiency since during that time no useful data is transmitted. Hence, FBMC-OQAM might not be the best option for sporadic sensor data transmission that transmits small packets of collected data. On the other hand, the linear filtering also leads to very low OOB emissions, so it leads to lower interference levels even when roughly synchronized devices are sharing subcarriers in operation. Therefore, devices can save energy be completing a simpler synchronization procedure.

C. Generalized Frequency Division Multiplexing

GFDM is somewhat similar to FBMC in the sense that it is also based in filter bank theory, and it is built upon a prototype filter response. However, GFDM implements circular filtering to shape the data symbols [70]. As the waveform presents a circular behavior, CP can be used to protect the multicarrier symbol against multipath propagation impairments.

At the GFDM transmitter, data symbols modulate the filters across a time-frequency lattice. This operation can be represented by a matrix multiplication yielding to

$$\mathbf{x} = \mathbf{A}\mathbf{d}, \tag{4}$$

where $\mathbf{x}$ represents the transmit vector before the CP addition, $\mathbf{d}$ represents the complex-valued data symbol vector with N elements, and $\mathbf{A}$ represents the transmit matrix with size $N \times N$. The transmit matrix, or modulation matrix can be obtained by circularly shifting the prototype filter to the kth subcarrier and to the mth subsymbol. Thus, $\mathbf{A}$ is composed by N versions of the prototype filter which yields to

$$\mathbf{A} = [\mathbf{g}_{0,0}\ \mathbf{g}_{1,0} \cdots \mathbf{g}_{K-1,0}\ \cdots\ \mathbf{g}_{0,M-1} \cdots \mathbf{g}_{K-1,M-1}], \tag{5}$$

where $\mathbf{g}_{k,m}$ represents the vector which contains samples from the circularly shifted prototype filter. Figure 7 shows the absolute value of the GFDM modulation matrix. As one can see a GFDM frame carries $N = KM$ complex valued data symbols, where K represents the total number of subcarriers and M the total number of subsymbols. The GFDM transceiver diagram is described by Fig. 6 [62].

In principle, GFDM subcarriers are not orthogonal to each other. As a consequence, they may exhibit intrinsic ICI and ISI depending on the prototype filter and on the demodulation method [71]. At the receiver side, transmitted data symbols are retrieved from the received vector also by a matrix operation given by

$$\hat{\mathbf{d}} = \mathbf{B}\mathbf{y}_{\text{eq}}, \tag{6}$$

where $\hat{\mathbf{d}}$ represents the estimated data symbols, $\mathbf{B}$ the demodulation matrix and $\mathbf{y}_{\text{eq}}$ the equalized received vector.

Three demodulation techniques are described in the literature. The zero forcing solution is able to cancel intrinsic ICI and ISI from non-orthogonal prototype filters. However, it generates the noise enhancement effect due to the non-contained frequency response of this demodulation matrix. The matched filtering solution is able to cancel intrinsic ISI if the prototype filter is half-Nyquist, and it maximizes the signal to

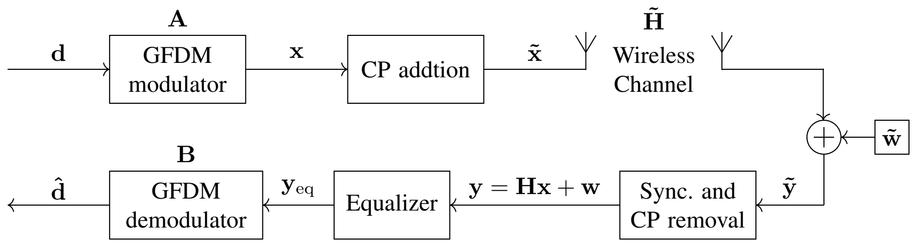

Fig. 6. Illustration of the GFDM transceiver diagram.

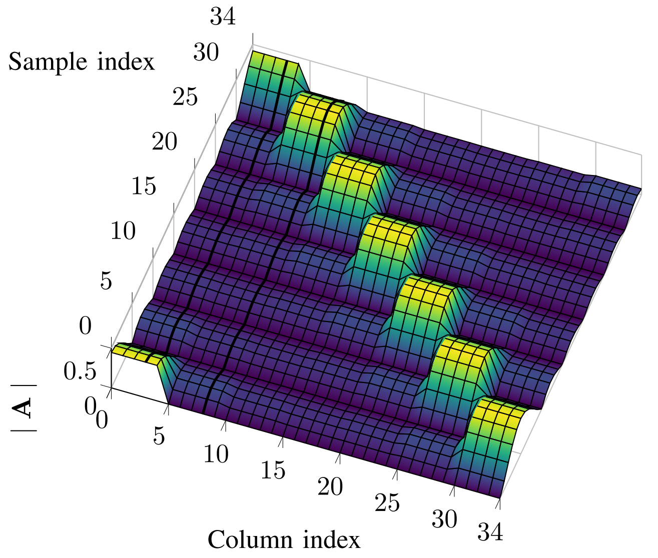

Fig. 7. Absolute value of the modulation matrix for $M = 7$ subsymbols, $K = 5$ subcarriers and Dirichlet pulse as prototype filter.

noise ratio at the sampling instants. However, it is not able to cancel intrinsic ICI. The minimum mean square solution is able to cancel intrinsic interferences while keeping a low level of noise enhancement since it takes into consideration the noise statistics. Additionally, it takes into consideration the channel statistics, so no previous equalization is necessary for estimating the transmitted data symbols from the received signal. These demodulation matrices are respectively given by

$$\mathbf{B}_{\text{ZF}} = \mathbf{A}^{-1} \tag{7}$$

$$\mathbf{B}_{\text{MF}} = \mathbf{A}^{\text{H}} \tag{8}$$

$$\mathbf{B}_{\text{MMSE}} = \left(\mathbf{R}_w + \mathbf{A}^{\text{H}}\mathbf{H}^{\text{H}}\mathbf{H}\mathbf{A}\right)^{-1} \mathbf{A}^{\text{H}}\mathbf{H}^{\text{H}}, \tag{9}$$

where $(\cdot)^{\text{H}}$ represents the Hermitian conjugate transpose operation and $\mathbf{R}_\mathbf{w} = \sigma^2\mathbf{I}_N$ represents the covariance matrix of the noise vector whose variance is represented by σ^2. $\mathbf{I}_N$ is an identity matrix of size $N \times N$.

OQAM can be used in combination with GFDM for dealing with intrinsic ICI, and further enhance GFDM's flexibility [73]. Even though OOB emission is reduced when compared to OFDM due to more a contained filter in frequency domain, abrupt transitions between GFDM frames lead to elevated OOB emissions. However, as demonstrated in [74] windowing can be used to achieve lower OOB emissions. Furthermore, the same low OOB emission of FBMC-OQAM can be achieved with GFDM by zero padding the prototype filter as shown in [75]. Therefore, GFDM presents the same benefits of FBMC-OQAM when it comes to low interference.

Low latency scenarios can benefit from the GFDM frame structure since different subsymbols can be addressed to different devices. Hence, it becomes an attractive alternative for mission-critical IoT applications where latency is an important metric. Moreover, it can be employed in coexistence with 4G signals [76].

D. Universal Filtered Multicarrier and Filtered OFDM

UFMC and F-OFDM can be thought as a compromise between OFDM and FBMC. In particular, FBMC uses a well located filter to filter each subcarrier, whereas OFDM implicitly applies a rectangular to filter each subcarrier. It is important to point out that although rectangular filters have good localization in time domain, they present poor localization in frequency domain, i.e., strong OOB emission. UFMC and F-OFDM apply the filtering over a block of subcarriers, i.e, subband wise. The size of this block can vary or can be set to a specific value, e.g., each block is composed by 12 subcarriers.

Differently from UFMC, F-OFDM filters the entire band occupied by a OFDM signal. Therefore, the main difference between UFMC and F-OFDM lies in the size of the filter band. UFMC employs a filter with a tail size comparable to the channel's delay profile. It is important to point out that the UFMC symbols do not cause ISI due to the filter tails. Therefore, the filter tail serves the same function as the CP in OFDM systems.

On the other hand, F-OFDM employs filters that overlap in time domain, so ISI among multicarrier symbols occurs and a CP is necessary for avoiding harmful ISI. This filters lead to lower OOB emissions when compared to UFMC [72]. However, CP must be inserted for ensuring interference free transmission [77]. In both systems, the OOB emission is attenuated when compared to OFDM. However, not as much as FBMC since it uses subcarrier filtering.

Figure 8 illustrates the UFMC transceiver block diagram. At the transmitter, a set of complex-valued data symbols represented by s_k are divided into B blocks, and inserted at a N-point IFFT. Then, each subband is independently filtered. The length of the filter can be chosen based on a trade-off, i.e.,

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

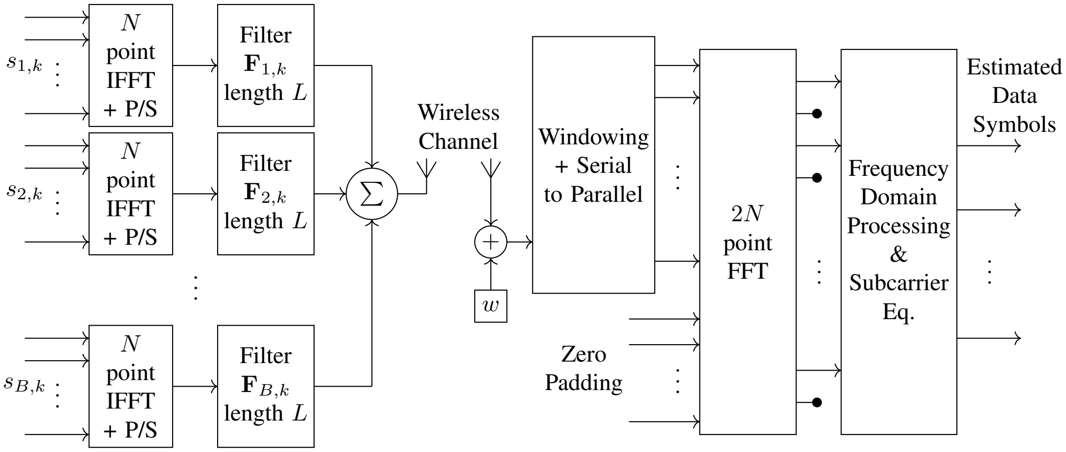

Fig. 8. Illustration of the UFMC transceiver diagram [72].

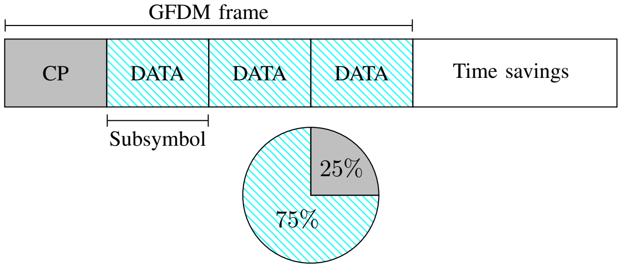

Fig. 9. GFDM symbol structure to achieve efficient low latency transmissions.

longer filters will lead to lower levels of OOB emission and robustness to frequency misalignment. On the other hand, short filters will lead to shorter multicarrier symbols, and therefore smaller latency [78].

V. WAVEFORM EVALUATION FOR THE IOT SCENARIO

The possibility of operating with relaxed orthogonality without major performance degradation is the main advantage that FBMC brings to IoT scenario. For instance, this characteristic allows rough synchronized users/devices to transmit without causing excessive interference to others [79]. However, FBMC falls short in terms of efficiency in the transmission of short data packets. Due to the linear filtering process involved, there is a ramp-up and ramp-down time of the filters, so in a small period of time it is not transmitting any useful data, and the transmission efficiency is reduced. If packets occupy more or less the same time as the ramp-up plus ramp-down, efficiency falls down to around 50% [80]. Since the FBMC waveform is generated by a linear filtering procedure, there is no reason to put a CP at the beginning of a symbol for protecting the transmit signal against interference caused multipath propagation. Therefore, this technique shows a more efficient use of time resources than OFDM if a long of stream data is transmitted [81]. It is also important to point out that due to the low out of band emission, FBMC suits the requirements to occupy spectrum holes, or television whites spaces (TVWS). Thus, allowing an efficient allocation of the fragmented spectrum [67]. Another drawback, unfortunately common to all the candidates, is the high PAPR [58].

Conversely, the GFDM circular filtering needs the CP at the beginning of the GFDM symbol to protect it against multipath propagation impairments. However, the CP that would protect K data symbols in OFDM will protect KM data symbols in GFDM. Meaning that GFDM presents a more efficient way to allocate time-frequency resources than FBMC considering short packet transmission, and OFDM [74]. GFDM shows a great deal of flexibility by being able to change its parameters according to the requirements. The core of 5G’s flexibility could be a software-defined waveform that will change its configurations depending on a software defined base station. GFDM waveform can be deployed as a framework to obtain the performance of other multicarrier techniques. For instance, GFDM can be used to generate OFDM and FBMC variations by changing its configuration parameters, such as the number of subsymbols (M), subcarriers (K), and prototype filter. As an example, GFDM’s modulation matrix (Fig. 7) has a circular filtering behavior. If the modulation matrix is changed to have a linear filtering behavior, the performance is then comparable to FBMC. Therefore, all the benefits that FBMC shows are possible to be obtained by GFDM. Since each GFDM subsymbol corresponds to one OFDM symbol, the subsymbol can be smaller than an OFDM symbol, and still have the same spectral efficiency. Hence, as the latency at the physical layer is dependent on the frame size, the system’s latency can be improved [74]. Fig. 9 shows a GFDM symbol configuration where better spectral efficiency and very low latency can be achieved when compared to OFDM.

Fig. 10 shows the power spectral density comparison between OFDM, FBMC, GFDM, and UFMC. FBMC presents

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

the lowest OOB emission, and therefore it is the candidate for roughly synchronized users since it will cause the least amount of interference in adjacent bands, i.e., other users. To compare the waveforms, we have used the root raised cosine filter with $\beta = 0.1$, $M = 9$ subsymbols, and $K = 128$ subcarriers for GFDM. For FBMC, the PHYDYAS [68] filter was used as a prototype filter, and the number of subcarriers was set to 128 as well. For Windowed GFDM, a cosine window was applied. OFDM and UFMC also have 128 subcarriers.

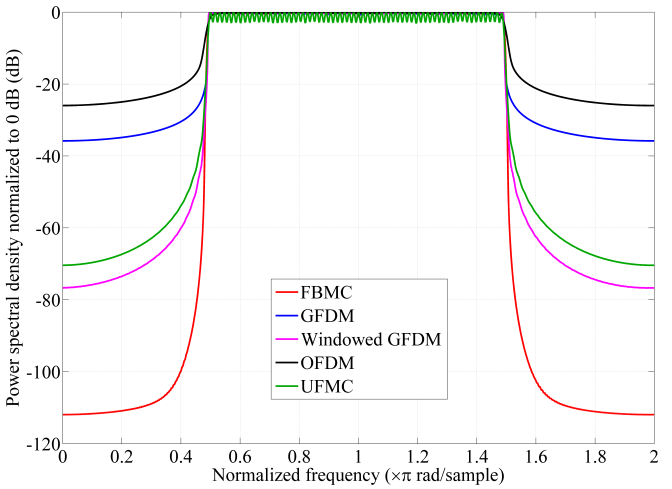

Fig. 10. Power spectral density comparison between 5G waveform candidates.

In UFMC, a post-sub-band filtering aims to reduce the pronounced OOB emission of OFDM [82]. The number of subcarriers within a sub-band can be chosen according to the requirements. The main advantage upon other candidates is the low complexity and easy system migration, since it is based on the current LTE radio access technology. As an example, for LTE compatibility it can be set equivalently to the smallest possible resource allocation of LTE’s resource grid, a resource block (RB), which is composed by 12 OFDM subcarriers [83]. When compared to FBMC in terms of latency, UFMC shows advantages. Since UFMC deploys the filtering operation in a group of subcarriers, the filter is broader in frequency, and shorter in time. As a result, the block size is shorter, and latency is reduced [64]. In comparison to GFDM, UFMC does not show intrinsic interference within one sub-band allowing a simpler receiver design. In general, the UFMC transceiver design is less costly in terms of computational complexity than GFDM [72].

An improvement to UFMC has been recently proposed in [84]. In the proposed scheme, the filtered sub-band size can change according to the user’s need, i.e., if the user needs several RBS, then, the filtering process occurs within this allocated band. As a result, the user’s computational processing burden is lightened. Therefore, energy consumption can be reduced at the user’s terminal. In addition, the reduced filter length leads to a lower latency when more than one RB is allocated.

Given these points, Table III presents a summary of the main characteristics of the waveform candidates [77][85][86]. The row that compares the OOB emission of the waveforms can be further comprehended with the help of Fig. 10.

VI. FINAL REMARKS AND FUTURE RESEARCH

The availability and reliability required by some critical IoT applications go against the desired 10 years battery life span of other more relaxed IoT applications. Thus, defining an approach for the PHY that fits all the IoT scope becomes challenging. This paper has shown that recent technologies present attractive solutions to address the IoT requirements. As shown, these technologies will not be totally replaced by the 5G cellular network since some of the current technologies employ drastically different PHY techniques from the 5G PHY candidates. Moreover, this paper presented an overview of 5G PHY capabilities to enable the IoT connectivity through the future 5G mobile network. The range of requirements that IoT scenario imposes goes, for example, against the requirements of high throughput scenarios. Consequently, flexibility at the physical layer is a vital characteristic to address such diversity. In such a manner, IoT power constrained devices and high data consuming smartphones can operate under the same network.

Alternative PHY techniques for 5G networks have been extensively studied in recent literature. UFMC presents an attractive ease evolution from the current system and also some benefits regarding roughly synchronized devices. FBMC shows interesting attributes regarding connectivity of rough synchronized devices allowing low battery consumption. Also, FBMC’s low out of band emission allows operation in fragmented spectrum. GFDM’s main advantages are flexibility, the most efficient use of the CP in short packet transmissions, and low latency. In addition, if prototype filters with good frequency localization are used, the synchronization exigency is lighted which translates to battery savings. GFDM can also present the benefits of other multicarrier techniques at the expense of transmitter/receiver complexity increase. As shown, the requirements for different 5G scenarios go against each other in some cases, so flexibility at the PHY becomes essential. Accordingly, finding approaches to increase energy efficiency and to diminish PAPR in multicarrier waveforms are important requirements that need to be satisfied for successfully employ 5G networks as the main gateway for IoT applications. For instance, predistortion techniques that aim to increase the linearity of power amplifiers lead to energy savings. Likewise, the complexity for transmitting and especially receiving such complex waveforms needs to be addressed for simple 5G transceiver design. To elaborate a flexible PHY that is able to modify itself for optimizing predetermined requirements remains an open issue. Research in real-life IoT environments should be conducted to confirm the best waveform choices for 5G. Thereupon, IoT objects should be connected through these novel waveforms, how and which one will be determined in the future 5G standard.

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

TABLE III
COMPARISON AMONG WAVEFORM CANDIDATES FOR 5G

Characteristic	OFDM	FBMC	GFDM	UFMC	F-OFDM
Mapping scheme	QAM	OQAM	QAM and OQAM	QAM	QAM
Orthogonality	Orthogonal	Orthogonal in the real domain	Non-orthogonal	Orthogonal inside subband	Orthogonal inside subband
Prototype filter	Rectangular	Half Nyquist	Arbitrary	Rectangular	Rectangular
Prototype filter convolution	Cyclic	Linear	Cyclic	Cyclic	Cyclic
Subband filter	Not existent	Not existent	Not existent	Typically Dolph-Chebyshev	Typically Raised Cosine
Subband filter bandwidth	Not existent	Not existent	Not existent	Arbitrary	Typically entire band
Subband filter convolution	Not existent	Not existent	Not existent	Linear	Linear
Out-of-band emission	Worse due to cyclic rectangular filtering	Best due to linear filtering	Limited due to cyclic filtering	Depends upon the subband filter	Depends upon the subband filter
OOB emission @ 0.2π rad/sample in Fig. 10	-28dBc	-112dBc	-37dBc	-72dBc	-72dBc
Symbol length	Data packet + CP	Typically $4\times$ data packet	Data packet + CP	Data packet + Filter length -1	Data packet + CP + Filter length -1
Cyclic prefix	Yes	No	Yes	No	Yes
Advantages for IoT	Simple transceiver structure	Robustness to asynchronous interference	Flexibility and low latency	Robustness to asynchronous interference and low latency	Simple transceiver structure

ACKNOWLEDGMENTS

This work was supported by national funding from the FCT - *Fundação para a Ciência e a Tecnologia*, through the UID/EEA/50008/2019 Project; by the Brazilian National Council for Research and Development (CNPq) via Grant No. $309335/2017-5$; FADCOM - *Fundo de Apoio ao Desenvolvimento das Comunicações*, presidential decree n° 264/10, November 26, 2010, Republic of Angola; by RNP, with resources from MCTIC, Grant No. 01250.075413/2018-04, under the *Centro de Referência em Radiocomunicações* – CRR project of the *Instituto Nacional de Telecomunicações* (Inatel), Brazil; and by RNP with resources from 5G-RANGE BR-EU project.

REFERENCES

[1] M. Agiwal, A. Roy, and N. Saxena, “Next generation 5G wireless networks: A comprehensive survey,” *IEEE Communications Surveys Tutorials*, vol. 18, no. 3, pp. 1617–1655, thirdquarter 2016.

[2] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, “What will 5G be?” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[3] P. Sethi and S. R. Sarangi, “Internet of things: architectures, protocols, and applications,” *Journal of Electrical and Computer Engineering*, vol. 2017, 2017.

[4] L. Atzori, A. Iera, and G. Morabito, “The internet of things: A survey,” *Computer networks*, vol. 54, no. 15, pp. 2787–2805, 2010.

[5] Ericsson, “5G Systems,” *White paper*, 2017.

[6] 3rd Generation Partnership Project, *Release 14*, 2017. [Online]. Available: http://www.3gpp.org/release-14

[7] G. Wunder, P. Jung, M. Kasparick, T. Wild, F. Schaich, Y. Chen, S. T. Brink, I. Gaspar, N. Michailow, A. Festag, L. Mendes, N. Cassiau, D. Ktenas, M. Dryjanski, S. Pietrzyk, B. Eged, P. Vago, and F. Wiedmann, “5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 97–105, February 2014.

[8] G. P. Fettweis, “The tactile internet: Applications and challenges,” *IEEE Vehicular Technology Magazine*, vol. 9, no. 1, pp. 64–70, March 2014.

[9] S. Zhang, X. Xu, Y. Wu, and L. Lu, “5G: Towards energy-efficient, low-latency and high-reliable communications networks,” in *2014 IEEE International Conference on Communication Systems*, Nov 2014, pp. 197–201.

[10] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, “A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges,” *Wireless Networks*, vol. 21, no. 8, pp. 2657–2676, Nov 2015. [Online]. Available: https://doi.org/10.1007/s11276-015-0942-z

[11] Ericsson. (Accessed: 03/06/2018) 5G radio access – capabilities and technologies. [Online]. Available: https://www.ericsson.com/assets/local/publications/white-papers/wp-5g.pdf

[12] M. R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, “Internet of things in the 5G era: Enablers, architecture, and business models,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 510–527, March 2016.

[13] 3rd Generation Partnership Project, *Release 15*, 2019. [Online]. Available: http://www.3gpp.org/release-15

[14] ——, *Release 16*, 2019. [Online]. Available: http://www.3gpp.org/release-16

[15] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. D. Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, “5G: A tutorial overview of standards, trials, challenges, deployment, and practice,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 6, pp. 1201–1221, June 2017.

[16] Y. Cao, T. Jiang, and Z. Han, “A survey of emerging M2M systems:

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, "5G Waveforms for IoT Applications," in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

Context, task, and objective," *IEEE Internet of Things Journal*, vol. 3, no. 6, pp. 1246–1258, Dec 2016.

[17] S. Andreev, O. Galinina, A. Pyattaev, M. Gerasimenko, T. Tirronen, J. Torsner, J. Sachs, M. Dohler, and Y. Koucheryavy, "Understanding the iot connectivity landscape: a contemporary m2m radio technology roadmap," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 32–40, September 2015.

[18] J. de Carvalho Silva, J. J. P. C. Rodrigues, A. M. Alberti, P. Solic, and A. L. L. Aquino, "LoRaWAN; a low power WAN protocol for internet of things: A review and opportunities," in *2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech)*, July 2017, pp. 1–6.

[19] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low power wide area networks: An overview," *IEEE Communications Surveys Tutorials*, vol. 19, no. 2, pp. 855–873, Secondquarter 2017.

[20] L. Vangelista, A. Zanella, and M. Zorzi, "Long-range iot technologies: The dawn of LoRa$^{\text{TM}}$," in *Future Access Enablers of Ubiquitous and Intelligent Infrastructures*, V. Atanasovski and A. Leon-Garcia, Eds. Bucharest: Springer, 2015, pp. 51–58.

[21] O. Georgiou and U. Raza, "Low power wide area network analysis: Can LoRa scale?" *IEEE Wireless Communications Letters*, vol. 6, no. 2, pp. 162–165, April 2017.

[22] A. Biral, M. Centenaro, A. Zanella, L. Vangelista, and M. Zorzi, "The challenges of m2m massive access in wireless cellular networks," *Digital Communications and Networks*, vol. 1, no. 1, pp. 1–19, 2015.

[23] L. D. Xu, W. He, and S. Li, "Internet of things in industries: A survey," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2233–2243, Nov 2014.

[24] Q. Zhang and F. H. Fitzek, "Mission critical iot communication in 5G," in *Future Access Enablers of Ubiquitous and Intelligent Infrastructures*, V. Atanasovski and A. Leon-Garcia, Eds. Bucharest: Springer, 2015, pp. 35–41.

[25] M. Swan, "The quantified self: Fundamental disruption in big data science and biological discovery," *Big Data*, vol. 1, no. 2, pp. 85–99, 2013.

[26] Bluetooth SIG, *Bluetooth Core Specification Version 5.0*, 2016.

[27] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "Performance evaluation of the ieee 802.15.4 mac for low-rate low-power wireless networks," in *IEEE International Conference on Performance, Computing, and Communications, 2004*, 2004, pp. 701–706.

[28] Sigfox®. (Accessed: 08/06/2018) Radio technology keypoints. [Online]. Available: https://www.sigfox.com/en/sigfox-iot-radio-technology

[29] Wi-Fi Alliance. (Accessed: 08/12/2018) Wi-fi alliance introduces low power, long range Wi-Fi HaLow. [Online]. Available: https://www.wi-fi.org/news-events/newsroom/wi-fi-alliance-introduces-low-power-long-range-wi-fi-halow

[30] R. Ratasuk, B. Vejlgaard, N. Mangalvedhe, and A. Ghosh, "NB-IoT system for M2M communication," in *2016 IEEE Wireless Communications and Networking Conference*, April 2016, pp. 1–5.

[31] D. Flore, "3gpp standards for the internet-of-things," *GSMA MIoT*, vol. 25, 2016.

[32] K. Chang, "Bluetooth: a viable solution for IoT? [industry perspectives]," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 6–7, December 2014.

[33] Bluetooth SIG, *Bluetooth Core Specification Version 4.0*, 2010.

[34] J. M. Rabaey, J. Ammer, T. Karalar, , B. Otis, M. Sheets, and T. Tuan, "PicoRadios for wireless sensor networks: the next challenge in ultra-low power design," in *2002 IEEE International Solid-State Circuits Conference. Digest of Technical Papers (Cat. No.02CH37315)*, vol. 1, Feb 2002, pp. 200–201 vol.1.

[35] M. Collotta, G. Pau, T. Talty, and O. K. Tonguz, "Bluetooth 5: A concrete step forward toward the IoT," *IEEE Communications Magazine*, vol. 56, no. 7, pp. 125–131, July 2018.

[36] H. Snellman, M. Savolainen, J. Knaappila, and P. Rahikkala, "Bluetooth 5, refined for the IoT," *White Paper, Silicon Labs*, pp. 1–12, 2017.

[37] S. M. Darroudi and C. Gomez, "Bluetooth low energy mesh networks: A survey," *Sensors*, vol. 17, no. 7, 2017. [Online]. Available: http://www.mdpi.com/1424-8220/17/7/1467

[38] IEEE Computer Society LAN/MAN Standards Committee, *IEEE Standard for Local and Metropolitan Area Networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*, 2011.

[39] D. Culler and S. Chakrabarti, "6LoWPAN: Incorporating IEEE 802.15. 4 into the IP architecture," *IPSO Alliance, White paper*, 2009.

[40] P. Castro, J. L. Afonso, and J. A. Afonso, "A low-cost zigbee-based wireless industrial automation system," in *CONTROLO 2016*. Springer, 2017, pp. 739–749.

[41] E. Callaway, P. Gorday, L. Hester, J. A. Gutierrez, M. Naeve, B. Heile, and V. Bahl, "Home networking with IEEE 802.15.4: a developing standard for low-rate wireless personal area networks," *IEEE Communications Magazine*, vol. 40, no. 8, pp. 70–77, Aug 2002.

[42] G. Mulligan, "The 6LoWPAN architecture," in *Proceedings of the 4th workshop on Embedded networked sensors*. ACM, 2007, pp. 78–82.

[43] LoRa Alliance Technical Committee, *LoRaWAN 1.1 Specification*, 2017.

[44] J. Petäjäjärvi, K. Mikhaylov, M. Pettissalo, J. Janhunen, and J. Iinatti, "Performance of a low-power wide-area network based on lora technology: Doppler robustness, scalability, and coverage," *International Journal of Distributed Sensor Networks*, vol. 13, no. 3, 2017.

[45] Semtech Corporation, *LoRa Modulation Basics AN1200.22*, 2015.

[46] LoRa Alliance Technical Committee, *LoRaWAN 1.1 Regional Parameters*, 2017.

[47] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: the rising stars in the iot and smart city scenarios," *IEEE Wireless Communications*, vol. 23, no. 5, pp. 60–67, October 2016.

[48] T. Adame, A. Bel, B. Bellalta, J. Barcelo, and M. Oliver, "IEEE 802.11AH: the WiFi approach for M2M communications," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 144–152, December 2014.

[49] IEEE Computer Society LAN/MAN Standards Committee, *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation*, 2016.

[50] E. Khorov, A. Lyakhov, A. Krotov, and A. Guschin, "A survey on ieee 802.11 ah: An enabling networking technology for smart cities," *Computer Communications*, vol. 58, pp. 53–69, 2015.

[51] 3rd Generation Partnership Project, *Cellular System Support for Ultra Low Complexity and Low Throughput Internet of Things: TR 45.820 V2.1.0*, 2015.

[52] J. Schlienz and D. Raddino, "Narrowband internet of things whitepaper," *White Paper, Rohde&Schwarz*, pp. 1–42, 2016.

[53] M. Chen, Y. Miao, Y. Hao, and K. Hwang, "Narrow band internet of things," *IEEE Access*, vol. 5, pp. 20 557–20 577, 2017.

[54] CR2032 Datasheet and Information Site. (Accessed: 11/21/2018). [Online]. Available: http://cr2032.co/

[55] A. D. Zayas and P. Merino, "The 3GPP NB-IoT system architecture for the Internet of Things," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, May 2017, pp. 277–282.

[56] F. Peng, J. Zhang, and W. E. Ryan, "Adaptive modulation and coding for IEEE 802.11n," in *2007 IEEE Wireless Communications and Networking Conference*, March 2007, pp. 656–661.

[57] R. Katiyar and K. V. Padmaja, "Performance analysis of time domain and frequency domain equalizer for ADSL," in *2016 International Conference on Communication and Signal Processing (ICCSP)*, April 2016, pp. 0513–0516.

[58] Q. He and A. Schmeink, "Comparison and evaluation between FBMC and OFDM systems," in *WSA 2015; 19th International ITG Workshop on Smart Antennas*, March 2015, pp. 1–7.

[59] R. Nissel, S. Schwarz, and M. Rupp, "Filter bank multicarrier modulation schemes for future mobile communications," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 8, pp. 1768–1782, Aug 2017.

[60] P. Pirinen, "A brief overview of 5G research activities," in *1st International Conference on 5G for Ubiquitous Connectivity*, Nov 2014, pp. 17–22.

[61] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM wireless communications with MATLAB*. John Wiley & Sons, 2010.

[62] L. Mendes, N. Michailow, M. Matthé, I. Gaspar, D. Zhang, and G. Fettweis, "GFDM: Providing Flexibility for the 5G Physical Layer," in *Opportunities in 5G Networks: A Research and Development Perspective*. CRC Press, 2016, pp. 325–390.

[63] M. Engels, *Wireless OFDM systems: How to make them work?* Springer US, 2002.

[64] F. Schaich and T. Wild, "Waveform contenders for 5G - OFDM vs. FBMC vs. UFMC," in *2014 6th International Symposium on Communications, Control and Signal Processing (ISCCSP)*, May 2014, pp. 457–460.

[65] B. Saltzberg, “Performance of an efficient parallel data transmission system,” *IEEE Transactions on Communication Technology*, vol. 15, no. 6, pp. 805–811, December 1967.

[66] R. Chang, “High-speed multichannel data transmission with bandlimited orthogonal signals,” *Bell Sys. Tech. J*, vol. 45, no. 10, pp. 1775–1796, 1966.

[67] M. Bellanger, “Physical layer for future broadband radio systems,” in *2010 IEEE Radio and Wireless Symposium (RWS)*, Jan 2010, pp. 436–439.

[68] M. Bellanger, D. Le Ruyet, D. Roviras, M. Terré, J. Nossek, L. Baltar, Q. Bai, D. Waldhauser, M. Renfors, T. Ihalainen *et al.*, “FBMC physical layer: a primer,” *PHYDYAS Project*, January, 2010.

[69] M. Schellmann, Z. Zhao, H. Lin, P. Siohan, N. Rajatheva, V. Luecken, and A. Ishaque, “FBMC-based air interface for 5G mobile: Challenges and proposed solutions,” in *2014 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, June 2014, pp. 102–107.

[70] G. Fettweis, M. Krondorf, and S. Bittner, “GFDM - generalized frequency division multiplexing,” in *VTC Spring 2009 - IEEE 69th Vehicular Technology Conference*, April 2009, pp. 1–4.

[71] M. Matthé, L. L. Mendes, and G. Fettweis, “Generalized frequency division multiplexing in a gabor transform setting,” *IEEE Communications Letters*, vol. 18, no. 8, pp. 1379–1382, Aug 2014.

[72] T. Wild, F. Schaich, and Y. Chen, “5G air interface design based on universal filtered (UF-)OFDM,” in *2014 19th International Conference on Digital Signal Processing*, Aug 2014, pp. 699–704.

[73] I. Gaspar, M. Matthé, N. Michailow, L. L. Mendes, D. Zhang, and G. Fettweis, “Frequency-shift Offset-QAM for GFDM,” *IEEE Communications Letters*, vol. 19, no. 8, pp. 1454–1457, Aug 2015.

[74] N. Michailow, M. Matthé, I. S. Gaspar, A. N. Caldevilla, L. L. Mendes, A. Festag, and G. Fettweis, “Generalized frequency division multiplexing for 5th generation cellular networks,” *IEEE Transactions on Communications*, vol. 62, no. 9, pp. 3045–3061, Sept 2014.

[75] I. B. F. de Almeida and L. L. Mendes, “Linear GFDM: a low out-of-band emission configuration for 5G air interface,” in *2018 IEEE 5G World Forum (5GWF) (WF-5G’18)*, Santa Clara, CA, USA, Jul. 2018.

[76] I. Gaspar, L. Mendes, M. Matthé, N. Michailow, A. Festag, and G. Fettweis, “LTE-compatible 5G PHY based on generalized frequency division multiplexing,” in *2014 11th International Symposium on Wireless Communications Systems (ISWCS)*, Aug 2014, pp. 209–213.

[77] X. Zhang, M. Jia, L. Chen, J. Ma, and J. Qiu, “Filtered-ofdm-enabler for flexible waveform in the 5th generation cellular networks,” in *Global Communications Conference (GLOBECOM), 2015 IEEE*. IEEE, 2015, pp. 1–6.

[78] G. Bochechka, V. Tikhvinskiy, I. Vorozhishchev, A. Aitmagambetov, and B. Nurgozhin, “Comparative analysis of ufmc technology in 5g networks,” in *2017 International Siberian Conference on Control and Communications (SIBCON)*, June 2017, pp. 1–6.

[79] D. Mattera, M. Tanda, and M. Bellanger, “Analysis of an FBMC/OQAM scheme for asynchronous access in wireless communications,” *EURASIP Journal on Advances in Signal Processing*, vol. 2015, no. 1, p. 23, 2015.

[80] F. Schaich, T. Wild, and Y. Chen, “Waveform contenders for 5G - suitability for short packet and low latency transmissions,” in *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*, May 2014, pp. 1–5.

[81] B. Farhang-Boroujeny, “OFDM versus filter bank multicarrier,” *IEEE Signal Processing Magazine*, vol. 28, no. 3, pp. 92–112, May 2011.

[82] V. Vakilian, T. Wild, F. Schaich, S. ten Brink, and J. F. Frigon, “Universal-filtered multi-carrier technique for wireless systems beyond LTE,” in *2013 IEEE Globecom Workshops (GC Wkshps)*, Dec 2013, pp. 223–228.

[83] R. Gerzaguet, N. Bartzoudis, L. G. Baltar, V. Berg, J.-B. Doré, D. Kténas, O. Font-Bach, X. Mestre, M. Payaró, M. Färber *et al.*, “The 5G candidate waveform race: a comparison of complexity and performance,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2017, no. 1, p. 13, 2017.

[84] H. Kim, J. Bang, S. Choi, and D. Hong, “Resource block management for uplink UFMC systems,” in *2016 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, April 2016, pp. 477–480.

[85] J. Abdoli, M. Jia, and J. Ma, “Filtered OFDM: A new waveform for future wireless systems,” in *Signal Processing Advances in Wireless Communications (SPAWC), 2015 IEEE 16th International Workshop on*. IEEE, 2015, pp. 66–70.

[86] A. Roessler, “5G waveform candidates application note,” *Rohde&Schwarz, Munich, Germany, Tech. Rep. 1MA271*, 2016.

Ivo Bizon Franco de Almeida received the five-year BSc. and MSc. degrees in Electrical Engineering from the Instituto Nacional de Telecomunicações (Inatel), Brazil in 2016 and 2018, respectively. Currently he is pursuing his PhD at Technische Universiät Dresden (TUD), Germany, and working as a research associate at the Vodafone Chair Mobile Communications Systems. His current research interests include signal processing, machine/deep learning and multicarrier modulation techniques for future wireless systems.

Luciano Leonel Mendes (male) received the BSc. and MSc. degrees in Electrical Engineering from Inatel, Brazil in 2001 and 2003, respectively. In 2007 he received the Doctor degree in Electrical Engineering from Unicamp, Brazil. Since 2001 he is a professor at Inatel. He has coordinated the Master Program at Inatel from 2010 to 2013 and he has led several research projects funded by FAPEMIG, FINEP and BNDES. From 2013 to 2015 he was a visiting researcher at the Technical University of Dresden in the Vodafone Chair Mobile Communications Systems, where he has developed his post-doctoral program sponsored by CNPq. Since 2015, he has acted as the Research Coordinator of the Radiocommunication Reference Center at Inatel. His main area of interest is solutions for 5G PHY, a research field where he has published several papers in the last years. He is also a CNPq level 2 research fellow since 2016. In 2017 he was elected Research Coordinator of the 5G Brasil Project.

Joel J. P. C. Rodrigues [S?01, M?06, SM?06] is a professor at the National Institute of Telecommunications (Inatel), Brazil; senior researcher at the Instituto de Telecomunicações, Portugal; and visiting professor at the Federal University of Piauí, Brazil. Prof. Rodrigues is the leader of the Internet of Things research group (CNPq), Director for Conference Development - IEEE ComSoc Board of Governors, IEEE Distinguished Lecturer, Technical Activities Committee Chair of the IEEE ComSoc Latin America Region Board, the President of the scientific council at ParkUrbis ? Covilhã Science and Technology Park, the Past-Chair of the IEEE ComSoc Technical Committee on eHealth, the Past-chair of the IEEE ComSoc Technical Committee on Communications Software, Steering Committee member of the IEEE Life Sciences Technical Community and Publications co-Chair, and Member Representative of the IEEE Communications Society on the IEEE Biometrics Council. He is the editor-in-chief of the International Journal on E-Health and Medical Communications and editorial board member of several high-reputed journals. He has been general chair and TPC Chair of many international conferences, including IEEE ICC, IEEE GLOBECOM, IEEE HEALTHCOM, and IEEE LatinCom. He has authored or coauthored over 700 papers in refereed international journals and conferences, 3 books, and 2 patents. He had been awarded several Outstanding Leadership and Outstanding Service Awards by IEEE Communications Society and several best papers awards. Prof. Rodrigues is a member of the Internet Society, and a senior member ACM and IEEE.

This document is a preprint of: I. Bizon Franco de Almeida, L. L. Mendes, J. J. P. C. Rodrigues and M. A. A. da Cruz, “5G Waveforms for IoT Applications,” in IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2554-2567, Jan 2019. DOI:10.1109/COMST.2019.2910817

Mauro Cruz is a PhD candidate of an international joint supervision between University Haute-Alsace (UHA) and National Institute of Telecommunications (Inatel). He received a MSc degree from Inatel, a five-year BSc degree (licentiate) in informatics engineering from the Universidade Católica de Angola (UCAN), Angola. His research interests include IoT, middleware for IoT and mobile computing.