Next Generation 5G OFDM-Based Modulations for Intensity Modulation-Direct Detection (IM-DD) Optical Fronthauling

Albert Gran Alcoz
Optical Communications Lab
Technical University of Catalonia
Barcelona, Spain
albert.gran@alu-etsetb.upc.edu

Abstract*—Next generation of cellular systems 5G is envisioned to provide higher data rates, lower end-to-end latencies, enhanced quality of service for end users and broadened diversity of multi-media applications. The substantial growth in the number of base stations required to fulfill these demands, which challenges the low-cost constraints imposed by operators, evidences the need of a paradigm-shift in modern networks design. In this direction, new distributed architectures have been recently gaining momentum, in which base stations are decoupled in simplified multiple remote radio heads (RRHs), providing high capacity to the network, and a reduced number of base-band servers (BBSs), gathering all the processing complexity to reduce capital and operational expenditures. Is in these new architectures, where optical fiber-fronthauling will play a very fundamental role, conveying information from the high-capacity wireless medium to the wired network counterparts. In general fiber communications, coherent modulations have shown to be the ones achieving highest levels of performance. However, for the next generation architectures, where simplicity is the main objective and the number of connections is expected to rapidly grow, alternative formats will need to be adopted, breaking the traditional coherent solutions' inherent complexity and reducing the consequent percentage of cost. In this article, the use of Intensity Modulation-Direct Detection, is proposed. For this purpose, the different modulation candidates that are expected to substitute OFDM in 5G are presented and widely compared, discussing their possibilities, main advantages and drawbacks. A novel implementation model is introduced for the conversion of complex-nature modulations to IM-DD schemes in a highly-efficient and cost-effective manner. Experimental work to analyze the behavior of IM-DD adapted modulations over a fiber setup is also presented. Obtained results show that the proposed scheme outperforms the state-of-the-art in terms of computational complexity, simplicity and ease of implementation, while performance is preserved in terms of throughput and bit error rate.

***Index Terms*—5G, Intensity Modulation-Direct Detection, IM-DD, Optical Fronthauling, FBMC, UFMC, GFDM**

I. Towards the new paradigm for 5G

As the research community focuses efforts on the next generation requirements of high data rate, reduced latency, low energy consumption, high scalability, improved connectivity, reliability, and higher security, one can have a more clear vision of how upcoming architectures facing these challenges will need to be designed. In order to achieve the required next degree of network capacity, the density of base stations is expected to increase, accompanied by the introduction femtocells and picocells providing higher levels of frequency reuse [3]. To reduce the cost that this raise in the number of base stations suppose, new distributed configurations have been already presented [2] [6], in which base stations are divided in a large number of remote radio heads (RRH) which are only responsible to transmit and receive radio signals to users, and a small number of base band processing units (BBUs), which perform all the complex base band processing in a centralized manner from the cloud (i.e. BBU pools in data-centers).

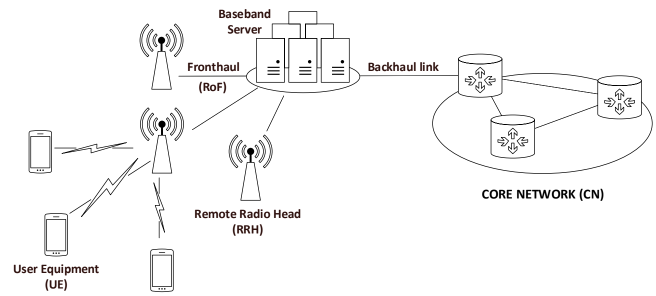


Fig. 1: Next generation distributed architecture.

a) Distributed architectures: BaseBand Servers (BBS) and Remote Radio Heads (RRH): This division of the traditional base station, which integrated all the functionalities of radio and baseband processing, into multiple only-transmitting simple and cheap RRHs, and a single cloud-hub BBS, centralizing all the complex processing, allows to extend the coverage regions, improve system capacity and facilitate scalability without much increase of the capital and operational expenditures [7]. In these distributed architectures, which have evolved to the deeper concept of Cloud-Based Radio Access Network including Software Defined Networking and Virtualization insights, the transmission of digital baseband signals from RRHs to the cloud is of crucial importance. Generally, optical transport links have been taken as fronthaul. However, as the number of RRHs increase, and therefore the number of links connecting them as well, traditional optical modulations demand a too high level of complexity and a too high impact in the price not desirable in most situations. It seems therefore clear as well, that simplified Radio over Fiber (RoF) schemes, allowing to transmit wireless directly-received signals through optical links, with higher rates and reliability but in a cheaper manner, will play a fundamental role.

b) Intensity Modulation-Direct Detection as an alternative: In this paper, following the cost-reduction philosophy, an intensity modulation-direct detection scheme is proposed as an alternative for the next generation RoF fronthaul links. IM-DD schemes allow the use of simplified transmitters and receivers, such as Vertical-Cavity Surface-Emitting Lasers (VCSEL), reducing by far the implementation cost. It is for this reason that their use in 5G fronthauls is straightforward, simplifying the task of RRHs, which will just need to transform the optical received signal to the wireless field (and vice versa) in a transparent manner. It is also known that there are currently different modulation candidates expected to substitute OFDM in 5G. All of them derive directly from the IDFT-based OFDM, being complex by nature. IM-DD schemes cannot transmit complex information as only one dimension (intensity) is modulated and used. And it seems that the conversion from the optical wired world to the wireless world would mean complexity at the RRH and even more if the complex-nature of wireless medium was not extended to the wired one. To face this challenge, and to be able to use real-signal IM-DD, we present in this paper a very simple model that adapts those complex signals to real ones by juxtaposing complex components in time. With this model the task of RRH is completely simplified, and the performance is shown to be maintained in terms of both throughput and bit error rate.

In Section II, the different advanced multicarrier modulations to be used in the next generation cellular systems are discussed, highlighting their main contributions and drawbacks as well as the scenarios and situations in which they will be of more relevance. In Section III an experimental analysis is described, with the implementation details of the different modulations and the configuration chosen to set up. In Section IV, the results from studying the different modulations are presented and performance of the diverse alternatives is compared. Finally some conclusions are extracted and potential future work is pointed up.

II. NEXT GENERATION CANDIDATE MODULATIONS

Although Orthogonal Frequency Division Multiplexing (OFDM) technique has been established as the dominant modulation scheme in the fourth generation of broadband systems, some of the drawbacks that it presents have brought the research community to think about other possible alternatives that could improve the global performance in the next generation. Despite it is quite clear that the evolution these alternatives propose is not as drastic as the jump we experienced from FDMA to CDMA, or from CDMA to OFDM, some of the characteristics they present are interesting enough to deserve a deep analysis on their performance. In particular, these new modulations may not be able to substitute OFDM as a general paradigm performing great in most of the different communication situations, but they might have remarkable interest in very specific applications or scenarios. Throughout this paper we will mainly analyze three of them that have gained more interest in recent times: Filter Bank Multi Carrier (FBMC), Universal-Filtered Multi-Carrier (UFMC) and Generalized Frequency Division Multiplexing (GFDM). All them have arisen to supply some of the drawbacks that OFDM present, and will be this fact and the properties following it, the ones that will make them suitable for determinate particular cases.

A. OFDM Main Drawbacks

OFDM has supposed a great revolution in the history of broadband communications, not only for the high spectral efficiencies that can achieve, with the definition of different orthogonal sub-carriers bringing each one an underlyingly-modulated symbol at the same time, nor for the reduction of inter symbol interference (ISI), and its robustness to channel delays, by just copying the last part of the generated signal at the beginning (cyclic prefix), but also for its low-complexity implementation thanks to algorithms like fast Fourier transform (FFT). However, the same characteristics that make OFDM so attractive in most scenarios, generate serious problems that we might need to overcome.

The most important drawback of OFDM is the high out-of-band radiation that it presents. The Sinc shape that defines the waveform of the different sub-carriers (and thanks to which several orthogonal symbols can be carried at the same time) generates secondary lobes of a significant size. These lobes extend further than the frequency band used to transmit data, converging to a loss in the global spectral efficiency. Furthermore, OFDM-Sincs secondary lobes high power forces a requirement of strict synchronization. If synchronization among different symbols is not achieved, the orthogonality is lost, and the effects of secondary lobes become sizable. An extended cyclic prefix can fix interference but again the price to pay is a reduction of the spectral efficiency.

To overcome these major factors, together with other weaknesses like the high Peak-to-Average Power Ratio (PAPR), or the high sensitivity to phase and frequency noises, new modulation techniques have been presented recently with the objective of being considered as an alternative for the next generation 5G communication systems.

B. FBMC

Filter Bank Multi Carrier modulation has recently gained attention as a potential solution to face the limitations of OFDM. In particular FBMC presents an improvement of the spectral efficiency and relaxes the strict synchronization constrains. It can be understood as just a modification of the general OFDM in which each of the different sub-carriers is filtered to minimize their side-lobes, and thus reduce interference among them and out-of-band effect of the global allocated bandwidth. The CP is therefore not needed, allowing achievement of high data rates, but making it difficult to support MIMO schemes. The long size of the filter adopted makes burst and short-time transmissions to be not effective. The greatest advantage of FBMC is the overlapping between sub-carriers, only restricted to adjacent ones, making it robust against synchronism problems. The price paid in exchange is computational complexity. Although some recent schemes adopt FFT and just modify its output, the number of operations required both in transmission and reception increase.

C. UFMC

In Universal-Filtered Multi-Carrier, instead of filtering OFDM sub-carriers one by one as done in FBMC, are groups of sub-carriers the ones filtered. By grouping sub-carriers, the filter length can be reduced in comparison to the one used in FBMC. Every group is applied an independent IFFT and the output is filtered independently (with the same filter, or even different filters can be applied if desired). As can be seen in Figure 2, the result of this filtering is summed at the output to achieve the final UFMC signal. With per-group individual filtering, the out-of-band spectral emissions can be reduced considerably. Moreover, sub-band filtering has the benefit of reducing the guards between sub-bands and also reducing the filter length, making this kind of modulation suitable for carrying sporadic short bursts [9]. UFMC is considered advantageous in comparison to OFDM by offering higher spectral efficiency.

D. GFDM

Generalized Frequency Division Multiplexing appears as an alternative to OFDM for scenarios in which narrow frequency bands are a must (e.g. IoT). In GFDM every sub-carrier does not need to be strictly orthogonal to each other. The characteristics of each individual sub-carrier can be adapted in a flexible manner. By interleaving different types of them in the same band, high spectral efficiency levels and low out-of-band emissions can be achieved. Cyclic prefix can still be incorporated, providing the system with MIMO support. GFDM should be understood as the alternative providing highest degree of flexibility, giving the possibility to modify it according to each situation requirements. However, this great flexibility makes one loose the complete control of the inbound emission, with a spectral efficiency also more relaxed in comparison to the rest of alternatives.

To date, there is not a clear decision on which will finally be the 5G waveform, even if only one of them will be used or several, but it is clear to see that the OFDM as core technology will evolve, and some of these advances on top of it have all the odds to be adopted.

III. Experimental Analysis

A. Adapting Complex Multicarrier Modulation to IM-DD

While being a great option for the next generation cellular systems optical fronthauling, both for its simplicity and low cost, Intensity Modulation-Direct Detection (IM-DD) schemes require transmitted signals to be strictly real and positive. This means that conventional OFDM cannot be directly used due to its intrinsic complex values. Several OFDM modifications have been presented in recent years, with the common objective to transmit only a unique real component without loosing the main characteristics of the original modulation. Traditionally the followed procedure has been to impose Hermitian Symmetry (HS) at the input of the inverse Fourier transform, which provides a real-result at the output, but involving twice the number of IFFT/FFT points in transmission and reception, increasing thus the computational complexity, requiring a higher power consumption and demanding bigger chip dimensions. To restrict negative magnitudes, different techniques have been proposed, consisting on just clipping negative values to zero which results in undesired noise or applying the corresponding DC bias increasing thus the global power. To avoid unnecessary IFFT and FFT computations, other approaches have been suggested like the use of the Hartley transform, which has the peculiarity of working in the real space, but constraining the input modulations to be only real as well, depriving us from using high density constellations such as M-QAM due to their complex nature. More modern schemes in which the real (Re) and imaginary parts (Im) of the complex-valued OFDM are separated and transmitted via consecutive symbols have accomplished interesting results.

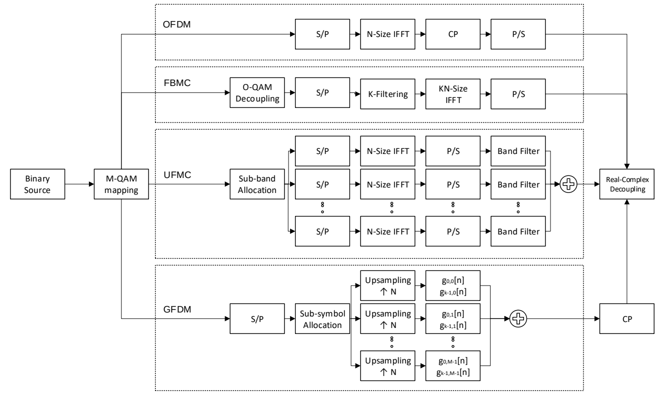


Fig. 2: Block diagram waveform modulator.

In this paper, we will follow the methodology presented in [4], which consists on decoupling the real and imaginary parts of the default complex OFDM generated signal (and obviously, doing the same for each of the inheritants FBMC, UFMC and GFDM when working with them), and juxtaposing them on the time domain. This technique, which exhibits the same performance than conventional OFDM systems, outperforms in terms of cost and complexity, with only paying a price in terms of capacity. The adoption of this scheme is not only positive in terms of the RRHs low-cost and complexity-reduction philosophy, but also for our objective of performing as little operations as possible in the RRHs, leaving the tough signal processing and forwarding for the data-center-placed base band units. With such kind of scheme, the FBMC/UFMC/GFDM wireless signals can be received by the RRH, and with very little amount of processing (only separating the complex and real parts of the signal and transmitting them sequentially), these signals can be transmitted through intensity modulated fronthaul fibers and reach BBU with a great behavior and a seamless manner.

B. Performance Analysis Over Fiber-Links

The general setup used for the experimental analysis is shown in Figure 3. The 5G candidate multicarrier modulations are generated offline using Mathworks Matlab$^{\mathrm{TM}}$, and transferred to an Arbitrary Waveform Generator (AWG). The AWG is configured to operate at 2GS/s and feeds the Mach-Zehnder Modulator (MZM) that externally modulates the light outputted by the Tunneable Laser Source (TLS). For the correct performance, the source-generated light is applied a polarization control before reaching the MZM. It is important to remark that intensity modulation could also be achieved by using a laser which directly modulates the generated light (e.g. VCSEL). MZM is biased at V_{PI}. A Variable Optical Attenuator (VOA) is used for controlling the power received at the detector input. Attenuation is varied accordingly to obtain the different bit error rate values needed to plot the characteristic BER curve. A power splitter is then used to determine the power reached at the detector. A 10% is deviated towards a Power Meter (PM) while the rest arrives directly to the optical Direct Detector. The detected signals are sent through an RF link to the Real Time Oscilloscope, that digitalizes them with a bandwidth of 4GHz. Signals are captured at 25GS/s, resampled and decimated before being compared with the original ones. No channel estimation nor pre-compensation is applied in reception, only the corresponding multiplicative power factor before demodulation is carried on.

Detailed modulation schemes for every case can be found in Figure 2. All the modulation and demodulation codes that have been used in this experiment, as well as the data processing required to obtain the bit error rates, are publicly available and can be downloaded from GitHub in [1]. It is important to remark that, as all the candidate modulations are still subject of intense research activity, new configuration proposals, improved algorithms and schemes are being constantly brought up. For this work, we have selected the most widely accepted techniques, and therefore the most commonly used, up to date. For FBMC, we have adopted the recent Offset-QAM (OQAM-FBMC) implementation, with the prototype filter used in PHYDYAS project, with K factor of 4, which has shown the highest stop-band attenuations with a good roll-off characteristic [5]. For GFDM we have chosen the Root Raised Cosine filter, with $G = 4$, $\alpha = 40$, and $l = 43$, for being the one with lowest spectrum leakage and highest flexibility. In UFMC, Dolph-Chebyshev is selected, with a 20 bands division of 30 subcarriers each. And for traditional OFDM, rectangular filter is chosen for having been the most popular one. In all cases, a 4-QAM has been used, with FFT order of 1024, with no cyclic prefix and with 212-point bands of guard, to obtain the Power Spectral Densities of Figure 4, and with no-guardband considered, to maximize efficiency, in the experimental setup.

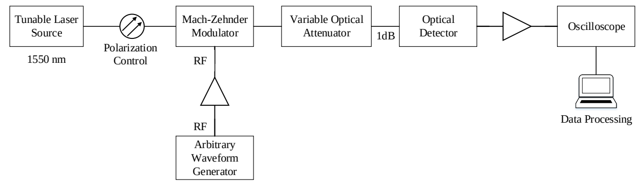


Fig. 3: Block diagram experimental setup.

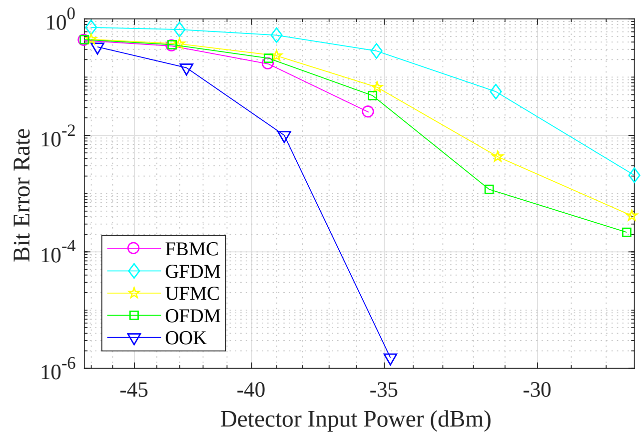
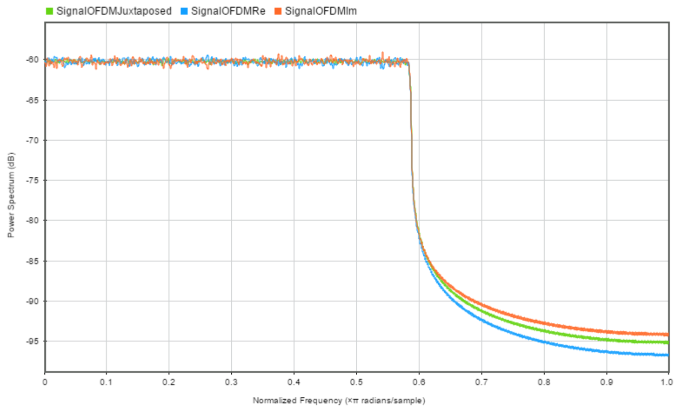


Fig. 4: Experimental Bit Error Rate (BER).

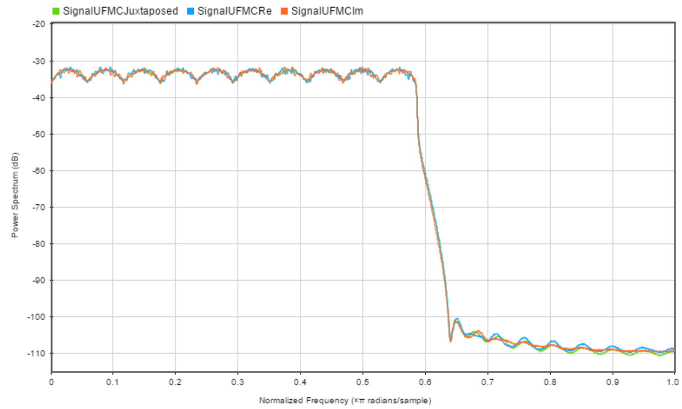
IV. Results

The results can be mainly summarized between Figures 4 and 5. In Figure 4, the experimental BERs from the different candidate modulations can be shown. The biggest observation that one should consider is that the obtained results match quite-precisely the theoretical performance of the different modulations [10]. In particular, it is noted that the BER of FBMC is the lowest from all waveforms throughout the whole range of power received. At the same time GFDM is the worst, while OFDM and UFMC stay in the middle being OFDM slightly better than UFMC. The fact that GFDM is the one with worst results is not surprising. It is well known that the main GFDM competitive advantage is its flexibility and that it needs to sacrifice BER and ICI at the cost of reducing band radiation. What can be more unexpected from our results is the fact that UFMC is performing worse than OFDM for the selected implementation. The biggest known cause for UFMC low BER performance is the called CFO (Carrier Frequency Offset), which generates a mismatch between sub-carriers [8]. Although usually the effect of CFO on UFMC is not greater than on OFDM, the optical medium characteristics might have derived for our case in worse result for UFMC.

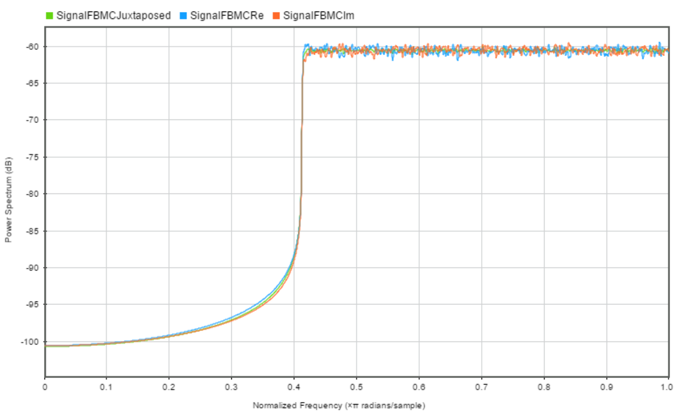
Figure 5 focuses on the performance of the time-juxtaposing technique that has been applied for the first time in this work to convert complex-nature FBMC, UFMC and GFDM signals, to real waveforms, making them able to be carried over IM-DD low cost links. As can be clearly observed, the real signals



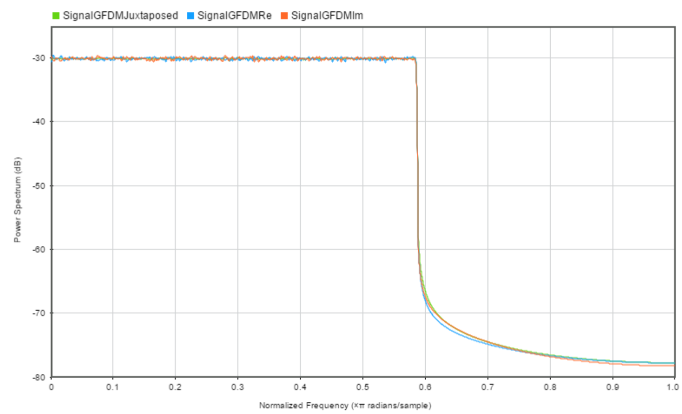
(a) Generated OFDM Signal Spectrum.



(b) Generated UFMC Signal Spectrum.



(c) Generated FBMC Signal Spectrum.



(d) Generated GFDM Signal Spectrum.

Fig. 5: Comparison of the IM-DD juxtaposing effect in the different modulation candidates.

obtained from the proposed scheme completely conserve the spectral characteristics of each modulation, which was the main critical concern. Juxtaposition of complex symbols is shown to maintain the original modulations profile while optimizing efficiency and reducing cost. The reader can notice how FBMC is still the one with lowest out-of-band leakage, followed by GFDM, UFMC and finally OFDM. The fact that all intrinsic characteristics of each candidate are still preserved, makes from our solution not only a valid option, but a very interesting approach to be considered in future networks design.

V. Conclusion

In this article, the use of Intensity Modulation-Direct Detection Optical Fronhauling has been proposed for the next generation 5G cellular systems. Direct conversion of the different waveform candidates from wireless radio access networks to fiber fronthauls through RRHs, has been introduced and experimentally tested. Obtained results prove that the presented solution outperforms the state-of-the-art in terms of computational complexity and efficiency, keeping the essential low out-of-band radiation and high data rates of each new modulation, while providing great scalability and lower-cost.

References

[1] A. Gran. Next Generation 5G OFDM-Based Modulations. *GitHub.com*.

[2] I. F. Akyildiz, S.C. Lin, and P. Wang. Wireless Software-Defined Networks (W-SDNs) and Network Function Virtualization (NFV) for 5G Cellular Systems: An overview and qualitative evaluation.

[3] I. F. Akyildiz, S. Nie, S.C. Lin, and M. Chandrasekaran. 5G roadmap: 10 key enabling technologies. *Computer Networks*, 106:17 – 48, 2016.

[4] F. Barrami, Y. Le Guennec, E. Novakov, J. M. Duchamp, and P. Busson. A novel FFT/IFFT size efficient technique to generate real time optical OFDM signals compatible with IM/DD systems. In *2013 European Microwave Conference*, pages 1247–1250, Oct 2013.

[5] 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, January*, 25(4):7–10, 2010.

[6] A. Gran, S. C. Lin, and I. F. Akyildiz. Towards Wireless Infrastructure-as-a-Service (WIaaS) for 5G Software-Defined Cellular Systems. In *2017 IEEE International Conference on Communications (ICC)*, pages 1–6, May 2017.

[7] E. Hossain and M. Hasan. 5G Cellular: Key enabling technologies and research challenges. *IEEE Instrumentation Measurement Magazine*, 18(3):11–21, June 2015.

[8] K. Lee and G. Choi. Effect of CFO on UFMC System. *The Journal of The Institute of Internet, Broadcasting and Communication*, 2016.

[9] L. Orús and C. Mateo. Diseño e implementación de una aplicación de transmisión y recepción de señales multiportadora enfocadas a redes 4G y 5G. 2016.

[10] H. Zhang, H. Lv, and P. Li. Spectral Efficiency Analysis of Filter Bank MultiCarrier (FBMC) Based 5G Networks with Estimated Channel State Information (CSI). In *Towards 5G Wireless Networks - A Physical Layer Perspective*, chapter 03. InTech, Rijeka, 2016.