5G New Radio Numerologies and their Impact on V2X Communications

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ABSTRACT

The 3GPP adopted Cyclic Prefix (CP)-OFDM as the only waveform for both uplink and downlink communications in 5G New Radio (NR). However, due to the variety of proposed deployment options and scenarios, a single numerology will not be enough to fulfil all performance requirements. A scalable OFDM numerology is required to enable diverse services on a wide range of frequencies and deployments, and finding the right numerology for each scenario is of special relevance for the proper functioning of 5G NR. Using a 3GPP calibrated simulator, this paper presents the performance evaluation of NR in a V2X scenario for different numerologies and device speeds. Results show that increasing subcarrier spacing boosts the protection of the system against Inter Carrier Interference (ICI) but makes Inter Symbol Interference (ISI) have a more predominant effect. This result allows concluding that each frequency operation has a different optimum numerology depending also on the deployment scenario.

Keywords: 5G, waveform, OFDM, NR, numerology, V2X, 802.11p, C-V2X.

1.- INTRODUCTION

The 3rd Generation Partnership Project (3GPP) has been working since 2016 on the standardization of the 5G New Radio (NR) [1], the global standard for 5G that will ensure the quality, performance, and interoperability of 5G devices and networks, as the next generation radio technology [2]. 5G NR will make services like automated intelligence, the Internet of Things (IoT) [3], autonomous vehicles, and virtual/augmented reality, come true. These technologies are based on more prompt, even faster, and more reliable inter-connectivity of everything, resulting in the need for the next generation of mobile communication systems.

5G is designed to provide a wide variety of services, and that is why there are three main challenges that 5G NR must solve in order to enable a truly networked society, these are: a higher traffic volume, massive growth in the number of devices, and a more reliable and low latency transmissions. These challenges result in three broad use cases [4]: Enhanced Mobile Broadband (eMBB), which requires very high data rates and large bandwidths, e.g., highly mobile UE connected to macrocells; Massive Machine Type Communications (mMTC), which requires low bandwidth, low energy consumption at the UE, and high connection density, e.g., collection of the measurements from a massive number of sensors; and Ultra Reliable Low Latency Communications (uRLLC) which requires very low latency, and very high reliability and availability, e.g., factory process, and power system automation.

Even before the formal beginning of the 5G NR standardization process, there have been different waveforms presented as candidates for this new specification [5]-[7]. Most of these candidates are multi-carrier waveforms, like Cyclic Prefix OFDM (CP-OFDM), Windowed-OFDM (W-OFDM), Universally Filtered-OFDM, also known as universal filtered multi-carrier (UFMC), Pulse Shaped OFDM (P-OFDM) and Filter-Bank Multi-Carrier (FBMC). However, in August 2016, after a long process of evaluation and deliberation, 3GPP agreed to adopt only CP-OFDM for both uplink and downlink in NR. This gives 5G NR an advantage, since being built upon OFDM (which is used on LTE and Wi-Fi) allows devices to keep low complexity and, consequently, low hardware costs. Nevertheless, a single OFDM numerology, i.e. subcarrier spacing and cyclic prefix length, cannot fulfil the performance constraints across the desired frequency range and all proposed deployment options and scenarios. This is why the OFDM numerology must be adapted to fit the specific requirements of services, operation frequencies and deployment scenarios [8]. Currently 3GPP is working on the calibration of a number of different OFDM numerologies.

This paper is framed on V2X [9] communications, which can be mapped as a type of ultra-reliable Machine-Type Communication (uMTC), that in turn is a use case that shares some characteristics of mMTC and uRLLC. V2X is currently covered with two main standards: 802.11p [10], and C-V2X (Cellular-V2X) [11]. Although there are some studies related to the V2X standards with regards to new 5G technologies [12]-[14] and other studies regarding OFDM numerology itself [15]-[17], there is currently no evaluation of the impact of numerology changes on V2X services performance, or any other service for that matter. This paper's main contribution is to provide performance results on the use of the different OFDM numerologies within a V2X scenario in order to draw the optimum configuration for each operation point.

The remaining sections of the paper are structured as follows. Section 2 describes current V2X most popular standards and their main features. Section 3 explains the configuration of the different 5G OFDM numerologies and the new frame structure. Section 4 presents the measurement results. Finally, Section 5 draws the main conclusions of this work.

2.- V2X STANDARDS

The Vehicle to Everything (V2X) communication is based on vehicles exchanging data with each other and the network infrastructure. V2X is attracting significant attention as it promises to reduce road fatalities, increase traffic efficiency, improve mobility, enable a high-level of vehicle automation, and even reduce environmental impacts and provide additional traveler services. V2X communications as defined in 3GPP consist of four types: V2V, V2I, V2N and V2P. V2V being the communication among vehicles; V2I the communication between vehicles and nearby infrastructure as traffic control devices, such as in the vicinity of road work; V2N the communication from vehicles to Internet-based networks such as for traffic operations; and V2P the exchange of information between vehicles and pedestrians. Figure 1 shows some examples. We can see how these communications are bidirectional, i.e., V2I and V2N also involve the infrastructure sending messages to the vehicles.

V2V and V2P transmissions primarily

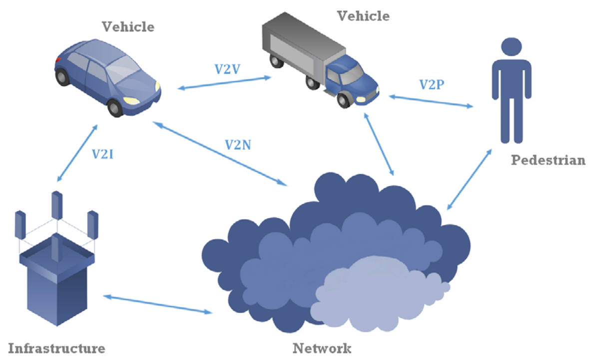

Figure 1: V2X Types

broadcast capability messages among vehicles, or between vehicles and vulnerable road users (e.g., pedestrian, cyclist), in order to provide information about direction, location and velocity to avoid accidents whenever the vehicle could take proactive actions in driving, in which it is known as autonomous driving. To accomplish this, autonomous vehicles require a variety of reliably-functioning sensors like camera, radar, and ultrasound, in order to detect and avoid obstacles or compute and follow optimum trajectories. That is why autonomous vehicles will depend on the fast processing of these sensors data, and processing delays and ambiguities could result in serious problems of safety. Here V2X can offer a better environmental perception by enabling sharing of sensor-data between vehicles and infrastructure, providing the system greater benefits to achieve the automated driving control function.

There are two key sets of specifications for V2X direct communications, both technologies operating on the 5.9 GHz spectrum. These are: 802.11p and C-V2X standards.

2.1.- 802.11p

IEEE 802.11p is a modification of the IEEE 802.11 standard that extends its applicability to V2V and V2I communications. IEEE 802.11p is supported as the lower layers of Wireless Acces in the Vehicular Environment (WAVE), which is a standard for V2V defined in USA, also known as Dedicated Short Range Communications (DSRC). It is also supported as the lower layers of the ITS-G5 standard defined in Europe.

With the purpose of supporting vehicular radio environments, the IEEE 802.11 community decided to adapt the 802.11a Wi-Fi technology. 802.11p is based on OFDM as it happens in all modern 802.11 standard, and which is also the case of Long Term Evolution (LTE) 4G technology. However, it has some changes introduced to enable communication among fast moving vehicles. Among the main advantages of the 802.11p specification is the fact that it uses a half-clocked version of 802.11a, making it capable of handling fast-changing multi-path reflections and Doppler shifts generated by relative speeds as high as 500 km/h.

In spite of the fact that 802.11p was innovative at its time, recent studies [18][19] have shown that vehicular communications based on IEEE 802.11p face several challenges due to some legacy features that are not well-suited for vehicular communications. First, 802.11 inherits a sub-optimal synchronization and channel estimation approach which is for non-highly time-variant radio channels. Besides, due to its physical and Medium Access Control (MAC) layer designs that have been originally optimized for Wireless Local Area Networks (WLAN) with low mobility, it lacks of Quality-of-Service (QoS) guarantee. On the other hand, since vehicles now have a number of active sensors like radar, lidar, and cameras, it forces the V2X system to deliver additional values, including longer range and reliability especially in Non-Line-of-Sight (NLoS) scenarios, where other vehicles and buildings obstruct the vehicle's vision systems. This is where 802.11p shows that its limited range and undetermined performance when scaling up the number of units transmitting, limits the usefulness and overall application-set that it can serve, certainly putting into question its ability to ensure safety.

2.2.- C-V2X

Initially, the 3GPP global cellular specifications evolved LTE Direct technology and optimized it for automotive applications, defining it as LTE V2X in 3GPP Release 14. However, the evolution of this concept into a solution allowing improvements in future releases (Release 15 and beyond) for LTE and for the 5G NR, is lately commonly referred to as C-V2X direct communications and called technically as PC5 or sidelink communications. C-V2X supports direct V2V, V2I and V2P communication links not being routed via an eNodeB; and at the same time it uses network-based communications, being able to communicate with the elements of the network (V2N).

One of the main advantages of C-V2X is the fact that it is based on a technology originally intended for high-speed mobile applications, which has been improved specifically for automotive use cases, paying special attention to the shortcomings observed in 802.11p over several years of research. The need to support data-intensive and low-latency new automotive applications to support improvements in safety and autonomous driving, along with essential enhancements in wireless communications, have also been key points for C-V2X. Modulation and coding enhancement, as well as better user equipment and overall advances in LTE technology can allow C-V2X to work with a better communication range, higher reliability (lower packet error rate), greater capacity, superior NLoS performance, and better congestion control in denser environments compared to 802.11p.

C-V2X is designed to deliver an evolution path to 5G NR-based C-V2X, taking advantage of the latest advances in wireless communications, while at the same time it accomplishes backward/forward compatibility to the previous releases of the same generation, enabling interoperability between generations and releases, guaranteeing that devices from different releases can communicate with each other. Backward compatibility also means that even after the 3GPP network is updated to a new release, all the devices working in earlier releases have to work properly and perform as expected, which is a very important feature, considering that vehicles typically remain in service for at least a decade. All this means that necessarily a 5G and an LTE device must be able to communicate with each other using V2V direct communication.

Finally, the conclusion reached after several considerations regarding how to map each V2V service to different 3GPP technologies, is that LTE will be only used for basic safety communications between vehicles, while 5G NR-based C-V2X will be used for advanced vehicular use cases for autonomous driving, so that LTE functionality is not duplicated or replaced. Therefore, in a first phase of deployment of cellular-based V2X, only LTE-V2X devices are expected to communicate. In a later phase, 5G UEs supporting C-V2X services will be dually supporting LTE and 5G.

3.- 5G NR NUMEROLOGY

As already mentioned, OFDM has a key role in 5G NR, although a single fixed OFDM numerology is not enough to meet all the requirements presented in the new 5G landscape. So far, LTE supports carrier bandwidths up to 20 MHz with a fixed OFDM numerology regarding cyclic prefix (CP) duration (TCP) and subcarrier spacing (Δf), which is a 15 kHz spacing between OFDM subcarriers, and 4.69 μs of CP. The idea for 5G NR is to introduce scalable OFDM numerology in order to support a wide range of frequencies, diverse scenarios and deployment models. One of the most critical requirements is that the OFDM subcarrier spacing must be able to scale with the channel bandwidth, so the processing complexity does not increase exponentially for wider bandwidths, as the FFT size scales.

Therefore, the main difference between LTE numerology (subcarrier spacing and CP length) and 5G NR numerology, is that the latter can support different types of subcarrier spacing. This subcarrier spacing is scalable according to the following factor: 15×2n kHz, where n is an integer and 15 kHz is the subcarrier spacing used in LTE. By using this 2n factor, 5G NR ensures that slots and symbols of different numerologies are aligned in the time domain, which is important to efficiently enable TDD networks.

Other features that change within the frame structure when 5G NR numerology is modified are slot duration, the symbol duration, and the number of slots per subframe, which are inevitably modified by changing the separation of carriers, with a general tendency to get shorter OFDM symbols as subcarrier spacing gets wider. This tendency comes from the nature of OFDM.

Finally, we have the number of OFDM symbols within a slot, which, despite not changing intrinsically when changing the numerology, it is necessarily adjusted so that the time alignment is not lost. For any numerology it will always be 14, unlike LTE that had two slots with 7 symbols each. The summary of

Δf = 15×2n (kHz)	Symbol duration (μs)	TCP (μs)	Slot Duration (ms)	Number of slots/ subframe	Number of sym-bols/slot
15	66.67	4.69	1	1	14
30	33.33	2.34	0.5	2	14
60	16.67	1.17	0.25	4	14

Table 1: Numerology Structures for 5G NR

5G NR numerology can be seen in Table 1.

The choice of a particular numerology depends on various factors including carrier frequency, mobility, type of deployment, service requirements (latency, reliability and throughput), and implementation complexity. For example, wider subcarrier spacing can be better suited for latency-critical uRLLC services, small coverage areas and higher carrier frequencies, which could be the case of a V2X scenario. A graphic explanation of the different channel widths and different scalable deployment types can be seen in the Figure 2.

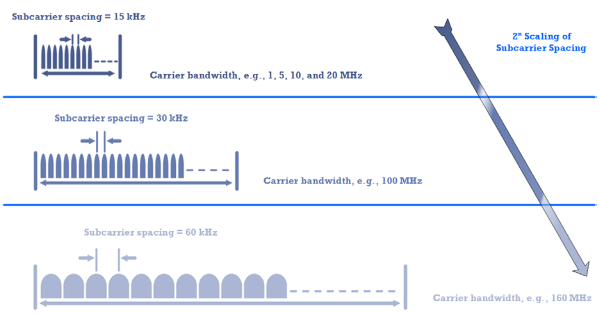

Figure 2: Example channel bandwidths, and subcarrier spacing

4.- PERFORMANCE RESULTS

The performance comparison of the different 5G NR numerologies at various speeds was made with 10000 Transmission Time Intervals (TTI) per numerology, using the PHY layer parameters of LTE, the parameters of the numerologies shown in Table I, a 64-QAM modulation, and a frequency of operation of 2 GHz. Based on a 3GPP calibrated simulator of the LTE PHY layer, changes were made to the CP and subcarrier spacing in order to set the V2X scenario.

The first result, shown in Figure 3, is the Block Error Rate (BLER) that was obtained from the 3GPP calibrated simulator, assuming a SISO case and a speed of 3 km/h. The purpose of presenting these results is to show how numerology affects the performance of the system. In this case, we can see how increasing the subcarrier spacing has an effect on the BLER. Indeed, when increasing the subcarrier spacing from 15 kHz to 30 kHz, the system undergoes a small improvement. This is because, the further apart the subcarriers are from each other, the less likely is that a frequency shift –produced by Doppler Effect– on any subcarrier will interfere with the contiguous subcarriers. For this reason, the system is more robust against the Doppler Effect and, therefore, it is better shielded against Inter-Carrier Interference (ICI).

By increasing the subcarrier spacing from 30 kHz to 60 kHz, one might think that the expected outcome is also an improvement in BLER performance since, obviously, the protection against ICI is even better. Although this is true, here it must be taken into account the effect that occurs in the time domain by increasing the subcarrier spacing, which is to decrease the OFDM symbol duration and, therefore, also the slot duration and the CP. Since the symbol duration and the cyclic prefix are four times shorter when the subcarrier spacing is 60 kHz compared to when it is 15 kHz, this system is less protected against multipath echoes that are produced by the topology of the scenario, which is independent on the numerologies. Hence, the system is more exposed to Inter-Symbol Interference (ISI), as the CP is not large enough to protect the signal from the echoes.

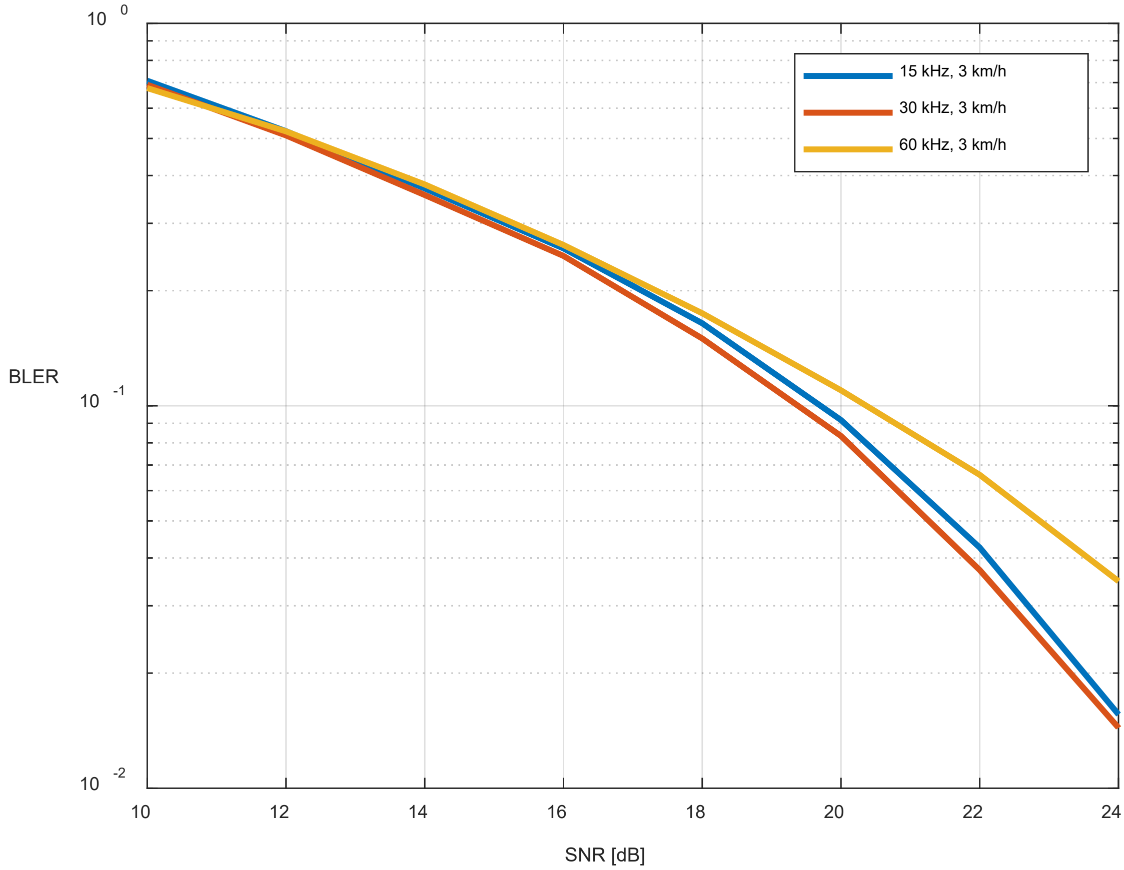

Figure 3: BLER with different numerologies at 3 km/h

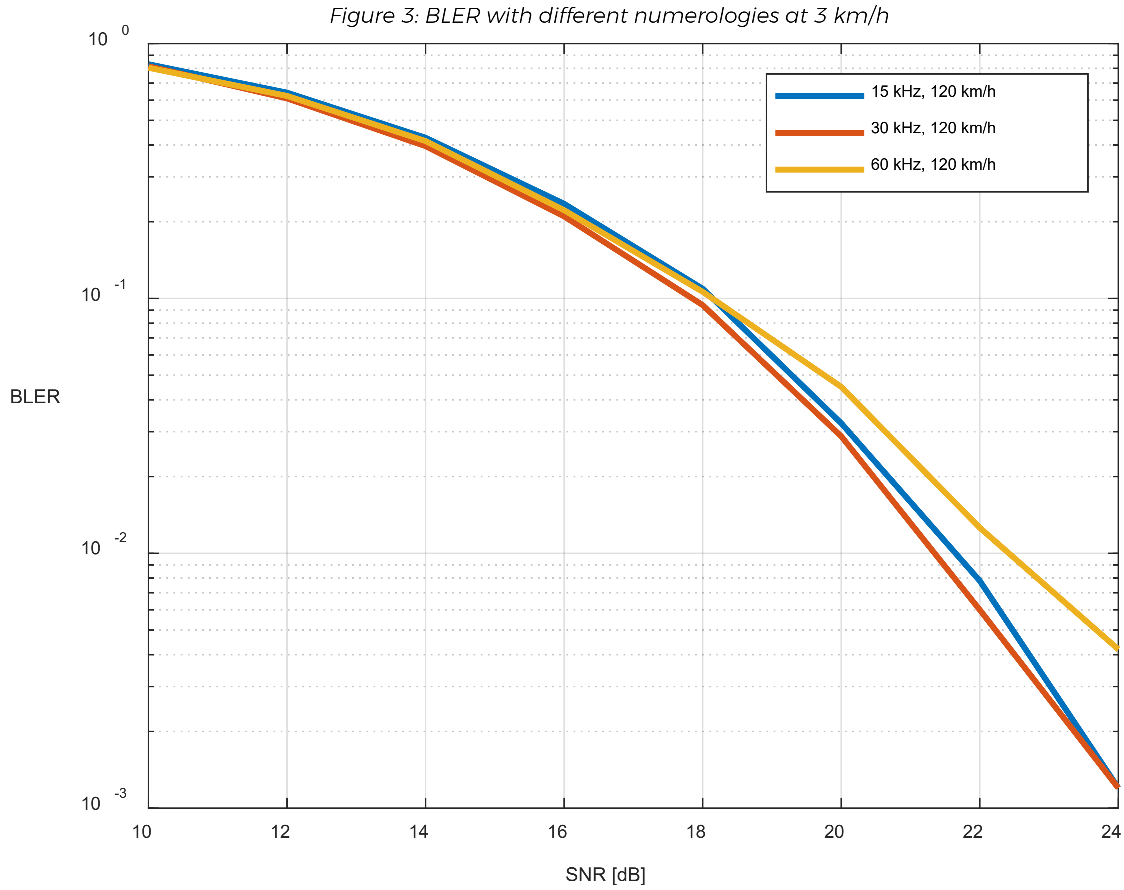

Figure 4: BLER with different numerologies at 120 km/h

Figure 4 shows the results of the same scenario detailed above, but at a speed of 120 km/h, in order to simulate the communication between vehicles moving at the highway speed limit. At first glance, it seems that the results are not what expected by increasing the speed, since it gives the impression that the behavior is the same as the 3 km/h scenario. However, by detailing the figure it can be seen that the values of the BLER are lower in this scenario with respect to the previous scenario since the Doppler effect is more significant and there is more ICI. As a consequence, it can be appreciated how the ISI effect has less influence over the BLER performance in this scenario. This is because increasing the system speed also increases the Doppler effect on the signal; therefore, if the subcarrier spacing is higher, the signal will be more protected against this effect.

5.- CONCLUSIONS

Changes in 5G NR numerology have a significant effect on the BLER performance within a V2X scenario. This has been verified according to the results obtained and the analysis thereof with respect to the presence of ICI, ISI and Doppler effect. However, as explained in the results section, increasing subcarrier spacing involves a trade-off between the ICI effect and the ISI effect over the performance of the system. Therefore, it is important to quantify the compromise that must be reached between both factors, in order to determine the best numerology for each V2X scenario. This trade-off quantification could be applied to any deployment type within the landscape of 5G.

Future work includes a deeper analysis and detailed calculation of the Doppler effect on the signal at different numerologies, so that it be possible to determine, according to the performance requirements of the diverse deployments, whether it is more convenient to be protected against ICI or against ISI.

It is worth noting that the Doppler effect depends on the operation band. Therefore, the optimum configuration of the CP and subcarrier spacing will depend on the frequency, being more subcarrier spacing needed whenever with increase the operation frequency.

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6.- BIOGRAPHIES

Josue Flores de Valgas was born and raised in Ecuador. He received the B.E. degree in Electronics and Telecommunications engineering from the Escuela Superior Politécnica del Litoral (ESPOL) in 2013, and the M.Sc. in Telecommunication Technologies, Systems and Networks from the Universitat Politècnica de València (UPV) in 2015. He is currently a Ph.D. student as a member of the Mobile Communication Group (MCG) at UPV, and a Grant Holder of the Ecuadorian Secretariat of Higher Education, Science, Technology and Innovation. His current research interests are mainly related to waveform design and harmonization. Before moving to Spain, he worked for three years on different Ecuadorian Telecommunications companies and a government project.

David Martín-Sacristán received the M.Sc. degree and the Ph.D. degree in telecommunications engineering from the Universitat Politècnica de València (UPV), in 2006 and 2016, respectively. He is currently a researcher with the iTEAM Research Institute, UPV. He has been involved in several European projects as a simulation expert, such as WINNER+ that was an External Evaluator of the IMT-Advanced Technologies for the ITU. He has also been involved in METIS and METIS-II, which lead the development of the 5G, and has contributed to two books about 5G design. He has participated in several contracts related to the automotive industry focused on vehicular communications. His research interests are focused on the modeling and simulation of communication networks, radio resource management, and vehicular communications.

Dr.-Ing. Jose F. Monserrat (H-index 21) received his MSc. degree with High Honors and Ph.D. degree in Telecommunications engineering from the Universitat Politècnica de València (UPV) in 2003 and 2007, respectively. He was the recipient of the First Regional Prize of Engineering Studies in 2003 for his outstanding student record receiving also the Best Thesis Prize from the UPV in 2008. In 2009 he was awarded with the best young researcher prize of Valencia. In 2016 he received the merit medal from the Spanish royal academy of engineering, in the young researcher category. He is currently an associate professor in the Communications Department of the UPV. His current research focuses on the design of future 5G wireless systems and their performance assessment. He has been involved in several European Projects, being especially significant his participation in NEWCOM, PROSIMOS, WINNER+, 5GXCAST and METIS/METIS-II where he led the simulation activities. He also participated in 2010 in one external evaluation group within ITU-R on the performance assessment of the candidates for the future family of standards IMT-Advanced. He co-edited two special issues in IEEE Communications Magazine on IMT-Advanced and 5G technologies and is co-editor of the Wiley book "Mobile and wireless communications for IMT-Advanced and beyond" and the Cambridge book "5G Mobile and Wireless Communications Technology". Jose Monserrat is senior member of the IEEE, manages around 0.5 M€ yearly budget, holds 6 patents and has published more than 50 journal papers. Currently the group headed by Prof. Jose F. Monserrat consists of 5 Postdoctoral fellows, 8 PhD students and 2 Master students.