Above-90GHz Spectrum and Single-Carrier Waveform as Enablers for Efficient Tbit/s Wireless Communications

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***Abstract*—The radio spectrum above 90GHz offers opportunities for huge signal bandwidths, and thus unprecedented increase in the wireless network capacity, beyond the performance defined for the 5G technology. This spectrum is essentially exploited for scientific services, but attracts nowadays many interest within the wireless telecommunications research community, following the same trend as in previous network generations. The BRAVE project that was launched at early 2018, aims at the elaboration of new waveforms able to efficiently operate in the 90–200 GHz spectrum. The researches rely on three complementary works: the definition of relevant communications scenarios (spectrum usage, application, environment, etc); the development of realistic models for the physical layer (propagation channel and RF equipments); and the elaboration of a single-carrier modulation compliant with the propagation channel properties, and allowing improvement on the spectral and energy efficiency. The motivation for this work, and the preliminary results on the waveform definition, are exposed in the present paper.**

***Index Terms*—Tbit/s, beyond-5G, above-90GHz, single-carrier.**

I. Introduction

The activities of research and industrialization concerning the fifth generation (5G) of wireless communication systems are well-under way. Several solutions are proposed for standardization starting with 5G-NR (New Radio) [1]. There are three main objectives driving the development of 5G: the support to extreme wireless broadband services for applications such as the virtual and augmented realities, the 3D 4K video, cloud services, etc.; the connectivity for massive Internet of Thing (IoT) applications as: smart cities and factories, wireless health care; and the support of mission-critical services such as for autonomous vehicle, or security, with strong requirements on latency, guaranteed throughput, etc.

All these target applications have highly different needs, but make 5G required to offer: throughputs in the order of Gbps with sub-millisecond latency along with 1000x capacity increase, and 100x connected devices per cell compared to nowadays existing mobile networks. Dense small-cell deployments, centralized RAN (Radio Access Network), advanced MIMO schemes and new millimeter-Wave (mmW) bands are key enablers to achieve the expected increase in spectral efficiency and capacity [2]. Frequency bands 26 or 28 GHz and 39 or 42 GHz will be likely selected for early 5G deployments.

Alongside these 5G initiatives, the scientific community has also launched many investigations on the beyond 5G (B5G) services and communications systems with a mid-term application perspective, let say after 2020. B5G scenarios consider more stringent application requirements, higher number of devices, and even denser networks [2]. B5G might go further in the expected network visualization and softwarization (xhaul, mobile edge computing and software defined network clouds) [2]. A relevant example is the recent call of the EC, ICT-09-2017: Networking research beyond 5G. This call was clearly research oriented with aim to reach several hundred of Gbits/s up to Tbits/s.

Very broad bandwidth of several tens GHz is required to offer such throughputs. It is well known that the classical radio-communication spectrum is overused and scarce. Many emerging techniques tend to improve the spectrum usage, e.g. cognitive radio, opportunistic or dynamic spectrum access, but this will not be sufficient. The future 5G millimeter wave bands along with multi-user beamforming should lead to user throughputs above 1 Gbit/s. However additional breakthrough technologies are necessary to reach the B5G throughput requirements. Therefore, for the first time in the telecommunication history, bands above 90 GHz are studied for future wireless communications systems.

The BRAVE project, which is funded by the French research agency (ANR), has been launched in early 2018 with the aim to create and evaluate new radio technologies that would operate in the 90-200 GHz spectrum and support B5G performance. This project will contribute to the migration of 5G networks towards radio access systems that support several hundreds of Gbit/s. Ultimate goal is the definition of a solution that would reach 1 Tbit/s. Taking into account the adversary nature of a communications channels in frequencies above 90 GHz, the project focuses on scenarios in which the connected nodes (end user, relay, access point, gateway) are in line-of-sight (LoS) or nearly LoS (i.e. only light obstruction). BRAVE revisit the PHY-layer by looking back on single-carrier (SC) modulations, thus allowing for improved spectral efficiency and reduced power consumption (i.e. from lower Peak-To-Average Power ratio (PAPR)). Indeed LoS transmission and the use of large antenna arrays make the propagation channel favorable to SC modulation. Besides, the propagation and RF impairments at frequencies above 90 GHz are investigated and modeled. This will serve three objectives: 1) implement realistic link- and system-level simulators; 2) design the new air interface based on well-understood physical constraints; 3) evaluate and demonstrate B5G scenarios. Based on the motivation and first results of the BRAVE project, this paper provides in Section II an overview on the above-90GHz opportunities and constraints. Then Section III presents single-carrier waveform examples that will be investigated within the BRAVE project expected to reach improved spectral and energy efficiency.

II. Promising opportunities and constraints

A. Spectrum opportunities for above-90GHz broadband communications

The radio spectrum above 90 GHz is today essentially known for being used by scientific services (e.g. astronomy observation, earth exploration and satellite services, meteorology, etc.) and has never been used effectively for radio wireless communications purposes [3].

It should however be noted that the radio regulations already allocated several frequency bands above 90 GHz to the fixed and mobile services. More specifically, within the range 90 – 200 GHz, the following frequency bands would provide opportunities to be considered for introducing terrestrial communication systems: 92 - 94 GHz, 94.1 - 100 GHz, 102 - 109.5 GHz, 111.8 - 114.25 GHz, 122.25 - 123 GHz, 130 - 134 GHz, 141 - 148.5 GHz, 151.5 - 164 GHz, 167 - 174.5 GHz, 174.5 - 174.8 GHz and 191.8 - 200 GHz. It can also be mentioned, that there is some ongoing work within CEPT (the European Conference of Postal and Telecommunications Administrations) organization aiming to facilitate the deployment of fixed services links in the frequency blocks already allocated to fixed services in the frequency ranges 92 - 115 GHz and 130 - 175 GHz.

B. Beyond-5G scenarios

Future wireless fronthaul/backhaul is one candidate for the exploitation of those frequencies. The last-mile pre-5G networks rely on two separated segments: the user access, and the backhaul access, that mostly consists in line-of-sight (LoS) microwave or fiber-based links connected to a gateway. Innovative solutions for wireless small-cell backhauling are now emerging which use the sub-6GHz bands to reach non-line-of-sight (NLoS) multi-points, or rely on a mesh street-level architecture by operating at mmW frequency and compatible with high-data rate. All those solutions are using multi-carrier Orthogonal frequency-division multiplexing (OFDM) waveform, and most of them implements beamforming.

The effort for achieving 5G and future B5G requirements has to be done at the same pace on the user access and the backhauling segments in order to avoid any bottleneck effect. As most processing that was traditionally done at the base stations or at the access points is intended to be deported to the core of future C-RAN networks, the requirements for high capacity and low latency at the fixed last-mile wireless links (or fronthaul) will be even higher. Line-of-sight wireless fronthaul/backhaul technology based on above-90GHz spectrum is viewed as a relevant extension of the emerging mmW commercial solutions in order to provide the expected speed (hundreds of GBit/s) to the access points installed at the user premises or being part of the mobile access network.

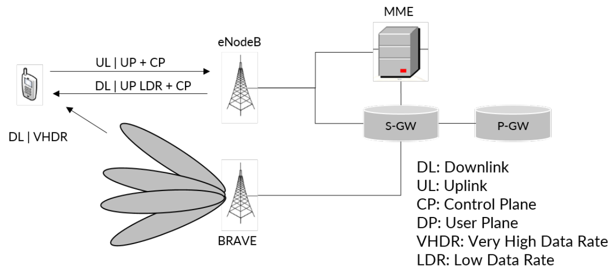

Fig. 1. Example of Kiosk application with offloading. The very-high data rate services are transmitted using the mmW downlink, while the others services (including control plane) are allocated to 4G/5G cellular network.

Several use cases of interest for Tbits/s systems operating above 90 GHz have been already identified. They will serve in the definition of the BRAVE solution requirements, evaluation and demonstration. Those use cases are:

- Kiosk application: very short-range (up to few meters) with very-high downlink data rate link, with possibly connection to several simultaneous users as depicted in Figure 1;
- Resolution of congestion issues in server farms;
- Small-range hot-spots with limited user mobility and demanding applications like virtual or augmented reality, high-resolution video ;
- Wireless backhaul infrastructure to deliver ultra-high data throughput and capacity.

The envisioned ultra-dense network topology in urban areas with extreme data rate, capacity and latency requirements makes the fiber-based backhauling highly desirable, but sometimes complicated due to current fiber networks penetration (variable from one country to the other) and related extension cost. High data rate wireless backhauling is a valuable competitive technology, which benefits from lower deployment costs and constraints [4][5]. LoS or nearLoS wireless xhaul (front or back-haul) technology based on above-90GHz spectrum is viewed as a relevant extension of the emerging mmW commercial solutions in order to provide the expected speed (hundreds of GBit/s) to the access points installed at the user premises or being part of the mobile access network. In-street mesh deployment will permit to feed a large number of remote access points via the wireless xhaul connected to a local Internet access.
The Fixed Wireless Access (FWA) is another possible backhauling application, where the mesh high-frequency infrastructure gives connectivity to the fixed CPE's (Customer Premise Equipment) installed on the rooftop or facade of houses, apartment buildings, offices, etc. This alternative to fiber optic connections is today gaining popularity in the United States (among other countries).

C. Constraints at the physical layer

The characteristics of the propagation channel and its modeling are critical inputs for several research tasks: definition of adequate scenarios (cell range, supported propagation environments); elaboration of PHY-layer algorithms (e.g. waveform, channel estimation, equalization among others); evaluation and refinement of multi-antenna systems, and link- and system-level simulations.

The scientific propagation community is today producing intensive activity on the mmW bands that are envisaged for future 5G backhauling and access solutions, including both indoor and outdoor environments, considering large-bandwidth and high antenna directivity. Propagation in those bands is characterized by very strong obstruction losses (from walls, vegetation, urban furniture, etc) and high sensibility to the environment details (small objects, surface roughness, etc.) [6]. Sparse propagation, i.e. composed of only few dominant paths, is generally observed, while the role of discrete scattering or diffusion is still under question. The channel stationarity or non-stationarity over the signal bandwidth and antenna array are still not fully assessed and modeled, but have a major impact on the system performance. Multi-link spatial consistency is another key feature that must be properly predicted for addressing ultra-dense small-range networks, but needs complex or deterministic modeling. Some stochastic models as those provided by the EU projects WINNER+, METIS, mmMAGIC, MiWEBA or 3GPP, already address the frequencies above 6 GHz, up to 100 GHz in some cases. New propositions are regularly made to refine the stochastic parameters or model structures, based on channel sounding measurements [7]. Besides, the ray-based deterministic simulators (using geographical representation), which were in the past mainly devoted to radio-planning before, are nowadays considered as a valuable tool able to reproduce all or part of the expected sparse channel characteristics in mmW band. They may generate channel samples for link or system simulations, or may be hybridized with stochastic processes as proposed in the 3GPP, MiWEBA or mmMAGIC models.

Most of the propagation and the model characteristics established for 5G mmW bands are expected to remain valid above 90 GHz, however the current models are not yet fulfilling all requirements, and (as always) adjustments will be mandatory. Besides, the radio propagation research and modeling above 100 GHz are gaining interest [8][9]. The first indoor results highlight that the predominance of the LoS still increases compared to sub-100GHz spectrum. However, the most powerful multi-paths remain quite similar (in terms of delay and angle) at 26 or 28 GHz and 140 GHz. Moreover, channel properties and models have been recently proposed in the range 245–350 GHz for the definition of future THz IEEE P802.15 WPAN standard.

Concerning the transceiver, mmW systems are critically impacted by the radio frequency (RF) impairments, such as non-linearities, IQ imbalance and phase noise. For high frequency broadband systems, the nonlinearity of analogue components used in RF front ends gives increased challenges in the modeling of circuits and in anticipating the compensation measures required for performance improvements. The RF front end is composed of all components between the antenna and the digital baseband system of a transceiver, namely mixer or modulator, phase shifter, and power amplifier (PA). At higher frequency, especially for Complementary Metal Oxide Semiconductor (CMOS) implementation, the PA efficiency and achievable output power decreases [9]. Therefore, it is important to reduce the required power back-off of the PA by considering near-constant envelope modulation or by implementing PAPR reduction schemes at baseband level. Mixers and oscillators are also sources of impairments, especially at high frequencies. Mixing the RF signal with the local oscillator (LO) realizes frequency conversion within the RF transceivers. The phase of the LO can be non-stationary or time varying. Ideally, the LO generates a single tone. However, due to impermanent, the tone is modulated and phase noise is introduced. Phase noise causes significant degradation in the performance. Therefore, design of low phase noise oscillators has been a popular research topic for decades, by exploring new semiconductor technologies and circuits design topologies. From the physical layer perspective, this has motivated extensive work on phase noise estimation and compensation [10][11].
Last but not least, digitalization constraints are also a bottleneck [12]. Data converters designed for high-end instrumentation have large bandwidth and resolution requirements. However the power constraint, integration as well as cost requirements are relaxed. One can imagine for certain scenario such as backhaul infrastructure high end equipment's without integration and power constraints. However for consumer applications, at the device (mobile equipment) side, digitalize a large amount of bandwidth with power and integration constraints is still a research topic. The digitalization of sub band of a few GHz, seems to be a consensus. Depending on the capacity of a mobile one or more sub channel could be acquired in parallel. The interference management in that case could limit the performance of the transceiver.

III. Towards more efficient waveforms

A. Analysis

The definition of an efficient physical layer (PHY-layer) in the considered frequency band is very challenging due to radio frequency impairments, as described previously, and complexity. The PHY-layer can be revisited by looking back on SC modulation for the waveform, and to investigate techniques for the transceiver combined with approaches close to analog systems. Similar studies were conducted in the 80's and some concepts, forgotten, could be resurrected. For instance, non-coherent modulations inherently robust to phase noise effect could be a good candidate for sub THz communication [13].

Multi-carrier systems were justified in frequency selective channels, in order to simulate a great number of flat small channels. The propagation above-90 GHz is often characterized by a dominant path [9], obtained either from LoS situation or antenna beam alignment. Therefore probability for the frequency-selective situation is very low. The channel characteristics make SC modulation schemes, as opposed to the popular multi-carrier schemes, potentially more appropriate for communication systems operating in such frequency bands above 90 GHz.

B. PAPR considerations

1) Multi-carrier case: The envelope of a multiplex of modulated signals (for both single-carrier and multi-carrier signals) is not constant. This is always true, for instance, for software radio signals like a multiplex of GSM signals (even if each one is actually of constant envelope). The large variations of the multi-carrier transmitted signals lead to a weak power efficiency of the power amplifier and, therefore, intensive energy consumption requiring a growing need for cooling is observed. All the classical multi-carrier systems, as the OFDM, suffer from high power fluctuations. The variations of the signal envelope generate non-linear distortions when the OFDM signal is introduced into a power amplifier. Based on the work in [14] , about 30% of the base station power consumption is due to the high power amplifier (HPA) and the associated cooling. Depending on in-site implementation technologies this value may reach 50%.

This explains the existence of huge scientific literature on HPA efficiency optimization methods. This last problem may be tackled at different levels [15].

The PAPR is a random variable which has been introduced to measure the power variations of the OFDM or any MC signal. A lot of researches have been conducted in order to reduce the PAPR effects and to analyze its probability distribution. A huge number of studies and developed techniques exist for the PAPR reduction that cannot be discussed in this paper. The reader may refer to many overview papers or books as [15], [16], [17], and to the recent work using Tone Reservation method in [18] to reduce this effect.

2) Single-carrier case: It is well known that, at the opposite of multi-carrier signal, single-carrier signal has much lower PAPR. Recent conducted researches for mmW communications focused on several SC modulations like; the Continuous Phase Modulated Single-Carrier Frequency Division Multiple Access (CPM SC-FDMA) [19] which is a generalization of SC-FDMA using samples of a Continuous Phase Modulation (CPM) signal as generalized coded modulation input symbols . The scheme can provide a low PAPR signal with very low spectral side lobes, the CPM parameters like the oversampling factor and the sub-carrier mapping have to be suitably selected. It is shown that a good PAPR versus spectral efficiency trade-off is obtained with an oversampling factor of two together with Interleaved Frequency Division Multiple Access (IFDMA) mapping. Another scheme is the Constrained Envelope Continuous Phase Modulation (ceCPM-SC) which is a true single-carrier scheme generalizing CPM by allowing controlled small envelope variations.

C. On going work on PHY

The arguments exposed in previous section (no need of MC modulation due to the channel frequency characteristics and the need for lower PAPR towards green communications) have motivated the choice for SC modulation in the BRAVE project. The design of SC waveforms that provide extra robustness against phase noise, Doppler, and carrier frequency offset at very high frequencies, is studied. As the maximum Doppler frequency increases linearly with the carrier frequency, frequencies above 90 GHz can suffer from very strong Doppler impairments under relatively low mobility conditions. In addition, phase noise in practical oscillators becomes one of the most difficult issues to combat. We explore novel SC waveforms aiming to provide extra robustness against the RF impairments. Frequency modulation of a constant envelope complex signal is investigated, where the information is carried in the phase rather than in the amplitude. A new constant envelope FSK-CPM waveform was recently proposed in [20]. Its frequency pulse has the property to directly generate a narrow single side band (SSB) spectrum. The original principle is directly inspired from quantum physics (levitons). This CPM modulation displays a very compact spectrum, with 99% of the power in the primary bandwidth. Its SSB property

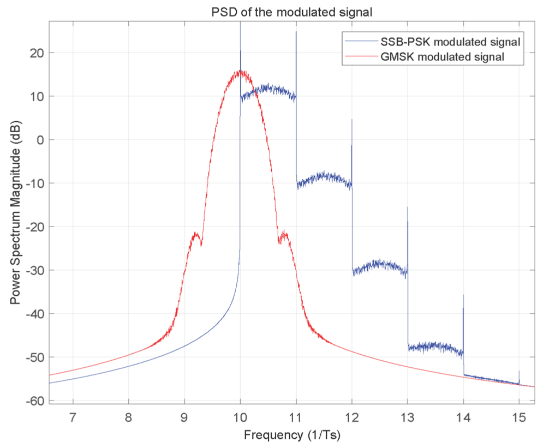

Fig. 2. New SSB-FSK waveform Power Spectrum Density [20].

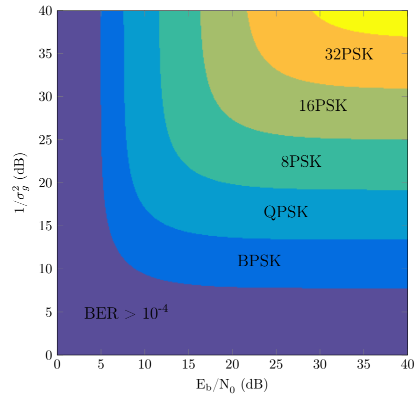

Fig. 3. Modulation Scheme Regions for M-PSK: highest modulation order M achieving BER $< 10^{-4}$ as a function of Eb/N0 and the inverse of phase noise variance.

makes this FSK-CPM scheme, hereby called SSB-FSK, is a promising solution robust to the image frequency degradation that allows large bit rates transmission. The SSB-FSK will also be investigated for communications at frequencies above 90 GHz in the framework of the project BRAVE.

To improve spectral efficiency, practical communication systems implement adaptive modulation schemes. Namely, the modulation order is inferred from a SNR estimation. In the case of a channel dominated by Gaussian Phase Noise, and assuming M-PSK modulation, the analytical BER expression enables to determine the greatest value of M while maintaining the error rate below a fixed target. As an example, Figure 3 depicts the modulation scheme regions for M-PSK, i.e. the highest modulation order M achieving BER $< 10^{-4}$ given Eb/N0 and Phase noise variance σ_g^2. It is shown that the performance is highly related to the phase noise variance, which should necessarily be considered and estimated in the link adaptation to maintain robustness.

The use of non-coherent modulation/demodulation scheme can also have a particular interest in some cases. For example, Differential PSK (DPSK) enables a non-coherent demodulation at the receiver. As a consequence, estimation of the carrier phase is not required. Moreover, a differential modulation is not subject to the cumulative nature of the phase noise (Wiener phase noise), and only slightly to the carrier frequency offset. This robustness is achieved at the expense of a BER

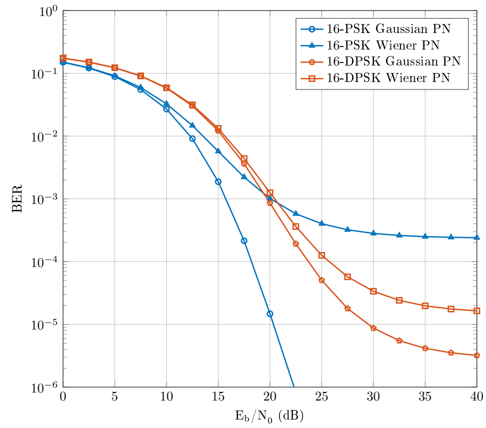

Fig. 4. BER performance of 16PSK and 16DPSK for Gaussian phase noise (PN) ($\sigma_g^2 = 10^{-3}, \sigma_w^2 = 0$) and Wiener PN ($\sigma_g^2 = 10^{-3}, \sigma_w^2 = \sigma_g^2/2$).

performance degradation. Yet, the stronger these impairments, the more valuable it seems to opt for differential encoding. As an example, the performance of a 16-PSK and 16-DPSK modulation for Gaussian and Wiener PN is depicted in Figure 4. The DPSK scheme exhibits a loss in BER performance for low phase noise level. But, when considering stronger Wiener phase noise then it is more robust than the PSK.

To reach the Tbit/s magnitude, the considered SC modulation is required to have a high spectrum efficiency. Constant envelope modulations like CPM could be limited due its low spectrum efficiency. Many symbols in the I/Q plan are needed but, in turn, this implies a non-negligible PAPR effect. Actually it is function of the used filter. In [21] it was proved that the PAPR increases when the roll-off factor of the Nyquist filter decreases. To decrease this PAPR, some mitigation techniques studied in the multi-carrier context could be adapted and applied in beyond 100 GHz band, such as the Modified Tone Reservation technique developed in [18]. The high-order Partial Response Signaling (PRS) modulation might also be able to improve the spectrum efficiency. Significant side-information like position and orientation is required. It may be provided by sensors, environmental map, device cooperation, etc, and will be used in a Cognitive Radio manner.

IV. Conclusion and Perspectives

The radio spectrum above 90GHz offers opportunities for huge signal bandwidths, and thus unprecedented increase in the wireless network capacity (beyond the performance defined for the 5G technology). This spectrum is essentially exploited for scientific services, but creates today some interest in the research telecommunications community. The community has to face new challenges at different system levels. First, it is important to define relevant scenarios and their requirements. Secondly, the definition of adequate physical layer is necessary to be inherently robust to the propagation channel as well as the RF impairments. Preliminary results demonstrate the benefits of single-carrier modulations. Finally, integrated system performance will be assessed by combining the new waveform definition, the RF impairments and above 90GHz radio planning tools developed within the framework of the BRAVE project.

V. Acknowledgment

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References

[1] 3rd Generation Partnership Project (3GPP), "Overall Description Stage 2," Technical Specification Group Access Network, 2017.

[2] H. J. Song and T. Nagatsuma, "Present and future of terahertz communications," *IEEE Transactions on Terahertz Science and Technology*, ,Vol. 1, Issue 1, pp.256-263. Year 2011.

[3] Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT), " The European table Of frequency allocations and applicationsin the frequency range 8.3 kHz to 3000 GHz (ECA TABLE) ," Tech. Rep., October 2017.

[4] F. Letourneux, G. Gougeon, M. Brau, Y. Corre, and Y. Lostanlen, "Small-Cell Wireless Backhaul and Access Networks: Realistic Modeling and Holistic Analysis," in *10th European Conference on Antennas and Propagation (EuCAP)*, 2016.

[5] R. Zhang, X. Jiang, T. Taleb, B. Li, H. Qin, Z. Zhong, and X. Zhang, "Connecting a City by Wireless Backhaul: 3D Spatial Channel Characterization and Modeling Perspectives," *IEEE Communications Magazine*, vol. 55, no. 5, pp. 62–69, May 2017.

[6] J. Stéphan, Y. Corre, R. Charbonnier, and Y. Lostanlen, "Increased Reliability of Outdoor Millimeter-Wave Link Simulations by Leveraging Lidar Point Cloud," in *12th European Conference on Antennas and Propagation (EuCAP)*, 2018.

[7] , "The EU project-mmMAGIC, code: H2020-ICT-671650. Technical report D4.1: "Preliminary radio Interface concepts for mm-wave mobile communications," Tech. Rep., June 2016.

[8] S. Nguyen, J. Järveläinen, A. Karttunen and K. Haneda, J. Putkonen, "Comparing Radio Propagation Channels Between 28 and 140 GHz Bands in a Shopping Mall," *in the Proc. of the 12th European Association on Antennas and Propagation (EurAAP'18)*, April 2018.

[9] L. Pometcu, R. Derrico, "Characterization of Sub-THz and mmWave Propagation Channel for Indoor Scenarios," *in the Proc. of the 12th European Association on Antennas and Propagation (EurAAP'18)*, April 2018.

[10] X. Yi, W. Shieh, and Y. Tang, "Phase estimation for coherent optical OFDM transmission," *COIN-ACOFT 2007 - Joint International Conference on the Optical Internet and the 32nd Australian Conference on Optical Fibre Technology*, 2007.

[11] F. Munier, E. Alpman, T. Eriksson, A. Svensson, and H. Zirath, "Estimation of phase noise for QPSK modulation over AWGN channels," *In the Pro. of the Seventh Symposium in GigaHertz*, 2003.

[12] S. Shahramian, "Millimeter-Wave Analog to Digital Converters: Technology Challenges and Architectures," *PhD Thesis*, 2011.

[13] A. G. Burr, "Comparison of coherent and noncoherent modulation in the presence of phase noise," *IEEE Proceedings I - Communications, Speech and Vision Vol. 139, Issue 2, pp. 147-155*, 1992.

[14] W. H. Doherty, "A New High Efficiency, Power Amplifier for Modulated Waves," *Proceedings of the IRE*, 1936.

[15] Y. Louet, J. Palicot, "A classification of Methods for Efficient Power Amplification of Signals," *Annals of Telecom*, 2008.

[16] S.H. Han, J. H. Lee, "An Overview of Peak-to-Average Power Ratio Reduction Techniques for Multi-Carrier Transmission," *IEEE Transactions on Wireless Communications*, Vol. 12, Issue 2, pp. 56-65, year 2005.

[17] H. B. G.Wunder, R. Fischer, S. Litsyn, "The PAPR Problem in OFDM Transmission: New Directions for a Long-Lasting," *IEEE Signal Processing Magazine*, 2013.

[18] M. L. Diallo, M. Chafii, J. Palicot, F. Bader, "Modified Tone Reservation for PAPR Reduction in OFDM Systems," *In the Proc. of the 24th European Signal Processing Conference (EUSIPCO'16)*, August 2016.

[19] M. P. Wylie-Green, E. S. Perrins, and T. Svensson, "Design and performance of a multiple access CPM-SC-FDMA transmission scheme," in *2009 International Waveform Diversity and Design Conference*, Feb 2009, pp. 286–290.

[20] H. Farès, D. C. Glattli, Y. Louët, J. Palicot, P. Roulleau, C. Moy, "Power Spectrum Density of Single Side Band CPM Using Lorenztian Frequency Pulses," *IEEE Wireless Communication Letters*, , vol. 6, no.6, pp.786-789, year 2017.

[21] J. Palicot, Y. Louet, "Power Ratio definitions and analysis in single carrier modulations," *In the Proc. of the 26th European Signal Processing Conference (EUSIPCO'05)*, September 2005.