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Indoor Coexistence Analysis Among 5G New Radio, LTE-A and NB-IoT in the 700 MHz Band

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ABSTRACT This work reports a common indoor experimental coexistence performance analysis among 5G New Radio (5G NR), 4G Long Term Evolution Advanced Pro (LTE-A Pro) and Narrowband Internet of Things (NB-IoT), using co-channel and adjacent channels in the 700 MHz Band. The required frequency offset for the 4G and 5G generations simultaneous operation has been evaluated, as a function of the modulation scheme in order to minimize the adjacent channel interference. A suitable management of the numerology and allocating time-frequency resources, configuring CORESET, enables a peaceful coexistence, as well as high performance for all evaluated systems. Experimental results demonstrate an efficient spectrum sharing of 10 MHz-bandwidth for a 5G NR, an LTE-A Pro and three NB-IoT downlink carriers, aiming to take advantage of 700 MHz propagation aspects for the current 4G and future 5G. Constellation and error vector magnitude (EVM_{RMS}) in accordance to the 3GPP requirements reinforce the successful 4G and 5G spectrum refarming implementation.

INDEX TERMS 4G, 5G NR, coexistence, LTE-A and NB-IoT.

I. INTRODUCTION

Mobile data traffic has been exponentially growing in the last years and is expected to increase five-fold by 2024 [1]. The fifth generation of mobile communication (5G) is going to operate over two frequency ranges, namely: FR1 from 410 MHz to 7.125 GHz with bandwidth up to 100 MHz; FR2 from 24.25 to 52.6 GHz with bandwidth up to 400 MHz. As a consequence, coexistence analyses with 4G and 5G systems are mandatory [2]–[4].

As in any other generation of mobile communications, we are going to have indoor and outdoor usage scenarios in 5G. Particularly, we are probably going to have even more small cells in 5G, including indoor small cells, when compared to 3G and 4G. Additionally, the most important players (such as Ericsson, Huawei and Nokia) provide indoor solutions in their 5G/4G product portfolio for Telecom operators. The main applications they have in mind are shopping, industries, stadiums, theater and big events. Nowadays, telecom operators need more spectrum and typically use different pieces of equipment for employing multiple technologies.

The favorable propagation conditions in the 700 MHz band have been attracting mobile telecom operators worldwide to deploy LTE Advanced Pro (LTE-A Pro) and 5G New Radio (5G NR), using this spectrum range. However, it is already congested with the current wireless systems, implying in tough technical challenges for 5G. Diverse approaches for promoting peaceful spectrum sharing among multiple technologies have been exploited [3]–[5], with the purpose of allowing a smooth user transition experience until the LTE switch-off. Particularly, the 5G network is expected to be deployed on top of the existing LTE-A Pro network, by using frequency division duplex (FDD) [4]. The first version of Non-standalone (NSA) mode, launched in December 2017, represents an important breakthrough for making this network upgrade feasible. The 3GPP Release 15 also standardizes the stand-alone (SA) 5G NR and NSA 5G NR/LTE dual-connectivity modes [5]–[7].

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The initial 5G networks were based on the NSA mode, in which the evolved packet core (EPC) coordinates both technologies and promotes packet scheduling for multiple services, giving rise to dual connectivity (DC). In other words, the mobile device might be simultaneously connected to two cells [5]–[11]. Wan Lei *et al.* investigated the 5G NR and 4G LTE coexistence in C-Band [8]. They proposed to use reserved resource blocks (RBs) in spectrum sharing as an option for multiple technologies coexistence, including LTE and Narrowband Internet-of-Things (NB-IoT). In [9], Kim *et al.* reported the coexistence analysis between NB- IoT and LTE uplink signals, using 15 and 3.75 kHz subcarrier spacing for LTE and NB-IoT uplink signals, respectively. The use of unlicensed spectrum for 5G is discussed in [11], demonstrating the importance of spectrum slicing 5G cost-effective solutions.

In parallel, an analytical coexistence approach based on the distortion level due to a nonguard band between bandwidth parts (BWPs) for the 5G NR numerology has been proposed in [12]. The 5G and 4G uplink coexistence in the C-band has also been discussed for seamless coverage using the existing LTE sites [13]. Basically, the authors proposed utilizing a common channel for LTE and 5G NR, with a single physical resource block guard band. In this way, no subcarrier shifting is required by 5G NR, as long as the power control accuracy is sufficient and LTE performance is not affected. The limited spectrum resources turned on the licensed assisted access-long term evolution (LAA-LTE), operating in the unlicensed spectrum, aiming to guarantee harmonious coexistence among LTE with other wireless systems [14].

Mufutau *et al.* demonstrated a hybrid fiber-wireless 4G/5G fronthaul based on Analog Radio over Fiber (ARoF) and free space optics (FSO) [15]. Additionally, Zhang *et al.* proposed an algorithm based on Machine Learning (ML) applied to time interval scheduling for 5G enhanced mobile broadband (eMBB) and ultra-reliable low latency communication (uRLLC) scenarios [16]. Their numerical results demonstrated an effective reduction on delay and packet loss rate in uRLLC services, while maintaining eMBB requirements.

Tan *et al.* evaluated the coexistence between 5G and fixed-satellite service in the C-band [17]. Monte Carlo simulations, experiments and field tests indicated an isolation distance of 1-2 km is required to avoid saturation interference in adjacent bands conditions. In order to reduce the isolation distance to 50 m, additional 35-dB isolation would be necessary, by means of installing a RF filter at the Low Noise Block (LNB) input. Xu *et al.* reported the studies of 5G coexistence in an unlicensed band, focusing on maximizing system capability, interference management and congestion control using statistical signal transmission (SST) technique [18]. The proposed SST transmission might be considered potential to facilitate harmonious 5G coexistence in unlicensed bands. Finally, Hammoodi *et al.* compared multiple 5G waveform candidates, using key performance indicators (KPI), such as computational complexity, peak-to-average-power ratio, spectral efficiency, filter length and latency [19]. In brief, they suggested the use of optimized waveforms, such as filtered bank multicarrier (FBMC) and universal filtered multicarrier (UFMC), for making the coexistence with CP-OFDM 4G networks easier.

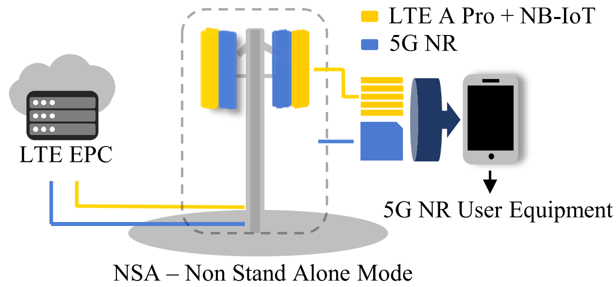

FIGURE 1. Coexistence analysis scenario using dual connectivity in a non-standalone mode for 5G new radio.

Particularly, 5G NR has a principle of ''ultra-lean design'' [6], in which the ''always-on'' signal is minimized in contrast to LTE, which is present only when data are transmitted. Correspondingly, mobile network operators can configure and allocate resources in time and frequency, using CORESET feature [6]. CORESET enables to allocate 5G NR channels in either time and frequency, with the purpose of minimizing interference between LTE- A Pro and 5G NR cells.

This work presents an indoor downlink coexistence analysis among 5G NR, LTE-A Pro and NB-IoT technologies, using co-channel and adjacent channels in the 700 MHz band, as schematized in Fig. 1. It illustrates a possible scenario of infrastructure-sharing deployment using NSA mode, in which a mobile user might take advantage of the 4G and 5G carriers simultaneously, applying dual connectivity. The EPC from LTE coordinates the control and data plane of both technologies in a DC NSA mode. In this way, Telecom operator can imply the spectrum refarming concept in order to shift part of older spectrum from 4G to new 5G wireless networks. Moreover, with NSA, carriers retain the same 4G core network and simply add 5G radios. Our co-channel technological solution based on a suitable management of the numerology and allocating time-frequency resources, configuring CORESET, enables a peaceful 4G/5G coexistence, as well as high performance for all evaluated systems.

The manuscript main contributions compared to our recent conference paper on the 4G and 5G coexistence in UHF [20] and others publications from the state-of-the-art are as follows: coexistence investigation in adjacent and co-channel scenarios, using 5G New Radio, LTE-A Pro and NB-IoT based on diverse modulation schemes; the use of CORESET feature from 5G NR for efficiently enabling co-channel coexistence; spectrum sharing and refarming, as a function of the frequency offset under real conditions for 5G NR in the 700 MHz band, aiming IoT and long-reach applications; coexistence analyses based on control and data signals, resource block allocation and equalization; the use of RF signals in accordance to the 3GPP TS 38.141-1 and 3GPP TS 38.141-2 base station conformance testing [21], [22].

TABLE 1. The transmitter and receiver main parameters.

Technology	Tx Power	Tx Antenna Gain	Rx Antenna Gain	Rx LNA Gain
5G New Radio	10 dBm	5 dBi	5 dBi	22 dB
LTE A Pro	10 dBm	5 dBi	5 dBi	22 dB
NB-IoT Cell ID 1	10 dBm	5 dBi	5 dBi	22 dB
NB-IoT Cell ID 2	10 dBm	5 dBi	5 dBi	22 dB
NB-IoT Cell ID 3	10 dBm	5 dBi	5 dBi	22 dB

The manuscript is structured in five sections. Section II presents the experimental setup for either co-channel and adjacent channels investigations. Their results are reported in Sections III and IV, respectively. Finally, the conclusions and future works are outlined in Section V.

II. EXPERIMENTAL SETUP

The experiments were focused on the 4G and 5G coexistence in the 700 MHz band, aiming supercells. For this reason, we have used only one antenna for both transmission and reception. An indoor experiment has been chosen for not interfering to commercial telecom networks. The coexistence frequency carriers have been cautiously chosen and experimentally validated in order to avoid those used by the local telecom operators. Fig. 2(a) summarizes the 4G and 5G transmission blocks, whereas Tab. 1 presents their main parameters.

An M82190 arbitrary waveform generator (AWG) in conjunction with a PSG E8267D vector signal generator, both from *Keysight*, were used to generate the 5G NR signal. Additionally, a second vector signal generator (EXG ASG 5173B), also from *Keysight,* has been applied to create the LTE-A Pro and NB-IoT signals. Fig. 2(b) reports a photograph of the implemented 8-meters indoor point-to-point link based on three commercial printed log-periodic antennas from Aaronia (Hyperlog 6080) at 1.85 m height. Two antennas, distanced by 1.5 meters (Fig 2(c)), have been applied for independently transmitting the 4G and 5G signal and another one for simultaneously receiving both RF signals (Fig 2(d)). At the receiver side, a 22-dB gain low noise amplifier (ZX60-83LN12+) has been added, before the signal performance evaluation using an MXA N9020A vector signal analyzer also from *Keysight*. All RF signals had been generated in accordance to the 3GPP TS 38.141-1 and 3GPP TS 38.141-2 base station conformance testing [21], [22].

III. ADJACENT CHANNEL COEXISTENCE SCENARIO

LTE Advanced Pro (LTE-A Pro), also known as 4.5G, was regulated by the 3GPP Releases 13 and 14. Release 13, launched in September of 2012, standardized 170 high-level features and studies. Narrowband Internet-of-Things (NB-IoT) has been defined as the radio technology for Internet of Things and appeared on the Release 13. Both technologies use orthogonal frequency division multiplex (OFDM) and precede the first 5G specification from the Release 15.

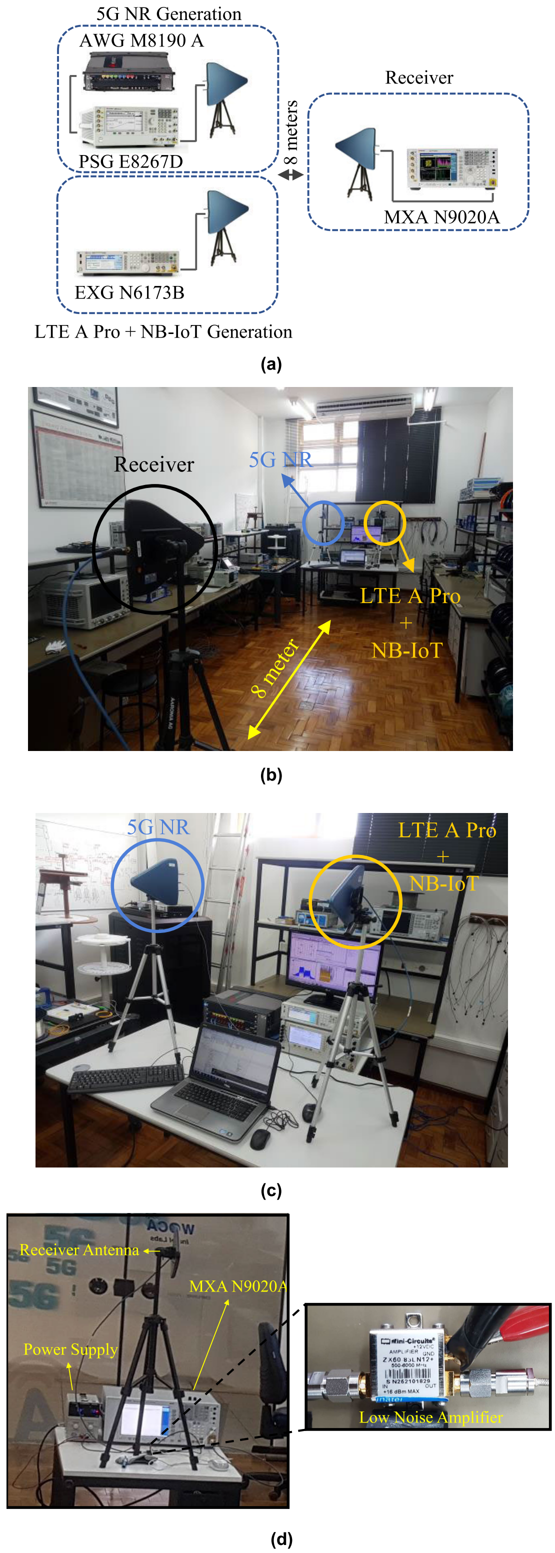

FIGURE 2. Indoor 4G and 5G coexistence analysis: (a) Transmission blocks; (b) 8-meters link; (c) Transmitter side, composed by an arbitrary waveform generator, two vector signal generators and two antennas; (d) Receiver side details with a low-noise amplifier and spectrum signal analyzer.

OFDM presents high spectrum efficiency, however, its out-of-band emission is high and might not be acceptable in

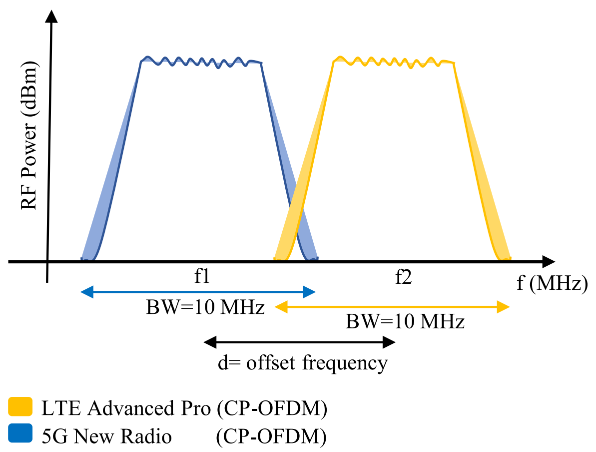

FIGURE 3. Schematic of the 4G and 5G coexistence analysis.

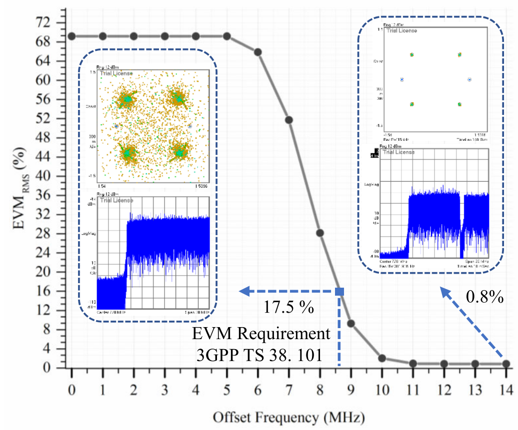

FIGURE 4. Coexistence analysis between 64-QAM LTE-A and QPSK 5G NR signals.

a coexistence scenario [23]. Diverse waveforms have been exploited for 5G in the last years. For instance, Alcatel-Lucent introduced UFMC [24], which relies on using filtering for a block of consecutive subcarriers for reducing the out-of-band (OOB) emission.

Generalized Frequency Division Multiplexing (GFDM) has been proposed by the Vodafone Chair Mobile Communication Systems group from Dresden-Germany, as an efficient solution in terms of out-of-band emission and complexity [25], [19]. The GFDM circular filtering reduces the OOB emission in several orders of magnitude when compared to OFDM. GFDM is based on the classic concept of multiple filter bank carriers, which allows each subcarrier to have multiple spectrum-enhancing bandwidths, giving rise to flexibility for cognitive radio applications [19]. Particularly, our research group has successfully reported the implementation of the integration of a GFDM-based 5G transceiver in a gigabit passive optical network (GPON), using radio over fiber technology [26]. Finally, filtered (F-OFDM) has been chosen as the standard waveform from the 5G NR (3GPP Release 15). Orthogonal subcarriers allow flexible use of bandwidth in small sub-bands, as well as adaptive modulation code schemes for maximizing efficiency and spectrum usage. Particularly for downlink, 5G NR uses OFDM with a Cyclic Prefix to avoid inter-symbol interference, CP-OFDM, which is compatible with LTE-A Pro.

The first proposed scenario was focused on the coexistence analysis between 5G NR and LTE-A Pro signals operating at adjacent channels, as described in Fig. 3. Two 10-MHz bandwidth downlink carriers were transmitted at +10 dBm with different modulation schemes in order to investigate a real and practical scenario. The frequency offset (d), difference between the two broadband CP-OFDM signals, has been varied for experimentally analyzing the 4G and 5G systems as a function of constellation and error vector magnitude (EVM_{RMS}). In this way, we could obtain a trade-off between spectrum sharing and performance.

The LTE-A Pro signal has been configured with 64-QAM (quadrature amplitude modulation) for all sub-carriers, whereas the 5G NR signal at 768 MHz has been based on QPSK (quadrature phase-shift keying), 16-, 64- and 256-QAM. The LTE-A Pro frequency offset has been set from 500 kHz to 14 MHz. Fig. 4 reports the EVM_{RMS} experimental results for the 5G NR signal with QPSK. One can note the 3GPP requirement for this modulation scheme ($EVM_{RMS} <$ 17.5 %) is fulfilled for frequency offset higher than 8.6 MHz, reaching 0.8 % for 14 MHz offset. The measured spectra and constellations for 8.6 and 14 MHz offset are shown in Fig. 4 insets.

Fig. 5 presents the coexistence analyses between 64-QAM LTE-A and 5G NR with three different QAM modulation orders, namely: 16-QAM (Fig. 5(a)); 64-QAM (Fig. 5(b)); 256-QAM (Fig. 5(c)). One more time, the measured spectra and constellations for 8.6 and 14 MHz offset are shown in the insets. As expected, the frequency offset needs to be increased, as the modulation order is increased. Therefore, the network planner must guarantee a minimum offset of 8.6, 9 and 9.4 MHz for 16-, 64 and 256-QAM, respectively, in order to satisfy the 3GPP requirements. Extremely clean and well-defined constellations have been obtained for 14 MHz offset, giving rise to EVM_{RMS} lower than 1.2 % for the three evaluated QAM modulation orders.

The main performance results are reported from Table 2 to Table 9. Particularly, the tables with even numbers (2, 4, 6 and 8) summarize the 5G NR channel demodulation performance as a function of EVM_{RMS} for the control and data channels, using 14 MHz offset frequency. Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), Physical Broadcast Channel (PBCH), Physical Broadcast Demodulation Reference Signal (PBCH DMRS), Physical Data Shared Channel (PSDCH), Physical Data Shared Channel for Demodulation Reference Signal (PDSCH DMRS) and Physical Data Shared Channel for Phase Tracking Reference Signal (PDSCH PTRS) have been evaluated and satisfied the 3GPP requirements, since EVM_{RMS} varied from 0.5 to 1.2 %. Furthermore, the tables with odd numbers (3, 5, 7 and 9) report the LTE-A Pro demodulation performance, as a function of EVM_{RMS} for control and data

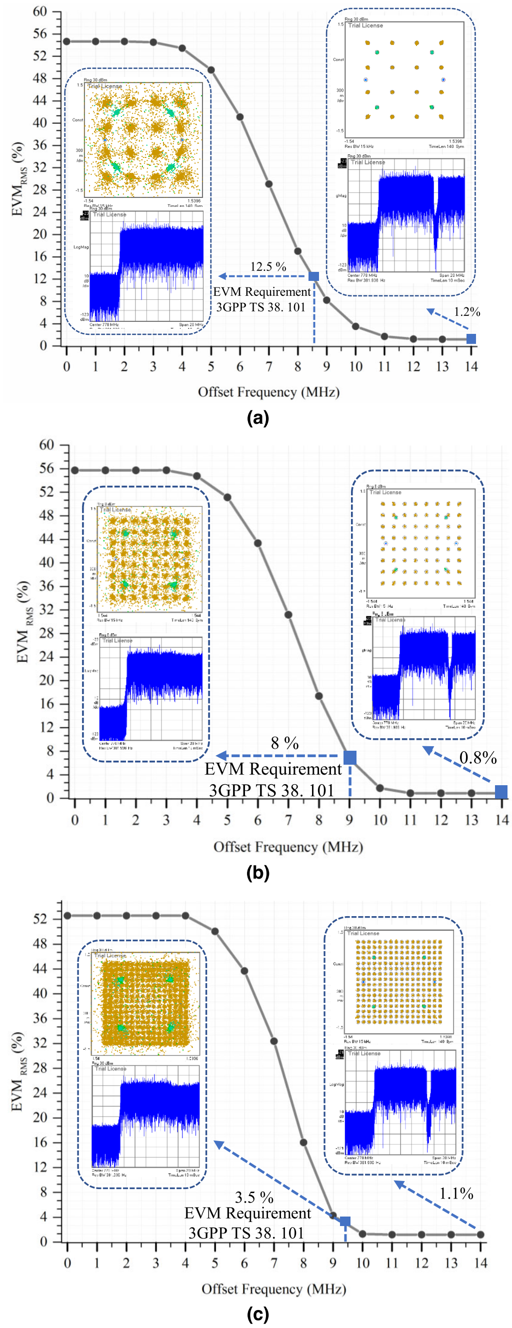

FIGURE 5. Coexistence analysis between 4G and 5G NR signals with three different QAM modulation orders: (a) 64-QAM LTE-A and 16-QAM 5G NR; (b) 64-QAM LTE-A and 64-QAM 5G NR; (c) 64-QAM LTE-A and 256-QAM 5G NR.

channels. Primary Synchronization Signal (P-SS), Secondary Synchronization Signal (S-SS), Physical Broadcast Channel (PBCH), Cell Reference Signal (C-RS), Physical Downlink Control Channel (PDCCH) and Physical Data Shared Channel (PDSCH) have been investigated, giving rise to excellent performance with EVM_{RMS} varying from 0.9 to 1.0 %.

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TABLE 2. Performance analysis of the QPSK 5G NR channels.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
PSS	0.5 %	BPSK	12
SSS	0.5 %	BPSK	12
PBCH	0.9 %	QPSK	20
PBCH DMRS	0.6 %	QPSK	19
PDSCH	0.8 %	QPSK	520
PDSCH DMRS	0.7 %	QPSK	499
PDSCH PTRS	0.8 %	QPSK	260

TABLE 3. Coexistence performance analysis between the 64-QAM LTE-A pro data and control channels with the QPSK 5G NR signal.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
P-SS	0.9 %	Z-Chu	7
S-SS	0.5 %	BPSK	7
PBCH	0.6 %	QPSK	7
C-RS	1.0 %	QPSK	150
PDCCH	0.8 %	QPSK	75
PDSCH	1.0 %	64 QAM	150

TABLE 4. Performance analysis of the 16-QAM 5G NR channels.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
PSS	0.9 %	BPSK	12
SSS	0.8 %	BPSK	12
PBCH	1.3 %	QPSK	20
PBCH DMRS	0.9 %	QPSK	19
PDSCH	1.2 %	16 QAM	520
PDSCH DMRS	1.1 %	QPSK	499
PDSCH PTRS	1.2 %	QPSK	260

TABLE 5. Coexistence performance analysis between the 64-QAM LTE-A pro data and control channels with the 16-QAM 5G NR signal.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
P-SS	0.5 %	Z-Chu	7
S-SS	0.7 %	BPSK	7
PBCH	0.7 %	QPSK	7
C-RS	1.0 %	QPSK	150
PDCCH	0.9 %	QPSK	75
PDSCH	1.0 %	64 QAM	150

TABLE 6. Performance analysis of the 64-QAM 5G NR channels.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
PSS	0.5 %	BPSK	12
SSS	0.5 %	BPSK	12
PBCH	0.8 %	QPSK	20
PBCH DMRS	0.6 %	QPSK	19
PDSCH	0.8 %	64 QAM	520
PDSCH DMRS	0.7 %	QPSK	499
PDSCH PTRS	0.8 %	QPSK	260

TABLE 7. Coexistence performance analysis between the 64-QAM LTE A pro data and control channels with the 64-QAM 5G NR signal.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
P-SS	1.0 %	Z-Chu	7
S-SS	0.6 %	BPSK	7
PBCH	0.7 %	QPSK	7
C-RS	0.9 %	QPSK	150
PDCCH	0.8 %	QPSK	75
PDSCH	1.0 %	64 QAM	150

TABLE 8. Performance analysis of the 256-QAM 5G NR channels.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
PSS	0.8 %	BPSK	12
SSS	0.8 %	BPSK	12
PBCH	1.2 %	QPSK	20
PBCH DMRS	0.9 %	QPSK	19
PDSCH	1.1 %	256 QAM	520
PDSCH DMRS	1.1 %	QPSK	499
PDSCH PTRS	1.2 %	QPSK	260

IV. COEXISTENCE USING CO-CHANNELS

Co-channel coexistence is the most challenging scenario of spectral sharing between two different cellular generations. The modulation cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) is used for both 5G NR and LTE A Pro technologies. However, it's intrinsic high out of band emission makes the coexistence very difficult. LTE-A Pro allows only one sub-carrier spacing (15 kHz), while the

TABLE 9. Coexistence performance analysis between the 64-QAM LTE A pro data and control channels with 256-QAM 5G NR signal.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
P-SS	1.0 %	Z-Chu	7
S-SS	0.5 %	BPSK	7
PBCH	0.6 %	QPSK	7
C-RS	0.9 %	QPSK	150
PDCCH	0.8 %	QPSK	75
PDSCH	1.0 %	64 QAM	150

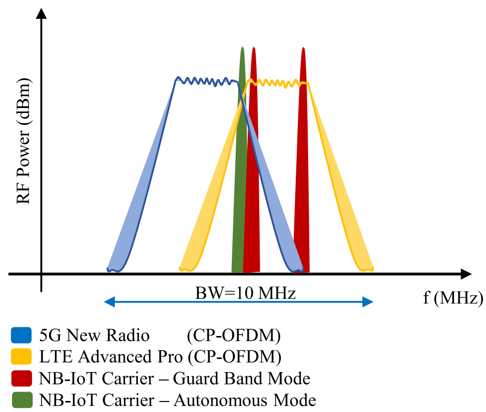

FIGURE 6. Co-channel coexistence scenario among 5G NR, LTE A pro, and NB-IoT signals in the 700 MHz band.

5G NR standard provides a flexible multicarrier spacing of $\mathbf{2^{\mu}*15}$, with $\mu = 0, 1, 2, 3$ or 4 [27], aiming multiples services and spectrum utilization. The cyclic prefix is scaled by a factor of. Particularly, the LTE CP length is 4.7 μs [28]–[30].

Our co-channel proposed scenario centered for multiple wireless standards in the 700 MHz band is illustrated in Fig. 6. The corresponding 10 MHz bandwidth has been shared by 5G NR, LTE- A Pro and three NB-IoT downlink carriers. The three NB-IoT carriers have been deployed in two different operation modes, i.e., two in the guard band mode and the last one in the autonomous mode, located at the center of the spectrum. Our proposed scenario is one possible implementation, which has been thought taking the coexistence scenario in mind, since it is part of 3GPP Release 15, called Dynamic Spectrum Sharing (DSS). Our experiments are in accordance to the 3GPP TS 38.141-1 and 3GPP TS 38.141-2 base station conformance testing [21], [22].

5G NR must be configurated with 15 kHz subcarrier spacing to accommodate the synchronism signals out of band of LTE signals in order to avoid collisions, as demonstrated in Fig. 7(a). In this way, there is a guard band for data and synchronization signals, i.e. subcarriers in time and frequency, avoiding interference in the LTE-A Pro synchronization and data resource blocks. Primary Synchronization Signal (PSS) has been configurated with one active index and 10ms period (case A), whereas physical downlink shared channel (PDSCH) has been configurated to

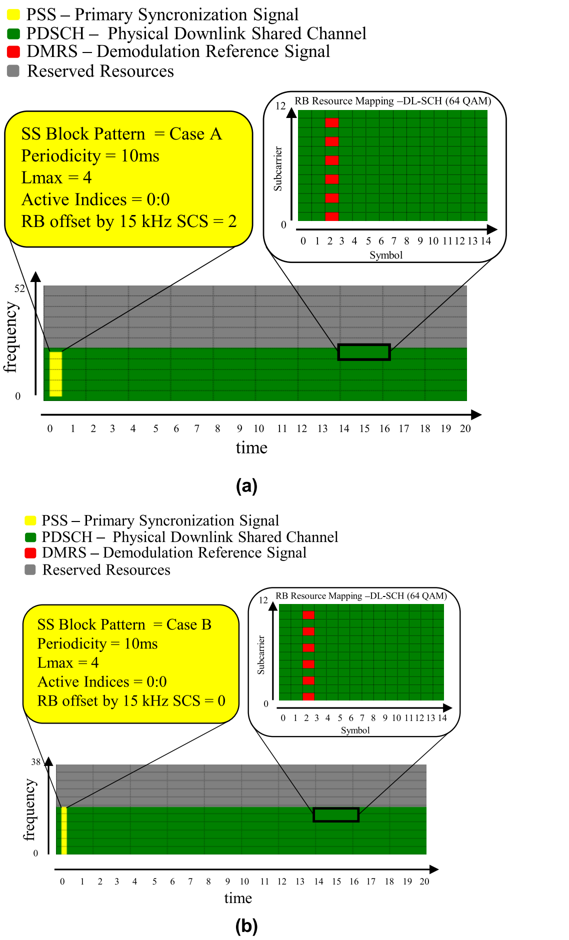

FIGURE 7. Resource mapping allocation of 5G NR: (a) 15 kHz numerology for 10 MHz bandwidth; (b) 30 kHz numerology for 15 MHz bandwidth.

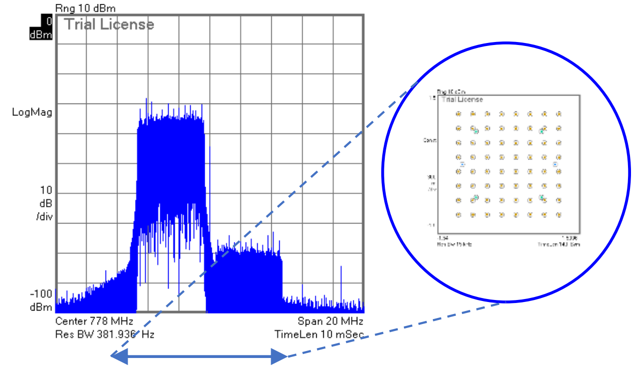

FIGURE 8. 5G NR spectrum and constellation, configured using CORESET.

TABLE 10. Performance analysis of the 5G NR data and control channels.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
PSS	0.3 %	BPSK	12
SSS	0.3 %	BPSK	12
PBCH	0.3 %	QPSK	20
PBCH DMRS	0.3 %	QPSK	19
PDSCH	0.4 %	64 QAM	240
PDSCH DMRS	0.4 %	QPSK	219
PDSCH PTRS	0.4 %	QPSK	120

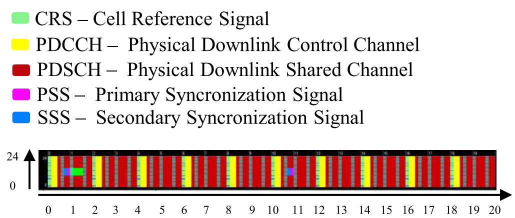

FIGURE 9. Resource mapping allocation for LTE advanced Pro.

use 240 resource blocks (RBs). The remaining RBs were empty using CORESET to perform coexistence with LTE-A Pro and NB-IoT carriers. Each RB contains 12 subcarriers with 14 symbols, allocated in one symbol and spaced by one subcarrier in each RB. Finally, the demodulation reference signal (DMRS) has been used to estimate the radio channel. Depending on the application, the 5G NR planner can deploy more DMRS pilots per resource block for enhancing the channel estimation.

In case the network planner chooses 30 kHz numerology for 5G NR, the primary synchronization signal (PSS) will allocate almost all OFDM subcarriers in the 10 MHz bandwidth and, consequently, collision and interference will take place. This would happen due to the PSS minimum length equal to 4, even adjusting an offset resource block for PSS. Therefore, using 30 kHz OFDM subcarrier spacing requires at least 15 MHz bandwidth for properly allocating the resource blocks, as described in Fig. 7(b).

PDSCH had been configurated with 240 resource blocks and 64-QAM. Table 10 displays the demodulation performance as a function of EVM_{RMS} for control and data channels. PSS, SSS, PBCH, PBCH DMRS, PSDCH, PDSCH DMRS and PDSCH PTRS have accomplished the 3GPP requirements, since EVM_{RMS} maximum was only 0.4 %, implying in an outstanding performance.

Fig 8 reports the obtained 5G NR spectrum at 778 MHz and its correspondent 64-QAM constellation for each channel. The spectrum slice had been turned on, however, the demodulation has been carried out using the entire 10 MHz-bandwidth channels. The empty spectrum has been prepared for LTE-A Pro and NB- IoT signals.

Fig. 9 presents the LTE-A Pro resource mapping allocation, using 5 MHz of bandwidth, 25 RBs at 781 MHz and a 15 kHz subcarrier spacing. Remembering the reference signals cannot be turned off (“always-on”) [6].

In accordance to the 3GPP Release-13, the narrow-band IoT main characteristics are the following ones [31]: OFDM; maximum coupling loss (MCL) 20 dB higher than that of LTE, reaching 164 dB MCL; 160 bps at layer 3; easy deployment; long battery life; low cost; a large number of mobile

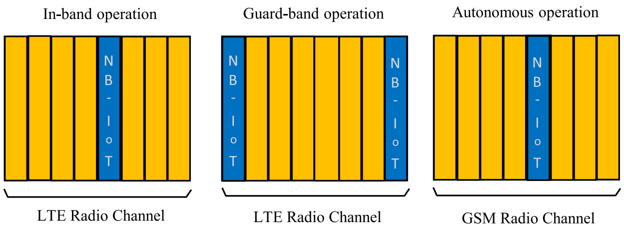

FIGURE 10. NB-IoT operation modes [23].

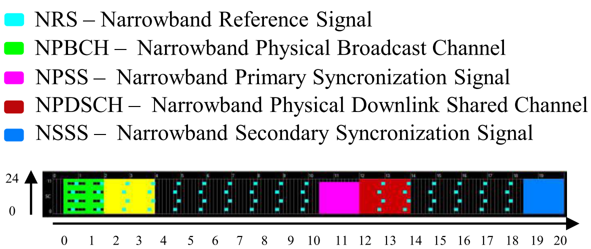

FIGURE 11. NB-IoT resource mapping allocation.

TABLE 11. EVM_{RMS} performance of the 5g NR data and control signals in the co-channel coexistence scenario.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
PSS	0.5 %	BPSK	12
SSS	0.5 %	BPSK	12
PBCH	0.9 %	QPSK	20
PBCH DMRS	0.6 %	QPSK	19
PDSCH	1.7 %	64 QAM	240
PDSCH DMRS	1.3 %	QPSK	219
PDSCH PTRS	1.8 %	QPSK	120

devices. NB-IoT uses 180 kHz bandwidth, which corresponds to 12 subcarriers in three operation modes [32], as described in Fig. 10, namely: in-band; guard-band; autonomous. Particularly, the autonomous mode allows the NB-IoT deployment using a GSM radio channel with 200 kHz. On the other hand, in the guard-band operation, the NB-IoT can be deployed using an LTE radio channel. Finally, NB- IoT in-band mode supports to use the same LTE carrier. We have chosen guard-band and autonomous modes, which are the two most used ones by the telecom operators [32]–[34]. The NB-IoT resource mapping allocation is displayed in Fig. 11. QPSK has been applied for narrowband physical downlink shared channel (NPDSCH) [35], [36].

Fig. 12 reports the experimental co-channel coexistence performance analysis among one 5G NR, one LTE-A Pro, and three NB-IoT carriers. The entire shared 10-MHz bandwidth is presented in Fig. 12(a), whereas the other subfigures display the constellation for each signal. Tables from 11 to 15 demonstrate the success of our co-channel coexistence proposal since all measured EVM_{RMS} were extremely low – from 0.5 to 1.9 % - and addressed the 3GPP requirements

TABLE 12. EVM_{RMS} performance of LTE-A pro data and control signals in the co-channel coexistence scenario.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
P-SS	1.2 %	Z-Chu	7
S-SS	1.3 %	BPSK	7
PBCH	1.8 %	QPSK	7
PDCCH	1.7 %	QPSK	75
C-RS	1.5 %	QPSK	150
PDSCH	1.9 %	64QAM	150

TABLE 13. EVM_{RMS} performance of NB-IoT Cell ID = 1 in the co-channel coexistence scenario.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
NPSS	1.8 %	Z-Chu	2
NSSS	1.7 %	Z-Chu	2
NPBCH	1.9 %	QPSK	2
NPDCCH	1.7 %	QPSK	2
NRS	1.0 %	QPSK	16
NPDSCH	1.7 %	QPSK	2

TABLE 14. EVM_{RMS} performance of NB-IoT Cell ID = 2 in the co-channel coexistence scenario.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
NPSS	0.9 %	Z-Chu	2
NSSS	1.0 %	Z-Chu	2
NPBCH	0.8 %	QPSK	2
NPDCCH	0.9 %	QPSK	2
NRS	0.6 %	QPSK	16
NPDSCH	0.8 %	QPSK	2

TABLE 15. EVM_{RMS} performance of NB-IoT Cell ID = 3 in the co-channel coexistence scenario.

Channel	EVM_{RMS}	Modulation	Number of Resource Blocks per Frame
NPSS	0.8 %	Z-Chu	2
NSSS	0.8 %	Z-Chu	2
NPBCH	0.8 %	QPSK	2
NPDCCH	0.6 %	QPSK	2
NRS	0.6 %	QPSK	16
NPDSCH	0.9 %	QPSK	2

for the applied modulation formats. Particularly, for 5G NR, EVM_{RMS} varied from 0.5 % (PSS with BPSK and 12 RBs) to 1.8 % (PDSCH_PRTS with QPSK and 120 RBs). The LTE-A Pro carrier at 781 MHz presented EVM_{RMS} from 1.2 % (PSS with Z-Chu modulation and 7 RBs) to 1.9 % (PDSCH with 64-QAM and 150 RBs).

The NB-IoT carriers have been tuned at 778 MHz (Cell ID=1), 778.65 MHz (Cell ID=2) and 783.85 MHz

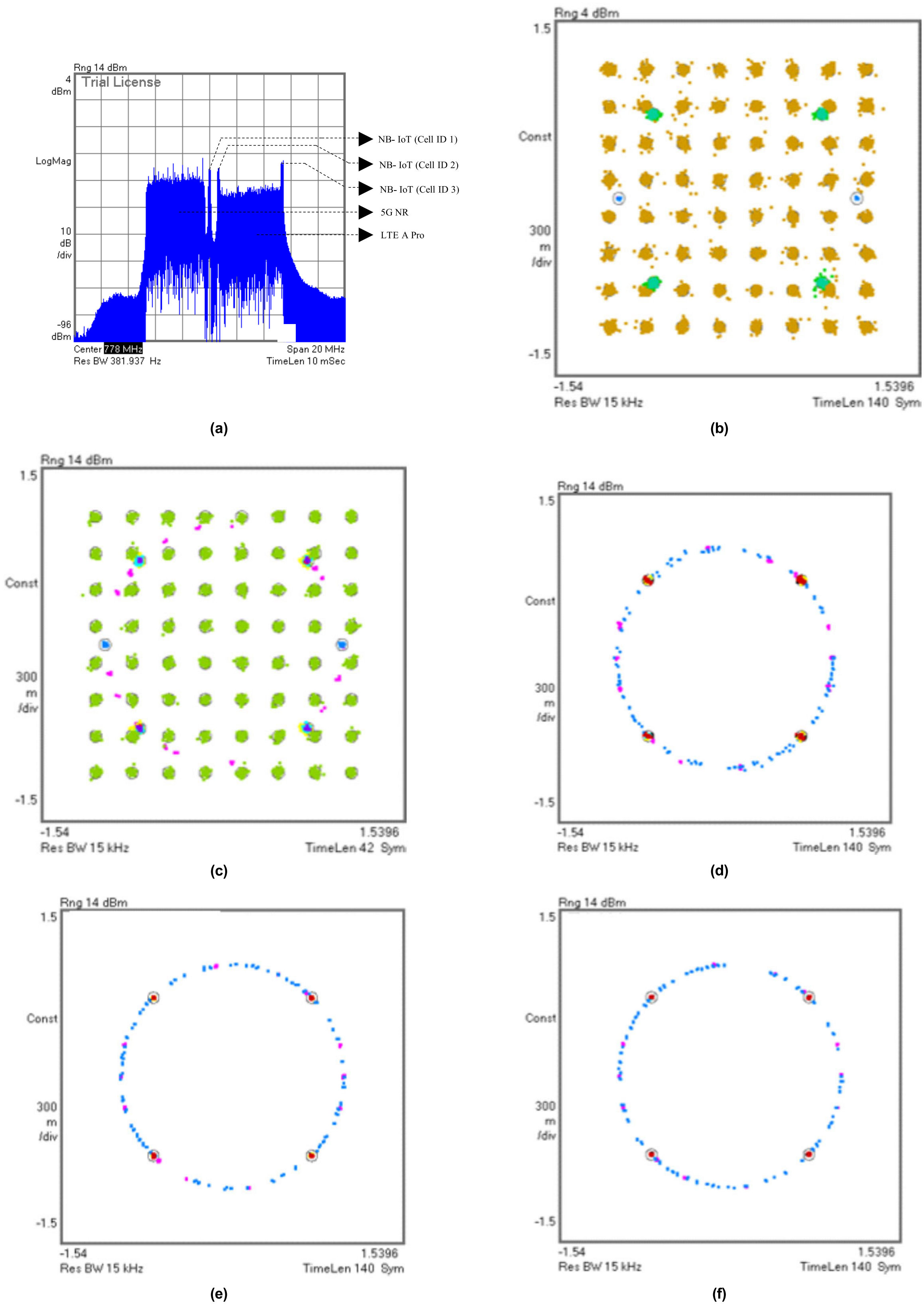

FIGURE 12. Co-channel coexistence among a 5G NR, an LTE-A Pro and three NB-IoT signals: (a) Measured spectrum; (b) 5G NR constellation; (c) LTE-A Pro constellation; (d) NB-IoT Cell ID 1 constellation; (e) NB-IoT Cell ID 2 constellation; (f) NB-IoT Cell ID 3 constellation.

(Cell ID=3). The Narrowband Primary Synchronism Signal (NPSS) EVM maximum was 1.8 %, Narrowband Physical Broadcast Channel (NPBCH) was 1.9 % and Narrowband Physical Shared Downlink Channel (NPDSCH) was 1.7% using QPSK modulation for small data transfer over devices.

Network planner must be careful with channel delay spread for the NB-IoT guard band mode. The maximum allowed delay spread is the LTE-A Pro CP length (4.7 μs) in order to ensure that the NB-IoT carrier would not interfere in the first OFDM subcarrier of LTE-A Pro.

V. CONCLUSIONS

Experimental performance analyses of downlink coexistence between 5G NR and LTE-A Pro signals, using co-channel and adjacent channels in the 700 MHz band, have been reported, as a function of frequency offset, constellation, error vector magnitude and modulation schemes. The best compromise has been obtained for 9.4 MHz frequency offset, which has accomplished the 3GPP requirements Release 15 [37] for all modulation schemes. Furthermore, a co-channel scenario has been successfully demonstrated using 10 MHz bandwidth to deploy multiple technologies, by means of applying the 5G NR CORESET to allocate the time-frequency resource blocks. Particularly, it has been attained EVM_{RMS} as low as 0.4%

This work might be considered as an important contribution for the current and very critical context of 4G and 5G spectrum refarming and update. As future works, we envisage analyses with the power imbalance between the 4G and 5G signals, using different bandwidths, as well as carrying out long-reach outdoor experiments as coexistence drive tests and using real networks from a partner Telecom Operator.

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REFERENCES

[1] K. Belbase, C. Tellambura, and H. Jiang, "Coverage, capacity, and error rate analysis of multi-hop millimeter-wave decode and forward relaying," *IEEE Access*, vol. 7, pp. 69638–69656, 2019.

[2] W. Dias, D. Gaspar, L. Mendes, M. Chafii, M. Matthe, P. Neuhaus, and G. Fettweis, "Performance analysis of a 5G transceiver implementation for remote areas scenarios," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2018, pp. 363–367.

[3] L. Wan, Z. Guo, Y. Wu, W. Bi, J. Yuan, M. Elkashlan, and L. Hanzo, "4G5G spectrum sharing: Efficient 5G deployment to serve enhanced mobile broadband and Internet of Things applications," *IEEE Veh. Technol. Mag.*, vol. 13, no. 4, pp. 28–39, Dec. 2018.

[4] A. Roessler, "Impact of spectrum sharing on 4G and 5G standards a review of how coexistance and spectrum sharing is shaping 3GPP standards," in *Proc. IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity (EMCSI)*, Aug. 2017, pp. 704–707.

[5] X. Lin, J. Li, R. Baldemair, T. Cheng, S. Parkvall, D. Larsson, H. Koorapaty, M. Frenne, S. Falahati, A. Grövlen, and K. Werner, "5G new radio: Unveiling the essentials of the next generation wireless access technology," 2018, *arXiv:1806.06898*. [Online]. Available: http://arxiv.org/abs/1806.06898

[6] S. Parkvall, E. Dahlman, A. Furuskar, and M. Frenne, "NR: The new 5G radio access technology," *IEEE Commun. Standards Mag.*, vol. 1, no. 4, pp. 24–30, Dec. 2017.

[7] S.-Y. Lien, S.-L. Shieh, Y. Huang, B. Su, Y.-L. Hsu, and H.-Y. Wei, "5G new radio: Waveform, frame structure, multiple access, and initial access," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 64–71, Jun. 2017.

[8] L. Wan, Z. Guo, and X. Chen, "Enabling efficient 5G NR and 4G LTE coexistence," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 6–8, Feb. 2019.

[9] H. Kim, S. C. Cho, and Y. Lee, "Interference analysis of guardband NB-IoT system," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2018, pp. 1370–1372.

[10] J. Oh and H. Song, "Study on the effect of LTE on the coexistence of NB-IoT," in *Proc. 10th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2018, pp. 610–612.

[11] S. Bayhan, G. Gür, and A. Zubow, "The future is unlicensed: Coexistence in the unlicensed spectrum for 5G," 2018, *arXiv:1801.04964*. [Online]. Available: http://arxiv.org/abs/1801.04964

[12] D. Demmer, R. Gerzaguet, J.-B. Dore, and D. Le Ruyet, "Analytical study of 5G NR eMBB co-existence," in *Proc. 25th Int. Conf. Telecommun. (ICT)*, Jun. 2018, pp. 186–190.

[13] T. Levanen, K. Ranta-Aho, J. Kaikkonen, S. Nielsen, K. Pajukoski, M. Renfors, and M. Valkama, "5G new radio and LTE uplink coexistence," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[14] S. Xu, Y. Li, Y. Gao, Y. Liu, and H. Gacanin, "Opportunistic coexistence of LTE and WiFi for future 5G system: Experimental performance evaluation and analysis," *IEEE Access*, vol. 6, pp. 8725–8741, 2018.

[15] A. O. Mufutau, F. P. Guiomar, M. A. Fernandes, A. Lorences-Riesgo, A. Oliveira, and P. P. Monteiro, "Demonstration of a hybrid optical fiber–wireless 5G fronthaul coexisting with end-to-end 4G networks," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 12, no. 3, pp. 72–78, Mar. 2020.

[16] J. Zhang, X. Xu, K. Zhang, B. Zhang, X. Tao, and P. Zhang, "Machine learning based flexible transmission time interval scheduling for eMBB and uRLLC coexistence scenario," *IEEE Access*, vol. 7, pp. 65811–65820, 2019.

[17] H. Tan, Y. Liu, Z. Feng, and Q. Zhang, "Coexistence analysis between 5G system and fixed-satellite service in 3400–3600 MHz," *China Commun.*, vol. 15, no. 11, pp. 25–32, Nov. 2018.

[18] T. Xu, M. Zhang, Y. Zeng, and H. Hu, "Harmonious coexistence of heterogeneous wireless networks in unlicensed bands: Solutions from the statistical signal transmission technique," *IEEE Veh. Technol. Mag.*, vol. 14, no. 2, pp. 61–69, Jun. 2019.

[19] A. Hammoodi, L. Audah, and M. A. Taher, "Green coexistence for 5G waveform candidates: A review," *IEEE Access*, vol. 7, pp. 10103–10126, 2019.

[20] L. C. Alexandre and S. A. Cerqueira, Jr, "Contribution for the coexistence analysis between 5G and 4G in the sub-1GHz band," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Nov. 2019, pp. 1–3.

[21] *NR: Base Station (BS) Conformance Testing, Part 1: Conducted Conformance Testing*, Standard 3GPP TS 38.141-1, 3rd Generation Parnership Project, Tech. Specification Group Radio Access Network, Dec. 2019.

[22] *NR: Base Station (BS) Conformance Testing, Part 2: Radiated Conformance Testing*, Standard 3GPP TS 38.141-2, 3rd Generation Parnership Project, Technical Specification Group Radio Access Network, Dec. 2019.

[23] J. Park, E. Lee, S.-H. Park, S.-S. Raymond, S. Pyo, and H.-S. Jo, "Modeling and analysis on radio interference of OFDM waveforms for coexistence study," *IEEE Access*, vol. 7, pp. 35132–35147, 2019.

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

[25] N. Michailow, M. Matthe, I. S. Gaspar, A. N. Caldevilla, L. L. Mendes, A. Festag, and G. Fettweis, "Generalized frequency division multiplexing for 5th generation cellular networks," *IEEE Trans. Commun.*, vol. 62, no. 9, pp. 3045–3061, Sep. 2014.

[26] R. M. Borges, T. R. R. Marins, M. S. B. Cunha, H. R. D. Filgueiras, I. F. da Costa, R. N. da Silva, D. H. Spadoti, L. L. Mendes, and A. C. Sodre, "Integration of a GFDM-based 5G transceiver in a GPON using radio over fiber technology," *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4468–4477, Oct. 2018.

[27] A. A. Zaidi, R. Baldemair, H. Tullberg, H. Bjorkegren, L. Sundstrom, J. Medbo, C. Kilinc, and I. Da Silva, "Waveform and numerology to support 5G services and requirements," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 90–98, Nov. 2016.

[28] Y. Qi, M. Hunukumbure, H. Nam, H. Yoo, and S. Amuru, "On the phase tracking reference signal (PT-RS) design for 5G new radio (NR)," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, Aug. 2018, pp. 1–5.

[29] A. Ali and W. Hamouda, "On the cell search and initial synchronization for NB-IoT LTE systems," *IEEE Commun. Lett.*, vol. 21, no. 8, pp. 1843–1846, Aug. 2017.

[30] A. Omri, M. Shaqfeh, A. Ali, and H. Alnuweiri, "Synchronization procedure in 5G NR systems," *IEEE Access*, vol. 7, pp. 41286–41295, 2019.

[31] M. Chen, Y. Miao, Y. Hao, and K. Hwang, "Narrow band Internet of Things," *IEEE Access*, vol. 5, pp. 20557–20577, 2017.

[32] H. Malik, H. Pervaiz, M. M. Alam, Y. Le Moullec, A. Kuusik, and M. A. Imran, "Radio resource management scheme in NB-IoT systems," *IEEE Access*, vol. 6, pp. 15051–15064, 2018.

[33] S.-M. Oh and J. Shin, "An efficient small data transmission scheme in the 3GPP NB-IoT system," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 660–663, Mar. 2017.

[34] J. Xu, J. Yao, L. Wang, Z. Ming, K. Wu, and L. Chen, "Narrowband Internet of Things: Evolutions, technologies, and open issues," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1449–1462, Jun. 2018.

[35] R. Ratasuk, N. Mangalvedhe, Z. Xiong, M. Robert, and D. Bhatoolaul, "Enhancements of narrowband IoT in 3GPP rel-14 and rel-15," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Sep. 2017, pp. 60–65.

[36] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, and J.-P. Koskinen, "Overview of narrowband IoT in LTE rel-13," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Oct. 2016, pp. 1–7.

[37] *5G; Study on New Radio (NR) Access Technology*, Standard 3GPP TR 138.912 Version 15.0.0 Release, 15, European Telecommunications Standards Institute (ETSI) 3rd Generation Partnership Project (3GPP) Technical Specification, 2018.

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