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Design and Analysis of the Low-PAPR Synchronization Sequences for Unlicensed Band

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Abstract. The similarity of topology and use cases between the 5G NR SL (Sidelink) and the IEEE 802.11 (Wi-Fi) technologies may provide an opportunity to extend Sidelink into unlicensed bands originally occupied mostly by Wi-Fi devices. However, for proper coexistence, Sidelink unlicensed band (SL-U) devices must adopt the current channelization in this band as well as channel access procedures. Channelization changes lead to the necessity of modifying the SL physical channels and signals to span across typical Wi-Fi 20 MHz channels. The simplest way to align the 5G NR numerology of synchronization sequences is a plain repetition of them in frequency domain to fill the all required bandwidth. However, such approach leads to a sharp increase in the peak-to-average power ratio (PAPR) value. In this paper, we provide a detailed performance analysis of the proposed design of SL-U synchronization sequences that achieve low PAPR values. The characteristics are studied in a non-stationary frequency-selective channel using a real model a power amplifier. It was shown that the use of an unmodified design of SL-U synchronization sequences has a decisive effect on their detection. The presented simulation results demonstrate comparable performance of the modified design of SL-U synchronization sequences with their design in a licensed band.

Keywords. 5G NR SL, SL-U, unlicensed band, synchronization sequences, S-SSB, PAPR, power amplifier

1. Introduction

One of the goals for further Sidelink development in the 5G NR Release 18 is supporting Sidelink transmissions in the unlicensed U-NII bands, widely used by Wi-Fi devices. A number of research works are devoted to this topic in the preparation of NR-U [1][2][3][4]. Based on the experience of developing Rel-16 NR-U, the main task in preparing SL-U was to modify the channels and physical layer signals of the licensed spectrum that would meet the regulatory requirements of the unlicensed spectrum. These requirements may vary by country or region, but necessarily include

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requirements such as Occupied Channel Bandwidth (OCB) (the bandwidth containing 99% of the signal power must be between 80% and 100% of the stated nominal channel bandwidth) and maximum PSD (Power Spectral Density) (e.g., 10dBm/MHz). To meet the requirements of unlicensed spectrum, an approach was adopted using interlaced physical channels and signals. This approach allows the physical channel or signal to be evenly distributed over the entire bandwidth and cover more than 80% of the bandwidth. However, the interlaced approach may not be the only solution to meet unlicensed spectrum requirements.

Recently, in addition to the interlaced form, a different approach has been adopted by the 3rd Generation Partnership Project (3GPP) consortium. The wideband signal is constructed by replication of the original Sidelink Synchronization Signal Block (S-SSB) in the frequency domain to fill the entire channel and meet the requirements of unlicensed spectrum (see Figure 1). This solution allows the reuse of most of the hardware and processing chains from the NR-bands SL to SL-U. However, the replication in frequency domain causes huge increase of the PAPR metric, which in the general case leads to operating in the power amplifier nonlinearity region, reducing the effective dynamic range and increasing the out-of-bands emission. As a consequence, it leads to worsening the performance of detection synchronization sequences. Thus, the PAPR increase should be mitigated by all means, and specific measures should be taken to avoid this for the newly designed S-SSB SL-U.

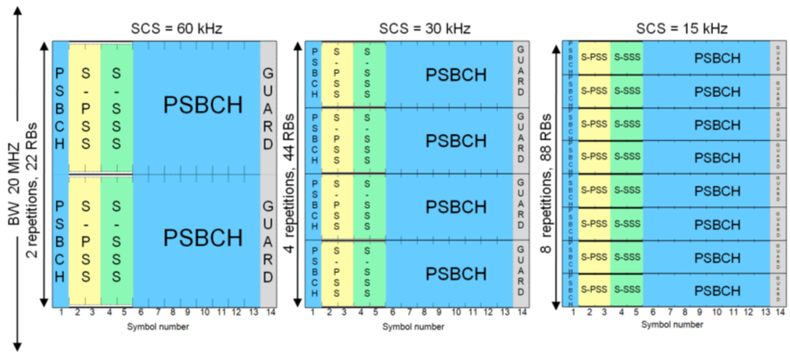

Figure 1 Configurations of the S-SSB SL-U design with a different number of repetitions

In this paper we present a detailed analysis of the SL-U synchronization sequences design and their detection performance under adequate power amplifier model conditions. The analysis is based on the results obtained by using the developed Link Level Simulator (LLS). Optimization parameters of the basic methods for reducing PAPR are presented, and a combined method is proposed that has a higher efficiency of PAPR adjustment. It was revealed that PAPR editing is necessary for successful detection of SL-U synchronization sequence by any of the available methods.

2. Design of the low-PAPR synchronization sequences

In Sidelink, the synchronization information is carried in the S-SSB, which consists of the Sidelink Primary Synchronization Signal (S-PSS), Sidelink Secondary Synchronization Signal (S-SSS) and Physical Sidelink Broadcast Channel (PSBCH). S-SSB occupies one slot and in the licensed spectrum it occupies 11 contiguous resource blocks (RBs) (132 subcarriers) in the frequency domain. Sidelink synchronization sequences (SLSS) are S-PSS and S-SSS, which are 127-bit sequences. According to [5], S-PSS and S-SSS sequences are as follows (Eq.(1)):

$$d_{S-PSS}(n) = 1 - 2x(m), \tag{1}$$

$$d_{S-SSS}(n) = \left[1 - 2x_0\big((n + m_0) mod\ 127\big)\right]\left[1 - 2x_1\big((n + m_1) mod\ 127\big)\right],$$

$$m = \left(n + 22 + 43N_{\mathrm{ID},2}^{\mathrm{SL}}\right) mod\ 127, \qquad m_0 = 15\left\lfloor \frac{N_{\mathrm{ID},1}^{\mathrm{SL}}}{112} \right\rfloor + 5N_{\mathrm{ID},2}^{\mathrm{SL}},$$

$$m_1 = N_{\mathrm{ID},1}^{\mathrm{SL}}\ mod\ 112,\ \ 0 \le n < 127,$$

$$N_{\mathrm{ID},1}^{\mathrm{SL}} \in \{0,1,\dots,335\}, N_{\mathrm{ID},2}^{\mathrm{SL}} \in \{0,1\},$$

where d_{S-PSS} and d_{S-SSS} are S-PSS and S-SSS sequences, x, x_0, x_1 are pseudo-random sequences with different initialization. S-PSS has two sequences in the set, generated from M-sequences and corresponding to two identifiers $N_{\mathrm{ID},2}^{\mathrm{SL}}$. S-SSS has two sequence sets of 336 sequences per set with identifiers $N_{\mathrm{ID},1}^{\mathrm{SL}}$ generated from Gold sequences. The identifiers $N_{\mathrm{ID},1}^{\mathrm{SL}}$ and $N_{\mathrm{ID},2}^{\mathrm{SL}}$ form 672 unique physical layer sidelink synchronization identifiers $N_{\mathrm{ID}}^{\mathrm{SL}}$.

The general problem of the PAPR reduction for the communication signals is a well-studied task and typically, solutions based on scrambling and pseudo-randomization are proposed, but details may widely vary depending on the specific communication system and its components, as shown in [6][7][8][9]. In our paper we are considering two basic methods of the PAPR reduction for SL-U synchronization sequences with frequency domain replication. Such approaches allow reusing most of currently developed SL hardware and software directly for SL-U without much modification.

The first method consists of adjusting the phase of the synchronization sequences replicated in the frequency domain. Considering that we need to fill 20MHz band (including guard bands) and S-SSB consists of roughly 132 subcarriers, for subcarrier spacing equal to 15 / 30 / 60 kHz we need to replicate the initial sequence 8 / 4 / 2 times respectively. For each replicated S-PSS and S-SSS frequency domain sequence, some phase rotation must be performed for each base sequence. For example, the S-PSS #0 sequence for K-times replication in the frequency domain with phase adjustment can be written as Eq.(2)

$$d_{K,S-PSS}^{0,ph} = [d_{S-PSS}^{0}, d_{S-PSS}^{0} e^{i\varphi_1}, \dots, d_{S-PSS}^{0} e^{i\varphi_{K-1}}] \tag{2}$$

where d_{S-PSS}^{0} is the base sequence S-PSS #0, $d_{K,S-PSS}^{0,ph}$ is the K-times replicated base sequence S-PSS with phase adjustment, $\varphi_1, \dots, \varphi_{K-1}$ are optimally selected phase rotation vector, providing a reduced PAPR value.

The second considered approach consists of stacking different synchronization sequences based on different $N_{\mathrm{ID}}^{\mathrm{SL}}$ instead of replication and phase rotation of the single sequence. In this case, the final wideband sequence consists of several smaller baseline NR S-SSB sequences. For example, the construction of the S-PSS #0 sequence with a combination of other sequences from the set for K-times replication in the frequency domain can be written as Eq.(3) :

$$d_{K,S-PSS}^{0,scr} = \left[d_{S-PSS}^{0}, d_{S-PSS}^{p_1}, \dots, d_{S-PSS}^{p_{K-1}}\right], \tag{3}$$

where $d_{K,S-PSS}^{0,scr}$is a resulting sequence constructed as a combination of synchronization sequences with different $N_{\mathrm{ID},2}^{\mathrm{SL}}$, $p_1, \dots, p_{K-1}$are indices of optimally selected sequences.

The first method will introduce a certain grade of diversity in the frequency domain and decrease the PAPR. At the same time, the same basic sequences are used, and, moreover, the same detection procedures can be applied with non-coherent combinations over the different repetitions, unlike the second method. The second method can introduce even more diversity and reduce PAPR even more, and at the same time the hardware/software processing can be similar to the base case.

Since there are only two possible variants in the set for S-PSS sequence, the second method offers only a limited improvement. At the same time, phase adjustment also yields a not very significant improvement. In this case, we propose to use both considered approaches jointly, for optimal PAPR reduction for the S-PSS design in the unlicensed spectrum. For the S-SSS, there are 672 sequence variants corresponding to different $N_{\mathrm{ID}}^{\mathrm{SL}}$. In this case, a good PARP reduction can be achieved even with $N_{\mathrm{ID}}^{\mathrm{SL}}$combinations, without phase changes.

The main task of the practical implementation of both methods is to find optimal phase values or combinations of sequences with different $N_{\mathrm{ID}}^{\mathrm{SL}}$, allowing us to reduce PAPR. This can be done through an exhaustive or optimized search across all possible options. Also, such a procedure can be performed for the proposed S-PSS design, based on simultaneous phase rotation and combination of existing S-PSS sequences. Basically, we need to find the modifications that minimize PAPR for the case of 15 kHz subcarrier spacing (SCS) (8 times replication), 30 kHz (4 times replication) and 60 kHz (2 times replications). However, since the total bandwidth for the channelization can be changed, we will perform optimizations for the x2, x4, x6, x8, x10 repetitions, without specifying SCS values.

Table 1shows the PAPR S-PSS values for different adjustment methods. This was done by using the optimized search that guarantees the final PAPR minimization values to be pretty close to the absolute minima. It should be noted that exhaustive search, especially in the case of 8 replications becomes prohibitively complex.

Table 1 PAPR (dB) comparison for different improvement methods for S-PSS sequence

Signal	**S-PSS #0 and S-PSS #1**			
S-SSB SL-U configuration	**Base**	**Phase adjustment**	**Sequences combination**	**Proposed joint method**
Legacy, 11RBs/132subc	5.43/5.94	N/A	N/A	N/A
2 repetitions, 2x11RBs	7.45/8.7	7.45/7.44	5.4/5.41	5.34/5.41
4 repetitions, 4x11RBs	9.91/11.72	6.6/7.01	8.22/8.23	4.95/4.58
6 repetitions, 6x11RBs	11.65/13.47	7.29/7.39	9.32/9.33	5.15/4.98
8 repetitions, 8x11RBs	12.87/14.71	6.6/6.77	10.34/10.35	5.1/4.82
10 repetitions, 10x11RBs	13.81/15.67	6.91/7.29	11.52/11.53	5.11/5.21

It can be seen from Table 1 that PARP value for S-PSS for 20MHz channels can be significantly improved with the proposed method in comparison with the previously considered phase and combinations approaches, not to say about baseline replication without any modifications. Proposed phase adjustments and sequences for S-PSS are summarized in Table 2.

Table 2 Proposed suboptimal phase adjustments and sequences orders

S-SSB SL-U configuration	**S-PSS#0 adjustments**		**S-PSS #1 adjustments**	
	Phase, radians	Sequences indexes	Phase, radians	Sequences indexes
2 repetitions, 2x11RBs	[0, 3.14]	[0, 1]	[0, 0]	[1, 0]
4 repetitions, 4x11RBs	[0, 0.26, 0.66, -2.24]	[0 0 1 1]	[0, 3.06,-3.04, -3.04]	[1 1 0 0]
6 repetitions, 6x11RBs	[0,2.71,2.32,-1.58, 2.71,-2.36]	[0,0,0, 1,1,1]	[0,1.93,0.37,0.37, -2.36,-2.36]	[1,1,1, 0,0,0]
8 repetitions, 8x11RBs	[0, -1.58, 3.10, -1.58,2.32, 0.76, 2.32, -2.36]	[0,0,0,0, 1,1,1,1]	[0,-1.58, 2.32, -2.36, -1.58, -3.14, -2.36, 0.80]	[1,1,1,1, 0,0,0,0]
10 repetitions, 10x11RBs	[0,-0.02,-3.14,3.1 -3.14,3.1,-0.02,3.1, -0.02, 3.1]	[0,0,1,1,0, 1,0,0,1,1]	[0,3.1,-3.14,-0.02, -0.02,-0.02,-0.02, -0.02,-0.02,-3.14]	[1,1,1,1,0, 1,0,0,0,0]

Table 3 summarizes these optimal rotations for repetitions x2, x4, x6, x8, x10, showing an improvement over the baseline PAPR. The phase rotation sets listed in the Table 3 optimize the average PAPR over the entire set of sequences for a certain number of repetitions of the number of repetitions.

Table 3 Phase rotations that optimize the Average PAPR

S-SSB configuration	**PAPR base, dB**	**Phase, radians**	**PAPR improved, dB**
2 repetitions, 2x11RBs			
S-PSS	8.12	[0,-3.14]	7.88
S-SSS	10.11	[0,-3.14]	10.08
4 repetitions, 4x11RBs			
S-PSS	10.9	[0,-0.34,-2.64,-0.24]	7.14
S-SSS	13	[0,-1.84,-1.84,-0.04]	9.38
6 repetitions, 6x11RBs			
S-PSS	12.65	[0,-0.8,2.32,-0.8,2.32,-3.14]	7.48
S-SSS	14.66	[0,-0.8,2.32,-0.8,2.32,-3.14]	9.74
8 repetitions, 8x11RBs			

S-PSS	13.89	[0,-1.58,-1.7,2.32,-0.8,1.48,1.66,-3.08]	6.33
S-SSS	15.79	[0,-1.58,-1.58,2.32,-0.8,1.54,1.54,-3.14]	8.75
10 repetitions, 10x11RBs			
S-PSS	14.84	[0,-1.58,-1.58,1.54,-1.58, 1.54,3.1,3.1,-1.58,-3.14]	7.47
S-SSS	16.63	[0,-1.58,-0.02,-1.58,-1.58, 3.1,-0.02,-0.02,1.54,3.1]	9.81

3. Performance of the proposed S-SSB SL-U design

To demonstrate the necessity for PAPR adjustments to SL-U synchronization sequences, a set of link layer simulations of the 5G NR system was performed. The key impairment for evaluating the PAPR-related performance degradation is the proper power amplifier model. In our simulations we have considered a practical model based on the real sub-6 GHz PA parameters described in [10]. Tests were performed for various S-SSB SL-U configurations with different numbers of repetitions in the frequency domain, as well as for comparison and for the base S-SSB configuration in the licensed spectrum. The distribution channel model used is a multipath TDL-C (Tapped Delay Line) model [11]. A non-coherent matched filter with a fixed probability of false alarms (P_{FA}) is used as a detector. The full list of LLS simulation parameters is given in Table 4.

Final performance results, namely probability of miss detection S-PSS+ S-SSS vs. signal-to-noise ratio (SNR), are shown in Figures 2-4 for the 8, 4, 2 replications of S-SSB SL-U respectively.

In the considered power amplifier model, the saturation power is chosen to be approximately 28 dBm, and the nominal gain is approximately 27 dB. Also the model specifies post-PA losses equal to 4 dB that is typically the mean for a baseline 23 dBm power output, the PA output should be 27 dBm, which corresponds to the 0 dBm power input. Therefore, the key feature of the model under consideration is that for the baseline 23 dBm TX antenna output power (27 dBm PA output) we are already operating in the highly non-linear region with large distortions, so even 2-3 dB PAPR will lead to clipping.

Table 4 Scenario parameters for performance analysis of detection synchronization sequences

Parameters	Assumption
Carrier Frequency	6GHz
Bandwidth	20 MHz
Waveform	CP-OFDM
SCS	15/30/60kHz
S-PSS/S-SSS configuration	SL: SCS = 15/30/60 kHz; 11 RBs SL-U: SCS = 15 kHz; 8 repeats, 88 RBs

	SCS = 30 kHz; 4 repeats, 44 RBs SCS = 60 kHz; 2 repeats, 22 RBs
Type PAPR adjustment	W/o Phase adjustment Use different $N_{\mathrm{ID}}^{\mathrm{SL}}$
Modulation	BPSK
Model PA	R4-163314 Nokia specifies sub 6GHz PA
Total power	23 dBm
MPR	0 dB
Propagation condition	AWGN TDL-C, 30ns DS, Doppler $f_D = 1400$ Hz
Antenna configuration	1x1
Detection algorithm	Practical, Non-coherent matched filtering, $P_{FA} = 0.01$

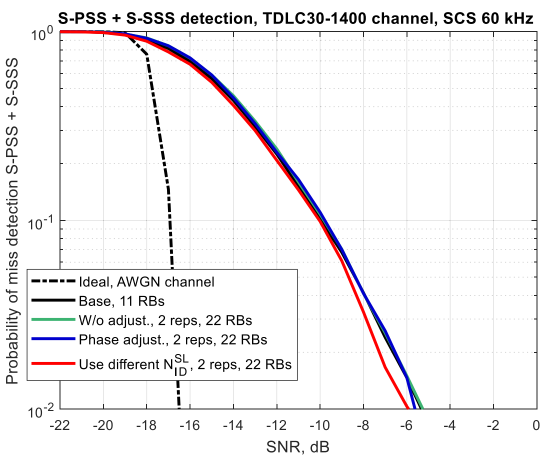

Figure 2 Probability of miss detection S-PSS + S-SSS vs. SNR ($P_{FA} = 0.01$) for 2 repetitions

The figures show that without adjusting the PAPR for the repeating S-SSB scheme in the case of 2 times and 4 times repetitions, the loss in coherent detection of synchronization signals will be approximately ~ 0.5 dB and 2.5 dB at the 10^{-1} level compared to the basic S-SSB design when setting MPR = 0 dB in the power amplifiers. The figures also show the detection result under AWGN channel conditions (black dash-dotted curve), which provides the maximum achievable performance. In the case of 8 times repetitions of S-SSB, correct detection of synchronization signals is impossible with a probability higher than 90%, even with a very high SNR (Figure 2, green solid curve).The difference in coherent detection performance between phase adjustment and the use of synchronization sequences with different $\boldsymbol{N_{\mathrm{ID}}^{\mathrm{SL}}}$ is small for the cases of 2 times and 4 times repetitions of S-SSB and is comparable to the performance of the base configuration. For x8 repetition of S-SSB, the method of using of synchronization sequences with different $\boldsymbol{N_{\mathrm{ID}}^{\mathrm{SL}}}$ is not optimal, resulting in a performance decrease of approximately ~2.5 dB at the 10^{-1} level compared to the base configuration, while phase correction has approximately the same performance as the basic configuration. This happens due to the fact that S-PSS have only two base sequence variants, and combining them 8 times choosing only from two of them is not optimal.

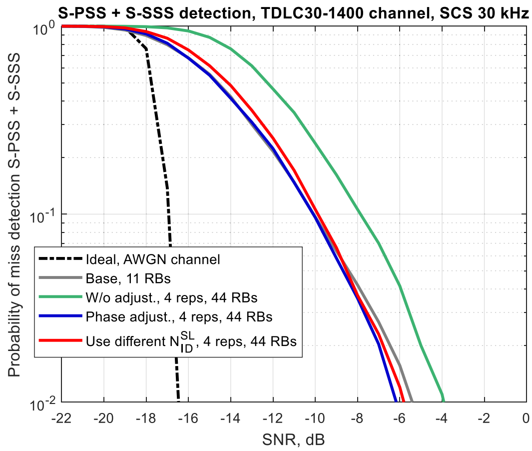

Figure 3 Probability of miss detection S-PSS + S-SSS vs. SNR ($P_{FA} = 0.01$) for 4 repetitions

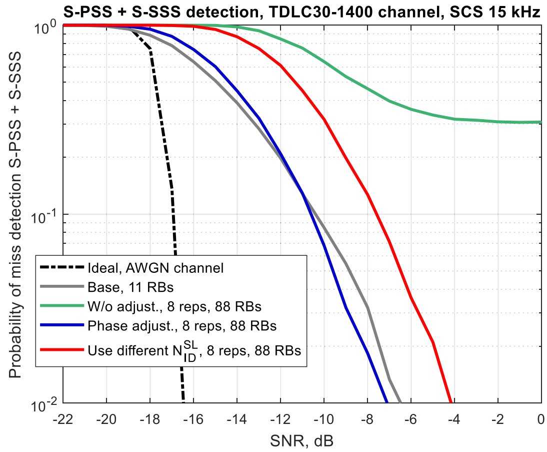

Figure 4 Probability of miss detection S-PSS + S-SSS vs. SNR ($P_{FA} = 0.01$) for 8 repetitions

4. Summary

In this paper we have presented a detailed analysis of the PAPR reduction methods for SL-U initial synchronization sequences and demonstrated their detection performance using a realistic power amplifier model. The values of phase rotations for the phase adjustment method, which optimize the average PAPR over the entire set of sequences for a certain number of repetitions, are provided, and for each variant of S-PSS an optimization parameter is provided for the considered basic methods. A combined PAPR improvement method for S-PSS is proposed, which provides a PAPR value lower than that of the base S-PSS sequence. The performance results of the synchronization sequences showed that for successful detection it is necessary to adjust the PAPR by any available method when there is a large number of frequency repetitions of S-SSB SL-U.

References

[1] Mohammed Hirzallah, Marwan Krunz, Balkan Kecicioglu, Belal Hamzeh. 5G New Radio Unlicensed: Challenges and Evaluation. In: IEEE Transactions on Cognitive Communications and Networking, pp. 689-701, December 2020. DOI: 10.1109/TCCN.2020.3041851.

[2] Yashraj Kakkad, Dhaval K Patel, Sagar Kavaiya, Sumei Sun, Miguel López-Benítez. Optimal 3GPP Fairness Parameters in 5G NR Unlicensed (NR-U) and WiFi Coexistence. In: IEEE Transactions on Vehicular Technology, pp. 5373-5377, April 2023. DOI: 10.1109/TVT.2022.3222964.

[3] Feifan Luo, Xinghua Sun, Yayu Gao, Wen Zhan, Peng Liu, Ziyang Guo. Optimal Coexistence of NR-U with Wi-Fi under 3GPP Fairness Constraint. In: ICC 2022 - IEEE International Conference on Communications, May 2022. DOI: 10.1109/ICC45855.2022.9838972.

[4] Bo Yin, Haonan Hu, Bing Xi, Qiaoshou Liu, Yanan Zheng, Zhizhong Zhang. Joint Radio Resources Allocation in the Coexisting NR-U and Wi-Fi Networks. In: IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), October 2021. DOI: 10.1109/PIMRC50174.2021.9569466.

[5] 3GPP. TS 38.211 NR; Physical channels and modulation; September 2023. Version 17.6.0 Release 17.

[6] Heshani Gamage, NandanaRajatheva, MattiLatva-aho. High PAPR Sequence Scrambling for Reducing OFDM Peak-to-Average Power Ratio. Print ISBN: 978-3-8007-4221-9, June 2016.

[7] Sheng-Ju Ku, Chin-Liang Wang, Chiuan-Hsu Chen. A Reduced-Complexity PTS-Based PAPR Reduction Scheme for OFDM Systems. In: IEEE Transactions on Wireless Communications, pp.2455-2460, July 2010. DOI: 10.1109/TWC.2010.062310.100191.

[8] Chan-Tong Lam, David D. Falconer, Florence Danilo-Lemoine. PAPR Reduction using Frequency Domain Multiplexed Pilot Sequences. In: IEEE Wireless Communications and Networking Conference, pp. 1429-1433, June 2007. Citation information: DOI 10.1109/WCNC.2007.269.

[9] EsmotAraTuli; Jae Min Lee; Dong-Seong Kim. Improved Partial Transmit Sequence Based PAPR Reduction of UFMC Systems, In: International Conference on Information Networking (ICOIN), January 2022. DOI: 10.1109/ICOIN53446.2022.9687143.

[10] 3GPP, Nokia, R4-163314, Realistic power amplifier model for the New Radio evaluation.

[11] 3GPP. TS 38.901 NR; Study on channel model for frequencies from 0.5 to 100 GHz; April 2022. Version 17.1.0 Release 17.