Performance Enhancement of 5G OFDM Systems Using Modified Raised Cosine Power Pulse

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Abstract

OFDM is a key modulation technology of current wireless communication systems such as 4G LTE/LTE-A. The fifth generation (5G) of wireless cellular networks is required to support a large variety of services such as extreme mobile broadband (xMBB) and novel machine type communication services. In this new scenario, wave-form shaping plays key role to reduce out-of-band (OOB) radiations. So pulse shaping based orthogonal frequency division multiplexing (OFDM) systems are the most promising proposals for 5G wireless cellular networks. These systems are designed on the success of LTE/LTE-A and many other present wireless cellular systems. In this paper, we have proposed a new pulse shaping window called Modified Raised Cosine Power pulse for N-subcarriers OFDM systems that suppresses OOB radiation and reduces peak to average power ratio (PAPR). It has been observed that the inter-carrier interference, signal to interference noise ratio, bit error rate and complementary cumulative distribution function of the PAPR versus threshold PAPR (PAPR0) performances of the OFDM system with proposed pulse shape filter is far better than all recently proposed pulse shaping function.

Keywords OFDM · Windowing function · ICI · Frequency offset · PAPR

1. Introduction

The designing of radio networks for fifth generation (5G) of mobile systems, is based on prediction that it will accommodate a large variety of use cases including many new scenarios as compared to fourth generation (4G) systems. Till now, telecommunication industry has broadly defined three main categories of 5G services, enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine type communication (mMTC)[1–3]. Each of these services is driving a very diverse set of requirements and opens new technical challenges for the 5G air interface.

The heart of 5G is a unified, more capable, new radio air interface called 5G new radio (NR). Which is not only enhancing mobile broadband, but also enabling new 5G services such as mission-critical control with ultra-reliability and virtual zero latency or URLLC and massive IoT with low power and wide area applications or mMTC. Therefore, 5G new radio interface adopts flexible framework that enables efficient service multiplexing. Based on these extreme variations of 5G requirements, the OFDM family is the right choice for 5G-NR to eMBB and beyond. This way 5G is going to be the first mobile generation that is not based on a totally new waveform and multiple access technique i.e. 5G NR will build upon OFDM, which LTE, WiMax and Wi-Fi are using presently. Key benefits of the OFDM family that make it most suitable to meet 5G requirements are [3]:

- Low complexity receiver devices even when scaling to wider bandwidths—enabling lower device cost.
- High spectral efficiency using low-complexity MIMO implementation which adds multiple data streams easily—getting closer to Shannon's limit.
- Low power consumption at uplink using single-carrier waveforms—uplink transmission to deliver more power-efficiency.
- Frequency localization to minimize in-band and out-of-band emissions which is critical for 5G service multiplexing—OFDM allows windowing/filtering for such enhancements.

Presently, LTE supports a fixed OFDM numerology of 15 kHz subcarrier spacing between OFDM. On the other hand, 5G -NR will introduce scalable OFDM numerology to support diverse frequency bands and deployment models, for example, mm Wave bands with 100 s of MHz wider channel widths (Fig. 1).

In order to support multiplexing of 5G services efficiently, it is required to minimize both in-band and out-of-band emissions. So that services which are utilizing adjacent frequency channels do not interfere with one another. OFDM allows post-processing of waveforms, such as windowing or filtering, to improve frequency localization. Figure 2 below showcases different 5G services, utilizing different 5G NR OFDM numerologies, multiplexed on the same frequency channel.

Other than frequency localization (in-band and out-of-band emissions), the major disadvantages of an OFDM system are its sensitivity to frequency offset and high peak to average power ratio (PAPR) of transmitted signal [1–3]. The OFDM systems sensitivity against carrier frequency offset causes attenuation and rotation of subcarriers, and intercarrier interference (ICI). The high PAPR introduces out-of-band radiation and intermodulation distortion.

To date, various schemes to reduce ICI and PAPR have appeared in the literature [4–12]. In this work, transmitter side pulse shape filtering method is used to improve frequency

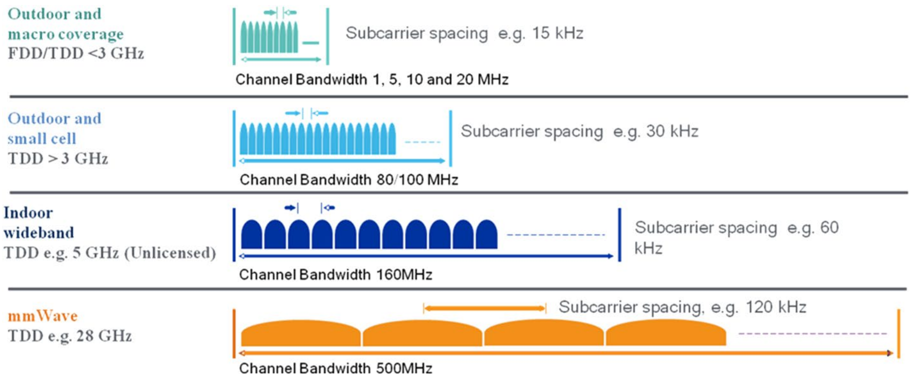


Fig. 1 Scalable OFDM numerology with scaling of subcarrier spacing [3]

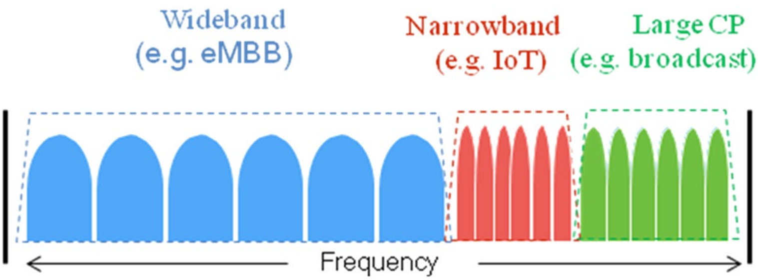


Fig. 2 5G NR with efficiently multiplexing of different services [3]

localization and reduce average ICI power and PAPR of N-subcarrier OFDM systems. The results show that proposed method provides better frequency localization, ICI, SINR, BER and CCDF versus $PAPR_o$ performance as compared to existing transmitter side pulse shaping methods in literature [9–11]. It is shown in the literature that pulse shape filtering methods in [9–11] outperform all previously reported work e.g., better than raised cosine (BTRC), raised cosine (RC) and rectangular pulse shapes [7–10], therefore the authors have compared their proposed pulse shape with sinc pulse (SP) [9], improved sinc pulse (ISP) [10] and phased modified sinc pulse (SM) [11] only.

The organization of the paper is as follows: The system model is introduced in Sect. 2. The different pulse shapes considered are described in Sect. 3. Section 4 derives the ICI and signal to interference noise ratio (SINR) as a function of the pulse shape Fourier transform. Section 5 derives the complementary cumulative distribution function (CCDF) as a function of threshold PAPR ($PAPR_0$). Results are investigated in Sect. 6. Finally, Sect. 7 concludes the paper.

2.SystemModel

The Fast Fourier Transform (FFT) based N-subcarrier OFDM system model with pulse shaping function is given in Fig. 3. The transmitted signal with pulse shaping $s(t)$ can be written as [9, 10]:

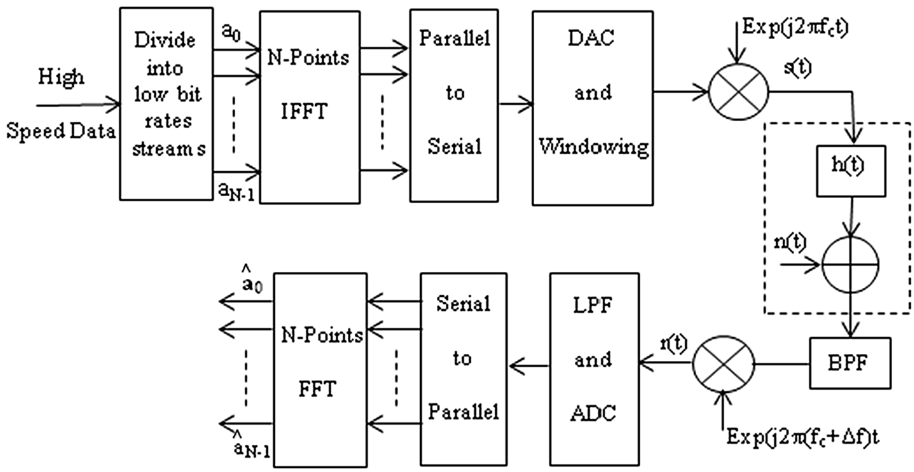


Fig. 3 N-subcarriers 5G OFDM system with pulse shaping/windowing filter

$$s(t) = \exp\{j2\pi f_c t\} \sum_{k=0}^{N-1} a_k p(t) \exp\{j2\pi f_k t\} \tag{1}$$

where f_c is the carrier frequency of OFDM system, N is number of subcarriers, a_k is the data symbol transmitted on the kth subcarrier, p(t) is the pulse shaping function and f_k is the kth subcarrier frequency, where $k = 0,1,\ldots\ldots\ldots, N-1$,.

The OFDM systems are susceptible to the carrier frequency offset, which results from the wireless channel distortion or the mismatch between the transmitter and the receiver oscillator frequency. The received signal r(t) at the receiver of OFDM system becomes [10, 11]:

$$r(t) = \exp\{j2\pi\Delta f t\} \sum_{k=0}^{N-1} a_k p(t) \exp\{j2\pi f_k t\} \tag{2}$$

where Δf is the carrier frequency offset.

3. Proposed Pulse Shaping Filter

The authors have proposed a new pulse shape filter called Modified Raised Cosine Power (MRCP) Pulse to reduce ICI and PAPR in OFDM systems. The authors got their inspiration to define MRCP pulse shape from Sinc Power (SP) pulse [9], improved sinc power (ISP) pulse [10], and raised cosine (RC) pulse [9], which is given as below

$$P(f) = \exp\{-a(fT)^2\} \left[\sin c(fT) \frac{\cos(\pi\alpha f T)}{1 + (2\alpha f T)^2}\right]^n \tag{3}$$

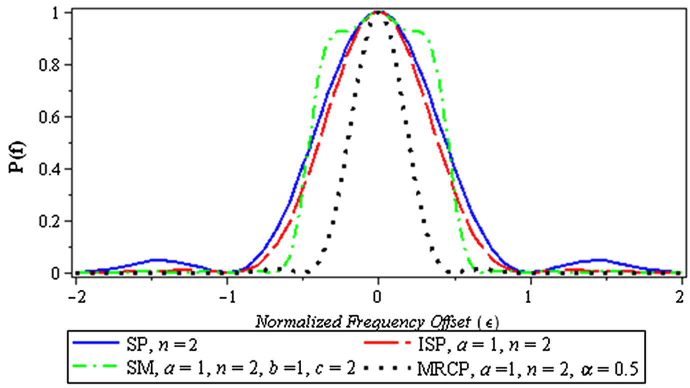


Fig. 4 Frequency localization comparison of proposed pulse shaping filter MRCP with SP, ISP and SM

where design parameter a adjusts amplitude, frequency spread and time spread of the MRCP pulse, α $(0 \le \alpha \le 1)$ is the roll off factor and n is the degree of the modified raised cosine function.

For comparison, we consider Sinc Pulse (SP) [9], Improved Sinc pulse (ISP) [10] and Phased modified sinc pulse (SM) [12] pulse shaping filters whose Fourier transforms are given, respectively as:

$$P_{SP}(f) = \sin c(fT)^n \tag{4}$$

$$P_{ISP}(f) = \exp\{-a(fT)^2\}\left[\sin c(fT)^n\right] \tag{5}$$

$$P_{SM}(f) = \exp\{-a(fT)^2\}\left\{\frac{\sin((\pi f - b\sin(c\pi f))T)}{(\pi f - b\sin(c\pi f))T}\right\}^n \tag{6}$$

Parameters b and c are used to control the phase of the sinc function. MRCP, SP, ISP and SM pulses are shown in Fig. 4 for $a=1$, $n=2$, $b=1$, $c=2$ and $\alpha=0.5$. The MRCP has lowest amplitude in the main lobe as well as at the sidelobes as compared to all frequencies. These properties of MRCP pulse substantially increases frequency localization by effectively reducing in-band and out-of-band emissions as compared to the other pulse shaping techniques. In Fig. 5, a MRCP pulse shape for $a=0.5$, 1 and 10 with roll off factor $\alpha=0.5$ and degree of modified raise cosine function $n=2$ is given. As shown, in the Fig. 5, with increase in *a,* amplitude of proposed pulse shape decreases in the frequency space.

4.ICIAnalysis

The average ICI power for the mth subcarrier $\overline{\sigma_{ICI}^m}$, can be written as [9, 10]:

$$\overline{\sigma_{ICI}^m} = \sum_{\substack{k=0 \\ k \neq m}}^{N-1} \left| P\left(\frac{k-m}{T} + \Delta f\right)\right|^2 \tag{7}$$

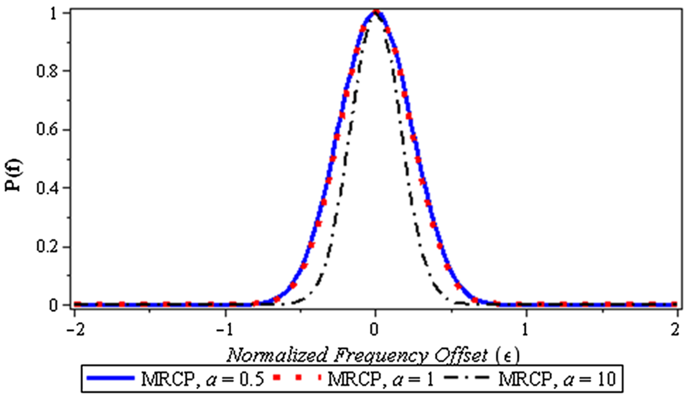


Fig. 5 MRCP pulse shapes for different values of a and $n=2$

By putting a value of P(f) in Eq. (7), results in the average ICI power for the newly proposed windowing function, which can be mathematically expressed as:

$$\overline{\sigma^{m}_{ICI\_\Pr oposed}} = \sum_{\substack{k=0\\k\neq m}}^{N-1}\left|\exp\left\{-a\left(\left(\frac{k-m}{T}+\Delta f\right)T\right)^{2}\right\}\left[\sin c\left(\gamma\left(\frac{k-m}{T}+\Delta f\right)T\right)\frac{\cos\left(\pi\beta\left(\frac{k-m}{T}+\Delta f\right)T\right)}{1+\left(2\beta\left(\frac{k-m}{T}+\Delta f\right)T\right)^{2}}\right]^{n}\right|^{2} \tag{8}$$

The ratio of average signal power to average *ICI* power is defined as signal to interference power ratio (SIR) and can be expressed as [10, 11]:

$$SIR = \frac{|P(\Delta f)|^{2}}{\sum_{\substack{k=0\\k\neq m}}^{N-1}\left|P\left(\frac{k-m}{T}+\Delta f\right)\right|^{2}} \tag{9}$$

Now, by inserting value of P(f) in Eq. (9) results in the SIR for the proposed windowing function, and can be expressed as:

$$SIR_{\Pr oposed} = \frac{\left|\exp\left\{-a(\Delta fT)^{2}\right\}\left[\sin c(\gamma\Delta fT)\frac{\cos(\pi\beta\Delta fT)}{1+(2\beta\Delta fT)^{2}}\right]^{n}\right|^{2}}{\sum_{\substack{k=0\\k\neq m}}^{N-1}\left|\exp\left\{-a\left(\left(\frac{k-m}{T}+\Delta f\right)T\right)^{2}\right\}\left[\sin c\left(\gamma\left(\frac{k-m}{T}+\Delta f\right)T\right)\frac{\cos\left(\pi\beta\left(\frac{k-m}{T}+\Delta f\right)T\right)}{1+\left(2\beta\left(\frac{k-m}{T}+\Delta f\right)T\right)^{2}}\right]^{n}\right|^{2}} \tag{10}$$

5.PAPRAnalysis

The peak to average power ratio (PAPR) is the ratio between the maximum power and the average power of the complex pass-band signal s(t), that is,

$$PAPR\{s(t)\} = \frac{\max|s(t)|^2}{E\{|s(t)|^2\}} \tag{11}$$

The input signals of *N*-point IFFT have independent and finite magnitudes which are uniformly distributed, therefore, by using the central limit theorem we can assume that the real and imaginary parts of the time-domain complex OFDM signal s(t) have asymptotically Gaussian distribution and hence the amplitude of the OFDM signal s(t) follows a Rayleigh distribution. Assuming $\{Z_n\}$ be the magnitudes of complex samples and the average power of s(t) is equal to $E\{s(t)\} = 2\sigma^2$, $\{Z_n\}$ are the i.i.d. Rayleigh random variables normalized with its own average power, which has the probability density function given by:

$$f_{z_n}(z) = \frac{z}{\sigma^2} e^{-\frac{z^2}{2\sigma^2}}, \quad n = 0, 1, 2, \dots N-1. \tag{12}$$

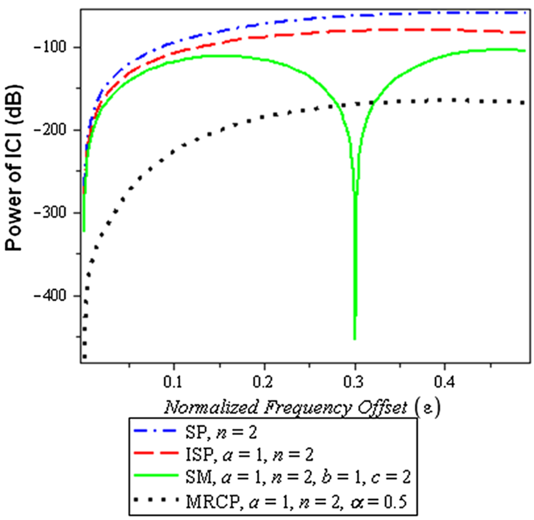
The cumulative distribution function (CDF) of maximum of Z_n (i.e. $Z_{\max} = \max_{n=0,\,1,\,2,\cdots,N-1} Z_n$) is given as:

$$F_{Z_{\max}}(z) = P(Z_{\max} < z) = P(Z_0 < z) \cdot P(Z_1 < z) \dots P(Z_{N-1} < z) = \left(1 - e^{-\frac{z^2}{2\sigma^2}}\right)^N \tag{13}$$

And the complementary CDF of maximum of Z_n (i.e. $Z_{\max} = \max_{n=0,\,1,\,2,\cdots,N-1} Z_n$) is given as:

$$\tilde{F}_{z_{\max}}(z) = 1 - \left(1 - e^{-\frac{z^2}{2\sigma^2}}\right)^N \tag{14}$$

Fig. 6 ICI performance of MRCP filter different filtering



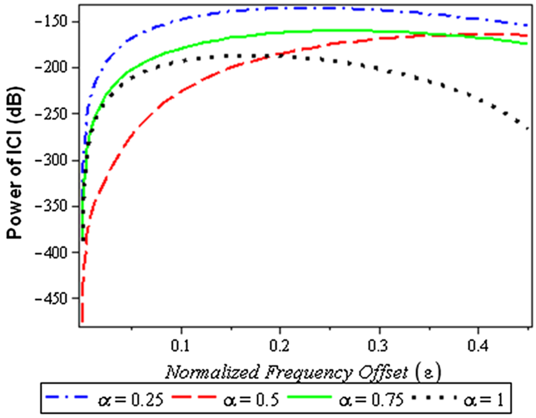


Fig. 7 ICI performance of MRCP filter for different values of α

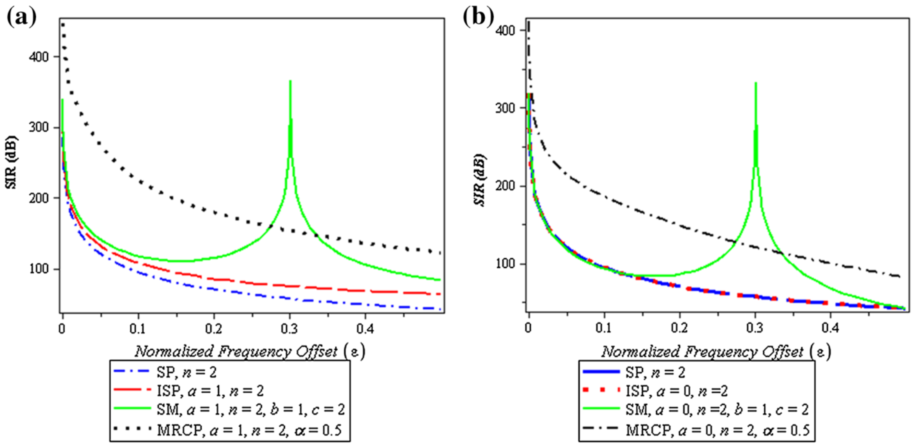


Fig. 8 SIR Performance of MRCP filter for **a** a = 1 and **b** a = 0

6. Results and Discussion

In this section, we present our numerical results for the performance enhancement of an OFDM system using transmitter side MRCP pulse shape. Figure 6, shows comparative performance of ICI with respect to the normalized frequency offset (ε) of proposed pulse shape to recently proposed transmitter side pulse shapes in the literature [10–12] for a 64-subcarrier OFDM system. For the normalized frequency offset $(\varepsilon) = 0.1$, ICI is -226.47 dB for the proposed windowing function which has improvements of 131.11 dB, 117.06 dB, and 106.13 dB with respect to SP, ISP and SM windowing functions respectively. Figure 4, shows a comparative performance of ICI with respect to the normalized frequency offset (ε) of proposed method to recently proposed transmitter side pulse shapes in the literature [9–11] for $a = 1$, $n = 2$. Figure 7, shows ICI performance of the proposed method for different values of α, and it can be seen that performance is more consistent for the value of $\alpha = 0.5$. Therefore, we have chosen $\alpha = 0.5$ in our analysis (Fig. 8).

The SINR versus normalized frequency offset (ε) performance of an OFDM system is presented in figure. As seen in these figures, MRCP pulse shape's SINR performance is

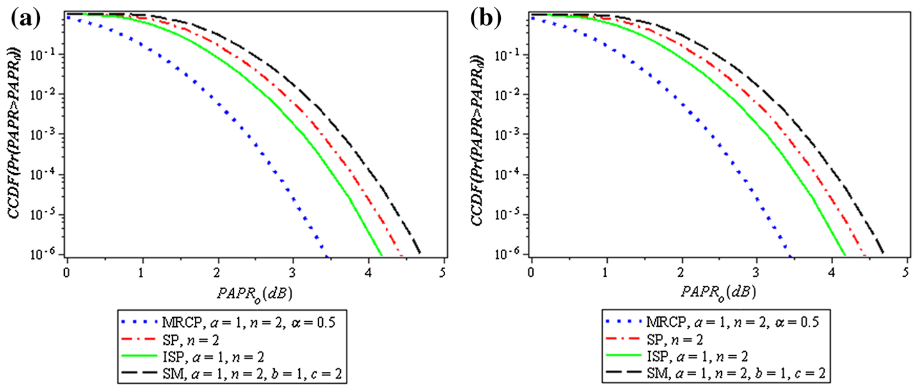


Fig. 9 CCDF of the PAPR performance of MRCP filter for **a** OFDM-QPSK and **b** OFDM-8QAM system

far better as compared to other recently proposed pulse shapes [9–11] for the same values of a and n. For $a=1$ and $\varepsilon=0.1$, MRCP pulse shape's SINR power is 224.49 dB that has 105.04 dB, 117.39 dB and 128.21 dB improvement as compared to SM pulse shape, ISP pulse shape and SP pulse shape, respectively.

In Fig. 9, different curves of the CCDF have been given for 10^4 random original OFDM symbols generated for different pulse shaping filters using QPSK and 8QAM modulation techniques. From Fig. 9, it is very clear that MRCP pulse shaping scheme can reduce the PAPR largely as compared to other pulse shaping schemes. For example, when QPSK scheme is used, for CCDF $=10^{-3}$ the PAPRs are 1.82 dB, 2.54 dB, 2.81 dB, and 3.08 dB for the MRCP pulse shape, ISP pulse shape, SP pulse shape and SM pulse shape, respectively.

In Fig. 10a–c, BER performance of QPSK, 16-QAM and 64 QAM OFDM system are presented using the MRCP pulse, SP pulse, ISP pulse and SM pulse with $\varepsilon=0.3$, $N=64$, for the values of the design parameters $a=0.25$, $n=2$, $b=0.25$, $c=2$, and $\alpha=0.5$. BER performance of MRCP pulse is better as compared to other pulse shaping schemes for all three modulation techniques. In QPSK-OFDM, for BER $=10^{-5}$, MRCP pulse require a SINR of 7.85 dB which is 0.91 dB, 1.92 dB and 2.12 dB lower as compared to SM pulse, SP pulse and ISP pulse, respectively.

7. Conclusion

5G new radio interface adopts flexible framework for enabling efficient service multiplexing. Based on extreme variations of 5G requirements, the OFDM family is the right choice for 5G-NR. In order to support multiplexing of 5G services efficiently, it is required to minimize both in-band and out-of-band emissions, so that services which are utilizing adjacent frequency channels do not interfere with one another. OFDM allows post-processing of waveforms, such as windowing or filtering, to improve frequency localization. In this paper, pulse shape filtering function is proposed that improves frequency localization in 5G OFDM systems which is called MRCP pulse shape. The MRCP filter not only enhances 5G OFDM system performance with respect to frequency localization, it also reduces ICI and PAPR of an OFDM system significantly. Authors investigated the ICI, SINR, CCDF

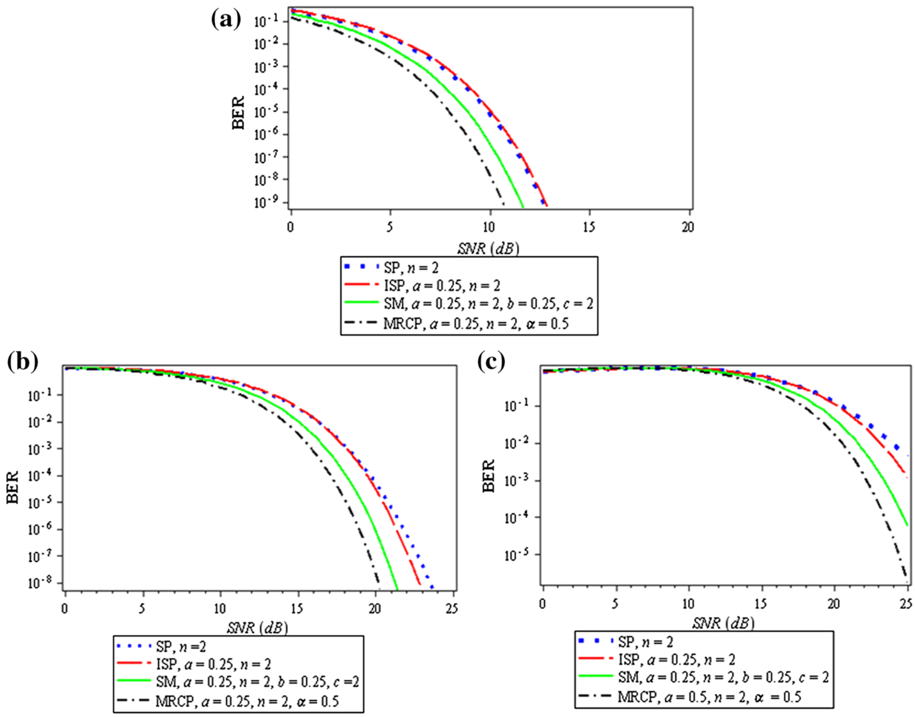


Fig. 10 BER performance of MRCP filter pulse for **a** OFDM-QPSK, **b** OFDM-16QAM and **c** OFDM-64QAM systems

Vs. $PAPR_o$ and BER performances of the proposed MRCP pulse shape for different OFDM systems.

References

1. Wu, J., Ma, X., Qi, X., Babar, Z., & Zheng, W. (2017). Influence of pulse shaping filters on PAPR performance of underwater 5G communication system technique: GFDM. *Wireless Communications and Mobile Computing*. https://doi.org/10.1155/2017/4361589.
2. Zhao, Z., Schellmann, M., Gong, X., Wang, Q., Böhnke, R., & Guo, Y. (2017). *Pulse shaping design for OFDM systems*. EURASIP Journal onWireless Communications and Networking: DOI. https://doi.org/10.1186/s13638-017-0849-8.
3. White Paper. (2016). *Making 5G NR a reality: Leading the technology innovations for a uniied, more capable 5G air interface*. Qualcomm Technologies, Inc.
4. Muschallik, C. (1996). Improving an OFDM reception using an adaptive Nyquist windowing. *IEEE Transactions on Consumer Electronic, 42*(3), 259–269.
5. Müller, S. H., Bäuml, R. W., Fischer, R. F., & Huber, J. B. (1997). OFDM with reduced peak-to-average power ratio by multiple signal representation. *Annales des Telecommunications, 52*(1–2), 58–67.
6. Beaulieu, Norman C., Tan, Christopher C., & Damen, Mohamed Oussama. (2001). A" better than" Nyquist pulse. *IEEE Communications Letters, 5*(9), 367–368.
7. Tan, P., & Beaulieu, N. C. (2004). Reduced ICI in OFDM systems using the "better than" raised-cosine pulse. *IEEE Communications Letters, 8*(3), 135–137.

8. Beaulieu, N. C., & Tan, P. (2005). Effect of transmitter Nyquist shaping on ICI reduction in OFDM systems with carrier frequency offset. *Electronics Letters, 41*(13), 746–748.
9. Mourad, Hebat-Allah M. (2007). Reducing ICI in OFDM systems using a proposed pulse shape. *Wireless Personal Communications, 40*(1), 41–48.
10. Kumbasar, Volkan, & Kucur, Oğuz. (2007). ICI reduction in OFDM systems by using improved sinc power pulse. *Digital Signal Processing, 17*(6), 997–1006.
11. Alexandru, N. D., & Onofrei, A. L. (2010). ICI reduction in OFDM systems using phase modified sinc pulse. *Wireless Personal Communications, 53*(1), 141–151.
12. Saxena, R., & Joshi, H. D. (2013). ICI reduction in OFDM system using IMBH pulse shapes. *Wireless Personal Communications, 71*(4), 2895–2911.

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