Enhancing Power Efficiency in NB-IoT Networks: PAPR Reduction in SC-FDMA

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Abstract. NB-IoT, short for NarrowBand IoT, is a communication standard for long-range connectivity of numerous devices. A key research area in NB-IoT is reducing Peak-to-Average Power Ratio (PAPR).

NB-IoT builds on 4G LTE (Long Term Evolution) and employs Single Carrier Frequency Division Multiple Access (SC-FDMA) in UpLink (UL) to minimize PAPR. To address power amplifier non-linearities, we propose applying the "clipping" technique, borrowing from OFDM.

In this paper, we examine the impact of Clipping Factor (CF) on PAPR reduction and the attenuation factors of Raised-Cosine (RC) filter and the Root Raised-Cosine (RRC) filter on PAPR probability distribution. Our analysis demonstrates a 2.5 dB (33.33%) reduction at a cumulative distribution function of 10^{-3}, with better results when using the Raised-Cosine (RC) filter.

Keywords: Peak to Average Power Ratio (PAPR) · Single-carrier FDMA (SC-FDMA) · Narrowband - Internet of Things (NB-IoT) Networks · Power efficiency

1 Introduction

With the rapid growth of Internet of Things (IoT) devices and their diverse applications, the need for efficient and reliable wireless communication technologies has become increasingly critical [1,2]. Narrowband Internet of Things (NB-IoT) networks [1] have emerged as a promising solution for providing connectivity to a large number of low-power IoT devices. However, power efficiency and performance optimization remain significant challenges in NB-IoT networks.

One of the key components in NB-IoT communication is the Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation technique, which offers advantages such as low Peak-to-Average Power ratio (PAPR) and spectral efficiency. However, the PAPR of SC-FDMA signals even low can lead to power inefficiency and performance degradation, especially in resource-constrained IoT devices [3].

A. Sere et al. (Eds.): AFRICOMM 2023, LNICST 587, pp. 100–112, 2025.
https://doi.org/10.1007/978-3-031-81570-6_7

In this article, we focus on addressing the PAPR issue in SC-FDMA for NB-IoT networks to enhance power efficiency and overall system performance. We investigate various techniques and algorithms for PAPR reduction and their impact on power consumption, spectral efficiency, and error performance. The aim is to provide insights into effective approaches that can mitigate PAPR while maintaining the desired power efficiency and performance levels in NB-IoT networks.

This article is organized as follows. Section 2 provides a brief description of the research methodology used in this study; the aim is to explore effective strategies for reducing PAPR in SC-FDMA signals to enhance power efficiency and performance in NB-IoT networks. Section 3 explores the related works while Sect. 4 decribes the proposed method for PAPR reduction in SC-FDMA and discuses the results obtained through simulations. Finally, Sect. 5 concludes the article and outlines potential future research directions in this area.

2 Research Methodology

The research methodology used in this study, consisted of investigating and analyzing various techniques and algorithms for reducing PAPR in OFDMA systems [3–5]. This has involved conducting an extensive literature review to gather relevant information on PAPR reduction methods.

The research methodology also incorporates the use of appropriate simulation tool Matlab [6] to simulate SC-FDMA systems integrating PAPR reduction techniques for enhancement of power efficiency in NB-IoT Networks.

Also, in this article, we deliberately choose to focus on the "adding signal" techniques for PAPR reduction [7], with a specific emphasis on those that are backward compatible. The selection of "adding signal" techniques is justified by their perceived lower complexity and their ability to meet the primary constraints (power consumption and integration) of an embedded system.

By following this research methodology, the study aims to provide valuable insights into effective strategies for reducing PAPR in SC-FDMA signals, thereby enhancing power efficiency and contributing to the advancement of NB-IoT technology.

3 Related Works

PAPR reduction has already been the subject of research, and several methods have been proposed [3–5,7,8]. However, it is only with the widespread adoption of OFDM modulation [3–5,7,8], due to its use in various telecommunications standards such as LTE, that the issue has become crucial in the literature, given that the signal has a non-constant envelope. In this section, we review different PAPR reduction techniques [8] in OFDM and SC-FDMA systems known as "adding signal" techniques for PAPR reduction [7,8].

While not as straightforward, it has been shown in [7] that various forms of clipping are "adding signal" techniques for PAPR reduction. In fact, any clipping technique can be formulated as an "adding signal" technique [9].

3.1 "Clipping" Techniques Overview

Intuitively, "clipping" is a class of methods that is very easy to understand. It involves reducing the maximum amplitude of a signal to a predetermined threshold by amplitude clipping. This process aims to decrease the power variation of the signal and, consequently, reduce its sensitivity to nonlinearities. However, this procedure degrades the resulting signal and it may not achieve the nominal performance at the receiver. Furthermore, since saturation is inherently a nonlinear element, all the inherent defects of such an element will also be present. Numerous clipping methods have been developed, as evidenced by the works in [10–13].

3.2 "Clipping and Filtering" Technique

This technique has been proposed since the early implementation of terrestrial OFDM (DVB-T) in the late 1990s [10,11]. Therefore, a signal x will be scrambled according to the following formula:

$$f\left(x\right)=\begin{cases} x & \left|x\right|\leq A \\ Ae^{j\phi(x)} & \left|x\right|>A \end{cases} \tag{1}$$

where $y=f\left(x\right)$ is the resulting signal, A is the clipping amplitude, the Clipping Factor (CF) is expressed as $\mathrm{CF}={}^{A}\!/_{\max\left(\left|x\right|\right)}$ and $\phi\left(x\right)$ and $\phi\left(x\right)$ is the phase of the signal x. "Clipping" as expressed in (1) is a source of distortions (Rise of secondary lobes, interference, etc.).

The articles by L.J Cimini [10,11] can be considered as the reference for this method. They analyze the effects of the previous three points on the power spectral density and the Bit Error Rate (BER). Of course, the BER is degraded by several dB due to clipping noise in the band. In [14], K.R. Panta and J. Armstrong demonstrate that this issue is less significant when the signal traverses a frequency-selective channel. They show that the error rate is predominantly due to subcarriers that are heavily affected by the channel, and in this case, the contribution of clipping noise to the BER is very low. Another analysis of this problem reveals that the degradation in signal-to-noise ratio can be effectively mitigated by using powerful codes such as Turbo codes [12] (though the addition of a Turbo code compromises its backward compatibility nature). A second result in this article states that reducing the PAPR through clipping will be more effective if the OFDM signal is oversampled before clipping.

3.3 PAPR Reduction in SC-FDMA Systems Proposed by MediaTek Inc. [15]

The article proposed in [15] presents an analysis of a PAPR reduction technique for UL NB-IoT based on SC-FDMA. The objective is to study the PAPR reduction offered by this technique and explore potential improvements in the context of UL NB-IoT.

In [15], it is demonstrated that PAPR can be significantly reduced by limiting the number of modulated subcarriers in SC-FDMA and applying temporal windowing of SC-FDMA symbols before band limiting the signal through filtering. Additionally, the application of windowing aids in reducing spectral leakage into the adjacent channel, known as the Adjacent Channel Leakage Ratio (ACLR). However, it has been found that symbol windowing in SC-FDMA has not only positive effects; it could increase InterSymbol Interference (ISI), which could lead to receiver performance degradation in frequency-selective fading channels.

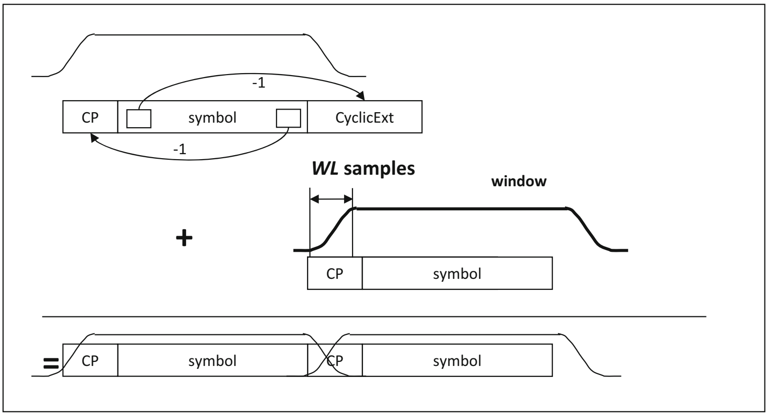


Fig. 1. Windowing of SC-FDMA symbols [15].

As shown in the Eq. (2), the remaining Cyclic Prefix (CP) length can be used for windowing without risking any significant performance degradation of the reception at the eNodeB [15].

$$\text{TotalCPDurationPerSlot} + 7\text{SC}-\text{FDMAsymbols}/\,(2.5\,\text{kHz subcarrier placing}) = {}^1\!/\!_2 \;\text{SubFrameLength} = 3\,\text{ms} \quad (2)$$

where

$$\text{TotalCPDurationPerSlot} = 200\mu\text{s}/\text{Slot}$$

Consequently, it can be deduced that the minimum duration of the Cyclic Prefix (CP) is 9/320 kHz = 28 μs, which is significantly greater than the typical effective delay spread of standard 3GPP channel models, which generally have a delay spread of less than 5 μs. It is demonstrated in [15] that two samples of the cyclic prefix (CP) length (i.e., the 9th and 10th samples) in SC-FDMA-based NB-IoT uplink are sufficient to account for the multi-path delay spread.

The performance analysis was conducted assuming an uplink (UL) NB-IoT based on SC-FDMA, with a channel bandwidth of 200 kHz occupying 72 subcarriers with a subcarrier spacing of 2.5 kHz and a guard band of 10 kHz at each end. The subcarriers are indexed from −36 to 35, with 0 corresponding to the

DC (Direct Current) subcarrier at the baseband before the half subcarrier offset as defined in the 3GPP LTE standard. The purpose of the offset is to reduce distortions.

Under the assumption of a sampling frequency Fs = 320 kHz, and the use of a 128-point Inverse Fast Fourier Transform (IFFT) to generate symbols, the cyclic prefix (CP) length is 9 samples, and the overlapping length (WL) characterizing the time window varies from 5 to 7 samples in the simulations. The windowing is illustrated in Fig. 1.

$$\text{IFFT} = 320\,[\text{kHz}]\,/180\,[\text{kHz}]\ \times 72\,[\text{subcarriers}] = 128$$

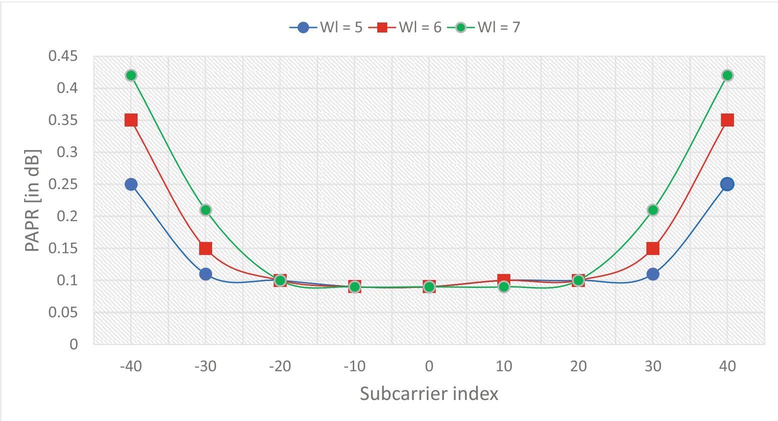


Fig. 2. PAPR [dB] as a function of the subcarrier index of the modulated subcarrier when a single SC-FDMA subcarrier is modulated by BPSK [15].

Figure 2 shows the PAPR statistics obtained as a function of the modulated subcarrier index and the WL parameter when a single SC-FDMA subcarrier is allocated to the mobile and BPSK symbols are used as input. The PAPR results vary across the subcarrier index due to the effects of the pulse shaping filter applied to the IFFT output, which limits the bandwidth.

The green, red, and blue curves represent the PAPR variation for a window length of 5, 6, and 7 symbols, respectively. The effect of windowing is noticeable at the edges where the PAPR values are higher. The longer the window, the less the signal is disturbed and the lower the PAPR. For example, as shown in Fig. 2, the PAPR of the subcarrier with index -36 is 0.25 for a window length of 7 symbols, 0.35 for 6 symbols, and 0.45 for a window length of 5 symbols. The PAPR increases towards the edges of the bandwidth as the window length WL decreases.

This similarity in results between a single subcarrier and two subcarriers modulated by BPSK in SC-FDMA can be explained by the fact that for a BPSK input, the Discrete Fourier Transform (DFT) used as a pre-coding transform leads to multiplexing between the two allocated subcarriers and modulating them by BPSK.

Additionally, it can be observed that SC-FDMA with one or two subcarriers can achieve a low PAPR of approximately 0.5 dB or less. However, the PAPR increases near the edges of the bandwidth compared to its value at the center of the subcarrier.

4 Proposed Method for PAPR Reduction in SC-FDMA

In this section, we present the proposed method for Peak-to-Average Power Ratio (PAPR) reduction in Single Carrier Frequency Division Multiple Access (SC-FDMA) within the context of NB-IoT networks, including the simulation setup and the subsequent discussion of results.

4.1 PAPR Reduction Methodology in SC-FDMA-Based NB-IoT Networks

SC-FDMA can be viewed as an OFDMA scheme where data symbols in the time domain are transformed to the frequency domain using Discrete Fourier Transform (DFT) before undergoing OFDMA modulation. The input binary signals are transformed into complex signals using a baseband modulator in a possible modulation format: BPSK, QPSK, 16-QAM. The functional block diagram of SC-FDMA is illustrated in Fig. 3; it includes the PAPR Reduction scheme.

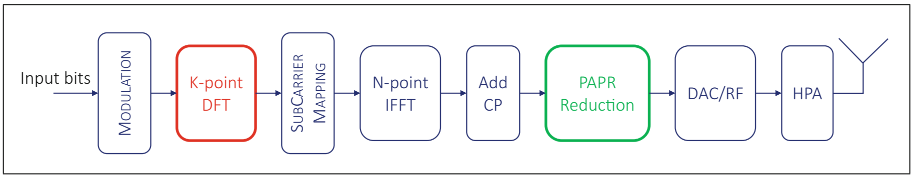


Fig. 3. SC-FDMA Transmitter including the PAPR Reduction Scheme.

In the proposed PAPR reduction technique for NB-IoT networks using SC-FDMA modulation in UL, we have chosen the clipping technique [10,11] for the following reasons: it offers backward compatibility and it has been extensively tested and experimented in OFDM systems [7]. Therefore we analyze the influence of the "Clipping Factor" (CF) on the PAPR reduction gain. To further optimize the reduction of the PAPR, we also studied the impact of the attenuation factor or "Roll-off Factor" (RoF) of two types of transmission filters, namely the Raised-Cosine (RC) filter and the Root Raised-Cosine (RRC) filter.

In SC-FDMA systems, the time-domain signal $x(t)$ can be written as

$$x\left(t\right)=\frac{1}{Q}\times\frac{1}{N}\sum_{k=0}^{N-1}X_{k}e^{2j\pi\frac{k}{T_s}t},\,0\leq t\leq T_s\,,\tag{3}$$

where X_k is mapped data for $k=0,1,2,...,N-1$, N is the number of subcarriers (IFFT size) and T_s is the OFDM symbol period and $Q=\frac{N}{K}$, where K is the DFT size as shown in Fig. 3.

The PAPR of $x\left(t\right)$ can be defined as

$$\mathrm{PAPR}_{[\mathrm{x}]}\triangleq\frac{\max\limits_{t\in[0,T_s]}\left|x\left(t\right)\right|^{2}}{\mathrm{P_{av}}},\tag{4}$$

where $\mathrm{P_{av}}$ is the average power defined as $\mathrm{P_{av}}\triangleq E\left\{\left|x\left(t\right)\right|^{2}\right\}$. Note that, it is more useful to consider ξ as a random variable and can be evaluated by using a statistical description given by the complementary cumulative density function (CCDF), defined as the probability that PAPR exceeds ψ_0, i.e., $\mathrm{CCDF}=\Pr\left\{\mathrm{PAPR}_{[\mathrm{x}]}>\psi_0\right\}$.

To approximate PAPR in (4) in discrete time-domain, an oversampled version of (3) can be used. In this case, the oversampled time-domain signal x_n can be written as

$$x_{n}=\frac{1}{Q}\times\frac{1}{N}\sum_{k=0}^{N-1}X_{k}e^{2j\pi k\frac{n}{NL}},\,0\leq n\leq NL-1\,,\tag{5}$$

where L is the oversampling factor. To better approximate the PAPR of continuous-time OFDM signals, $L\geq4$ is used to capture the peaks of the continuous time-domain signals. The time-domain samples x_n are NL-point IFFT of the data block with $\left(L-1\right)N$ zero-padding. The PAPR computed from the L-times oversampled time domain SC-FDMA signal samples can be defined as

$$\mathrm{PAPR}_{[\mathrm{x}]}=\frac{\max\limits_{0\leq n<NL}\left|x_{n}\right|^{2}}{\mathrm{E}\left[\left|\mathrm{x_n}\right|^{2}\right]}.\tag{6}$$

4.2 NB-IoT Using SC-FDMA Simulation Setup

The parameters used for PAPR reduction in NB-IoT systems using SC-FDMA are summarized in Table 1. A SC-FDMA system over a bandwidth of5.10^6 KHz with QPSK and 16QAM modulation is considered.

4.3 Results and Discussion

Figure 4 depicts the CCDF of the PAPR reduced by Clipping Technique with various Clipping Factor (CF) values. Based on the simulation results shown in Fig. 4, depicting the distribution of SC-FDMA PAPR for various clipping factor values, which are summarized in comparison performance Table 2 for PAPR

Table 1. Simulation parameters setup.

Parameters	Values
Sampling frequency Fs	5. MHz
Pulse-shaping filter	Raised-Cosine filter (RC) Root Raised-Cosine filter (RRC)
Roll-off Factor (RoF)	0.99; 0.85; 0.6; 0.4
DFT Size	16
Size IFFT	512
Clipping Factor (CF)	0.75; 0.8125; 0.875; 0.9375

reduction, the following observation can be made: The greater the signal clipping (through a low clipping factor), the greater the reduction gain of PAPR. In our example, at a 10^{-3} CCDF (Fig. 4), we observe a PAPR reduction gain of 2.5 dB for a Clipping Factor (CF) of 0.75, whereas it is 0.75 dB for a Clipping Factor (CF) of 0.9375.

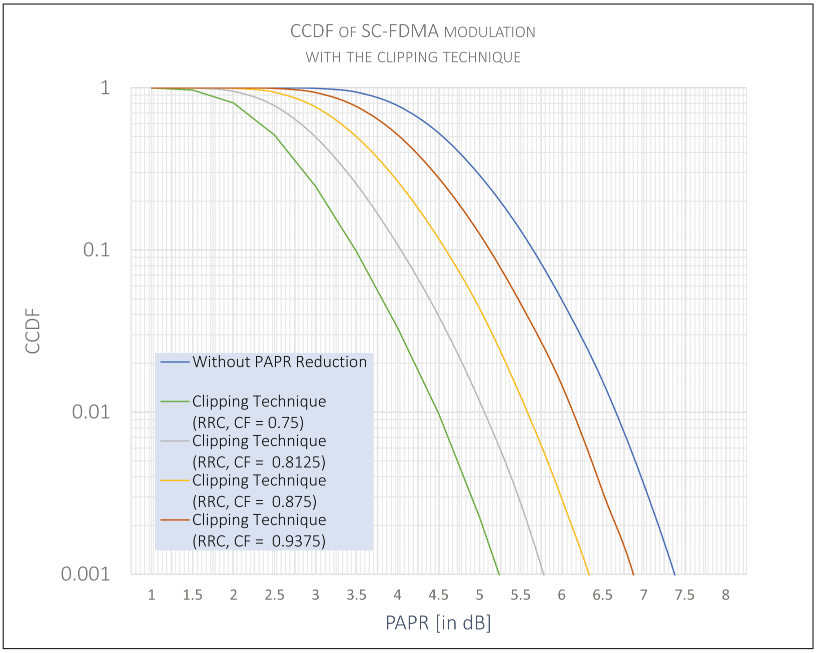
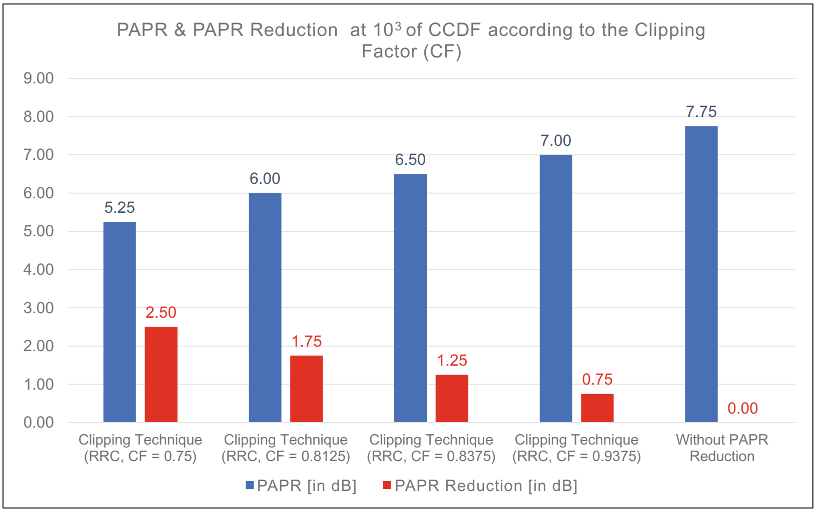


Fig. 4. SC-FDMA PAPR Reduction using Clipping Technique with different Clipping Factor (CF) values.

Table 2. PAPR reduction according to the Clipping Factor (CF).



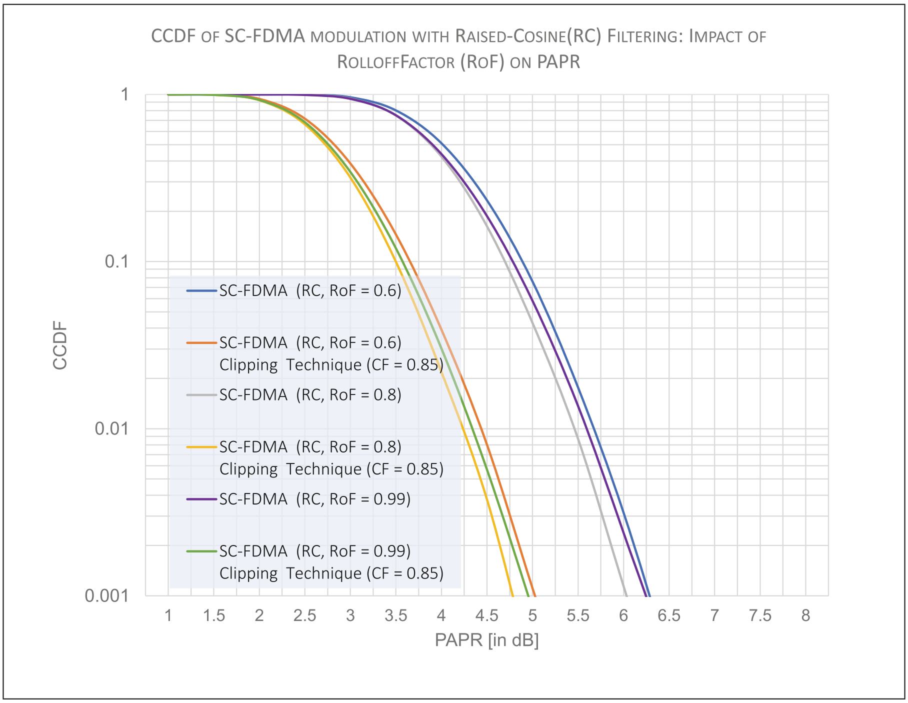


Fig. 5. CCDF of SC-FDMA modulation with Raised-Cosine(RC) filtering Impact of Roll-off Factor (RoF) on PAPR.

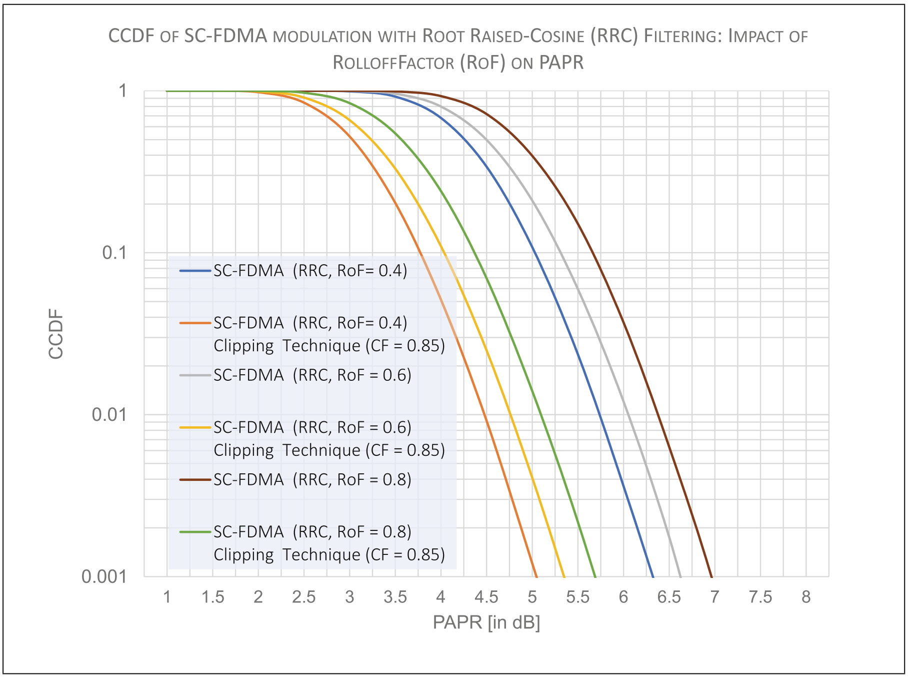


Fig. 6. CCDF of SC-FDMA modulation with Root Raised-Cosine(RRC) filtering Impact of Roll-off Factor (RoF) on PAPR.

In reality, in the SC-FDMA system as well as in most transmission systems, there is a commonly known emission shaping filtering called the transmit filter, which is used to adapt the signal to the propagation channel.

In our case study, we have considered two (02) filters: the Raised Cosine (RC) filter and the Root Raised Cosine (RRC) filter. For each type of filtering, we will analyze the impact of the attenuation factor or Roll-off Factor (RoF), which is a measure of the excess bandwidth of the filter, on the distribution of PAPR. We selected these two filters based on their capability to minimize intersymbol interference (ISI). Figure 5 and Fig. 6 show PAPR reduction performance within SC-FDMA system operating on the one hand with the Raised Cosine (RC) filter and on the other hand with the Root Raised-Cosine (RRC) filter.

The PAPR of SC-FDMA whatever the filtering (RC or RRC filters) increases with the Roll-off Factor (RoF), both in the presence or absence of PAPR reduction techniques (such as clipping). Indeed, as shown in Fig. 5, with Raised-Cosine(RC) filtering, at a CCDF of 10^{-3}, the PAPR of SC-FDMA is 6.00 dB, 6.25 dB, and 6.30 dB for a RoF of 0.6, 0.9, and 0.99, respectively. With a clipping technique using a constant clipping factor (CF) of 0.85, at a CCDF of 10^{-3}, the PAPR of SC-FDMA is 4.75 dB, 4.95 dB, and 5.10 dB for a RoF of 0.6, 0.8, and 0.99, respectively.

In Fig. 6, with Root Raised-Cosine(RRC) filtering, at a CCDF of 10^{-3}, the PAPR of SC-FDMA is 6.25 dB, 6.8 dB, and 7.00 dB for a RoF of 0.4, 0.6, and

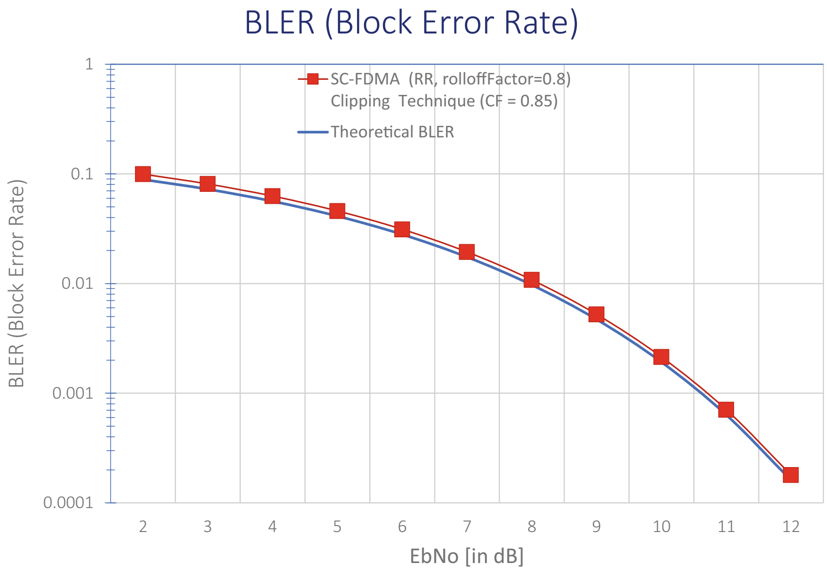


Fig. 7. BLER of SC-FDMA System (RR, RoF = 0.8) using clipping and filtering technique where CF = 0.85.

0.8, respectively. With a clipping technique using a constant clipping factor (CF) of 0.85, at a CCDF of 10^{-3}, the PAPR of SC-FDMA is 5.00 dB, 4.30 dB, and 5.70 dB for a RoF of 0.4, 0.6, and 0.8, respectively.

Raised Cosine (RC) and Root Raised Cosine (RRC) a filtering are used in wireless communication systems including SC-FDMA systems to shape the spectrum of transmitted signals, reducing out-of-band emissions and interference. When the Roll-off Factor (RoF) increases, the rate of transition of the RC or RRC filter becomes steeper, leading to more pronounced peaks in the time domain. This contributes to higher PAPR values, even without considering PAPR reduction techniques as showed in Fig. 5 where RRC filtering is deployed and Fig. 6 where RRC filtering is used.

Figure 7 evaluates the impact of the clipping technique on the performance of the transmission in our SC-FDMA model.

Figure 7 shows the performance of the Block Error Rate (BLER) in the presence of the clipping technique. It should be noted that clipping, by its nature, degrades the BLER as it generates distortions [7]. Since our constraints require us to maintain the BLER without degradation, in addition to clipping, filtering is performed to reduce the distortions generated by clipping. Ultimately, based on the results shown in Fig. 7, the BLER curve with the PAPR reduction technique remains aligned with the reference curve (theoretical BLER curve) which corresponds to the BLER of SC-FDMA System without any PAPR reduction.

5 Conclusion

NB-IoT is a dedicated technology for the Internet of Things, providing extensive coverage and various advantages. The NB-IoT technology utilizes SC-FDMA modulation, a close relative of OFDMA, for its uplink transmission. However, the high peak-to-average power ratio (PAPR) in SC-FDMA signals leads to the degradation of subcarrier orthogonality due to amplifier non-linearities, resulting in significant energy consumption from the battery at the transmitter.

In this article, we have studied and analyzed several commonly applied methods in OFDM, enabling us to adapt the clipping technique to SC-FDMA. After implementing and simulating the clipping technique, our results demonstrated a significant reduction in PAPR without degrading the signal's Block Error Rate (BLER). We observed that the PAPR decreased with the Roll-off Factor (RoF). Combining the clipping method with filtering techniques such as Root Raised-Cosine (RRC) or Raised-Cosine (RC) allowed us to achieve satisfactory results in terms of reduction gain and signal degradation correction.

In this article, our findings mainly focus on the clipping technique. Therefore, an extension of simulations for other types of clipping functions, such as Smooth Clipping or Deep Clipping, could be explored to leverage their unique properties and characteristics.

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