Performance evaluation of companded localized FDMA for LTE uplink communications

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Abstract

The maximum-to-expected power ratio is critical metric in the current day mobile communications. Single-carrier frequency division multiple access is the most promotional scheme to reduce the peak-to-average power ratio in order to compromise the bit error rate for mobile communications. The proposed companding functions play a vital role in SC-FDMA than in OFDMA for LTE uplink systems. Here, in this paper the nonlinear companding functions like μ -law, error, logarithmic, exponential, trapezoidal and airy function are more attractive to solve the problem and analyze PAPR and BER. The μ -companding is not recommended to use because of its average power and outband radiation. This paper proposed a companding functions based on special function to limit power ratio without enhancing the average power. The novel airy function gives suitable trade-off with their power ratio PAPR and error rate BER. The suggested method maintains superior performance with and without decompanding function in SC-FDMA systems at the receiver side without effecting the complexity.

Keywords Bit error rate · μ -Law · Error function · Logarithmic function · Exponential function · Trapezoidal function · Airy function · Peak-to-average power ratio

1 Introduction

Single-carrier FDMA (SC-FDMA) systems are executed in LTE uplink communications than orthogonal multiple access systems (OFDMA), because of its lessen PAPR due to less envelope fluctuations. The localized mapping is easier to implement than distributed/interleaved mappings in SC-FDMA, particularly in adaptive digital modulations [1, 2]. The power amplifiers having highly linear and D/A converters have high resolution which are needed to meet high power requirements. But they require additional complexity and cost to reduce the power efficiency. The partial transmit sequence and selected mapping techniques aligned with companding functions are about the methods to minimize PAPR [3, 4]. These practices need excess bandwidth and also broadcast the side information

and complicated. One easy way to cut PAPR is companding without side information, due to its negligible execution complexity. The authors in [5, 6], to recommend a new SC-FDMA system via the DCT type-II and DCT's, result in a lower error rate (BER) than DFT. Also, considering real arithmetic rather than complex arithmetic preferred in DFT. It concludes that DCT-based SC-FDMA system outperforms DFT-based SC-FDMA system in terms of error probability (BER) but not PAPR. To accommodate the mitigation PAPR, power amplifiers operate in the large linear range required which are complex and expensive to design [5, 6].

The basic μ -companding is generally used to reduce PAPR at 255 to be recommended to propose in OFDMA and SC-FDMA systems, and it raises the average power of companded signal [7–9]. In [7–9], the localized FDMA is discussed to reduction in PAPR and BER than OFDMA for

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both the cases μ and modified μ -law. The new error function, logarithmic function, absolute exponential function and trapezoidal functions are that authors assumed that an SC-FDMA signal follows a Gaussian distribution but proved that amplitude of SC-FDMA signal does not follow [10–13]. In [14], the novel nonlinear companding function is proposed to manage the compressed large signals and maintains the average power constant than exponential function, error function, logarithmic functions in OFDMA. The authors also suggested that trapezoidal function [15, 16] has more effective and favorable trade-off belonging that more design flexibility in OFDMA. The airy functions [17, 18] are to mitigate PAPR and BER requirements in OFDMA, also having most attractive for its simplicity and effectiveness. In [19], the hybrid companding function has proposed to transform approximated distribution to uniform distribution toward reducing PAPR without effecting the average power in SC-FDMA. As of now the mobile device is power limited, and this case is more severe in uplink communications and the proposed system avoids this severity and offers more advantageous than the conventional system. However, they cut PAPR at the expense of complexity, less throughput, bandwidth enlargement or BER degradation.

In this paper, Sect. 2 describes about single-carrier FDMA transceiver schematic and Sect. 3 calls the nonlinear companding function categories. After that Sect. 4 helps the proposed methodology SC-FDMA model with companding functions rather than the OFDMA model. Finally, Sect. 5 evaluates the performances of special functions analyzed and followed by conclusion in Sect. 6.

2 Preliminaries

As per the DFT-based spreading practice, we believe that DFT related identical size as IFFT is managed as a spreading code. Now, the multi-carrier OFDMA is same as the single-carrier FDMA (SC-FDMA) because the both transform (DFT) and inverse transform (IDFT) actions are almost canceled by each other. In this phenomenon, the cancellation converts multi-carrier system into single-carrier system. In OFDMA, the subcarriers can be split and allocated to multiple users correspondingly (let M). Unlike downlink transmission, each terminal transmits with its proper data via the set of subcarriers in uplink and rest of the subcarriers filled with zeros. In this case, M -pt DFT is managed for spreading and then followed to assigned to the IFFT subcarriers. The effect of diminishing PAPR rests on the way of conveying the subcarriers to each terminal. As represented in Fig. 1, there are two ways of subcarriers allocation among the users: DFDMA (distributed FDMA) and LFDMA (localized FDMA) [1, 2].

Fig. 1 Subcarrier mapping for uplink systems: DFDMA and LFDMA

Subcarrier mapping, in which the M samples at the output of the M -point FFT are mapped to the N subcarriers, is a key operation in SC-FDMA, a block representation of which can be seen in the SC-FDMA transmitter schematic in Fig. 3. The various possible SC-FDMA subcarrier mappings are illustrated through the following example. Consider $M=4$ SC-FDMA symbols and $N=12$ subcarriers. Let $x(0), x(1), x(2), x(3)$ denote the symbols and $X(0), X(1), X(2), X(3)$ denote the corresponding $M=4$ -point FFT samples which are to be loaded onto the subcarriers. Let the number of subcarriers be $N=12$ in interleaved FDMA (IFDMA) shown in Fig. 2, and the sample $X(i)$ is interleaved with zeros. In LFDMA, it is also employed in the uplink of the 4G mobile standard LTE. The samples are loaded as a block onto the subcarriers, with appropriate zero padding. This is shown in Fig. 2. Post this subcarrier mapping, the rest of the procedure prior to transmission proceeds as shown in the SC-FDMA transmitter block [2].

3 Performance factors

3.1 Bit error rate

Consider the OFDM subcarrier mechanism model. Therefore, the system model represents a standard Rayleigh fading channel of power gain L with receiver noise $N(k)$ of variance $N\sigma_n^2$. Therefore, the average SNR is $LP/N\sigma_n^2$. Hence, the BER is given by the standard expression for that of a Rayleigh fading wireless channel as

$$\text{BER}_{\text{OFDM}} = \frac{1}{2} \left(1 - \sqrt{\frac{LP/N\sigma_n^2}{2 + LP/N\sigma_n^2}} \right)$$

Fig. 2 SC-FDMA various sub-carrier mapping schemes

Fig. 3 Transmitter of companded-SC-FDMA system model

3.2 Peak-to-expected power ratio

It can be noted that the PAPR in an OFDM system is N , which is much greater compared to single-carrier system, which is 1. Further, interestingly, this power ratio rises with subcarriers N which is proportionally varied. This high power ratio, i.e., PAPR, occurs due to the IFFT processing. The symbols across the subcarriers can sum up to highest peak signal. For instance, in an OFDM with 512 subcarriers and BPSK, the PAPR is high 10 dB. The PAPR of an OFDM is characterized by the CCDF, i.e., the complementary CDF judges the behavior of PAPR. The CCDF $\bar{F}_x(x)$ of a random variable X is given as the probability that $X > x$ is expressed as

$$\bar{F}_x(x) = P(X > x)$$

Naturally, the CCDF is related to the CDF (CCDF = 1 – CDF), i.e., cumulative distribution function $F_x(x)$ of X as

$$F_x(x) = P(X \leq x)$$

$$= 1 - P(X > x) = 1 - \bar{F}_x(x)$$

The complementary CDF of the PAPR then shows the probability that the PAPR, which is a random quantity, exceeds a particular threshold [2, 4].

4 Proposed methodology

Generally companding means compressing at transmitter and expanding at receiver to recover the information without loss. The companding functions are categorized into linear and nonlinear functions which will affect on power amplifier property. Here, nonlinear companding is more sophisticated to implement the OFDMA and SC-FDMA.

4.1 Companded-OFDMA system model

4.1.1 μ -Law

A μ -law companding is popular in Europe and some other countries whereas μ -law companding is used more in the USA and Japan. μ -Law has higher dynamic range but at the cost of worse proportional distortion in small signals. The C_μ is companded signal that can be represented as

$$C_\mu = C(\tilde{x}) = \text{sgn}(\tilde{x})V \left(\frac{1 + \frac{\mu(\tilde{x})}{V}}{1 + \mu} \right)$$

The authors [7–9] investigate companding effects on the BER in the existence of AWGN channel by properly choosing companding coefficients. The higher-order

terms are smaller than first few terms and hence can be neglected.

4.1.2 Logarithmic function

Here the data $\tilde{x}_m$ are processed via compander $h(\tilde{x}_m)$ prior to adding CP. The companding scheme is described for minimizing the PAPR in SC-FDMA with logarithmic function has been used [10, 13]. This method improves performance of BER for conventional SC-FDMA. Moreover, it is quite simple which does not need any side data to be transmitted.

The governing equations are: The $C_{\log}$ log companding is expressed as

$$C_{\log} = h(\tilde{x}_m) = \log(k|\tilde{x}_m| + 1) \sin(\tilde{x}_m)$$

where k is +ve number which controls the quantity of companding.

The $D_{\log}$ log decompanding is given as

$$D_{\log} = h^{-1}(x'_m) = \left| \exp\left(\frac{|x'_m|}{k}\right) - 1 \right| \sin(x'_m)$$

4.1.3 Error function

Generally, SC-FDMA has lower PAPR in comparison with OFDMA due to less variation of signal in the former. Even then, there is pressing necessity to decrease PAPR in SC-FDMA systems. The new companding technique related to the error function to reduce PAPR in SC-FDMA in LTE uplink communication as well as to improve BER performance [11, 13]. The new error function companding envisages a scheme which is shown in the equations, where x_m is processed by compander earlier to CP. The inverse operation is carried out on the receiver side, and data r_m are passed through the decompander and then to M-point FFT.

Error companding function C_{erf} is based on the work of [9] and gives the companding as

$$C_{\text{erf}} = h(\tilde{x}_m) = 2\sigma \text{erf}\left(\frac{|\tilde{x}_m|}{\sqrt{2}\sigma}\right) \text{sgn}(\tilde{x}_m)$$

Here σ is the SD of $\tilde{x}_m$, $\text{erf}(\cdot)$ is the error function, and $\text{sgn}(x)$ is the signum function.

The corresponding error decompanding function D_{erf} is given by

$$D_{\text{erf}} = h^{-1}(x'_m) = \left| \sqrt{2}\sigma \text{erf}^{-1}\left(\frac{x'_m}{\sqrt{2}\sigma}\right) \right| \text{sgn}(x'_m)$$

The transformation profiles of error function represented as companding and decompanding in [9] are suggested.

4.1.4 Exponential companding

In contrast to μ -companding which ensures that only small signals are enlarged, thereby average power increased, companding schemes based on exponential method adjust both small and large signals keeping the average power at the same load. In this scheme, original OFDM signals are transformed into uniformly distributed up to certain value resulting in reduction of PAPR for various modulation and sizes of subcarriers. Moreover, μ -companding causes generation of spectrum side lobes which are reduced in case of exponential companding [10–14].

The companding function can be written as

$$h(x) = \text{sgn}(x) \sqrt[d]{\alpha \left[1 - \exp\left(-\frac{x^2}{\sigma^2}\right) \right]}$$

Here $\text{sgn}(x)$ is sign function, and α is constant which decides the mean power of output signals, to maintain the common mean power level, and it can be assumed as

$$\alpha = \left[\frac{E[|x|^2]}{E\left[\sqrt[d]{1 - \exp\left(-\frac{|x_n|^2}{\sigma^2}\right)}\right]^2} \right]^{d/2}$$

In the receiver side, the inverse function can be used decompanding as

$$h^{-1}(x) = \text{sgn}(x) \sqrt{-\sigma^2 \ln\left(1 - \frac{x^d}{\alpha}\right)}$$

where $d \geq 2$, and the $h(x)$ function suggested by [12] compresses huge signals and expands minor signals simultaneously. μ -Companding, on the other hand, can only enlarge small signals leading to higher average power levels of the output. It is also worth noting that for $d \geq 8$, difference among exponential function variables. Comparing with μ -companding, exponential scheme for $d=2$ offers much smaller BER. The required SNR under μ -companding and exponential companding is 16 dB and 12 dB, respectively [12, 14].

4.1.5 Trapezoidal companding

Uniformly distributed companding scheme cannot satisfy all the performance requirements, and to meet such

condition [15], a scheme is proposed based on trapezium distribution which provides satisfactory compromise of the PAPR and BER metrics.

Case i The companding function $C_{TC}(x_n)$ is to be written as

$$C_{TC}(x_n) = \frac{\sqrt{6}}{1-2q} \left(\sqrt{\frac{\sigma^2}{3-2q} \left(q^2 + (1-2q^2) \operatorname{erf} \left(\frac{y}{\sqrt{2}\sigma^2} \right) \right)} - q \sqrt{\frac{\sigma^2}{3-2q}} \right)$$

and decompanding $C_{TC}^{-1}(y_n)$ is to be written as

$$C_{TC}^{-1}(y_n) = \sqrt{2\sigma^2} \operatorname{erf}^{-1} \left(\frac{(3-q)y' \left((1-2ah_p)y' + 2q \frac{\sqrt{6\sigma^2}}{3-2q} \right)}{6\sigma^2} \right)$$

Overall, the trapezium scheme offers high ratio power reduction with little trade-off BER like uniformly distributed or piecewise, and parameter 'a' can be varied for Q-PSK or 16-QAM, AWGN channels to achieve the performance requirements [16].

Case ii The companding function is to be written as

$$= \operatorname{sgn}(x) \sqrt{\frac{\frac{k\alpha}{2} - \frac{1}{\alpha} - \sqrt{\left(\frac{1}{\alpha} - \frac{k\alpha}{2} \right)^2 + 2k \left(1 - \exp \left(\frac{|x|^2}{\sigma^2} \right) \right)}}{k}}, \quad k \neq 0$$

$$= \operatorname{sgn}(x_n) \sqrt{\alpha \left(1 - \exp \left(|x_n|^2 / \sigma^2 \right) \right)}, \quad k = 0$$

The decompanding function is to be written as

$$= \operatorname{sgn}(x_n) \sqrt{-\sigma^2 \ln \left(1 - \frac{1}{2} |x_n|^2 \left(k |x_n|^2 + \frac{2}{\alpha} - k\alpha \right) \right)}, \quad k \neq 0$$

$$= \operatorname{sgn}(x_n) \sqrt{-\sigma^2 \ln \left(1 - \frac{1}{2} |x_n|^2 \right)}, \quad k = 0$$

4.1.6 Novel companding

The novel companding proposed [17] can efficiently perform maximum-to-expected power ratio and error rate of transmitted OFDM signal. Furthermore, this new outline has a key feature of constant expected power level. The input symbols can be statistically independent and identically distributed over the system. By central limit, x_n be approximated as a Gaussian procedure and is complex when subcarriers are more (e.g., $N \geq 64$). The x_n is with '0' mean and variance ' σ^2 ', so its magnitude $|x_n|$ has a Rayleigh density and distribution function (CDF/PDF) given by [18], where $\operatorname{sgn}(x)$ indicates the sign function.

Case i Thus, the companding function can be formulated as

$$h(x) = x' \quad |x| \leq \sigma/\sqrt{6}$$

$$= \operatorname{sgn}(x) \sqrt{6\sigma} \left(\frac{2}{3} - \frac{1}{2} \exp \left(\frac{1}{6} - \frac{|x|^2}{\sigma^2} \right) \right) \quad |x| > \sigma/\sqrt{6}$$

The decompanding function is formulated as

$$h^{-1}(x') = x \quad |x| \leq \sigma/\sqrt{6}$$

$$= \operatorname{sgn}(x) \frac{\sigma}{6} \left(6 - 36 \ln \left(\frac{4\sigma - \sqrt{6}|x|}{3\sigma} \right) \right) \quad |x| > \sigma/\sqrt{6}$$

The PAPR of the novel scheme can be specified as follows:

$$\text{PAPR} = 10 \log_{10} \frac{\max |x_n'^2|}{E[X_n'^2]}$$

It portrays the profiles of exponential function, and novel companding outlines are observed in simulations. The scheme is offered better BER reduction than the exponential scheme but slightly more PAPR [17, 18].

Case ii The companding function can be formulated as

$$f(x) = \beta \operatorname{sgn}(x) [\operatorname{airy}(0) - \operatorname{airy}(\alpha|x|)]$$

$$\beta = \sqrt{\frac{E[|X|^2]}{E[|\operatorname{airy}(0) - \operatorname{airy}(\alpha|x|)|^2]}}$$

At the receiver side, the decompanding function can be formulated as

$$f^{-1}(x) = \frac{1}{\alpha} \operatorname{sgn}(x) \operatorname{airy}^{-1} \left[\operatorname{airy}(0) - \frac{|x|}{\beta} \right]$$

4.2 Companded-SC-FDMA system model

The above-specified six companding functions are applied to localized SC-FDMA (LFDMA), which are namely μ -law, logarithmic, error function, exponential, trapezoidal distribution and novel companding airy functions that are discussed. The companded-SC-FDMA has lower PAPR

when compared to companded-OFDMA, conventional SC-FDMA, OFDMA. But conceding the complexity for localized SC-FDMA with companding function, the modulation symbols are clustered into blocks, each covering with N symbols and followed N -point FFT. Then, the subcarrier mapping and M -point IFFT actions are performed [2, 4].

The FFT signal can be treated as

$$X_k = \sum_{n=0}^{N-1} X_n e^{-\frac{j2\pi}{N} kn} \quad k = 0, 1, \dots, N-1$$

The inverse FFT is performed as

$$\bar{x}_m = \frac{1}{M} \sum_{l=0}^{M-1} X_l e^{-\frac{j2\pi}{N} ml} \quad m = 0, 1, \dots, M-1$$

The resulting signal is applied through the companding function at the transmitter. The companded-SC-FDMA system model is represented as in Figs. 3 and 4.

The same companding functions are applied in OFDMA that also implements in SC-FDMA. These nonlinear companding functions are μ -law, logarithmic, error function, exponential function, trapezoidal, and novel companding functions result better than OFDMA to reduce the crucial metrics [10, 13]. The special function outperforms basic functions for their performance metrics. The SC-FDMA systems are optimized maximum to expected power ratio and compromising the error rate which is acceptable.

4.3 Equalization

The equalization schemes are briefly categorized into two FDE receivers, those are MMSE and ZF equalization. The detection procedure for k th user is only discussed in the coming sections.

- ZF equalizer:

$$W(k) = \frac{1}{H(k)} \quad k = 0, 1, \dots, N_{\text{FFT}} - 1$$

The ZF is equalizer which nulls the ICI and ISI. However, noise enhancement befalls, and the performance of this ZF equalizer is significantly affected by the noise effect.

- MMSE equalizer:

$$W(m) = \frac{H^*(m)}{|H(m)|^2 + (E_b/N_0)^{-1}} \quad m = 0, 1, \dots, N_{\text{FFT}} - 1$$

The MMSE is usually favored to the ZF equalizer owing to its better behavior to noise and always enhanced fall-outs [20].

4.4 Complexity

The receiver complexity increases when the equalizers are implemented in communication system; at the same time, the cost proportionality is also affected. So in order to reduce the receiver systems, the researchers developed without decompanding at the receivers stage, but it slightly increases the error rate. The decompanding function is at the receiver with and without usage of particular function the performance is observed in the simulations.

5 Performance evaluation

The simulation results describe metrics like PAPR and BER for OFDMA versus SC-FDMA based on companding functions. The modulations QAM order of 16 (16-QAM), oversampling factor $L=4$, number of subblocks $N=256$. Here, higher order says that performance changes some other metrics effected, those are PAPR and BER. The nonlinear companding functions are μ -law, logarithmic, error, exponential, trapezoidal, and novel companding functions are discussed and analyzed. From the μ -law, peak-to-average ratio decreases with $\mu=10,255$, but a bit error rate is effected and compared to μ -law the exponential companding is better. In the exponential function also the parameter ' d ' has good results when it is $d=2$, and also researchers say that $d=1$ to 8. The PAPR is inversely proportional to ' d ' and outbounds that it is rising the maximum level near $d=8$ for BER. The superiority of SC-FDMA has been established by the subcarrier mapping schemes that are shown in spreading of the input signal by processed by IFFT/IDCT, so that the PAPR of OFDM to

Fig. 4 Receiver of companded-SC-FDMA system model

single-carrier transmission application of this spreading has been presented for IFDMA and LFDMA.

The plots of BER versus SNR of OFDMA and SC-FDMA are shown that it might be worth for noting specific values of BER (10^{-3}). Both OFDMA and SC-FDMA have slightly variant SNR. It is observed that PAPR of SC-FDMA is marginally less than that OFDMA, whereas Q-PSK is better than 16-QAM. For BER, log-functions outperform with all discussed compandings for OFDMA and SC-FDMA, but it degrades the PAPR performance. For PAPR, exponential companding performs good among the all specified compandings for OFDMA as well as SC-FDMA and also switches well suited for BER.

Here, the OFDMA and LFDMA are analyzed with their superficial factors, power ratio and error rate which is completely discussed based on simulation parameters which are oversampling factor, subcarrier mapping, modulation scheme and type of companding used. The nonlinear companding function is applied at transmitter and decompanding at the receiver without affecting their performance, and meanwhile, the complexity behavior is also chosen better into consideration. The 16-QAM is preferable in this situation than QPSK to achieve the manageable considerations in LTE uplink communications. The simulation results declared that Airy function is chosen to better tradable than other companding functions.

5.1 Companded-OFDMA simulations

Figures 5 and 6 initiate exponential companding (EC) outperforms in PAPR in 16-QAM than existing techniques. But error companding is better in BER among all techniques with degrading PAPR. So exponential (EC) function

Fig. 5 PAPR analysis of companding functions (log, err, EC, TC, NC functions) with 16-QAM, subcarriers $N=128$, oversampling factor $L=8$ (OFDMA)

Fig. 6 BER analysis of companding functions (log, err, EC, TC, NC functions) with 16-QAM, subcarriers $N=128$, oversampling factor $L=8$ (OFDMA)

performs well in trade-off the PAPR and BER for OFDMA (Figs. 7, 8).

5.2 Companded LFDMA simulations

Figures 9 and 10 initiate exponential companding (EC) outperforms in PAPR in 16-QAM than existing techniques. But logarithmic companding is better in BER among all techniques with degrading PAPR. So EC function performs well in trade-off the PAPR and BER for LFDMA.

In Table 1, exponential companding outperforms at $d=2$ than μ -companding at specific μ also is not

Fig. 7 PAPR analysis of μ -companding ($\mu=10$ & 255) and EC-companding function ($d=1$ and 2) with 16-QAM, subcarriers $N=512$, oversampling factor $L=8$ (LFDMA)

Fig. 8 BER analysis of μ -companding ($\mu=10$ and 255) and EC function ($d=1$ and 2) with 16-QAM, subcarriers $N=512$, oversampling factor $L=8$ (SC-FDMA)

Fig. 10 BER analysis of companding functions (log, err, EC, TC, NC functions) with 16-QAM, subcarriers $N=512$, oversampling factor $L=8$ (SC-FDMA)

Fig. 9 PAPR analysis of companding functions (log, err, EC, TC, NC functions) with 16-QAM, subcarriers $N=512$, oversampling factor $L=8$ (SC-FDMA)

acceptable even in the PAPR or BER consideration for localized FDMA than OFDMA. But PAPR is negligibly less in exponential function than in μ -function. In Table 2, the exponential companding outperforms the other companding functions logarithmic (log), error (erf), exponential (EC), trapezoidal (TC), novel companding (NC) functions which are less preferable for LFDMA than OFDMA. But logarithmic function is better in BER among the other functions.

Table 1 PAPR and BER for μ -function and EC function based on decompanding

Technology	Type	μ -Function		EC function	
		$\mu=10$	$\mu=255$	$d=1$	$d=2$
LFDMA	PAPR in dB	4.438	2.141	4.480	2.752
	BER	With decompanding at receiver			
		0.0795	0.1318	0.0588	0.0608
		Without decompanding at receiver			
OFDMA	PAPR in dB	5.500	2.600	5.260	3.380
	BER	With decompanding at receiver			
		0.0384	0.2316	0.1253	0.1285
		Without decompanding at receiver			
		0.0995	0.1819	0.1104	0.1314

6 Conclusion

This paper designates companding functions suitable for PAPR reduction in OFDMA/SC-FDMA covering specifically on μ -law, logarithmic, error function, exponential, trapezoidal distribution as well as the novel airy function. Greater emphasis has been given to localized subcarrier mapping for SC-FDMA (LFDMA). It has been found that exponential function has the best performance; however, as a parameter ' d ' varies, the metrics such as PAPR and BER change necessitating a novel companding function. In this paper, a novel airy companding function has been proposed for reducing PAPR and BER to trade-off among metrics. The BER at the receiver remains almost

Table 2 PAPR and BER for proposed companding with existing functions

Technology	Type	Proposed function with existing companding functions at CCDF = 10^{-3} , SNR = 15 dB				
		log	erf	EC	TC	NC
LFDMA	PAPR in dB BER	4.610	3.854	3.393	6.490	3.967
		With decompanding at receiver				
		0.0008	0.2704	0.0430	0.7409	0.1864
		Without decompanding at receiver				
		0.0012	0.0566	0.1212	0.7604	0.0751
		6.389	4.471	4.045	5.743	4.645
OFDMA	PAPR in dB BER	6.389	4.471	4.045	5.743	4.645
		With decompanding at receiver				
		0.2533	0.1108	0.0679	0.2541	0.1919
		Without decompanding at receiver				
		0.0168	0.1092	0.1207	0.2532	0.0169

unaffected and independent despite decompanding or not. However, to reduce the complexity of receiver, decompanding is almost not preferable and the airy function outperforms the other in LFDMA and OFDMA case. Finally, it concludes that exponential function is better for considering decompanding when airy function is not mostly preferable. The further work can be extended through probabilistic techniques, and hybrid techniques via probabilistic techniques are combining the companding functions may achieve good features.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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