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Spectrally Efficient Enhanced PAM-OFDM Based on RF Wireless Communication System

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Keywords:
ePAM-OFDM; PAM-OFDM; QAM-OFDM; Spectral Efficiency; Energy Efficiency; BER.

Highlights:
- *Spectral efficiency enhancement by using ePAM-OFDM in RF communication Systems.*
- *The performance of ePAM-OFDM over AWGN and Rayleigh Fading Channels has been investigated.*
- *Energy Efficiency improvements for ePAM-OFDM.*

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Abstract: An efficient modulation scheme called enhanced pulse amplitude modulation based orthogonal frequency division multiplexing (ePAM-OFDM) is proposed in this paper. It has been proved that clipping and simple reordering, the half-length of the PAM-OFDM time domain signal is enough to carry all the information. This idea allows for increasing spectral efficiency (SE) by (100%) when compared with PAM-OFDM and quadrature amplitude modulated biased OFDM (QAM-OFDM) for the same modulation order. Moreover, the proposed scheme has an improved energy efficiency compared to spectrally equivalent PAM-OFDM, and it reduces the transmitted energy by half compared to QAM-OFDM when the comparison is set at the same spectral efficiency. Hence, ePAM-OFDM can relatively close the gap in performance between PAM-OFDM and QAM-OFDM scheme. The comparisons of these schemes are explored by theoretical analysis and computer simulations over additive white Gaussian noise AWGN and Rayleigh fading channels.

تقنية PAM-OFDM المحسنة ذات الكفاءة الطيفية القائمة على نظام الاتصالات اللاسلكية RF

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الخلاصة

في هذه الورقة، تم اقتراح مخطط تعديل فعال يُسمى تعديل سعة النبضة المُحسَّن القائم على تقسيم التردد المتعامد (ePAM-OFDM). وقد ثبت أن القص وإعادة الترتيب البسيط ونصف طول إشارة المجال الزمني لـ PAM-OFDM يكفيان لحمل جميع المعلومات. تسمح هذه الفكرة بزيادة الكفاءة الطيفية (SE) بنسبة (١٠٠٪) عند مقارنتها بـ PAM-OFDM و OFDM المُتحيز بتعديل سعة التربيع (QAM-OFDM) لنفس ترتيب التعديل. علاوة على ذلك، يتميز المخطط المقترح بكفاءة طاقة مُحسَّنة مقارنةً بـ PAM-OFDM المكافئ طيفيًا، ويُقلل الطاقة المُرسلة بمقدار النصف مقارنةً بـ QAM-OFDM عند ضبط المقارنة على نفس الكفاءة الطيفية. وبالتالي، يُمكن لـ ePAM-OFDM سد الفجوة في الأداء بين مخططي PAM-OFDM و QAM-OFDM نسبيًا. يتم استكشاف المقارنات بين هذه المخططات من خلال التحليل النظري والمحاكاة الحاسوبية على قنوات الضوضاء الغوسية البيضاء المضافة AWGN وتلاشي رايلي.

الكلمات الدالة: ePAM-OFDM، PAM-OFDM، QAM-OFDM، الكفاءة الطيفية، كفاءة الطاقة، معدل البتات (BER).

1.INTRODUCTION

The dramatic growth of wireless communication applications and the increasing demand for ubiquitous services represent the main driving force to call for more spectrally and energy efficient schemes [1-3], since energy efficiency (EE) and spectral efficiency (SE) are of utmost significant parameters which ensure the quality of service. EE refers to the transmission of reliable information with an optimum energy rate. While, SE describes the amount of transmitted information over a finite bandwidth [4-6]. Actually, the EE-SE trade-off is always detailed by researchers and reports. It is admitted that in order to maximize one, the other will be reduced [7, 8]. Previous works indicated that to enhance EE, transmit and circuit powers should be minimized [9-11]. Such an approach seems to be successful when it determines SE. The focus on maximizing SE resulted in the development of many technologies such as OFDM, which is one of the most significant multicarrier modulation schemes. The competence of OFDM arises from the ability to transmit data in orthogonal parallel channels [12-14]. Typically, different data modulation schemes can be employed with OFDM, such as PAM, QAM, or phase-shift keying (PSK), with relative success depending on the targeted application [8, 15]. In point of fact, their performance can significantly vary according to which system parameters are considered such as bit error rate (BER), data rate, system complexity, interference robustness or maximum transmit power with respect to channel capacity and transceiver distance [16-18]. For instance, when minimum complexity is targeted, and the system is highly sensitive to phase noise, M-PAM modulation would be the best choice. While, if interference robustness and power efficiency are the parameters to consider with a low bit rate, BPSK, and QPSK can be the best candidates [17, 19]. On the other hand, M-QAM helps maximize the data rates transmitted over the wireless channels with reduced transmitted power compared to the mentioned schemes. However, it is very sensitive to channel estimation and in-phase and quadrature-phase (I/Q) imbalance is one of the major problems associated with direct conversion transceivers [7, 19, 20]. To sum up, in terms of high bit rate schemes, PAM brings simplicity at the cost of power inefficiency, while QAM suffers from modulation/demodulation complexity, but is highly power efficient [13, 21, 22]. In this work, a modified modulation scheme, ePAM-OFDM, is presented, which brings the advantages of QAM and PAM schemes at the same time. That is, it satisfies the modulation/demodulation simplicity of PAM and the energy efficiency of QAM since the average energy per bit of ePAM-OFDM is reduced by half compared to the QAM-OFDM for the same spectral efficiency. These improvements can be quickly deduced from the fact that transmitting only half of the PAM-OFDM samples is sufficient for conveying all the data, which results in a twofold increment in the bit rate of e PAM-OFDM without bending the spectrum. This paper is arranged as follows. Section 2 presents the concept of ePAM-OFDM and its theoretical analysis. Spectral and energy efficiency derivatives are presented in section 3. A detailed performance comparison between PAM-OFDM and QAM-OFDM is provided for validation purposes in section 4. Finally, section 5 summarizes the findings of this paper.

2.SYSTEM DESCRIPTION OF EPAM-OFDM

The block diagram of the ePAM-OFDM system is shown in Fig 1. The OFDM time-domain signal generated by inverse fast Fourier transform (IFFT) with a length of N is written as [23]:

$$x(n)=\frac{1}{N}\sum_{K=0}^{N-1}X[K]e^{\frac{2\pi jkn}{N}}\quad k=0,1,2,\ldots,N-1 \qquad (1)$$

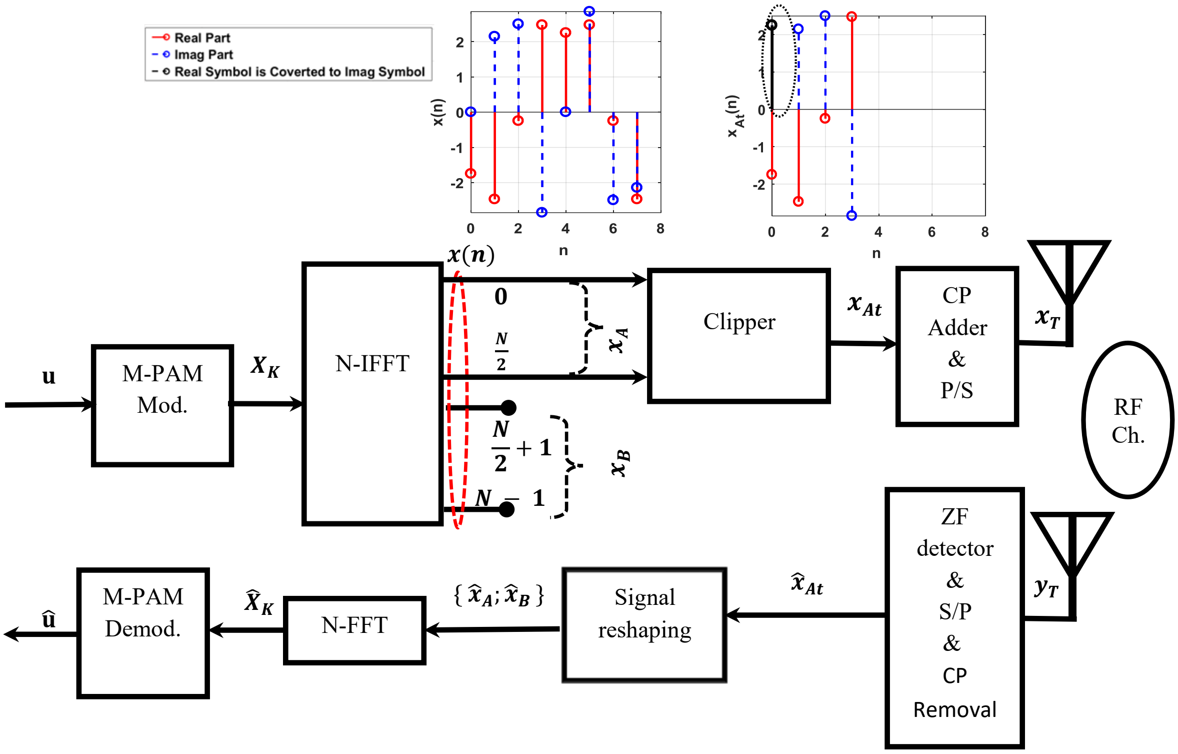

Fig. 1 ePAM -OFDM System Diagram.

where $X[k]$ are pulse-amplitude modulated symbols; $x(n) = a_n \pm jb_n$ is time domain signal. In Fig. 1, it can be seen that $x(n)$ exhibits an anti-symmetry; since the imaginary parts of both ($x[0]$ and $x[N/2]$) are equal to zero, and $a_n \pm jb_n = a_{n-N} \mp (jb_{n-N})$. In effect, clipping away x_B will not discard any useful data, as the same information can be recovered from x_A. The fact of Imaginary of ($x[0]$) and $\left(x\left[\frac{N}{2}\right]\right)$ are zeros allows to make a plain reordering to get an OFDM sample of length ($\frac{N}{2}$) instead of ($\frac{N}{2}$ + 1) .Simply, real parts of ($x[0]$) and $\left(x\left[\frac{N}{2}\right]\right)$ are combined as x [0] = $a_0 + ja_{N/2}$ and carried by 1st sample order as shown in x_{At}. Then, it is easy to note that the length of the ePAM-OFDM signal is reduced by exactly half compared to the original PAM-OFDM signal. Hence, ePAM-OFDM can transmit two OFDM signals simultaneously. The signal is passed through a wireless communication channel. Rayleigh fading channel model is a very common multipath fading channel model with Non-Line-of-Sight (NLOS) signal propagation components. It is described through impulse response h(t):

$$\boldsymbol{h(t) = \sum_{b=0}^{B-1} a_b\, e^{j\theta_b} \delta(t-\tau_b)} \quad \textbf{(2)}$$

$$\boldsymbol{y(t) = x_T * h(t)} \quad \textbf{(3)}$$

where B is the number of multipath component receivers, a_b is the amplitude of b^{th} multipath component, τ_b is propagation delay, θ_b is a signal phase. Once $y(t)$ is received, the zero forcing equalizer is applied to estimate the transmitted signal. When $\hat{\boldsymbol{x}}_{At}$ is estimated the coefficients of $\hat{\boldsymbol{x}}_{At}(0)$ are rearranged to take their original place. Afterwards, reconstruction of the clipped away samples can easily be achieved by flipping the conjugate of the received signal, for $1 \le n \le \frac{N}{2} - 1$. Finally PAM-OFDM signal demodulation is applied to get the original transmitted one. When demodulating this way, the noise effect is increased due to recovered clipped samples, and the signal-to-noise ratio (SNR) which is known as the basis of BER performance becomes:

$$\boldsymbol{SNR_{ePAM\_OFDM} = \frac{E_b}{2N_o}} \quad \textbf{(4)}$$

where E_b denotes the average bit energy, and N_o represents the energy density of the noise. Based on the BER performance derivative of PAM-OFDM introduced in [24], the BER performance of ePAM-OFDM under AWGN and Rayleigh fading channel can be expressed as:

$$\boldsymbol{P_b(SNR)_{AWGN} = \frac{1}{log_2\,(M)} \sum_{m=1}^{M-1} C_m^M\, erfc\left((2\,m - 1)\sqrt{\mu_\rho\, SNR_{ePAM\_OFDM}}\right)} \quad \textbf{(5)}$$

$$\boldsymbol{P_b(SNR)_{Rayleigh} = \frac{1}{log_2\,(M)} \sum_{m=1}^{M-1} C_m^M \left(1 - \sqrt{\frac{\left(\sqrt{2}\left((2\,m-1)\sqrt{\mu_\rho\, SNR_{ePAM\_OFDM}}\right)\right)^2}{2+\left(\sqrt{2}\left((2\,m-1)\sqrt{\mu_\rho\, SNR_{ePAM\_OFDM}}\right)\right)^2}}\right)} \quad \textbf{(6)}$$

where $\mu_\rho = \frac{3\log_2(M)}{(M^2-1)}$, M is the constellation size, and C_m^M coefficients are shown by Table 1 of [24].

3.SPECTRAL AND POWER EFFICIENCY

The spectral efficiency of PAM-OFDM and QAM-OFDM schemes can be almost described in (bps/Hz) as [25]:

$$\eta \approx \log_2 M \quad (7)$$

Since in the proposed ePAM-OFDM, half of the time domain signal is enough to carry the intended information, the spectral efficiency of ePAM-OFDM η_{ePAM} is calculated by the following:

$$\eta_{ePAM} \approx 2 \times \log_2 M = \log_2 M^2 \quad (8)$$

Hence, the spectral efficiency gain α_η of ePAM-OFDM over PAM-OFDM or QAM-OFDM when applied at the same M can be expressed as:

$$\alpha_\eta = \frac{\eta_{ePAM}}{\eta} = 2 \quad (9)$$

Hence, the proposed scheme ePAM-OFDM can achieve the same spectral efficiency of PAM-OFDM or QAM-OFDM by reduced constellation size as derived bellow:

$$M \approx 2^{\eta} \quad (10)$$

$$M_{ePAM} \approx 2^{\left(\frac{\eta}{2}\right)} \quad (11)$$

where M_{ePAM} is the constellation order required by ePAM-OFDM to archive the same spectral efficiency η obtained by PAM-OFDM and QAM-OFDM schemes. From Eqs. 9 and 10:

$$M = M_{ePAM}^2 \quad (12)$$

From all above, we conclude that the proposed ePAM-OFDM effectively reduces the consumed average energy per bit compared to PAM-OFDM and QAM-OFDM, from [25]:

$$E_{PAM\_OFDM} = \frac{M^2-1}{6\,log_2(M)} \cdot \varepsilon_g \quad (13)$$

$$E_{QAM\_OFDM} = \frac{M-1}{3\,log_2(M)} \cdot \varepsilon_g \quad (14)$$

$$E_{ePAM\_OFDM} = \frac{M_{ePAM}^2-1}{6\,(2\times log_2(M_{ePAM}))} \cdot \varepsilon_g \quad (15)$$

where E is the average energy per bit in (joule /bit), and- ε_g is the energy of the signal pulse shape g(t). Substituting Eq. 11 in Eqs. 12 and 13 gives:

$$E_{PAM\_OFDM} \frac{M_{ePAM}^4-1}{6\,log_2(M_{ePAM}^2)} \cdot \varepsilon_g \quad (16)$$

$$E_{QAM\_OFDM} = \frac{M_{ePAM}^2-1}{3\,log_2(M_{ePAM}^2)} \cdot \varepsilon_g \quad (17)$$

Dividing 14 by 15 and 16 gives:

$$\alpha_{EP} = \left(1 - \frac{E_{ePAM\_OFDM}}{E_{PAM\_OFDM}}\right) \times 100\,\% = \left(\frac{2^{2\eta}-2^{\eta}}{2^{2\eta-1}}\right) \times 100\,\% \quad (18)$$

$$\alpha_{EQ} = \left(1 - \frac{E_{bavg}(ePAM)}{E_{bavg}(QAM)}\right) \times 100\,\% = \left(1 - \frac{1}{2}\right) \times 100\,\% = 50\,\% \quad (19)$$

where, α_{EP} and α_{EQ} indicate the energy saving factor of the proposed system over PAM-OFDM and QAM-OFDM respectively. Finally we can sum up the most relevant parameters in Table 1.

Table 1 Comparisons of Spectral Efficiency and Average Power for different Schemes.

Modulation scheme	Spectral Efficiency (η)	Average energy per bit
ePAM-OFDM	$\log_2 M^2$	$\frac{M_{ePAM}^2-1}{6\,(2\times log_2(M_{ePAM}))} \cdot \varepsilon_g$
PAM-OFDM	$\log_2 M$	$\frac{M^2-1}{6\,log_2(M)} \cdot \varepsilon_g$
QAM-OFDM	$\log_2 M$	$\frac{M-1}{3\,log_2(M)} \cdot \varepsilon_g$

4.SIMULATION RESULTS

In this part, the performance of the proposed ePAM-OFDM was investigated and compared with PAM-OFDM and QAM-OFDM at different constellation sizes. The simulation was employed over two-types of channels: a more general AWGN channel, and a 5-tap Rayleigh fading channel. The number of subcarriers was 128. Since the spectral efficiency of ePAM-OFDM was double than the SE of PAM-OFDM or QAM-OFDM as given in Fig. 2, M-ePAM-OFDM should be compared with the M^2-PAM-OFDM and M^2-QAM-OFDM, e.g., 4 ePAM-OFDM should be compared with 16 QAM-OFDM, and 16 PAM-OFDM, etc. Fig. 3 and Fig. 4 depicted simulation results where the performance of ePAM-OFDM, PAM-OFDM, and QAM-OFDM were compared over an AWGN channel and a Rayleigh fading channel respectively, at forward error correction (FEC) threshold at 3.8 e−3. It is clear that for all the presented cases, the BER performance of ePAM-OFDM surpassed the BER performance of PAM-OFDM for the same SE. The performance improvements of ePAM-OFDM over PAM-OFDM started at 4 dB and 2.4 dB under AWGN and Rayleigh fading channels, respectively at spectral efficiency η = 2 bps /Hz. While at η = 3 bps /Hz, the energy gain of ePAM-OFDM increased to 11.5 dB under AWGN and 8.7 dB at Rayleigh fading channel. It was interesting to note that for higher constellation sizes, ePAM-OFDM became more energy efficient. The savings in SNR reached about 17.1 dB and15 dB at the AWGN channel and Rayleigh fading channel respectively, at η = 4 bps /Hz. Typically, the M-PAM and M^2-QAM have identical BER curves; hence, it was expected to get congruent curves for ePAM-OFDM and QAM-OFDM at the same spectral efficiency. However, this is not the case. It turned out from Fig. 3 and Fig. 4 that for all the given curves, the energy loss of M-ePAM-OFDM was still 3 dB when compared with M-QAM-OFDM as a consequence of the additional detection of time domain clipped samples. The performance of the theoretical model was drawn along with Monte Carlo simulations in Fig. 5 and Fig. 6 for AWGN and Rayleigh fading channels respectively. It was verified that the presented model was identical to simulations that were conducted.

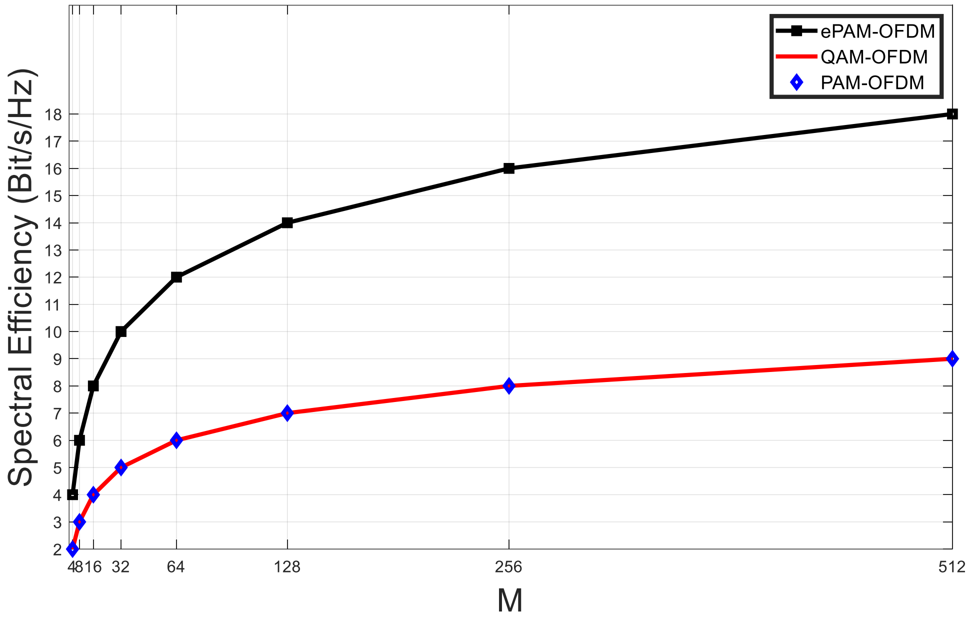

Fig. 2 Spectral Efficiency for ePAM-OFDM, PAM-OFDM, and QAM -OFDM, Versus different Modulation Orders.

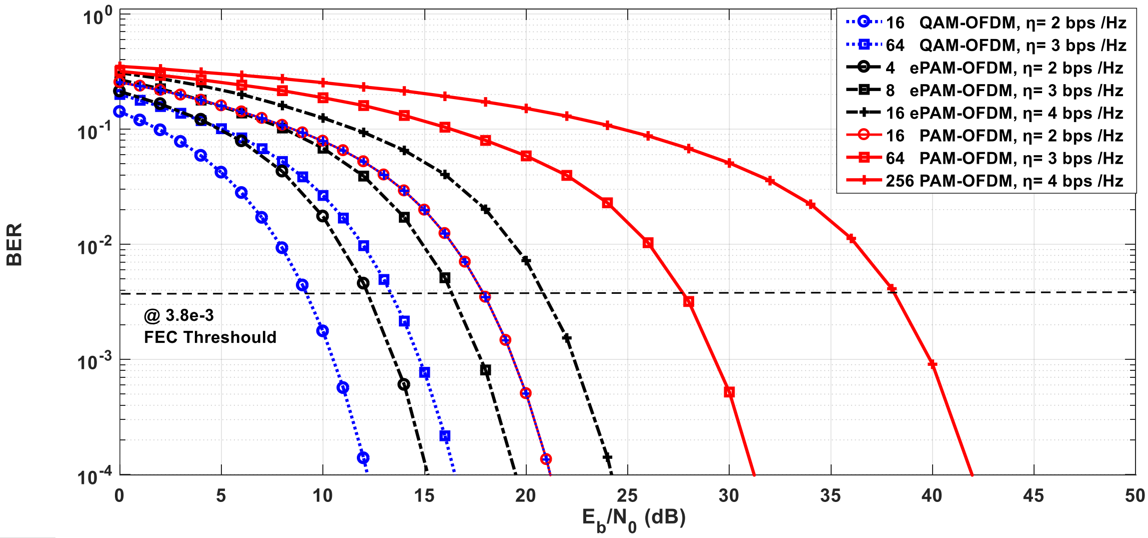

Fig. 3 BER Performance of ePAM-OFDM, PAM-OFDM, and QAM-OFDM under an AWGN Channel.

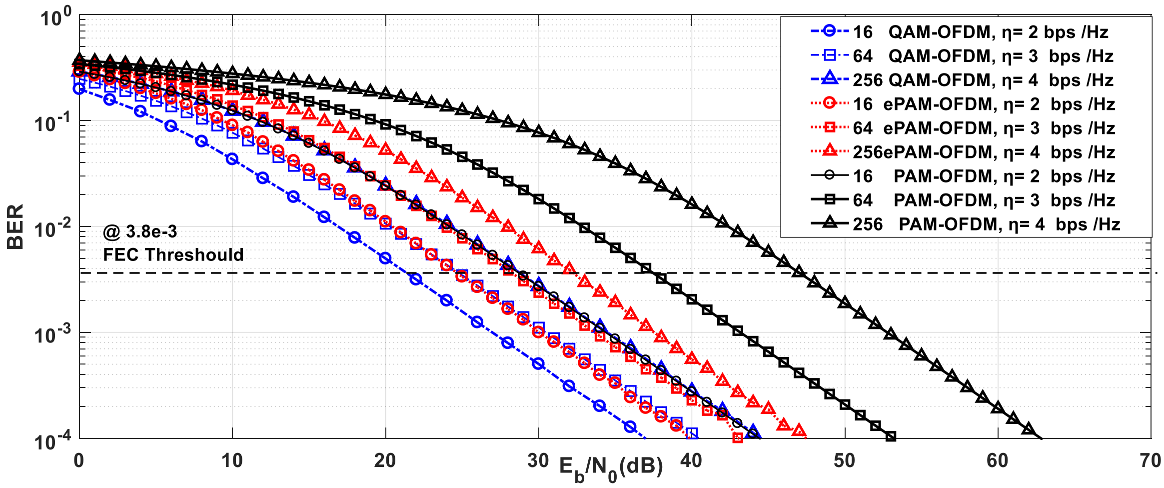

Fig. 4 BER Performance of ePAM-OFDM, PAM-OFDM, and QAM-OFDM under a Rayleigh Fading Channel.

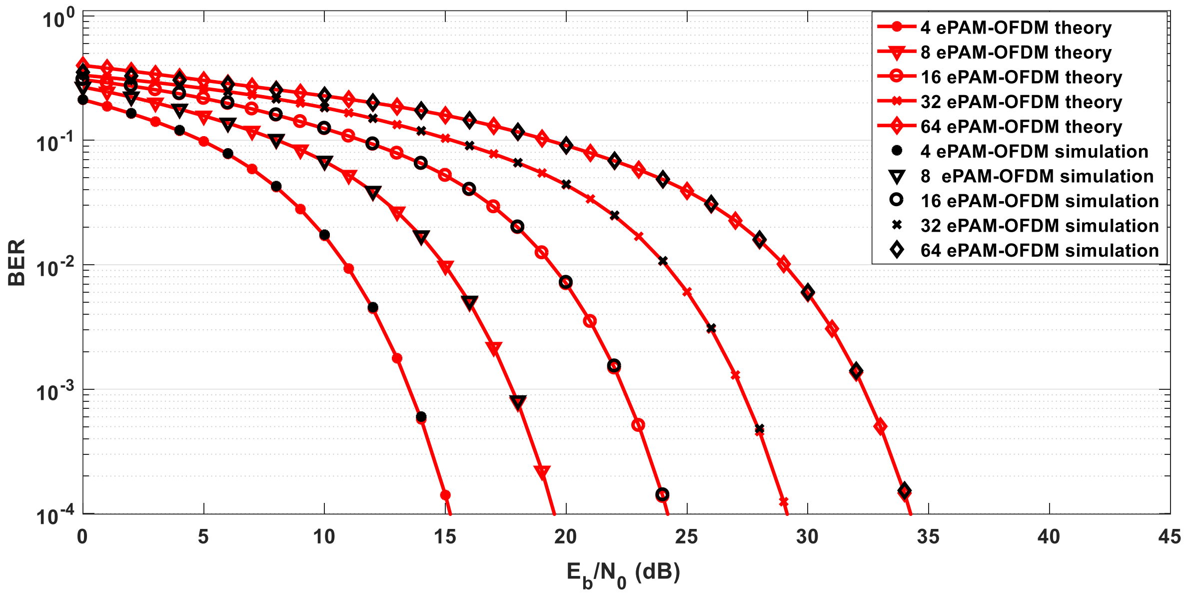

Fig. 5 Theoretical Performance vs. Simulations ePAM-OFDM in an AWGN Channel.

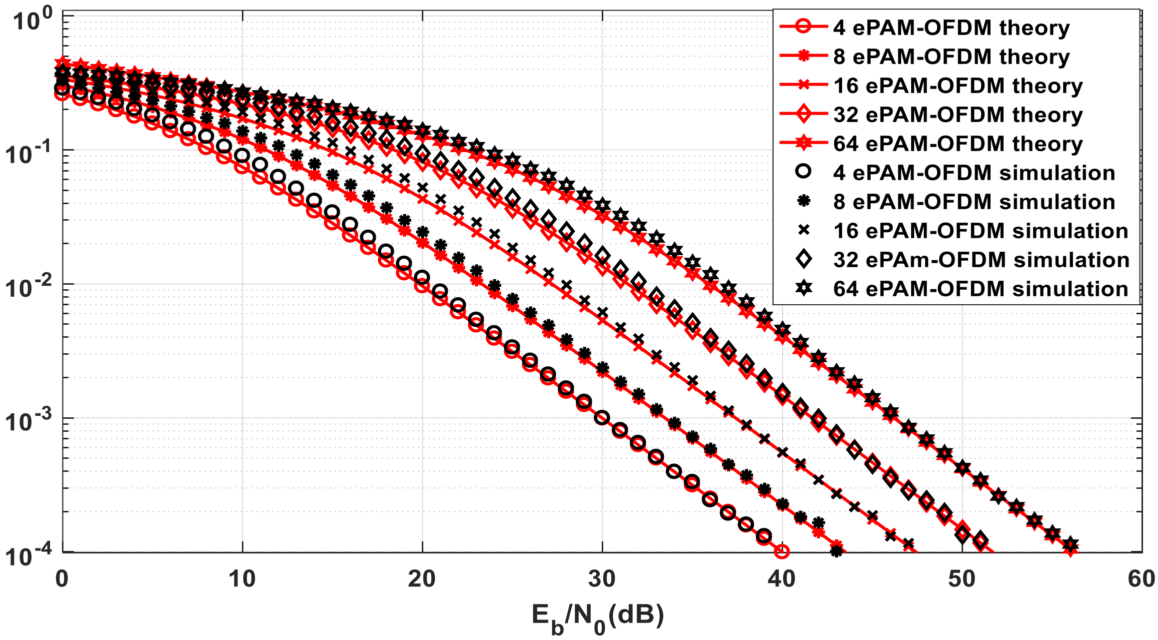

Fig. 6 Theoretical Performance vs. Simulations ePAM-OFDM in a Rayleigh Fading Channel.

5.CONCLUSION

This work proposes an efficient enhanced modulation scheme for wireless communication systems called ePAM-OFDM. The proposed scheme can achieve a twofold increase in spectral efficiency compared to existing RF modulation schemes such as PAM-OFDM and QAM-OFDM. Moreover, the proposed ePAM-OFDM can achieve the same SE as the previously mentioned schemes at lower modulation orders; therefore, it can highly save the transmitted power. Theoretical results show that the saving energy factor of ePAM-OFDM is always 50% over QAM-OFDM, while it is 99% over PAM-OFDM at SE ≥ 7bps/Hz. Simulation results prove that ePAM-OFDM outperforms the PAM-OFDM scheme in terms of BER performance. However, in all the presented cases, the energy loss of M-ePAM-OFDM is still 3 dB compared to M-QAM-OFDM due to the additional noise of clipped sample detections. Significant BER performance improvements are noted at higher spectral efficiencies, such as at SE = 4 bps/Hz, the ePAM-OFDM requires 20.8 dB of SNR instead of 38 dB over AWGN. At the same time, ePAM-OFDM saves 15 dB of energy over Rayleigh fading channels. Thus, it demonstrates its potential application in high-speed RF systems.

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