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# Enhanced Performance of Amplify and Forward Cooperative OFDM System in a Hostile Environment

**Hussein A. Leftah**

Electrical Power Department, Basra Engineering Technical College (BETC), Southern Technical University, Basrah/ Iraq

## Abstract

This paper introduces a cooperative orthogonal frequency division multiplexing (CO-OFDM) based on amplify and forward (AF) relay and utilizing a fast low complexity T-transform as a subcarriers modulation scheme. The proposed cooperative system is developed by changing the modulation/demodulation algorithms which significantly enhanced the immunity of the system to deep notches of the multipath channels. Thereafter, the paper presents a mathematical analytic model for the proposed amplify and forward CO-T-OFDM scheme. The use of T-transform in the transceiver of the proposed system enhances the signal diversity. Therefore, the presented AF cooperative system is efficient in enhancing the signal diversity, mitigating the effects of multipath fading channels and achieving more reliable bit-error-rate (BER) performance than the state-of-the-art cooperative system. It also moderates the peaks power of the signal. The BER of the developed AF cooperative system is evaluated by Monte Carlo simulation over frequency-selective multipath channels when AF relay is used, and compared with the BER performance of the standard AF cooperative system. The results show that the developed AF cooperative technology achieves better BER than the classic CO-OFDM under different transmission scenarios.

***Keywords:*** Cooperative OFDM (CO-OFDM), Bit error rate (BER), Amplify and forward (AF), Signal-to-noise ratio (SNR), Zero-Forcing equalizer (ZF).

## 1. Introduction

Relays in cooperative systems have been recognized as an effective technique that provides the required quality of service to the users in next generation wireless systems **[1]**, **[2]** and **[3]**. This is owing to the exceptional characteristics of cooperative systems in extending the coverage of wireless network and enhancing systems resiliency to multipath channels **[4]** and **[5].** With increased reliance on wireless cellular communications, cooperative systems are constantly being developed to further increase the diversity of transmitted symbol, simplify channel equalization and mitigate the inter symbol interference (ISI) between following after transmitted symbols.

Recently, the orthogonal frequency division multiplexing (OFDM) is used in the cooperative technology to produce a scheme that is frequently known as CO-OFDM. It combines the popular characteristics of the both systems **[6]-[8].** The produced CO-OFDM system is efficient in enhancing the signal diversity, avoiding the ISI and reducing the complexity of channel equalization where simple equalizer is employed in the CO-OFDM system. However, the OFDM has some drawbacks, for instance, deep notches in channel transfer function of frequency selective multipath channel, which needs to be alleviated. The channel dips in the spectrum of multipath channel can cause signal level falls below the noise level on some specific subchannels and ultimately causing data lost.

In this paper, we utilize the T-transform which is presented by Boussakta **[9]**, in the modulation/demodulation of the transceiver of cooperative system to produce a new cooperative scheme called CO-T-OFDM. Beside the ISI mitigation and channel equalizer simplification, the proposed amplify and forward CO-T-OFDM scheme provides a certain improvement in complexity and peak-to-average power ratio (PAPR) reduction and multipath resilient. The proposed CO-T-OFDM is superior to the standard AF cooperative scheme in the BER performance over a several transmission scenarios; distinct channel models, symbol mapping and ZF and MMSE equalizers. The number of mathematical operations required in the developed cooperative system is fewer than that of the standard CO-OFDM. This is owing to the new modulation/demodulation technique in the transceivers of the presented system.

Briefly, the contribution of this paper is

- Proposing a developed amplify and forward (AF) cooperative system with an efficient modulation scheme in the transceivers instead of the state-of-the-art fast Fourier transform.
- Derive a mathematical model for the proposed AF cooperative system.
- Using Monte Carlo simulation to perform the proposed AF cooperative scheme and compared it with the classic AF cooperative system over different

transmission scenarios.

- Unlike the state-of-the-art cooperative system, the presented system is found to be efficient in reducing the effects of multipath phenomena even over a multipath channels with a deep notches.
- The proposed AF cooperative scheme is also has the superiority of having lower PAPR in comparison to the standard AF cooperative system.

The reminder of this paper is arranged as: Section 2 presents the T-transform. Section 3 presents the modulation model of the developed system. The transmission system model analysis of the proposed cooperative system with amplify and forward relay is given in section 4. Section 5 shows the advantage of developed scheme in the PAPR reduction. The results and, discussion are presented in section 6 and.

## 2. T-Transform

The T-transform is first developed in **[9]**. The Walsh-Hadamard transform (WHT) can be expressed as

$$\Pi_N = \begin{bmatrix} \Pi_{\frac{N}{2}} & \Pi_{\frac{N}{2}} \\ \Pi_{\frac{N}{2}} & -\Pi_{\frac{N}{2}} \end{bmatrix} \quad (1)$$

On the other hand the inverse DFT ($F_N^h$) can be written as

$$F_N^h = \begin{bmatrix} \varpi_{\frac{N}{2}} & \varpi_{\frac{N}{2}} \\ W_{\frac{N}{2}} & -W_{\frac{N}{2}} \end{bmatrix} \quad (2)$$

where $(.)^h$ is the Hermitian conjugate. Consequently, the ITT can be expressed as

$$T_N^h = \begin{bmatrix} 2\varpi_{\frac{N}{2}}\Pi_{\frac{N}{2}} & 0 \\ 0 & -2W_{\frac{N}{2}}\Pi_{\frac{N}{2}} \end{bmatrix} \quad (3)$$

,where T-transform of length N is written as **[10]**

$$T^h = \frac{N}{2}\begin{bmatrix} \frac{N}{2}\varpi_2\pi_2 & 0 & 0 & \dots & 0 & 0 \\ 0 & \frac{N}{2}W_2\pi_2 & 0 & \dots & 0 & 0 \\ 0 & 0 & \frac{N}{4}W_4\Pi_4 & & 0 & 0 \\ \ddots & \ddots & \ddots & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 4W_{\frac{N}{4}}\Pi_{\frac{N}{4}} & 0 \\ 0 & 0 & 0 & \cdots\ 0 & 2W_{\frac{N}{2}}\Pi_{\frac{N}{2}} \end{bmatrix} \quad (4)$$

## 3. Modulation System Module

The system block diagram of the enhanced AF cooperative scheme that utilizes the proposed modulation technology is given in Fig. 1.

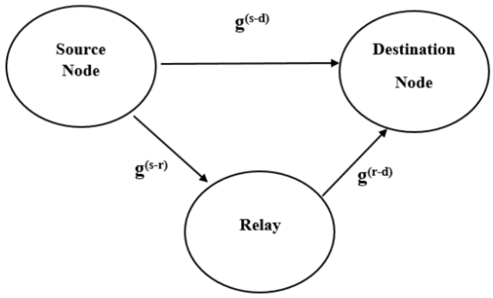



Fig. 1 The AF cooperative System block diagram.

We deal with a block data transmission based on the T-transform as a modulation scheme. The developed cooperative scheme could use any kind of data mapping, however, two types of data mapping, QPSK and 16-QAM in this research paper to explain the benefit of the presented cooperative system over the conventional one. The binary data set, $\chi$, are firstly mapped to M-QAM or M-PSK symbols which modulate N subcarriers to construct a signal,

$$\chi = \begin{bmatrix} \chi_{1,0} & \chi_{1,1} & \cdots & \chi_{1,N-1} \\ \chi_{2,0} & \chi_{2,1} & \cdots & \chi_{2,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ \chi_{m,0} & \chi_{m,1} & \cdots & \chi_{m,N-1} \end{bmatrix} \quad (5)$$

where $\chi_{p,q} \in \{0, 1\}$. Either PSK or QAM mapping exploits each column in $\chi$ to perform the data symbols information vector $x = [x_0, x_1, \cdots, x_{N-1}]^T$.

The data symbols of *N* subcarriers. Each neighboring subcarriers are orthogonal in phase. As a result of orthogonality, the subcarriers will not overlapped with each one another. As a result, the OFDM can utilize the bandwidth efficiently. The orthogonal basis are produced by the T-transform. These basis carry the information symbols with enhanced diversity. Let the information symbols, $x^T = [x_0, x_1, ..., x_{N-1}]$, are processed by the T-transform as

$$S = T^h x \quad (6)$$

Hence a cyclic prefix (CP) attached to the transmitted symbol. To fully avoid the ISI between the successive symbols, the CP length ought to be larger than or equal to the greater delay taps of the multipath channel. The CP has two main advantages; firstly, the CP changes the linear convolution into a circular convolution **[11]**. Hence the circular convolution of the signal with the channel would be a simple multiplication in frequency domain which makes single one tap equalizer applicable. Secondly, it avoids the ISI between the successive symbols. The produced signal is given as

$$u = \Lambda_{cp} s, \quad (7)$$

where $\Lambda_{cp}$ is a matrix of $N_t \times N$ dimensions and can be expressed as

$$\Lambda_{cp} = \begin{bmatrix} 0_{Ng\times(N-Ng)} & \mathbf{I}_{Ng} \\ \mathbf{I}_N & \end{bmatrix} \quad (8)$$

## 4. Transmission System Model

The cooperative relay diagram is shown in Fig. 1 where two-hop cooperative relay scheme is used in this system. It includes three points; source (S), one relay (R) and destination (D). In first phase, the source node S transmits T-OFDM signal toward the destination node S and the relay R. At the second phase, the relay re-send the signal to the destination node after amplification to increase the reliability of transmission.

The channels between the system nodes are represented as $h_n^{(s-d)} = \sum_{i=0}^{L} \alpha_i^{(s-d)} \delta(n-\tau_i)$, from source to relay $h_n^{(s-r)} = \sum_{i=0}^{L} \alpha_i^{(s-r)} \delta(n-\tau_i)$ and from relay to destination, where $\alpha_i$ is the attenuation of the $i_{th}$ path and $\delta(t)$ is the delta function with amplitude 1when t=0 and zero elsewhere. Mathematically, this is given as

$$y_n^{(1)} = u_n * g_n^{(s-d)} + v_n^{(1)} = \sum_{i=0}^{L} u_{n-i}\alpha_i^{(s-d)} + v_n^{(1)} \quad (9)$$

In (9), $y_n^{(1)}$ is the received signal during the first phase of transmission, $*$ denotes the convolution operation, $v_n$ is the $n_{th}$ sample of the additive white Gaussian noise (AWGN) vector $v = [v_0, v_1, \ldots, v_{n-1}]^T$. The AWGN samples are of variance $\sigma_v^2 = E\{|v_n|^2\}$, and $E\{.\}$ denotes the expectation operation.

At the receiver side, the CP samples are discarded from the arrived signal $y_n^{(1)}$ to avoid the ISI. The received signal is then after being transformed by the FFT is given as

$$Y(1)k = G_k^{(s-d)} r_k + \Omega_k^{(1)} \quad (k = 0,1,2,\ldots,N-1), \quad (10)$$

where $\Omega_k$ is the transfer function of the AWGN and $G_k^{(s-d)} = \sum_{l=0}^{L} g_l^{(s-d)} e^{-\frac{2\pi kl}{N}}, (0 \le k \le N-1)$ is the $k_{th}$ tap source-destination channel transfer function.

During the same phase, first phase, and the received signal at the relay that coming from the source is given as

$$r_n^{(1)} = u_n * g_{(s-r)}^{u} + v_n^{(r)} = \sum_{i=0}^{L} u_{n-1}\, \alpha_i^{(s-r)} + v_n^{(r)} \quad (11)$$

where $v_n^{(r)}$ is the AWGN at the relay.

At the second phase, the source S is not sending any signal whereas the relay is amplify the signal in r with a gain G = 1 and forward it to the destination node. Therefore, the arrived signal can be written as

$$y_n^{(2)} = r_n^{(1)} * g_n^{(r-d)} + v_n^{(2)}, \quad (12)$$

where $v_n^{(2)}$ is the AWGN noise at the receiver end from the second phase transmission. Substituting (11) into (12) yields

$$y_n^{(2)} = u_n * g_n^{(s-r)} * g_n^{(r-d)} + v_n^{(r)} * g_n^{(r-d)} + v_n^{(2)} \quad (13)$$

After discarding the CP extension, the FFT is then used to produce the frequency domain version of the received signal. Thus the produced signal is then expressed as

$$Y_k^{(2)} = G_k^{(s-r)} G_k^{(r-d)} r_k + G_k^{(r-d)} \Omega_k^{(r)} + \Omega_k^{(2)}. \quad (14)$$

All $\Omega_k^{(1)}, \Omega_k^{(2)}\, and\, \Omega_k^{(r)}$ have the same power (standard deviation $\sigma_v^2$). Thus the equivalent AWGN noise in (14) can be calculated as

$$\Omega_k = G_k^{(r-d)} \Omega_k^{(r)} + \Omega_k^{(2)} \quad (15)$$

The produced AWGN noise power is $\sigma_v^2 = E\{|\Omega_k|^2\}$. Thus

$$\overline{\sigma_v^2} = |G_k^{(r-d)}|^2 \sigma_v^2 + \sigma_v^2$$

$$= \left(|G_k^{(r-d)}|^2 + 1\right)\sigma_v^2 \quad (16)$$

Thus the equivalent AWGN noise $\Omega_k = \sqrt{\overline{\sigma_v^2}}$ is then given as

$$\sqrt{\Omega_k} = \left(\sqrt{|G_k^{(r-d)}|^2}\right) + \Omega_k \quad (17)$$

Substituting equation (17) into equation (14), the latter can be written as

$$Y_k^{(2)} = G_k^{(s-r)} G_k^{(r-d)} r_k + \left(\sqrt{|G_k^{(r-d)}|^2 + 1}\right)\Omega_k \quad (18)$$

To generalize equation (18) for all $k = 0,1,\ldots,N-1$, the following notation is used: $\mathbf{G}^{(s-d)} = \sum_{n=0}^{N-1} t_{n,m} G_m^{(s-d)}$, $\mathbf{G}^{(s-r)} = \sum_{n=0}^{N-1} t_{n,m} G_m^{(s-r)}$ and $\mathbf{G}^{(r-d)} = \sum_{n=0}^{N-1} t_{n,m} G_m^{(r-d)}$, where $t_{n,m}$ is the $n_{th}$ row kth column kernel parameter of the T-transform. We also use $Y^{(1)} = (Y_k^{(1)})_{k=0}^{N-1}$, $Y^{(2)} = (Y_k^{(2)})_{k=0}^{N-1}$, $\Omega = (\Omega_k)_{k=0}^{N-1}$. The received signal from the first and second phase transmission can be written as

$$\begin{bmatrix} \mathbf{Y}^{(1)} \\ \mathbf{Y}^{(2)} \end{bmatrix} = \begin{bmatrix} \mathbf{G}^{(s-d)} \\ \mathbf{G}^{(s-r)}\mathbf{G}^{(s-d)} \end{bmatrix} \mathbf{r} + \begin{bmatrix} \mathbf{I}_N \\ \overline{\sqrt{|\mathbf{G}^{(r-d)}|^2 + \mathbf{I}_N}} \end{bmatrix} \mathbf{\Omega} \quad (19)$$

The received symbol is then expressed as

$$Z = \left(\left|\mathbf{G}^{(s-d)}\right|^2 + \left|\mathbf{G}^{(s-r)}\right|^2\left|\mathbf{G}^{(r-d)}\right|^2\right)\mathbf{r} + \left(\mathbf{G}^{*(s-d)} + \mathbf{G}^{*(s-r)}\mathbf{G}^{*(r-d)}\sqrt{|\mathbf{G}^{(r-d)}|^2 + \mathbf{I}_N}\right)\boldsymbol{\Omega} \qquad (20)$$

The compensation for channel gain is then achieved by performing the channel equalization. In the case of zero-forcing (ZF) equalizer, the recovered signal is then given as

$$\hat{\mathbf{r}} = \mathbf{r} + \frac{\left(\mathbf{G}^{*(s-d)} + \mathbf{G}^{*(s-r)}\mathbf{G}^{*(r-d)}\sqrt{|\mathbf{G}^{(r-d)}|^2 + \mathbf{I}_N}\right)}{(|\mathbf{G}^{(s-d)}|^2 + |\mathbf{G}^{(s-r)}|^2|\mathbf{G}^{(r-d)}|^2)}\boldsymbol{\Omega} \qquad (21)$$

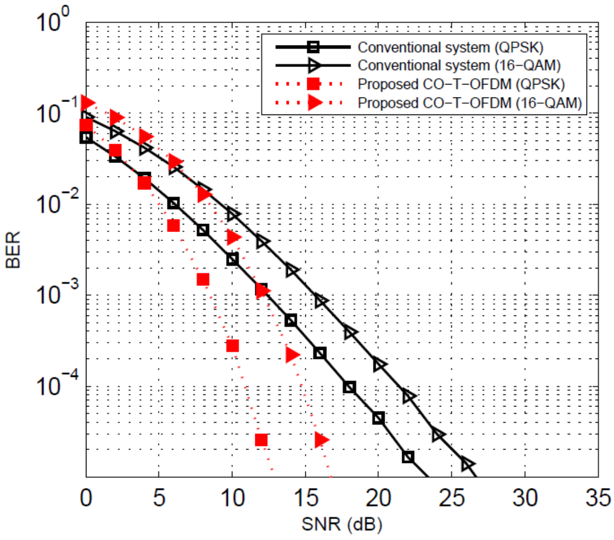
It is clear from equation (21) that unlike the conventional AF cooperative scheme, as $\mathbf{G}^{(s-d)} = \sum_{n=0}^{N-1} t_{n,m} G_m^{(s-d)}$ is the average of all channel taps, even if the transmitted signal face deep notches, for example $G_k{}^{(s-d)} = 0$, its average $\mathbf{G}^{(s-d)}$ will not be zero. Therefore, the noise part in equation (21) does not amplified and the signal can be recovered from the other (s – r) and (r – d) channel paths. Therefore, the proposed scheme achieves more robust to deep dips in multipath channels and provide better signal diversity.

## 5. Peak-to-average power Ratio (PAPR)

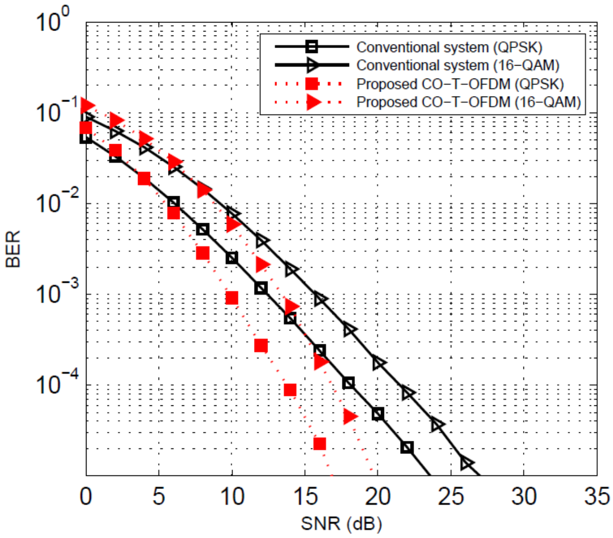
The main drawbacks of any multicarrier technology is peak signal power in comparison to its average power. This requires wide range of the high power amplifier to embrace the entire signal without clipping and hence signal distortion. Practically, such amplifier is not applicable or costly unsuitable. Therefore, for any multicarrier system to stand as accepted candidate for a wireless transmission such as cooperative scheme, its peak-to-average power ratio must be acceptable. As the T-transform, which acts as a modulation transform in the suggested scheme, has a block diagonal structure shown in equation (4). Therefore, the maximum number of subcarriers that performs each transmitted sample reduces to N/2 instead of N in the classic cooperative system and hence reducing the PAPR.

## 6. Numerical Results and Discussions

In this section, Monte Carlo simulation is used to prove the superiority of the developed amplify and forward cooperative scheme over the traditional AF cooperative system. In this simulation, the cooperative diversity is source, amplify and forward relay and destination. QPSK and 16-QAM symbol mapping is used in this section. A hostile transmission environment represented by multipath fading channel defined by international telecommunication union (ITU) vehicular A and pedestrian B channel is used. The bandwidth is 2.5 MHz, and the subcarriers N=256.



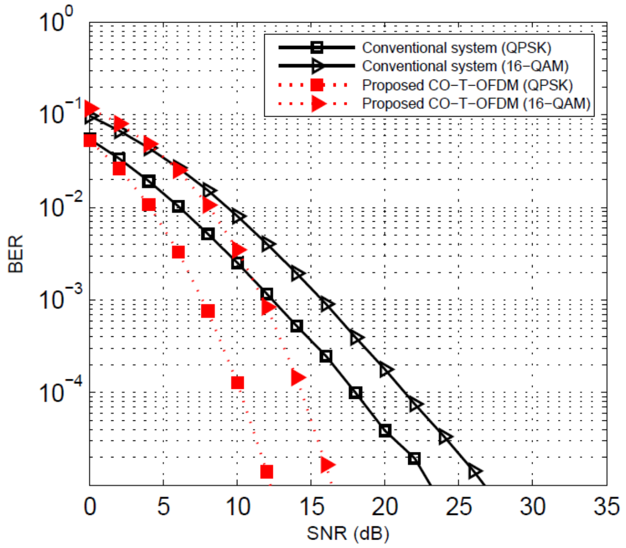

(a) ITU Pedestrian B channel model



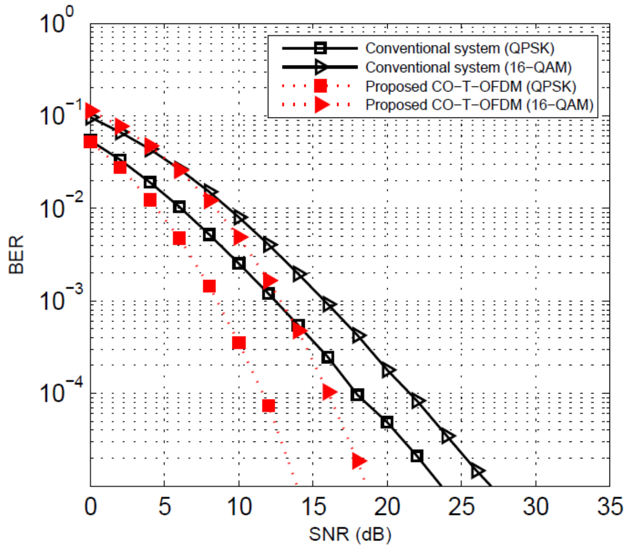

(b) ITU Vehicular A channel model

Fig. 2 The BER of the presented AF cooperative system and the traditional AF cooperative scheme **[12]** with ZF equalizer and over ITU (a) pedestrian B and (b) vehicular A channel models.

Fig. 2 shows the BER performance of the developed system and compared it with the state-of-the-art amplify and forward cooperative system **[12]** for zero forcing (ZF) equalizer. The BER performance is shown for two types of channel models, Fig. 2(a) for the pedestrian B and Fig. 2(b) is for the vehicular a channel models. It is noticeable from Fig. 2 that at 10 BER, the proposed cooperative system outperforms the standard AF cooperative scheme by around 10 dB signal-to-noise ratio (SNR) for both QPSK and 16-QAM mapping. Unlike the classic AF cooperative scheme, the developed AF cooperative scheme, with its modified−5 modulation algorithm, distribute the signal among more number of subcarriers and thus increase the signal diversity and immunity against the multipath channels severity.




(a) ITU Pedestrian B channel model




(b) ITU Vehicular A channel model

Fig. 3 The BER of the presented AF cooperative system and the traditional AF cooperative scheme **[12]** with MMSE equalizer and over ITU (a) pedestrian B and (b) vehicular A channel models.

For further demonstration in the validity of the proposed scheme, MMSE equalizer is used. The BER performances of the enhanced AF cooperative system is compared with that of the traditional AF cooperative system **[12]** is shown in Fig. 3. The BER for the case of pedestrian B channel model is shown in Fig. 3(a) whereas Fig. 3(b) shows the BER for vehicular A channel model. It is obvious that the presented AF cooperative is significantly superior the standard cooperative scheme and achieves better SNR gain. This simulation results support our early assert in equation (21) that the proposed AF cooperative scheme more robust to hostile multipath environment even over a channel with deep notches.

The key factor in the advanced AF cooperative scheme for achieving better BER performance than the standard cooperative scheme is that the system proposed in this paper achieves higher subcarrier diversity in its transmitted signal than the state-of-the-art AF cooperative scheme. This is because the proposed scheme utilize efficient modulation/demodulation transform in its transceivers structure instead of the traditional FFT [12] in the structure on the standard cooperative system transceivers. The benefit of using T-transform in OFDM system is to increase the transmitted signal diversity and ultimately increase the resilience to multipath channel. In contrast, our proposed CO-T-OFDM system can achieve significant diversity exploitation inherently without the need to external technique.

To verify the superiority of the PAPR reduction of the system under consideration in comparable to the classic AF cooperative system, Monte Carlo simulation is used over 100 000 transmitted symbols. Fig. 2 shows the PAPR of the enhanced AF cooperative scheme and compared with that of the standard AF cooperative scheme for number of subcarrier, N = 1024. The complementary cumulative density function (CCDF) shows a perceptive glimpse of the PAPR statistics. It is clear from Fig.4 that the proposed AF cooperative scheme reduces the PAPR about 1 dB in comparison to the standard AF cooperative system.

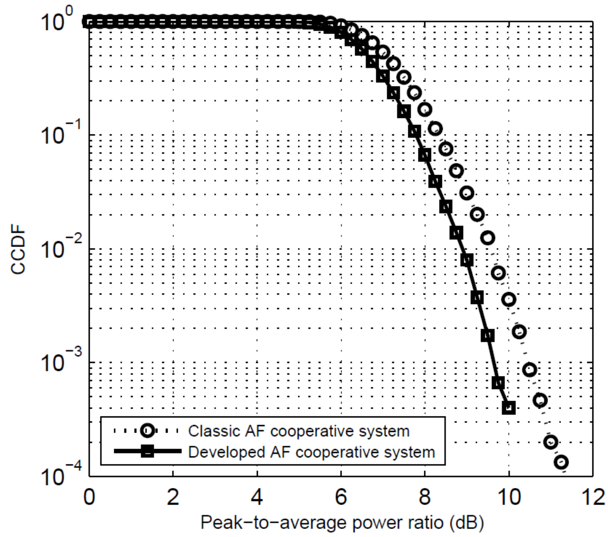



Fig. 4 PAPR of the suggested AF cooperative scheme in comparision to the PAPR of the standard AF cooperative scheme.

## Conclusions

In this paper, a developed AF cooperative OFDM system has been presented. The modulation and demodulation algorithm in the transceiver architecture of the suggested system is based on the T transform instead of the state-of-the-art DFT in the standard AF cooperative system. Mathematical model for the transmission process of the proposed scheme was also derived in this paper. It has been shown by simulation that the developed AF cooperative system achieved better BER performance than the standard system over multipath fading channel and a hostile environments. The proposed AF cooperative scheme not only mitigated the deleterious ramification effects of multipath channels but also reduces the peak power of the transmitted symbols in comparison to its average power. The proposed AF cooperative scheme CO-T-OFDM can be a successful alternative candidate to the forthcoming wireless communications and wireless sensor network.

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