

Error Performance and Energy Efficiency Analyses of Fully Cooperative OFDM Communication in Frequency Selective Fading

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Abstract: This paper devises for the first time a comprehensive analysis of decode-and-forward, space-time coded, fully cooperative OFDM systems from both error performance and energy efficiency perspectives, in either identically or non-identically distributed frequency selective Rayleigh fading channels. Our analyses show the interesting result that the fully cooperative OFDM is better than direct OFDM transmission from both perspectives in many cases, especially at a low power and low signal-to-noise ratio regime, making it particularly useful for emerging low power applications, such as wireless body area networks.

1. Introduction

Cooperative communication comprises two main streams, namely relay-based cooperative communication (widely known as cooperative communication in the literature) and fully cooperative communication, which is substantially different from its counterpart (detailed below). The term “fully cooperative communication” has been adopted from [1]. It has also been referred to as user cooperative systems in some particular contexts in the literature. To distinguish between the relay-based cooperative networks and the fully cooperative counterpart, in this paper, we refer to the former as *relay networks* and to the latter as *fully cooperative networks*.

In relay networks, transmission from the source(s) to the destination is assisted by either a single or multiple relaying nodes which do not transmit their own signals. To forward the sig-

nals from the sources to the destinations, relays typically use either an Amplify-and-Forward (AF), a Decode-and-Forward (DF) technique [1], [2], or a coded cooperation [3]. To improve further the system performance, AF and DF have also been associated with Space-Time Block Codes (STBCs) [4] (with or without Orthogonal Frequency Division Multiplexing (OFDM)) to take advantage of Multiple-Input Multiple-Output (MIMO) systems. These combined systems are referred to as *(distributed) space-time coded cooperative communication* in the literature. The combination of AF (or DF) and STBC has been widely examined for the relay networks, such as in [5]– [9]. Regardless of their particular name, most of the existing works in the literature only considered relay networks, rather than fully cooperative networks. *Relay networks have been intensively researched and are thus out of the scope of this paper.*

Unlike relay networks, in a fully cooperative network [1], nodes act as both source nodes transmitting their own data, and as relays forwarding their partners' signals. Additionally, fully cooperative communication can be applied to a multi-user network where each user (source node or sensor) collects, for example, different types of human bodies' physiological parameters, and multiple users cooperate with each other to transmit their data to the destination (a hub). **For this reason, fully cooperative networks are also referred to as user cooperative networks.** Finally, because nodes are not only able to send their data but are also capable of forwarding data for their partners, by their nature, fully cooperative networks facilitate a mesh topology between sensors and coordinators. In fully cooperative networks, nodes are within the coverage of each other with the possible applications including emerging Wireless Body Area Networks (WBAN), Wireless Sensor Networks (WSNs), Internet of Things (IoT), and indoor entertainment applications.

While relay networks have been extensively researched, fully cooperative networks have been far less researched because these networks are more specific application-targeted. Specially, fully cooperative networks in frequency selective fading channels using OFDM associated with STBCs have been unexplored. Therefore, this paper aims to analyze fully cooperative OFDM communication from both error performance and energy efficiency perspectives in frequency selective fading channels. To the best of our knowledge, the closest work to our paper is [10], where the authors devised the symbol error rate (SER) of a fully cooperative non-OFDM system, with single-antenna nodes and BPSK modulation, in identically distributed flat Rayleigh fading chan-

nels. However, [10] did not consider a fully cooperative OFDM system in either identically or non-identically distributed frequency selective Rayleigh fading channels. It did not consider an arbitrary M-PSK modulation and multi-antenna nodes. In addition, no comprehensive energy efficiency analysis was mentioned there. Addressing these matters is the main motivation and contribution of this paper. The novel contributions of this paper include

1. Novel exact SER of the decode-and-forward, space-time block coded, fully cooperative OFDM network has been derived in both identically and non-identically distributed frequency selective Rayleigh fading channels. This SER analysis has been devised with an arbitrary number of receive antennas per node and an arbitrary M-PSK modulation scheme. The validity of the SER formulas has been confirmed by simulations. Our analysis shows that fully cooperative OFDM could be significantly better than direct OFDM transmission in many cases, especially at a low SNR regime.
2. Given certain channel knowledge, the formulated SER allows the source nodes to pre-justify whether the collaboration with their neighbors is better than their direct transmission, and thus decide beforehand whether they should really engage in the cooperative communication. This ensures that cooperative communication always useful once it is in place. Note that a proposal of a switching algorithm back and forth between direct OFDM transmission and fully cooperative OFDM modes is out of the scope of this paper.
3. Energy efficiencies of direct OFDM transmission and of the fully cooperative OFDM have been formulated, and confirmed by simulations. Our analysis confirms that fully cooperative OFDM not only potentially improves the system error performance, but is also better than direct OFDM transmission from the energy efficiency perspective in many cases, especially at low transmission power regimes.

Notations: Throughout the paper, we use the notations and terms listed in Table 1.

2. System Model

Fig. 1 depicts a typical WBAN, which is one of several possible applications of the fully cooperative system. Similar to [11], we refer to the case $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$ as the identically distributed fading

Table 1 Notations and terms used throughout the paper.

Parameters/Terms	Values/Meaning
S_1, S_2, D	two source nodes and destination node
n_T	number of transmit (TX) antennas per node ($n_T = 1$)
n_R	number of receive (RX) antennas per node (typically $n_R = 1$)
M	constellation size of unit-energy M-PSK modulation
$\bar{\gamma}_{ij}, \bar{\gamma}_{u1}, \bar{\gamma}_{u2}$	average SNR per symbol in internode links $S_1 \leftrightarrow S_2$ and uplinks $S_1 \leftrightarrow D, S_2 \leftrightarrow D$
$\bar{\beta}_{ij}, \bar{\beta}_{u1}, \bar{\beta}_{u2}$	average SNR per subcarrier
d_{ij} and d_u	distance of the internode links and the uplinks (assume that $d_{u1} \approx d_{u2} := d_u$)
Lower/upper case bold letters	vectors and matrices, respectively
$(\cdot)^*, (\cdot)^T, (\cdot)^H, \bullet$	complex conjugation, transposition, Hermitian transposition, vector dot product
$P(\Xi)$	probability of the random event Ξ
$\mathcal{CN}(0, \sigma^2), \text{Rayleigh}(\bar{\gamma})$	complex Gaussian and Rayleigh distributions with the corresponding parameters
$\text{Nakagami-m}(m, \Omega)$	Nakagami-m distribution with the corresponding parameters
'cooperative system'	fully cooperative OFDM system (not the well-known cooperative communication)
'direct transmission'	OFDM transmission from one source (e.g., S_1) to D without cooperation
'conventional Alamouti'	Alamouti code in a traditional OFDM (non-distributed, non-cooperative) system

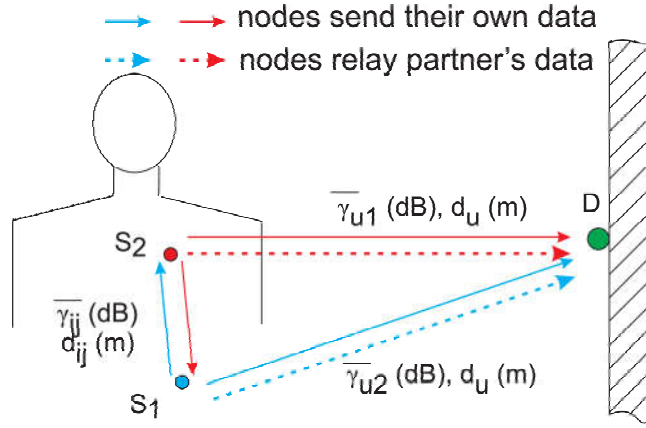


Fig. 1. Typical network topology of the fully cooperative OFDM communication system.

ing, and as the non-identically distributed fading if otherwise. Block frequency selective Rayleigh fading is assumed, i.e., channel coefficient vectors between S_1, S_2 and D are constant during the transmission of an Alamouti STBC [4], but change randomly from block to block. Channel coefficients are independent, identically or non-identically distributed complex random variables (RV), while noises follow $\mathcal{CN}(0, \sigma^2)$. Uncoded M-PSK signals are transmitted by the scheme shown in Table 2, where $\hat{s}$ denotes the forwarded version of the partner's signal s (possibly $s \neq \hat{s}$ due to transmission errors in the internode links). Clearly, there are two main phases, namely the internode information exchange (Phase I, involving time slots 1, 2), where the source nodes interchange their own data, and the (distributed) Alamouti OFDM transmission (Phase II, all time slots), where an Alamouti-like space-time code $\sqrt{\frac{P_t}{2}}[s_1 \ s_2; -\hat{s}_2^* \ \hat{s}_1^*]$ is effectively transmitted.

Table 2 Transmission scheme in the fully cooperative OFDM system.

Time slot 1	Time slot 2	Time slot 3
$\sqrt{\frac{P_t}{2}}\mathbf{s}_1 \quad (S_1 \rightarrow S_2, D)$	$\sqrt{\frac{P_t}{2}}\mathbf{s}_2 \quad (S_2 \rightarrow S_1, D)$	$-\sqrt{\frac{P_t}{2}}\hat{\mathbf{s}}_2^* \quad (S_1 \rightarrow D)$ $\sqrt{\frac{P_t}{2}}\hat{\mathbf{s}}_1^* \quad (S_2 \rightarrow D)$

The post-processed OFDM symbol received at the partner S_j in the frequency domain, denoted as $\mathbf{r}_{ij} = [r_{ij1}, \dots, r_{ijN_{\text{FFT}}}]$, is

$$\mathbf{r}_{ij} = \sqrt{\frac{\mathcal{P}_{rij}}{2}}\mathbf{s}_i \bullet \left(\sum_{n=1}^{n_R} \mathbf{H}_{ij}^n \right) + \mathbf{N}_{ij}, \quad (1)$$

where $\mathbf{s}_i$ is the OFDM symbol transmitted from S_i , $i \in \{1, 2\}$. $\mathcal{P}_{rij}$ is the average receive power per symbol. $\mathbf{h}_{ij}^n = [h_{ij,1}, \dots, h_{ij,L}]$, $n = 1, \dots, n_R$, is the channel vector between the TX antenna of S_i and the n -th RX antenna of S_j (L is the number of multipaths in each link). $\mathbf{H}_{ij}^n = [H_{ij1}, \dots, H_{ijN_{\text{FFT}}}] := \text{FFT}(\mathbf{h}_{ij}^n)$, $\mathbf{n}_{ij} = [n_{ij,1}, \dots, n_{ij,n_R}]$ is the noise vector at n_R RX antennas of S_j , and $\mathbf{N}_{ij} = \text{FFT}(\mathbf{n}_{ij}) \sim \mathcal{CN}(0, \sigma^2)$. After Phase I completes, the OFDM symbol $\mathbf{s}_i$ is estimated (by the partner S_j , $j \in \{1, 2 | j \neq i\}$) as $\hat{\mathbf{s}}_i$ based on the following Maximum Ratio Combining (MRC) decision metric

$$\hat{\mathbf{s}}_i \leftarrow \hat{\mathbf{s}}_i = \mathbf{r}_{ij} \bullet \sum_{n=1}^{n_R} (\mathbf{H}_{ij}^n)^H. \quad (2)$$

The source nodes will then forward the estimated signals to the destination in the next time slots in the forms of $-\hat{\mathbf{s}}_2^*$ and $\hat{\mathbf{s}}_1^*$ as shown in Table 2. Eq. (2) suggests that each M-PSK symbol s_{ik} at the k -th subcarrier, $k = \{1, \dots, N_{\text{FFT}}\}$, within the OFDM symbol $\mathbf{s}_i$ can be estimated, denoted as $\hat{s}_{ik}$, as follows

$$\hat{s}_{ik} \leftarrow \hat{s}_{ik} = r_{ijk} \left(\sum_{n=1}^{n_R} H_{ijk}^n \right)^*. \quad (3)$$

After Phase I and Phase II complete, the post-processing received signals at the destination are

$$\begin{aligned} \mathbf{r}_1 &= \sqrt{\frac{\mathcal{P}_{ru1}}{2}} \sum_{n=1}^{n_R} \mathbf{H}_1^n \bullet \mathbf{s}_1 + \sqrt{\frac{\mathcal{P}_{ru2}}{2}} \sum_{n=1}^{n_R} \mathbf{H}_2^n \bullet \mathbf{s}_2 + \mathbf{N}_1, \\ \mathbf{r}_2 &= -\sqrt{\frac{\mathcal{P}_{ru1}}{2}} \sum_{n=1}^{n_R} \mathbf{H}_1^n \bullet \hat{\mathbf{s}}_2^* + \sqrt{\frac{\mathcal{P}_{ru2}}{2}} \sum_{n=1}^{n_R} \mathbf{H}_2^n \bullet \hat{\mathbf{s}}_1^* + \mathbf{N}_2, \end{aligned} \quad (4)$$

where $\mathbf{H}_i^n = \text{FFT}\{\mathbf{h}_i^n\}$, $i \in \{1, 2\}$, and $\mathbf{h}_i^n = [h_{iD,1}, \dots, h_{iD,L}]$, $n = 1, \dots, n_R$, is the channel vector between the TX antenna of S_i and the n -th RX antenna of the destination. Note that Eq. (4) considers both identically (if $\mathcal{P}_{ru1} = \mathcal{P}_{ru2}$) and non-identically distributed channels ($\mathcal{P}_{ru1} \neq \mathcal{P}_{ru2}$). The average receive power per symbol in the internode links, denoted as $\mathcal{P}_{rij}$, and those in the uplinks, denoted as $\mathcal{P}_{ru1}$ and $\mathcal{P}_{ru2}$, relate to the average transmit power $\mathcal{P}_t$ as $\mathcal{P}_{rij(ru1, ru2)} = \frac{\mathcal{P}_t G_m}{L_{ij(u1, u2)}}$, where $L_{ij(u1, u2)}$ is the pathloss of the internode link (or uplink $S_1 \rightarrow D$, $S_2 \rightarrow D$, respectively), and G_m denotes the overall gain factor of the TX and RX antenna gains, their total connector loss and polarization mismatch, the link budget margin to compensate for other losses, etc. For simplicity, we assume G_m to be the same for both internode links and uplinks. $L_{ij(u1, u2)}$ are functions of the distances d_{ij} and d_u , respectively. Note that because we also consider the non-identically distributed channels, e.g., when the uplink $S_1 \rightarrow D$ is persistently obstructed by an obstacle, e.g., an identity card in the patient's pocket, L_{u1} also takes into account this additional loss. Thus $L_{u1} \neq L_{u2}$ in the non-identically distributed scenario, resulting in $\mathcal{P}_{ru1} \neq \mathcal{P}_{ru2}$.

From (4), s_{ik} at the k -th subcarrier of the transmitted OFDM symbols $\mathbf{s}_i$ can be estimated as

$$\begin{aligned} \underline{s}_{1k} &\leftarrow \tilde{s}_{1k} = r_{1k} \left(\sum_{n=1}^{n_R} H_{1k}^{n*} \right) + r_{2k}^* \left(\sum_{n=1}^{n_R} H_{2k}^n \right), \\ \underline{s}_{2k} &\leftarrow \tilde{s}_{2k} = r_{1k} \left(\sum_{n=1}^{n_R} H_{2k}^{n*} \right) - r_{2k}^* \left(\sum_{n=1}^{n_R} H_{1k}^n \right). \end{aligned} \quad (5)$$

Eqs. (3) and (5) are exactly the same as those of a non-OFDM flat fading system, except that the single channel coefficient per branch in a non-OFDM system, denoted as h_{ij}^n (or h_1^n and h_2^n), is replaced by its corresponding frequency-domain coefficient H_{ijk}^n (or H_{1k}^n and H_{2k}^n) in the OFDM system. This important observation allows us to apply the methods used to analyze the SER of a non-OFDM flat fading system to a multipath OFDM system as detailed in the next section.

Note that s_i , $\hat{s}_i$ and $\underline{s}_i$ are M-PSK symbols, and the factor $\frac{1}{\sqrt{2}}$ in Table 2 and in Eqs. (1) and (4) is to guarantee that the total average transmission power from the two source nodes during the Alamouti transmission process is always $\mathcal{P}_t$, which is the same as that in a single antenna, direct transmission system for a fair comparison.

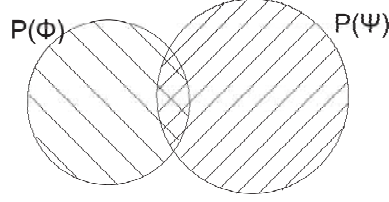


Fig. 2. Component probability model for SER analysis.

3. Symbol Error Rate

Let us consider the pair of M-PSK symbols (s_{1k}, s_{2k}) at the k -th subcarrier, $k = 1, \dots, N_{\text{FFT}}$, within the corresponding OFDM symbols $\mathbf{s}_1$ and $\mathbf{s}_2$. For brevity, the subindex k is omitted. Denote P_{ij} and P_A as SER of the internode link $S_i - S_j$ and of the Alamouti STBC transmission, respectively, assuming that M-PSK modulation is used in all links in the system. Denote Φ and Ψ as the events where the cooperative system has errors due to the erroneous information exchange between the sources and due to the errors during the Alamouti transmission, respectively. Thus $\Phi + \Psi$ presents the event where the cooperative system has errors. Since Φ and Ψ are not mutually exclusive of one another, all possibilities of Φ and Ψ , indicated by the two circles in Fig. 2 and denoted as $P(\Phi)$ and $P(\Psi)$ respectively, might partially overlap each other. From Fig. 2, we have

$$P(\Phi + \Psi) = P(\Psi) + P(\Phi|\bar{\Psi}), \quad (6)$$

where $P(\Phi|\bar{\Psi})$ is the probability of Φ conditioned on the negation of Ψ . Eq. (6) can be interpreted as follows: SER of the cooperative system equals the sum of SER of the Alamouti transmission (i.e., P_A) and SER of the cooperative system when there is no error during the Alamouti transmission. $P(\Phi|\bar{\Psi})$ can be written further as

$$P(\Phi|\bar{\Psi}) = P(\Phi|\bar{\Psi}, s_1) + P(\Phi|\bar{\Psi}, s_2) + P(\Phi|\bar{\Psi}, s_1, s_2), \quad (7)$$

where the three terms of Eq. (7) stand for SER of the cooperative system when s_1 is erroneous (s_2 is correct), s_2 is erroneous (s_1 is correct), and both are erroneous, respectively. Note that no error occurs in the uplinks.

Because two internode links $S_1 \rightarrow S_2$ and $S_2 \rightarrow S_1$ are independent fading channels with the

same average SNR, $\bar{\gamma}_{ij}$, it is reasonable to assume $P(\Phi|\bar{\Psi}, s_1) = P(\Phi|\bar{\Psi}, s_2) = P(\Phi|\bar{\Psi}, s_1, s_2) = P(\Phi|\bar{\Psi}, s_1, s_2) = 0.25$. Given that P_{ij} is the symbol error probability of an M-PSK transmission over a fading channel, the probability of either symbol being erroneous is $0.25P_{ij}(1-P_{ij})$, resulting in $P(\Phi|\bar{\Psi}, s_1) = P(\Phi|\bar{\Psi}, s_2) = 0.25P_{ij}(1-P_{ij})(1-P_A)$. Similarly, the probability that both transmissions are erroneous is $0.25P_{ij}^2$, resulting in $P(\Phi|\bar{\Psi}, s_1, s_2) = 2 \times 0.25P_{ij}^2(1-P_A) = 0.5P_{ij}^2(1-P_A)$, where the factor 2 reflects that there are two symbol errors. Thus Eq. (7) becomes

$$P(\Phi|\bar{\Psi}) = 0.5(1-P_A)[P_{ij}(1-P_{ij}) + P_{ij}^2] = 0.5(1-P_A)P_{ij}. \quad (8)$$

From (6) and (8), the SER of the cooperative system is

$$P_C := P(\Phi + \Psi) = P_A + 0.5(1-P_A)P_{ij}. \quad (9)$$

We now work out the formulas for SER of the information interchange process, P_{ij} , and the Alamouti transmission process, P_A , in both identically and non-identically distributed multipath Rayleigh fading channels. The following theorems are helpful for our subsequent analysis.

Theorem 1: If $\mathbf{h} = [h_1, \dots, h_L]$ where $h_l \sim \mathcal{CN}(0, \Omega)$ (i.e., $|h_l| \sim \text{Rayleigh}(\Omega)$, $l = 1, \dots, L$), and $\mathbf{H} = [H_1, \dots, H_{N_{\text{FFT}}}] := \text{FFT}(\mathbf{h})$, then H_k , $k = 1, \dots, N_{\text{FFT}}$, are also Rayleigh random variables (RVs) $|H_k| \sim \text{Rayleigh}(\frac{L\Omega}{N_{\text{FFT}}})$.

Proof: Note that a Rayleigh RV $|h_l| \sim \text{Rayleigh}(\Omega)$ can be considered as a Nakagami-m RV *Nakagami* – $m(1, \Omega)$. It has been shown that $|H_k|$ follows *Nakagami* – $m(\acute{m}, \acute{\Omega})$, where $\acute{m} = \frac{Lm}{Lm-m+1} = \frac{L}{L-1+1} = 1$ and $\acute{\Omega} = \frac{1}{N_{\text{FFT}}} \sum_{l=1}^{L-1} \Omega = \frac{L\Omega}{N_{\text{FFT}}}$ [12, p.485]. This means $|H_k| \sim \text{Rayleigh}(\frac{L\Omega}{N_{\text{FFT}}})$. ■

As with a non-OFDM system where the average SNR per symbol in the internode links (uplinks) is $\bar{\gamma}_{ij(u1, u2)} = \frac{\mathcal{P}_{rij(ru1, ru2)}}{\sigma^2}$, the average SNR per subcarrier in the internode links (uplinks) in an OFDM system is $\bar{\beta}_{ij(u1, u2)} = \frac{\bar{\gamma}_{ij(u1, u2)} L \Omega}{N_{\text{FFT}}}$ [12]. For simplicity, we assume that the numbers of multipaths, L , of the internode and uplinks are the same, and that L is smaller than the length of the cyclic prefix. In the most general case (non-identically distributed fading channels), $\mathcal{P}_{ru1} \neq \mathcal{P}_{ru2}$, thus $\bar{\gamma}_{u1} \neq \bar{\gamma}_{u2}$.

Theorem 2: SER of a M-PSK modulation in a MRC, non-OFDM system with one TX and n_R

RX antennas in flat Rayleigh fading channels is ($\bar{\gamma}$ denotes the average SNR per symbol)

$$P_{MRC} = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma} \sin^2(\pi/M)}{\sin^2(\phi)} \right)^{-n_R} d\phi. \quad (10)$$

Proof: The proof has been shown in [11, Eq.(9.15)]. ■

The closed-form of Eq. (10) can be found in [11, Eq.(9.42)] as below

$$P_{MRC} \approx \frac{1}{(4\bar{\gamma} \sin^2(\pi/M))^{n_R}} \left[\binom{2n_R}{n_R} \frac{M-1}{M} - \sum_{n=1}^{n_R} \binom{2n_R}{n_R-n} (-1)^n \frac{\sin(2\pi n/M)}{n\pi} \right] \quad (11)$$

Since OFDM turns frequency selective fading into flat fading within each subband, from Eq. (10) and the fact that $\bar{\beta}_{ij} = \frac{\bar{\gamma}_{ij} L \Omega}{N_{\text{FFT}}}$, SER of the internode links in our cooperative OFDM system is

$$P_{ij} = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma}_{ij} L \Omega \sin^2(\pi/M)}{N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} d\phi, \quad (12)$$

and SER of the direct transmission link $S_1 (S_2) \rightarrow D$, denoted as $P_{D1(2)}$, in our OFDM system is

$$P_{D1(2)} = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma}_{u1(u2)} L \Omega \sin^2(\pi/M)}{N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} d\phi. \quad (13)$$

Error performance of the conventional Alamouti STBC in a $2\text{In}_R\text{O}$ (2 TX antennas, n_R RX antennas) configuration can be worked out from that of the corresponding MRC system with a $1\text{I}2n_R\text{O}$ configuration in a non-identically distributed fading scenario by replacing the average SNR per symbol $\bar{\gamma}_{u1}$ and $\bar{\gamma}_{u2}$ by $\bar{\gamma}_{u1}/2$ and $\bar{\gamma}_{u2}/2$, respectively, to reflect the fact that power per symbol transmitted from each TX antenna in the Alamouti process is half the power in the MRC system [4]. Therefore, SER of the conventional Alamouti STBC OFDM system, P_A , would be ¹

$$P_A = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma}_{u1} L \Omega \sin^2(\pi/M)}{2N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} \left(1 + \frac{\bar{\gamma}_{u2} L \Omega \sin^2(\pi/M)}{2N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} d\phi. \quad (14)$$

From Eqs. (9), (12) and (14), SER of the cooperative OFDM system in non-identically distributed multipath Rayleigh fading channels is given in Eq. (15).

¹Eq. (14) is the exact SER of the conventional Alamouti STBC OFDM system with arbitrary M-PSK modulation in non-identically distributed multipath Rayleigh fading channels. Derivation of this equation is also the novel contribution of our paper.

$$\begin{aligned}
P_C = & \frac{1}{\pi} \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma}_{u1} L \Omega \sin^2(\pi/M)}{2N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} \left(1 + \frac{\bar{\gamma}_{u2} L \Omega \sin^2(\pi/M)}{2N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} d\phi + \\
& \frac{1}{2\pi} \left[1 - \frac{1}{\pi} \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma}_{u1} L \Omega \sin^2(\pi/M)}{2N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} \left(1 + \frac{\bar{\gamma}_{u2} L \Omega \sin^2(\pi/M)}{2N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} d\phi \right] \times \\
& \int_0^{(M-1)\pi/M} \left(1 + \frac{\bar{\gamma}_{ij} L \Omega \sin^2(\pi/M)}{N_{\text{FFT}} \sin^2(\phi)} \right)^{-n_R} d\phi. \tag{15}
\end{aligned}$$

$$\begin{aligned}
P_C \approx & \frac{1}{\left(\frac{2\bar{\gamma}_{u1} L \Omega}{N_{\text{FFT}}} \sin^2(\pi/M) \right)^{2n_R}} \left[\binom{4n_R}{2n_R} \frac{M-1}{M} - \sum_{n=1}^{2n_R} \binom{4n_R}{2n_R-n} (-1)^n \frac{\sin(2\pi n/M)}{n\pi} \right] + \frac{1}{2\pi} \left\{ 1 - \right. \\
& \frac{1}{\left(\frac{2\bar{\gamma}_{u2} L \Omega}{N_{\text{FFT}}} \sin^2(\pi/M) \right)^{2n_R}} \left[\binom{4n_R}{2n_R} \frac{M-1}{M} - \sum_{n=1}^{2n_R} \binom{4n_R}{2n_R-n} (-1)^n \frac{\sin(2\pi n/M)}{n\pi} \right] \left. \right\} \times \\
& \frac{1}{\left(\frac{4\bar{\gamma}_{ij} L \Omega}{N_{\text{FFT}}} \sin^2(\pi/M) \right)^{n_R}} \left[\binom{2n_R}{n_R} \frac{M-1}{M} - \sum_{n=1}^{n_R} \binom{2n_R}{n_R-n} (-1)^n \frac{\sin(2\pi n/M)}{n\pi} \right]. \tag{16}
\end{aligned}$$

The exact SER of fully cooperative networks for the identically distributed Rayleigh channels can be found from Eq. (15) by replacing $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$. From Eq. (11), we can easily find the closed-form of Eqs. (12)–(14) (assume that $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$), thus the closed-form of Eq. (15) in case $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$ is given in Eq. (16).

4. Energy Efficiency

This section analyzes the Energy Efficiency (EE) of the fully cooperative OFDM. EE is defined as the ratio between the amount of successfully transmitted data, denoted as C (bits), and the total energy required to achieve that throughput, E_{total} (Joules)². Let us denote L_p (bits) and L_d (bits) as the length of the whole packet and the length of payload data in each packet, respectively. Assume that a packet is dropped if its Cyclic Redundancy Check (CRC) code fails. Denote R_b (bits/s) as the system bit rate and $b = \log_2(M)$ for a M-PSK modulation scheme, respectively. For simplicity, in this section, we consider the case $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$.

The average Packet Error Rate (PER), denoted as $\overline{\text{PER}}_D$, of the direct transmission scheme ($S_1 \rightarrow D$) is calculated as $\overline{\text{PER}}_D = (1 - P_D)^{L_p/b}$ [14], where P_D follows Eq. (13). Thus the

²EE can also be defined as the ratio between the system ergodic capacity (bits/s) and the consumed power (Watts) [13].

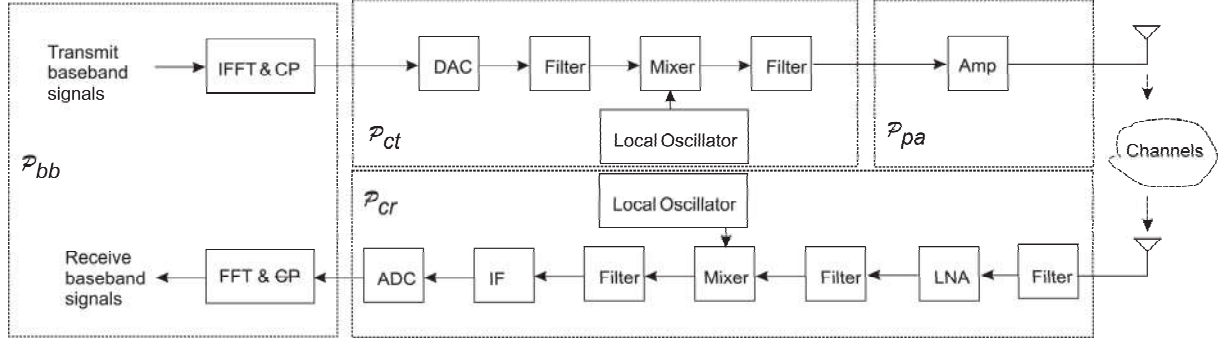


Fig. 3. Component MIMO OFDM power model for energy efficiency analysis.

effective throughput of the direct transmission is $C_D = L_d \overline{\text{PER}}_D = L_d(1 - P_D)^{L_p/b}$.

To calculate the total required energy, the component MIMO OFDM power model (see Fig. 3), which is similar to that in [13], is considered. The total power consumption can be written as $\mathcal{P}_{total} = \mathcal{P}_{pa} + \mathcal{P}_{ct} + \mathcal{P}_{cr} + \mathcal{P}_{bb}$, where $\mathcal{P}_{pa}$ is the amplifier power (PA) consumption (at the transmitter). $\mathcal{P}_{ct} = \mathcal{P}_{DAC} + \mathcal{P}_{mix} + \mathcal{P}_{filt} + \mathcal{P}_{syn}$ is the TX circuit power consumption (excluding both PA and the baseband processing power at the transmitter). $\mathcal{P}_{cr} = \mathcal{P}_{LNA} + \mathcal{P}_{filr} + \mathcal{P}_{mix} + \mathcal{P}_{syn} + \mathcal{P}_{IF} + \mathcal{P}_{ADC}$ is the RX circuit power consumption (excluding the baseband processing at the receiver). $\mathcal{P}_{bb}$ is the baseband power consumption (including IFFT and FFT blocks) in both TX and RX, respectively. Note that, except the power consumption, $\mathcal{P}_{syn}$, of the synchronization block which is assumed to be shared for all RF chains, other terms should be applied to each RF chain from a transmitter to a receiver. The values of these terms can be estimated by the model proposed in [15]. The PA consumption $\mathcal{P}_{pa}$ includes the actual transmitted power $\mathcal{P}_t$ and the wasteful power dissipation, thus $\mathcal{P}_{pa} = \frac{\mathcal{P}_t}{\eta}$, where η is the PA efficiency. The following analysis of energy efficiency is applied to multipath Rayleigh fading channels.

Consider the direct transmission with M-PSK modulation, one TX antenna, and n_R RX antennas. Energy required to transmit one packet with the data rate R_b (bits/s) is

$$E_{total}^D = \frac{L_p}{R_b} \left(\frac{\mathcal{P}_t}{\eta} + \mathcal{P}_{ct} + n_R \mathcal{P}_{cr} + \mathcal{P}_{bb} \right). \quad (17)$$

Hence, EE of the direct OFDM transmission is

$$EE_D = \frac{C_D}{E_{total}^D} = \frac{R_b L_d}{L_p} \frac{(1 - P_D)^{L_p/b}}{\left(\frac{\mathcal{P}_t}{\eta} + \mathcal{P}_{ct} + n_R \mathcal{P}_{cr} + \mathcal{P}_{bb}\right)} \quad (\text{bits}/J). \quad (18)$$

To calculate EE of the fully cooperative OFDM system, the transmission scheme in Table 2 is considered. In the first (second) time slot, S_1 (S_2) broadcasts its own packet through its single TX antenna to n_R RX antennas of its partner as well as n_R RX antennas of the destination with the data rate R_b . The energy consumption in the first and second time slot can be approximated as

$$E_1 = E_2 \approx \frac{L_p}{R_b} \left(\frac{\mathcal{P}_t}{2\eta} + \mathcal{P}_{ct} + 2n_R \mathcal{P}_{cr} + 1.5\mathcal{P}_{bb} \right). \quad (19)$$

In Eq. (19), the factor $1/2$ of $\mathcal{P}_t$ reflects the fact that the signal power transmitted from each source node in one active time slot is half the power in the direct transmission. The factor $2n_R$ of $\mathcal{P}_{cr}$ is because the partner and the destination have total $2n_R$ RX antennas. The factor 1.5 of $\mathcal{P}_{bb}$ ($\mathcal{P}_{bb}$ is the baseband power consumption of one complete RF chain from TX to RX) approximates the power consumption of ‘one and a half’ complete RF chains, which includes the baseband processing blocks in a source node and those in the destination (one complete RF chain) plus those in the receiving partner (roughly half a complete RF chain).

Similarly, the energy consumption in the third time slot can be approximated as

$$E_3 \approx \frac{L_p}{R_b} \left(\frac{\mathcal{P}_t}{\eta} + 2\mathcal{P}_{ct} + n_R \mathcal{P}_{cr} + 1.5\mathcal{P}_{bb} \right). \quad (20)$$

In Eq. (20), $\mathcal{P}_t$ does not have the factor $1/2$ because S_1 and S_2 transmit simultaneously, which also explains the factor 2 of $\mathcal{P}_{ct}$. The factor n_R of $\mathcal{P}_{cr}$ indicates there are n_R RX antennas at the destination. The factor 1.5 of $\mathcal{P}_{bb}$ approximates the power consumption of ‘one and a half’ complete RF chain, which includes the baseband processing blocks in the two transmitting nodes and those in the destination. Thus the total energy required to transmit two packets is the sum of E_1 , E_2 and E_3 . The average total energy required to transmit one packet of L_p bits is

$$E_{total}^C = \frac{\sum_{j=1}^3 E_j}{2} \approx \frac{L_p}{R_b} \left(\frac{\mathcal{P}_t}{\eta} + 2\mathcal{P}_{ct} + 2.5n_R \mathcal{P}_{cr} + 2.25\mathcal{P}_{bb} \right). \quad (21)$$

Consequently, EE of the fully cooperative OFDM is

$$EE_C \approx \frac{R_b L_d}{L_p} \frac{(1 - P_C)^{L_p/b}}{\left(\frac{P_t}{\eta} + 2\mathcal{P}_{ct} + 2.5n_R\mathcal{P}_{cr} + 2.25\mathcal{P}_{bb}\right)} \quad (\text{bits}/J), \quad (22)$$

where P_C is calculated by Eq. (15) (with $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$). Eqs. (17) and (21) reveal that the energies required for RF transmission in both direct OFDM transmission and fully cooperative OFDM communication are the same for a fair comparison as a result of our transmission schemes mentioned in Table 2, but the energies required for TX and RX circuits and baseband processing are slightly increased in the cooperative network.

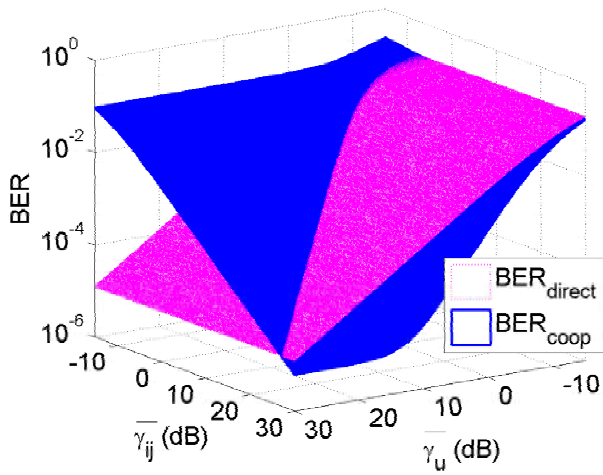
The EE gain achieved by the fully cooperative OFDM over the direct OFDM transmission is

$$G_{EE} = \frac{EE_C}{EE_D} = \left(\frac{1 - P_C}{1 - P_D}\right)^{L_p/b} \left(\frac{\frac{P_t}{\eta} + \mathcal{P}_{ct} + n_R\mathcal{P}_{cr} + \mathcal{P}_{bb}}{\frac{P_t}{\eta} + 2\mathcal{P}_{ct} + 2.5n_R\mathcal{P}_{cr} + 2.25\mathcal{P}_{bb}}\right). \quad (23)$$

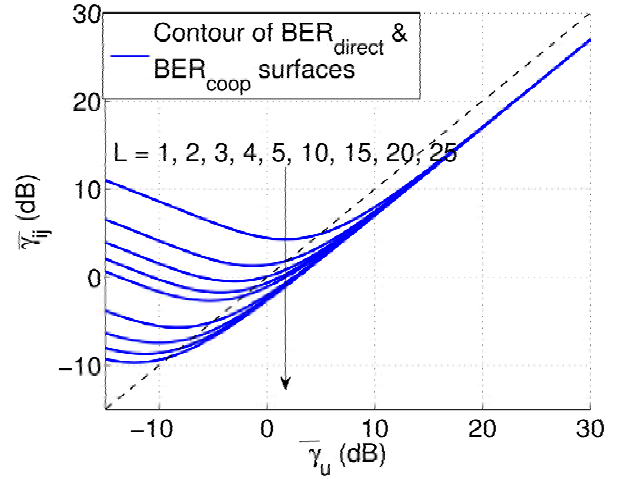
Note that P_D and P_C are functions of $\bar{\gamma}_{ij}$ and $\bar{\gamma}_u$, which are in turn calculated in dB as $\bar{\gamma}_{ij(u)} = 10 \log_{10}(\mathcal{P}_t) - L_{ij(u)} - N_0 + (G_T + G_R - L_c)$, where $L_{ij(u)}$ denotes the pathloss of the internode link (uplink), N_0 is the noise power, and G_T , G_R , L_c denote the TX antenna gain, RX antenna gain, and total loss of connectors at both TX and RX antennas. For simplicity, we assume $(G_T + G_R - L_c)$ to be the same for both internode links and uplinks. L_{ij} and L_u are functions of the distances d_{ij} and d_u , respectively. If internode links are the on-body to on-body communication links and the uplinks are the on-body to external links in WBANs, then L_{ij} can be estimated by the IEEE WBAN CM3 pathloss model while L_u follows the CM4 one [16].

5. Simulation Results and Discussions

This section presents various analytical and simulated results to verify our aforementioned theoretical analyses. The numerical analysis in this section shows that the fully cooperative OFDM system could be better than the direct OFDM transmission from both error performance and energy efficiency perspectives in many cases, especially at a lower SNR regime. Note that, due to the lack of existing performance analyses in the literature for the fully cooperative OFDM system in frequency selective Rayleigh fading channels (cf. Section 1), we will compare the fully cooperative



(a) Fully cooperative OFDM vs. direct OFDM transmission in a three-dimensional Cartesian coordinate system with $L = 20$ paths.



(b) Dependence of the contour of the two surfaces on the number of multipaths ($L = 1$ is corresponding to a Rayleigh flat fading channel).

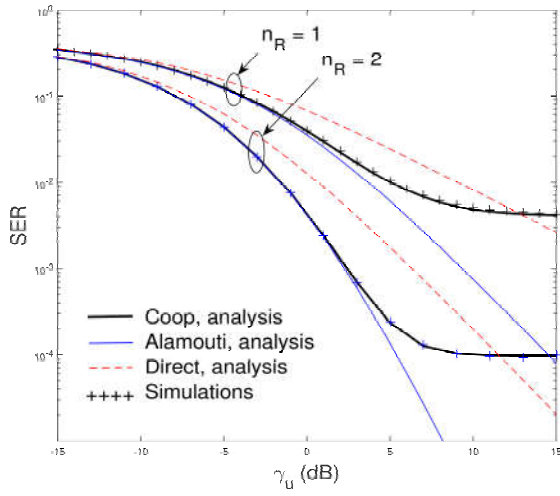
Fig. 4. BER performance of fully cooperative OFDM vs. direct OFDM transmission, with BPSK modulation, $\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$, $n_R = 1$, $N_{\text{FFT}} = 128$, and $N_{CP} = 32$ in multipath fading channels.

Table 3 Observations from Fig. 4(b).

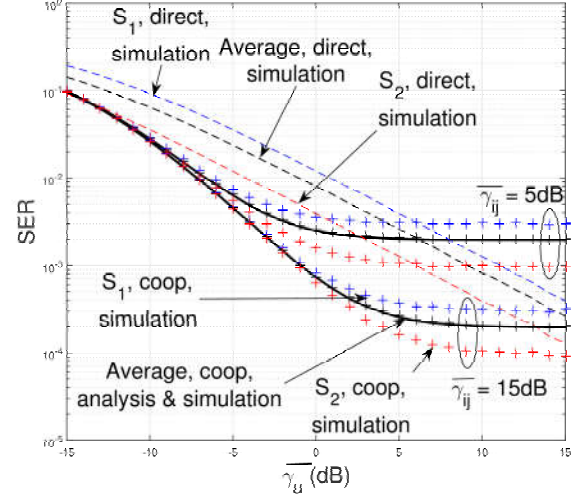
Observations	Interpretation and comments
Fully cooperative OFDM is better than direct OFDM transmission even when $\bar{\gamma}_{ij} < \bar{\gamma}_u$.	This can be seen by adding the dotted line presenting $\bar{\gamma}_{ij} = \bar{\gamma}_u$. The region between this dotted line and the contour is where the fully cooperative OFDM is better than the direct OFDM even $\bar{\gamma}_{ij} < \bar{\gamma}_u$.
Given $\bar{\gamma}_{ij}$ and $\bar{\gamma}_u$, one knows whether the fully cooperative OFDM could be useful.	If the point $(\bar{\gamma}_{ij}, \bar{\gamma}_u)$ is above the contour, the fully cooperative OFDM is useful and vice versa.

OFDM system with the two benchmark systems, namely the direct OFDM transmission system and the conventional Alamouti OFDM system.

Fig. 4(a) plots the SER (also BER) of the direct OFDM transmission system and the fully cooperative OFDM system, based on (13) and (15) with $M = 2$ (BPSK) and $n_R = 1$ in identically distributed multipath Rayleigh fading channels. For a given $\bar{\gamma}_u$, when $\bar{\gamma}_{ij}$ reaches a certain value, the cooperative system becomes better than the direct transmission, indicated by the P_C surface going under the P_D one. Fig. 4(b) plots the contour of the intersection between the P_D and P_C surfaces, which is the border between the region where the fully cooperative OFDM communication is better (above the contour) and the region where the direct OFDM transmission is better (below the contour). Two observations drawn from Fig. 4(b) are detailed in Table 3.



(a) Identically distributed fading ($\bar{\gamma}_{u1} = \bar{\gamma}_{u2} = \bar{\gamma}_u$), $\bar{\gamma}_{ij} = 10$ dB, BPSK, $n_R = 1$ and 2 , $L = 3$ paths.



(b) Non-identically distributed fading ($\bar{\gamma}_{u2} = \bar{\gamma}_{u1} + 5$ dB), $\bar{\gamma}_{ij} = 5$ and 15 dB, BPSK, $n_R = 1$, $L = 20$ paths.

Fig. 5. Error performance of the fully cooperative system in identically and non-identically distributed frequency selective Rayleigh channels.

Fig. 5(a) plots Eqs. (13)–(15) with BPSK and QPSK modulations with one and two RX antennas in identically distributed frequency selective Rayleigh fading channels. We consider a fixed value $\bar{\gamma}_{ij}$, e.g., $\bar{\gamma}_{ij} = 10$ dB, while varying $\bar{\gamma}_u$. For comparison, we also plot SERs of the direct OFDM transmission and the conventional Alamouti OFDM. From Fig. 5(a), four important observations are detailed in Table 4.

Fig. 5(b) presents the case of non-identically distributed frequency selective Rayleigh channels, which are generated based on the assumption that $\bar{\gamma}_{u2} = \bar{\gamma}_{u1} + 5$ dB. An example of non-identically distributed channels is when one among the two sensors is persistently impeded by obstacles, e.g., an identity card in the patient's pocket. Individual SERs of S_1 and S_2 as well as their average SER are benchmarked with those of the direct OFDM transmission from each node to the destination. The solid curves indicate the theoretical SER of the fully cooperative system (cf. Eq. (15)), while other curves are the simulation results. Two interesting observations can be made from Fig. 5(b). First, the error performance of each individual node is better than its own direct OFDM transmission at a low-to-medium SNR range if the node cooperates with its partner. **Second, the average error performance of the two nodes in the fully cooperative system is not only better**

Table 4 Observations from Fig. 5(a).

Observations	Interpretation and comments
Simulated SER curves fit well theoretical ones.	This confirms the validity of Eq. (15).
Given $\bar{\gamma}_{ij}$, there is no point to keep increasing $\bar{\gamma}_u$ because SER will be saturated at some point . This saturation does not appear in conventional Alamouti OFDM.	In the fully cooperative communication, a large value of $\bar{\gamma}_u$ almost nullifies P_A in Eq. (15), thus SER depends on $\bar{\gamma}_{ij}$ only. Conventional Alamouti OFDM does not involve in the information exchange between S_1 and S_2 .
Fully cooperative OFDM is better than direct OFDM transmission at a lower $\bar{\gamma}_u$ s.	The higher $\bar{\gamma}_{ij}$, the better the fully cooperative system.
Fully cooperative OFDM approaches conventional Alamouti OFDM at lower $\bar{\gamma}_u$ s.	Fully cooperative system approaches the full diversity order ^a (as the Alamouti OFDM). Typical WBAN applications work at low SNRs, making the fully cooperative system especially attractive.

^aUnlike in a conventional MIMO system, diversity order of the cooperative system is a function of both $\bar{\gamma}_{ij}$ and $\bar{\gamma}_u$. In this paper, it is considered as the slope of the SER curve with respect to $\bar{\gamma}_u$, given a certain value of $\bar{\gamma}_{ij}$.

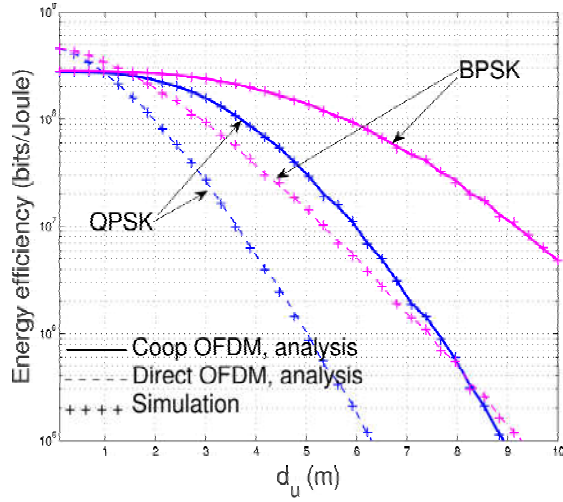
Table 5 Parameters for simulations of energy efficiency

Parameters	Values	Parameters	Values
PA efficiency	$\eta = 35\%$ [13], [15]	Packet length	$L_p = 176$ (22 octets)
Transmission power	$P_t = 470$ nW (if d_u fixed)	Payload length	$L_d = 128$ bits (16 octets)
Circuit power	$P_{ct} = 100$ nW, $P_{cr} = 80$ nW	Modulation	BPSK or QPSK
Baseband power	$P_{bb} = 50$ nW	PSD of noise	-174 dBm/Hz [15]
Frequency	900 MHz [16, p.7]	Pathloss model	IEEE WBAN model [16]
Bandwidth	25 MHz		Internode - CM3, uplinks - CM4
Data rate	$R_b = 1$ Mbps	Distances	$d_{ij} = 0.3$ m
$G_T + G_R - L_c$	2 dB		$d_u = 0.1 - 10$ m [16] (if P_t fixed)
FFT size	$N_{FFT} = 128$	No of multipaths	$L = 3$ or 20
Cyclic prefix	$N_{CP} = 32$	No of RX antennas	$n_R = 1$ or 2

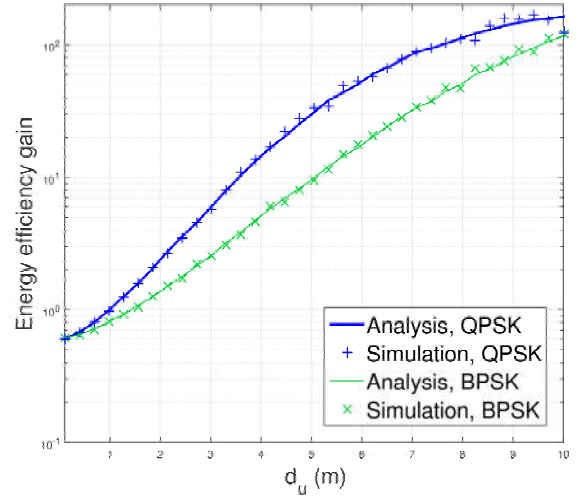
than that in the direct OFDM transmission, but may also be better than the best direct OFDM transmission performance among the two nodes at a low-to-medium SNR range. It is worth noting that two source nodes here can be considered as two different users in a more general multi-user WSN/WBAN scenario.

To evaluate EE of the fully cooperative OFDM communication, we consider a typical WBAN scenario with the simulation parameters listed in Table 5. Note that the actual radio hardware transmitting as low as some hundreds nW has been reported in the literature, such as [17].

Fig. 6(a) presents the analytical EE of the fully cooperative system (cf. Eq. (22)), indicated by the solid curves, and of the direct OFDM transmission (cf. Eq. (18)), indicated by the dashed curves, with $L = 3$ paths, $n_R = 1$, and either BPSK or QPSK. This figure shows EE as a function of the distance d_u from the sources to the destination, which could be up to 10 m for a typical



(a) EE .



(b) G_{EE} .

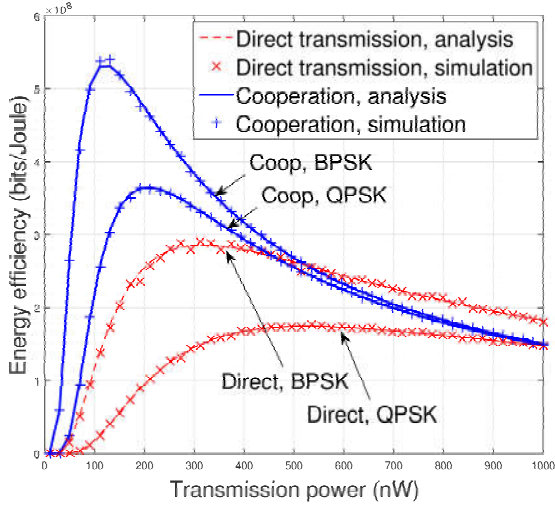
Fig. 6. Analytical and simulated EE and G_{EE} as functions of d_u with $n_R = 1$, BPSK and QPSK, and $L = 3$ paths.

Table 6 Observations from Fig. 6.

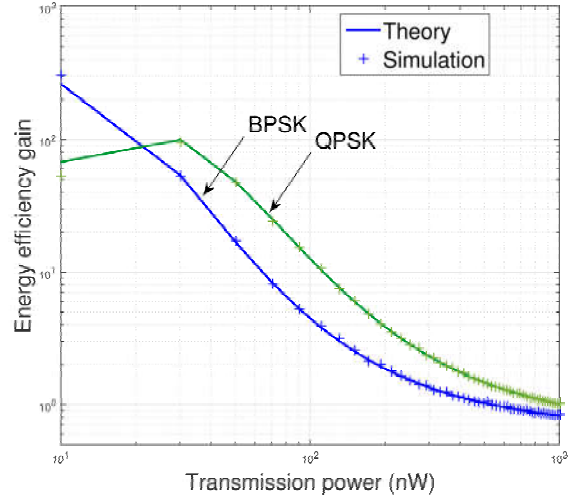
Observations	Interpretation and comments
Fully cooperative OFDM provides a much larger EE than direct OFDM transmission when d_u is large enough (1.4 m or further for $n_R = 1$ and BPSK)	This is another attractive feature of fully cooperative OFDM system, especially when $n_R = 1$, since d_u usually exceeds this distance in a typical WBAN application.
Because $\bar{\gamma}_u = 14.6$ dB at $d_u = 1.4$ m, fully cooperative OFDM is better than direct OFDM if $\bar{\gamma}_u < 14.6$ dB from EE perspective. From error performance perspective, it is better than the latter if $\bar{\gamma}_u < 13$ dB (cf. Fig. 5(a)).	Fully cooperative OFDM is better than direct OFDM from both perspectives if $\bar{\gamma}_u < 13$ dB. Similar observations hold for different n_R and M . This is an interesting discovery of the fully cooperative OFDM system ever known.

WBAN application. The simulated EE s of the two systems are also plotted to confirm the validity of Eqs. (18) and (22). Meanwhile, Fig. 6(b) presents the simulated EE gain (cf. Eq. (23)) achieved by the fully cooperative OFDM system over the direct OFDM transmission. From Fig. 6, we have two interesting observations as shown in Table 6.

Fig. 7 presents the analytical EE and the corresponding EE gain as functions of the transmission power $\mathcal{P}_t$. Interestingly, the fully cooperative OFDM system has a better EE than the direct OFDM transmission at the lower transmission power regime of few hundreds of nanowatts. This feature is very useful for WBAN applications where the maximum transmission power is regulated by rigorous regulations (e.g., $15.24\mu W$ EIRP (Effective Isotropic Radiated Power) by the European Telecommunications Standards Institute [18, p.21]).



(a) EE .



(b) G_{EE} .

Fig. 7. Analytical and simulated EE and G_{EE} as functions of $\mathcal{P}_t$ with $n_R = 1$, BPSK and QPSK, and $L = 20$ paths.

6. Conclusions

This paper has derived for the first time the exact SER for a decode-and-forward, space-time coded, fully cooperative OFDM system with arbitrary M-PSK modulation and an arbitrary number of RX antennas, in both identically and non-identically distributed frequency selective Rayleigh fading channels. Exact SERs have also been derived for the direct OFDM transmission and the conventional Alamouti OFDM, which have been used as the benchmarks. Further, the energy efficiencies of the three systems have also been analyzed. Throughout the paper, simulation results have been shown to match well and thus verify our theoretical analyses.

Our analyses and simulations have proved that the fully cooperative OFDM is better than the direct OFDM transmission in many cases, especially at a low power, low SNR regime (a typical working condition of WBANs) from both error performance and energy efficiency perspectives. This novel contribution of our paper provides answers to the commonly asked questions of whether, when and to what extent the fully cooperative OFDM communication would be useful, compared to the direct OFDM transmission. Inspired by WBAN applications, our analyses are also readily applied to generic Rayleigh wireless channels, such as in wireless IoT and indoor entertainment applications.

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