

Energy Savings in OFDM Systems through Cooperative Relaying

Ho Van Khuong and Hyung Yun Kong

Energy savings in orthogonal frequency division multiplexing (OFDM) systems is an active research area. In order to achieve a solution, we propose a new cooperative relaying scheme operated on a per subcarrier basis. This scheme improves the bit error rate (BER) performance of the conventional signal-to-noise ratio (SNR)-based selection relaying scheme by substituting SNR with symbol error probability (SEP) to evaluate the received signal quality at the relay more reliably. Since the cooperative relaying provides spatial diversity gain for each subcarrier, thus statistically enhancing the reliability of subcarriers at the destination, the total number of lost subcarriers due to deep fading is reduced. In other words, cooperative relaying can alleviate error symbols in a codeword so that the error correction capability of forward error correction codes can be fully exploited to improve the BER performance (or save transmission energy at a target BER). Monte-Carlo simulations validate the proposed approach.

Keywords: Cooperative relaying, selection relaying, OFDM, forward error correction codes.

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I. Introduction

The recently developed multiple antenna techniques have considerable potential to meet the challenges caused by fading channels together with power and bandwidth limitations [1]-[4]. These techniques, obtained by deploying antenna arrays at both transmitter and receiver, enable communications systems to exploit either high performance provided by spatial diversity available or high data-rate provided by the capacity available in multi-input multi-output channels, or both. However, a wireless device may not always be able to support multiple antennas due to size, cost, and hardware limitations [5]. This is the case for most handsets in current cellular networks or for the nodes of wireless sensor networks and mobile ad-hoc wireless networks [6]. These devices are usually small and light. If they are equipped with multiple antennas, the spatial separation between antennas must be at least half a wavelength to guarantee the statistical independence of faded signals for optimal performance [7]. For small devices, this spatial separation requirement is difficult to satisfy. Therefore, power utilization efficiency becomes a great priority in wireless devices, but the lightweight feature limits the power capability and signal processing that the devices can support.

Cooperative relaying (or cooperative communications) is a solution to overcome the above limitations [5]. It allows single-antenna devices to gain some benefits of spatial diversity without the need for physical antenna arrays. The philosophy is that in a multi-user network, two or more users share their information and transmit jointly as a virtual antenna array [8]-[10]. As a result, redundant messages are generated and delivered over multiple independent paths in the network. This redundancy enables the receiver to essentially average channel fluctuations, thus improving the communications performance

or saving transmission energy at a target bit error rate (BER) since the probability that all propagation paths to the destination are deeply faded is significantly reduced. In addition, cooperative relaying can extend coverage range thanks to path-loss reduction [11].

Orthogonal frequency division multiplexing (OFDM) modulation is a bandwidth-efficient technique to obviate inter-symbol interference by transmitting multiple narrowband subcarriers together and inserting a cyclic prefix [12]. However, in a multi-path fading channel, these subcarriers will experience different fading levels; thus, some subcarriers may be completely lost because of deep fades. Therefore, forward error correction coding across subcarriers is essential to correct errors of lost subcarriers up to a certain limit. To take the best advantage of the error correction capacity of forward error correction codes, we must find an additional solution to improve subcarriers statistically so that the total number of lost subcarriers can not exceed this limit. That is our motivation in applying cooperative relaying to enhance the reliability of subcarriers through spatial diversity. Indeed, since cooperative relaying provides spatial diversity gain for each subcarrier, thus statistically enhancing the reliability of subcarriers at the destination, the total number of lost subcarriers due to deep fading is reduced. In other words, cooperative relaying can alleviate error symbols in a codeword so that the error correction capability of forward error correction codes can be fully exploited to improve the BER performance (or save transmission energy at a target BER).

In this paper, we only consider dual-hop communications in OFDM systems with some wireless devices operated as relays using selection relaying [13]. Note that we limit our analysis to the physical layer. These relays operate very simply as shown in Fig. 1. They only multi-carrier demodulate their received signals to perform the selection relaying on each subcarrier without demapping, deinterleaving, or decoding as a conventional OFDM receiver does. To forward their data to the destination, they also need an OFDM modulator. Therefore, processing time and processing energy at relays are considerably alleviated.

The selection relaying means that the relay must make a decision whether to detect and forward source information to the destination [13]. Different performance criteria for making a decision at the relay were mentioned. In [14], a cyclic redundancy check is used but causes the waste of transmission bandwidth due to redundant information insertion. A more common alternative criterion without any loss of bandwidth efficiency is instantaneous signal-to-noise ratio (SNR) or the squared amplitude of the channel coefficient [13]. In SNR-based selection relaying, only received signals with quality exceeding a predetermined threshold are detected and

retransmitted to the destination.

Since SNR-based selection relaying only relies on instantaneous fading level and noise variance to decide retransmission without accounting for instantaneous noise level at the relay, it partially reflects characteristics of received signals. Based on a new symbol error probability (SEP) expression related directly to the reliability of received symbols derived recently in [15], we propose selection relaying based on SEP instead of SNR. Because the new SEP includes both instantaneous fading level and instantaneous noise level, SEP-based selection relaying mitigates the risk of error retransmission induced by the relay; thus, its BER performance is better than that of SNR-based selection relaying. This is confirmed by a variety of Monte-Carlo simulations.

The rest of this paper is organized as follows. Section II presents the proposed cooperative relaying in OFDM systems. Monte-Carlo simulations are performed in section III to verify its validity and to compare the reference communications schemes. Finally, the paper is concluded in section IV.

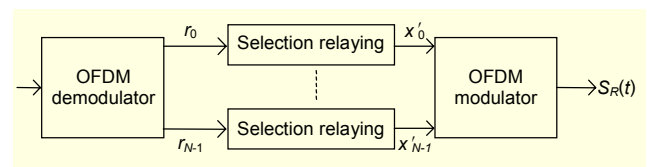


Fig. 1. Baseband block diagram of a relay transceiver.

II. Proposed Cooperative Relaying

Consider dual-hop cooperative relaying in OFDM systems where information is transmitted from a source (S) to a destination (D) with the assistance of a relay (R) as shown in Fig. 2. All wireless devices equipped with single-antenna transceivers and sharing the same frequency band are under investigation. Each wireless device transmits and receives signals at different times to mitigate implementation complexity since considerable attenuation over wireless channels and insufficient electrical isolation between transmit and receive circuitry make a wireless device's transmitted signal dominate the signals of the others at its receiver input. Towards this end, we adopt time division multiplexing for channel access in this paper.

Cooperative relaying includes two phases of equal duration in order to retain the parameters of the conventional OFDM systems such as the number of subcarriers and the cyclic prefix duration. Thus cooperative relaying only brings performance improvement or energy savings without significantly changing the OFDM transceiver structure or increasing the implementation complexity. The source uses the first phase for its data transmission and the relay performs selection relaying in the second phase.

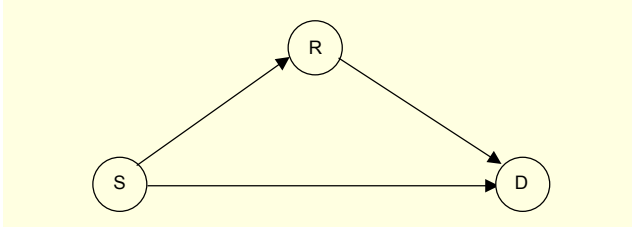


Fig. 2. Cooperative relaying model.

1. Signal Processing at the Source

All signal processing operations at the source take place in the first phase. A baseband block diagram of its transmitter is shown in Fig. 3. Binary data is first encoded by a forward error correction code. The encoded data is then interleaved and mapped onto complex symbols, namely, M -ary quadrature amplitude modulation (M -QAM) or M -ary phase shift keying (M -PSK). The interleaving is to randomize error bursts that occur when successive subcarriers are lost in a deep fade. Finally, the complex symbols are serial-to-parallel converted before they are modulated using an OFDM modulator. Note that for simplicity without loss of generality, Fig. 3 only plots the useful signal processing blocks but does not mention other blocks, such as pilot insertion.

The equivalent low-pass transmitted signal can be written as

$$s_s(t) = \sum_{n=0}^{N-1} \sqrt{\frac{E_S}{NT}} x_n e^{j2\pi \frac{n}{T_S} t}, \quad 0 \leq t \leq T, \quad (1)$$

where x_n is the complex symbol of unit average power (that is, $E[x_n^2]=1$ with $E[\cdot]$ denoting expectation) transmitted at subcarrier n , N the total number of subcarriers of the OFDM modulator, E_S the average OFDM symbol energy, T_S the complex symbol duration, and T the total OFDM symbol duration, with $T - T_S = T_{CP}$ being a cyclic prefix duration inserted between consecutive OFDM symbols to eliminate the inter-symbol interference due to the channel delay spread.

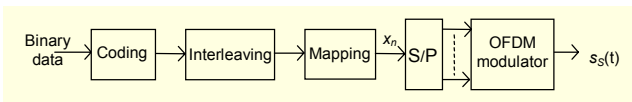


Fig. 3. Baseband block diagram of a source transmitter.

2. Fading Channel Model

We consider a multi-path fading channel with a coherence bandwidth smaller than the total bandwidth of the OFDM system, thus seen as frequency selective fading. We also assume that the fading process is stationary and slowly varying compared with the OFDM symbol duration. It is

approximately constant during one symbol duration T but independently changes to the next. Because of slow fading, accurate channel estimation is possible at receivers [16], [17]. Therefore, we will assume perfect channel state information at all the respective receivers but not at the transmitters.

The complex equivalent low-pass time-variant impulse response of the channel between transmitter i and receiver j can be written as

$$h_{ij}(t) = \frac{K}{d_{ij}^{\beta/2}} \underbrace{\sum_{l=1}^{L_{ij}} \alpha_{ij,l}}_{F_2} \delta(t - \tau_{ij,l}), \quad (2)$$

where L_{ij} is the number of resolvable paths, $\tau_{ij,l}$ the time delay of the l -th path, $\alpha_{ij,l}$ an independent complex Gaussian random variable tap weight, d_{ij} the distance between transmitter i and receiver j , β the path-loss exponent, K a constant that depends on the environment, and $\delta(\cdot)$ the Dirac delta function; $i \in \{S, R\}$ and $j \in \{R, D\}$ hereafter. We further assume that

$$\sum_{l=1}^{L_{ij}} \mathbf{E} \left[|\alpha_{ij,l}|^2 \right] = 1.$$

Note that in (2), we captured the effect of relay geometry in the cooperative relaying by assuming that the channel is composed of long-term path-loss F_1 and short-term Rayleigh fading F_2 [18].

3. Signal Processing at the Relay

A baseband block diagram of a relay transceiver is shown in Fig. 1. After OFDM demodulation, the output sample at subcarrier n and time instant T can be given by

$$r_n = H_{SR,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} x_n + n_{SR,n}, \quad 0 \leq n \leq N-1, \quad (3)$$

where

$$H_{SR,n} = \frac{K}{d_{SR}^{\beta/2}} \sum_{l=1}^{L_{SR}} \alpha_{SR,l} e^{-j2\pi m \tau_{SR,l} / T}$$

is the attenuation coefficient due to the source-relay channel at subcarrier n , $n_{SR,n}$ is a zero-mean complex Gaussian noise sample with variance N_R at the relay, and the ratio T_{CP}/T represents the percentage of energy loss due to cyclic prefix insertion. Then, the resultant signals r_n are processed in parallel by selection relaying blocks. Their function is to evaluate the quality of r_n and to check whether it satisfies a predetermined requirement. If this is the case, the selection relaying block n outputs the detected complex symbol x'_n . Otherwise, it assigns $x'_n=0$.

The relay detects the source symbols x_n using the maximum likelihood decision rule:

$$x'_n = \arg \max_{q_m \in \{q_1, q_2, \dots, q_M\}} \Pr(r_n | x_n = q_m, H_{SR,n}) \quad (4)$$

with q_m being the m -th M -ary signal in signal constellation, $m \in \{1, 2, \dots, M\}$ and

$$\Pr(r_n | x_n = q_m, H_{SR,n}) = \frac{1}{\pi N_R} \exp \left(-\frac{1}{N_R} \left| r_n - H_{SR,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} q_m \right|^2 \right). \quad (5)$$

Finally, the symbols x'_n are input to the OFDM modulator to generate the transmitted signal as

$$s_R(t) = \sum_{n=0}^{N-1} \sqrt{\frac{E_S}{NT}} x'_n e^{j2\pi \frac{n}{T} t}, \quad 0 \leq t \leq T. \quad (6)$$

The signal in (6) is sent to the destination in the second phase.

We realize that the proposed transceiver structure of the relay makes it consume much less signal processing energy and process signals faster than the source for the following reasons. First, there are not operations of demapping, deinterleaving, decoding, encoding, interleaving, or mapping. Therefore, the processing time at the relay is significantly reduced, leading to less processing energy consumption. Moreover, the absence of these operations shows that the implementation complexity at the relay is negligible. Second, the average number of subcarriers which carry the information ($x'_n \neq 0$) in the second phase is less than the total number of subcarriers N allocates to each device because some subcarriers may be deeply faded and therefore do not satisfy the predetermined requirement. Consequently, transmission energy savings is obtained due to the absence of transmission of idle subcarriers. It is well-known that a device spends most of its energy on signal transmission rather than signal processing [6]; therefore, transmission energy savings on idle subcarriers is important, especially for small light devices.

Two methods can be used by the relay to make a decision on whether to detect the source symbols x_n . The predetermined requirement is that the instantaneous SEP must be below a predetermined threshold, T_{SEP} . The first method, CSR, is based on SNR, which is applied in the conventional selection relaying. And the second method, PSR, is based on SEP which is our proposal.

A. Based on SNR (CSR)

Since the symbol error probability of any modulation scheme is a monotonically decreasing function $g(\cdot)$ in SNR, the

condition $\{\text{SEP} \leq T_{SEP}\}$ is equivalent to the condition $\{\text{SNR} \geq T_{SNR}\}$, where $T_{SNR} = g^{-1}(T_{SEP})$ with $g^{-1}(\cdot)$ being an inverse function of $g(\cdot)$. The reason we turn attention from $\{\text{SEP} \leq T_{SEP}\}$ to $\{\text{SNR} \geq T_{SNR}\}$ is that $g(\cdot)$ is usually a complicated function or integral, while the relay does not need to be equipped with powerful mathematical processors to calculate it for each instantaneous SNR.¹⁾ For example, the SEP of M -PSK modulation is given in [19] as

$$T_{SEP} = g(T_{SNR}) = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \exp \left(-\frac{T_{SNR} \sin^2(\pi/M)}{\sin^2 \theta} \right) d\theta. \quad (7)$$

Given T_{SEP} , finding T_{SNR} in (7) is straightforward using numerical methods. Then, T_{SNRS} corresponding to T_{SEPS} can be stored in a look-up table for later use.

The SNR-based selection relaying performs as follows. It first calculates the received SNR γ_n for each subcarrier n according to (3): $\gamma_n = |H_{SR,n}|^2 (E_S (1 - T_{CP}/T)/N)/N_R$. Then it detects x_n according to (4) if $\gamma_n \geq T_{SNR}$. Otherwise, it assigns $x'_n = 0$. Consequently, data retransmission of the relay only depends on the instantaneous fading level $H_{SR,n}$ and the noise variance N_R regardless of the instantaneous noise level $n_{SR,n}$ in (3). Therefore, it partially reflects characteristics of the received signal. Thus in several cases, the condition based on SNR does not guarantee that the relay can detect the source symbols reliably at a previously desired degree. As a result, if the relay resends incorrectly detected symbols, the cooperation can be detrimental to the eventual detection of symbols at the destination.

B. Based on SEP (PSR)

In [15], the conditional SEP was derived, given $H_{SR,n}$ and r_n , as

$$\Pr(x_n \neq x'_n | r_n, H_{SR,n}) = 1 - \frac{1}{\sum_{m=1}^M e^{-\Lambda_m}}, \quad (8)$$

where the reliability of symbol q_m is given by

$$\Lambda_m = \frac{\left| r_n - H_{SR,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} q_m \right|^2 - \left| r_n - H_{SR,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} x'_n \right|^2}{N_R}. \quad (9)$$

Given (8), we propose selection relaying based on the SEP as follows. First, the relay computes the SEP in (8), and then decides to forward x'_n on the subcarrier n in (4) if

¹⁾ By "SNR-based selection relaying," we actually mean SNR with average noise statistics rather than instantaneous ones.

$$\Pr(x_n \neq x'_n | r_n, H_{SR,n}) \leq T_{SEP}. \quad (10)$$

Otherwise, it assigns $x'_n=0$.

From (8)-(10), we realize that the proposed SEP-based selection relaying is different from the conventional SNR-based selection relaying in that the condition of retransmitting x'_n in (4) accounts for both fading and noise terms embedded in r_n since $\Pr(x_n \neq x'_n | r_n, H_{SR,n})$ is a function of r_n and $H_{SR,n}$. Therefore, if (10) holds, the probability that x_n is successfully detected by the relay at a previously desired degree is rather high. As a result, it is expected that the error retransmission caused by the relay will be reduced significantly; therefore, the proposed SEP-based selection relaying will result in better performance than the SNR-based selection relaying.

Note that there is a small difference in the order of testing the received signal quality and detecting the source symbols between CSR and PSR. In CSR, testing $\gamma_n \geq T_{SNR}$ is followed by detecting x_n in (4). In PSR, detecting x_n in (4) which results in x'_n for use in calculating $\Pr(x_n \neq x'_n | r_n, H_{SR,n})$ in (8) is followed by testing $\Pr(x_n \neq x'_n | r_n, H_{SR,n}) \leq T_{SEP}$.

By observing (5) and (9), we can rewrite (8) as

$$\Pr(x_n \neq x'_n | r_n, H_{SR,n}) = 1 - \frac{A}{\sum_{m=1}^M \Pr(r_n | x_n = q_m, H_{SR,n})}, \quad (11)$$

where $\Pr(r_n | x_n = q_m, H_{SR,n})$ is given in (5) and A is a constant conditioned on x'_n :

$$A = \frac{\exp\left(-\frac{1}{N_R} \left| r_n - H_{SR,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} x'_n \right|^2\right)}{\pi N_R}. \quad (12)$$

From (4), (11), and (12), it is realized that $\Pr(x_n \neq x'_n | r_n, H_{SR,n})$ in (8) can be found immediately after the detection of x_n has been completed since $\Pr(r_n | x_n = q_m, H_{SR,n})$ are common terms of both (4) and (11). According to the order of test-and-detect, if the received signal quality at the relay is good enough (that is, if the predetermined requirement is satisfied and the detection of x_n takes place), the processing time and the processing energy of PSR and CSR are approximately equal. Otherwise, PSR takes more time to test the received signal quality than CSR, especially for large constellation sizes.

4. Signal Processing at the Destination

A baseband block diagram of a destination receiver is shown in Fig. 4. Since the destination receives signals from both the source and the relay, the output sample of the OFDM demodulator at subcarrier n in phase p ($p \in \{1, 2\}$) is denoted

by $r_{n,p}$. Its form is given by (3), that is,

$$r_{n,1} = H_{SD,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} x_n + n_{SD,n}, \quad (13)$$

$$r_{n,2} = H_{RD,n} \sqrt{\frac{E_S}{N} \left(1 - \frac{T_{CP}}{T}\right)} x'_n + n_{RD,n}, \quad (14)$$

where

$$H_{SD,n} = \frac{K}{d_{SD}^{\beta/2}} \sum_{l=1}^{L_{SD}} \alpha_{SD,l} e^{-j2\pi m \tau_{SD,l}/T},$$

$$H_{RD,n} = \frac{K}{d_{RD}^{\beta/2}} \sum_{l=1}^{L_{RD}} \alpha_{RD,l} e^{-j2\pi m \tau_{RD,l}/T},$$

and $n_{SD,n}$ and $n_{RD,n}$ are zero-mean complex Gaussian noise samples with variance N_D at the destination.

The destination combines $r_{n,1}$ and $r_{n,2}$ based on maximum ratio combining (MRC) [20] to result in y_n as²⁾

$$y_n = H_{SD,n}^* r_{n,1} + H_{RD,n}^* r_{n,2}. \quad (15)$$

The combining technique in (15) yields spatial diversity gain for subcarriers because when subcarriers are not lost due to the fading of the source-relay channel, the relay detects correctly and resends versions of the source symbols over an uncorrelated channel to the destination. In addition, cooperative relaying benefits from path-loss reduction. The relay located between the source and the destination will receive the information transmitted by the source much more reliably than the destination.

The above advantages which cooperative relaying brings significantly contribute to the overall performance improvement at the destination. This is obvious because the symbols which are precisely detected at the relay may reduce the total number of error symbols in a codeword at the destination through spatial diversity; thus, the error correction capability of some code is fully exploited to mitigate the error probability.

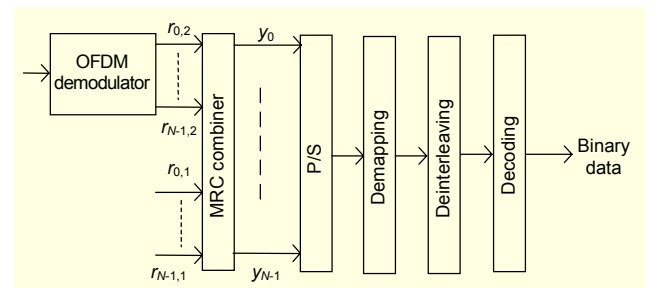


Fig. 4. Baseband block diagram of a destination receiver.

2) When $x'_n=0$, the term $r_{n,2}$ in (15) is considered as zero. This case is recognized since the destination can detect the presence of x'_n by measuring the received signal strength at the corresponding subcarrier n in the second phase.

In order to restore the binary data of the source, the destination performs the reverse operations of the source transmitter including parallel-to-serial conversion, demapping, deinterleaving, and decoding.

Since, in the first phase, the destination-only multi-carrier demodulates the signals received from the source and stores them in the buffer without performing any other operation such as demapping, deinterleaving, or decoding, the structure and the implementation complexity of its receiver are almost the same as those of the conventional OFDM receivers. In other words, cooperative relaying can bring performance enhancement without increasing system complexity.

III. Simulation Results

In this section, we describe Monte-Carlo simulations to evaluate the BER performance of the proposed system. The complex baseband-equivalent model is used for simulations. For illustrative purpose, we chose simulation parameters: the number of subcarriers $N=8$, (n, k) Reed-Solomon code (the code rate is k/n), a block interleaver operating on an 8×8 block of 64 symbols where input symbols are written in a matrix row-by-row and read out column-by-column, 8-PSK modulation ($M=8$), and equal noise variances at the relay and the destination ($N_R=N_D=N_0$).

We consider a two-path slowly varying channel model with equal power split between the paths and delays: $\tau_{ij,1}=0$, $\tau_{ij,2}=0.1T$. We also assume all source-relay, relay-destination, and source-destination channels follow this power delay profile for simplicity of exposition. To completely suppress the inter-symbol interference, the cyclic prefix duration T_{CP} must be larger than the maximum channel delay spread $\tau_{ij,2}$. Therefore, we adopt $T_{CP}=0.15T$.

The network geometry is examined where the relay lies on a straight line between the source and the destination [21]. The source-destination distance is normalized to 1. We also denote the source-relay distance as d . Moreover, we only consider $K=1$ in (2).

We compare the BER performance of five communication schemes with the same average OFDM symbol energy for both the source and the relay, and approximately equal bandwidth efficiency. Bandwidth efficiency here is defined as the number of bits per modulated symbol. For example, a system with (n, k) Reed-Solomon code and M -PSK modulation obtains the bandwidth efficiency of $k \log_2(M)/n$ bits/symbol.

- The first scheme is direct transmission (DT). Data transmission from the source to the destination is not assisted by the relay and only takes place in one phase. In

this scheme, the source encodes the data with $(5, 1)$ Reed-Solomon code; thus, its bandwidth efficiency is 0.6 ($=\log_2(8)/5$) bits/symbol. The remaining four schemes require two phases, leading to their bandwidth efficiency of $k \log_2(M)/n/2$ bits/symbol where the factor 1/2 reflects the bandwidth efficiency loss of cooperative relaying (2 phases) compared to the direct transmission (1 phase). In order to compensate for such a loss, they use the $(7, 3)$ Reed-Solomon code; thus, the bandwidth efficiency is 0.643 ($=3 \log_2(8)/7/2$) bits/symbol.

- The second scheme is multi-hop transmission (MH). Direct transmission between the source and the relay is followed by direct transmission between the relay and the destination, without diversity combining.
- The third scheme is conventional SNR-based selection relaying (CSR).
- The fourth scheme is the proposed SEP-based selection relaying (PSR).
- The last scheme is direct transmission with additional repetition coding (DTRC). The source transmits the same data directly to the destination in both phases and the destination invokes the maximum ratio combining of the received signals in the first phase and the second phase on a per subcarrier basis. Without channel coding, it is obvious that DTRC obtains the diversity order of 2 due to the time diversity.

Note that three schemes—CSR, PSR, and DTRC—have identical receiver structures at the destination and attain the same diversity order. In addition, with the above simulation parameters, the two-phase communications schemes have slightly higher bandwidth efficiency than DT.

It is difficult to analyze quantitatively the computational complexity and the signal processing energy of these five schemes since DT uses the low code rate while the others use the high rate but with additional signal processing in the second phase. Moreover, as mentioned in section II, most of the energy a device consumes is due to signal transmission rather than signal processing. Consequently, we only focus on comparing their average two-phase transmission energies.

Since the source and the relay transmit the signals with the equal average OFDM symbol energy, E_S , the average two-phase transmission energy is $2E_S$ for DT, MH, and DTRC while that of PSR and CSR is $E_S(1+n_C/N)$, where n_C is the average number of active subcarriers in the second phase, $C \in \{\text{PSR}, \text{CSR}\}$. Clearly, cooperative relaying (PSR and CSR) can save the two-phase transmission energy compared to DT, MH, and DTRC. This is also illustrated in Fig. 5 with $\beta=4$, $d=0.4$, and $T_{SEP}=10^{-3}$. Note that the y-axis represents the average two-phase transmission energy-to-noise ratio, that is, $2E_S/N_0$ for

DT, MH, DTRC, and $E_S(1+n_C/N)/N_0$ for PSR and CSR. We observe that CSR consumes the least energy among the considered communication schemes and the consumed energy difference between CSR and PSR is less than 0.5 dB. Moreover, the gap in energy consumption between DT (or MH, DTRC) and CSR (or PSR) is reduced when E_S/N_0 increases. For example, this gap is 1 dB at E_S/N_0 of 12 dB while around 0 dB at E_S/N_0 of greater than 20 dB. This is obvious because when E_S/N_0 increases, the relay is likely to receive information from the source more reliably; thus, it uses almost all subcarriers available or $n_C \approx N$.

Digital communication demands high quality of service and a BER of considerable interest is usually less than 10^{-3} . As such, we only pay attention to the range of E_S/N_0 in which the BER of the five communication schemes can be less than 10^{-3} .

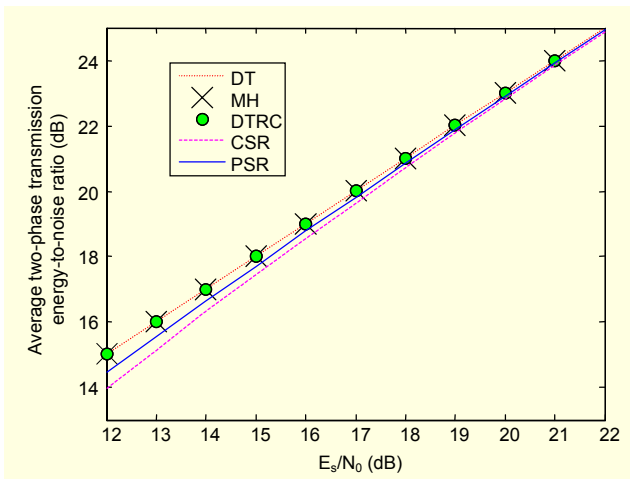


Fig. 5. Average two-phase transmission energy-to-noise ratio comparison among DT, MH, DTRC, CSR, and PSR ($\beta=4$, $d=0.4$, and $T_{SEP}=10^{-3}$).

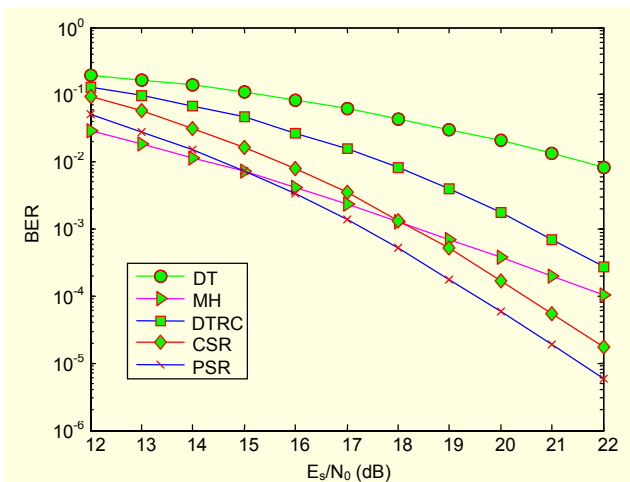


Fig. 6. BER comparison among DT, MH, DTRC, CSR, and PSR ($\beta=4$, $d=0.4$, and $T_{SEP}=10^{-3}$).

Figure 6 compares the BER performance of the communication schemes with $\beta=4$, $d=0.4$, and $T_{SEP}=10^{-3}$. It clearly demonstrates that three communications schemes, namely, DTRC, CSR, and PSR achieve the same diversity order as do DT and MH. In addition, the proposed scheme, PSR, performs the best in the BER range of interest (less than 10^{-3}) and dramatically better than DT even though DT employed the forward error correction code of lower code rate. For example, the average OFDM symbol energy-to-noise ratios E_S/N_0 required to attain a BER of 10^{-3} are 17.3 dB, 18.3 dB, 18.5 dB, and 20.6 dB for PSR, CSR, MH, and DTRC, respectively. From Fig. 5 (by zooming out), the average two-phase transmission energy-to-noise ratios corresponding to E_S/N_0 of 17.3 dB, 18.3 dB, 18.5 dB, and 20.6 dB for PSR, CSR, MH, and DTRC are 20.1 dB, 21.1 dB, 21.5 dB, and 23.6 dB, respectively. Therefore, at the target BER of 10^{-3} , PSR can save the average two-phase transmission energy of 1 dB, 1.4 dB, and 3.5 dB over CSR, MH, and DTRC, respectively. Moreover, PSR provides further improvement with increasing E_S/N_0 . This is because PSR benefits from spatial diversity gain and path-loss reduction.

Figures 5 and 6 demonstrate that cooperative relaying in OFDM systems can save transmission energy compared to the conventional communications schemes in the BER range of interest because it reduces transmission energy at the relay and improves BER performance. However, transmission energy reduction at the relay thanks to some idle sub-carriers is unexpected in cooperative relaying since this does not help to statistically improve the reliability of subcarriers at the destination. What causes some subcarriers to be idle is high path-loss, leading to the received signals at the relay not meeting the predetermined condition by PSR and CSR. The path-loss is controlled in part by the path-loss exponent β . The smaller the β , the more severe the path-loss (since we are considering a source-relay distance of less than 1). In order to quantitatively examine the impact of β on the energy saving efficiency of cooperative relaying, Figs. 7 and 8 illustrate the average two-phase transmission energy-to-noise ratios and the BER performances of all communication schemes for $\beta=3$, $d=0.4$, and $T_{SEP}=10^{-3}$. In this case, transmission energy at the relay is decreased compared to the previous case of $\beta=4$ as shown in Fig. 7. Specifically, the transmission energy difference between PSR and CSR, and between PSR and DT (or MH, DTRC) is approximately 1 dB at E_S/N_0 of 12 dB, and this difference reduces as E_S/N_0 increases. This phenomenon is obvious due to the severity of the path-loss leading to the received signal quality at the relay not exceeding the requirement. As such, the relay may not be able to provide a second diversity path for some subcarriers so that combining the received signals in both phases on a per subcarrier basis at

the destination can yield spatial diversity gain. Consequently, the BER performance of the cooperative relaying schemes is degraded as shown in Fig. 8 but shows drastic improvement over DT across the whole range of E_s/N_0 . Specifically, the average OFDM symbol energy-to-noise ratios E_s/N_0 required to attain a BER of 10^{-3} are 19.1 dB, 20.3 dB, 20.7 dB, and 20.6 dB for PSR, CSR, MH, and DTRC, respectively. From Fig. 5, the average two-phase transmission energy-to-noise ratios corresponding to the E_s/N_0 of 19.1 dB, 20.3 dB, 20.7 dB, and 20.6 dB for PSR, CSR, MH, and DTRC are 21.8 dB, 22.9 dB, 23.7 dB, 23.6 dB, respectively. Therefore, at the target BER of 10^{-3} , PSR can save the average two-phase transmission energy of 1.1 dB, 1.9 dB, and 1.8 dB (note that in the case of $\beta=4$, these numbers are 1 dB, 1.4 dB and 3.5 dB) over CSR, MH, and DTRC. These statistics show that for small β , PSR's superiority to CSR and MH increases but that to DTRC decreases.

IV. Conclusion

In this paper, we first proposed applying a new performance index for evaluating the reliability of a received signal, the symbol error probability expression in (8), to selection relaying. Then we analyzed the performance of dual-hop communications between a source and a destination with the assistance of a relay in OFDM systems based on the proposed SEP-based cooperative relaying. Transceiver diagrams of the source, the relay, and the destination were also presented. Simulation results showed that PSR saves transmission energy over the conventional communication schemes such as DT, MH, DTRC, and CSR under the same average OFDM symbol energy for both the source and the relay and approximately equal bandwidth efficiency without increasing the implementation complexity. Since PSR is a very simple but energy-efficient scheme, it should be considered a promising technical solution for cooperative relaying in future networks to improve the quality of information transmission and extend the coverage area as well.

The purpose of testing the received signal quality at the relay in PSR is to limit error retransmission to the destination. In general, the small threshold T_{SEP} is enough to achieve this purpose. However, which T_{SEP} is optimum is still an open question. In addition to equally allocating transmission energy for the source and the relay as presented in this paper, we can perform optimum transmission energy allocation for them. In doing so, we expect a further performance improvement. Nevertheless, in order to solve these two problems to complete the framework of PSR, we need to establish its closed-form BER expression and then optimize the arguments of this expression to obtain the desired quantities. This is challenging and needs further research.

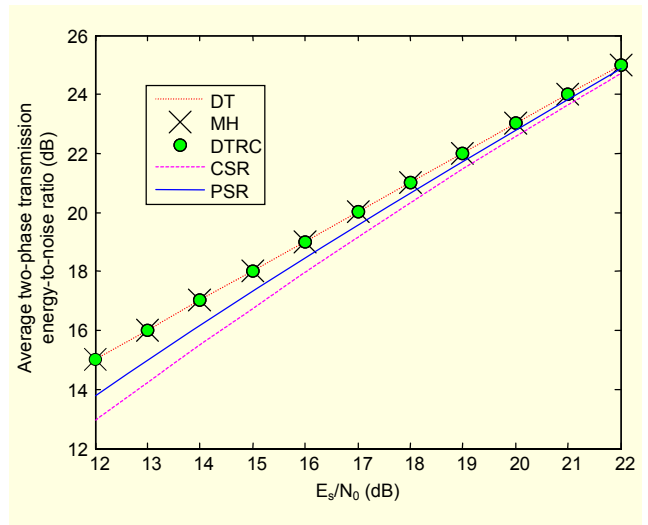


Fig. 7. Average two-phase transmission energy-to-noise ratio comparison among DT, MH, DTRC, CSR, and PSR ($\beta=3$, $d=0.4$, and $T_{SEP}=10^{-3}$).

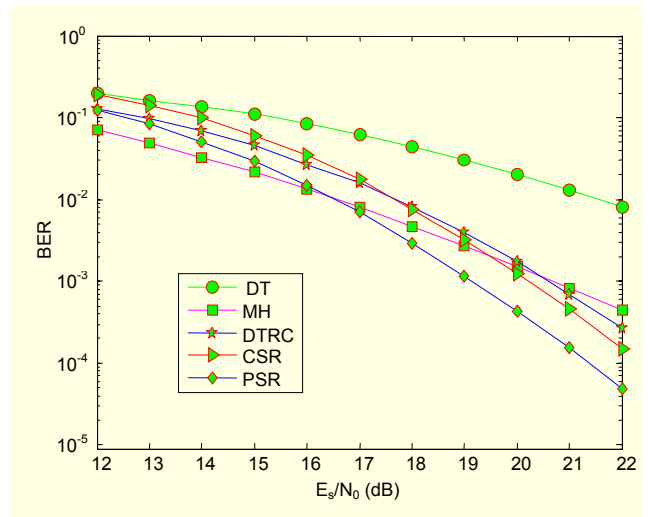


Fig. 8. BER comparison among DT, MH, DTRC, CSR, and PSR ($\beta=3$, $d=0.4$, and $T_{SEP}=10^{-3}$).

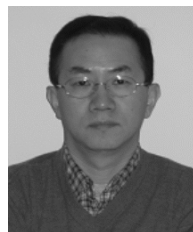
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