Decode-and-Forward Cooperative Communications: Performance Analysis with Power Constraints in the Presence of Timing Errors

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Abstract. Applying cooperative techniques for saving transmit power and the related performance analysis with timing synchronization errors is discussed in this paper. The performance of a three-node decode-and-forward, power constrained, cooperative communication system over Rayleigh fading channels with timing synchronization error is considered here. The synchronization capabilities at the three nodes (the source, relay and destination), depending on the synchronization technique, number of samples used and the signal-to-noise-ratio at the nodes, play a vital role in the achievable overall quality of service (Bit error rate in this case) of the cooperative system. We present some simulation results to study and compare the performance using a computationally friendly near maximum likelihood timing synchronization method with signal-to-noise-ratio combining (SNRC) technique for the non-cooperative and cooperative scenarios. Our results show that power allocations at the source and relay nodes for transmissions, and the related timing errors at the relay and the destination nodes have some considerable effect on the bit error rate performance for power constrained cooperative communications.

Keywords: decode-and-forward, timing error, power allocation, green communications, power constraint.

1 Introduction

The paradigm shift towards green communication for developing power efficient communication systems has currently attracted many stakeholders such as manufacturers, vendors and telco-operators. Green communications can save cost by optimizing the power usage in wireless communication systems. The current 3G systems have a tendency to rapidly dissipate energy in the mobile devices due to the power hungry applications which is of great concern considering that such

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devices depend on batteries for their energy. The future 4G devices are expected to be always connected supporting higher data rates and multiple radios also requiring more and more power. To advance in these directions with the motivation of saving power in wireless systems many research issues are required to be addressed.

Therefore, in the recent past, cooperative networks have been strongly proposed to provide power efficient wireless systems at the expense of additional complexity and other overheads [1–3]. In this paper we present cooperative communication techniques for saving power and the related performance considering the timing synchronization issues in cooperative systems. Depending on the timing synchronization technique and the other related parameters which affect synchronization performance at a particular receiver the overall energy efficiency in cooperative systems can be affected. To the knowledge of the authors no research work has addressed such issues prior to this work considering synchronization errors and related power efficiency in cooperative wireless systems.

On the other hand, we provide some literature review addressing the synchronization issues in cooperative wireless networks. The analytical and numerical results outlining substantial performance degradation due to synchronization errors in a cooperative system have been reported in [4–8]. In [4] the effect of timing synchronization errors in a cooperative multiple input single output (MISO) system is investigated considering relays to destinations links only and it is found that if the timing errors are large, the benefit of the cooperation would even vanish in terms of diversity gain. In [6] it is shown that although the performance of parallel relays for relays to destinations links deteriorates gracefully when synchronization errors are small, the performance degradation is large when synchronization errors are large. The bit-error-rate (BER) degradation for static timing errors for a detect-and-forward cooperative communications for larger signal constellations are shown numerically in [8]. Power constraints for cooperative communications when there are timing errors received much less attention. However, power allocations for cooperative communications with perfect timing were addressed by many researchers [9–11]. Equal power allocation is in general not optimum in cooperative communications. A power allocation scheme for cooperative communication system over channels with path loss and fading for exact timing is demonstrated in [9]. An optimum power allocation is given in [10] based on symbol error rate (SER) performance analysis for exact timing. Outage probability based power allocation algorithm is presented in [11].

In this paper, we consider a three-node decode-and-forward cooperative communications operating under Rayleigh fading channels under certain power constraints. We consider signal-to-noise-ratio combining (SNRC). Timing errors are considered for each communication links which degrade the performance, where as equal power allocations seems to be not the optimal solution when there are timing errors.

The rest of the paper is organized as follows. In the next section we present the system model. Power constraints in cooperative and non-cooperative scenarios are presented in Section 3. Section 4 describes a non-data-aided near maximum

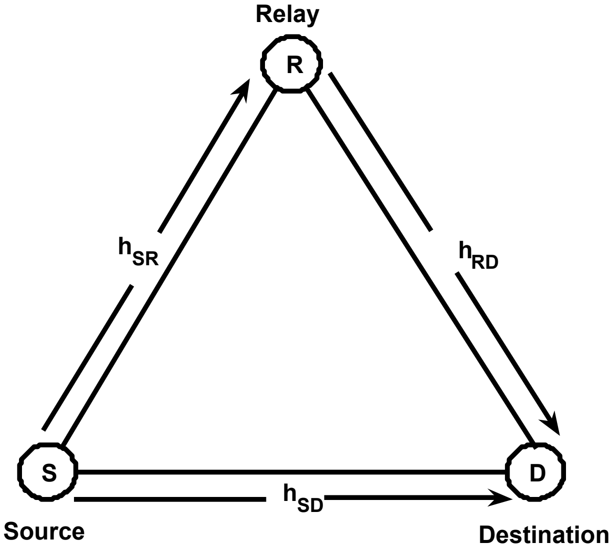

Fig. 1. A cooperative system with single-antenna source and single-antenna relay

likelihood (ML) timing estimation technique. Section 5 presents the cooperative transmission protocol, relaying strategy and the combining method. The numerical results and discussions are presented in Section 6 before the paper is concluded in Section 7.

2 System Model

We consider a system with a source node S communicating with a destination D with the help of a relay node R. Figure 1 illustrates this system. Cooperative communication can be divided into two phases. In the first phase, S sends the message whilst D and R listen. In the second phase, R processes the signal from S, transfers it to D, and D combines the signal received from both R and S. Each of the received signal at relay R or at destination D, from the transmission end U where $U = \{S, R\}$ to the receiving end V where $V = \{R, D\}$ can be represented as

$$z_{UV}(t) = \sum_{m=-\infty}^{\infty} \sqrt{P_{UV}} c_m h_{UV}^m p(t - mT - \tau_{UV}) + \eta_{UV}(t) \tag{1}$$

where P_{UV} is the transmitted power at the end U, c_m's are the transmitted symbols, $p(\cdot)$ is the pulse shape used to control the spectral characteristics of the transmitted signal and T is the signaling interval ($\frac{1}{T}$ is the symbol rate). The c_m's are assumed to be independent and identically distributed, and take on the values ±1 with equal probability. τ_{UV} is the delay introduced by the channel, and the $\eta_{UV}(t)$ is stationary and Gaussian with a mean of zero and double sided power spectral density of $\frac{N_0^{UV}}{2}$ W/Hz each. h_{UV}^m denotes the multiplicative fading process introduced by a Rayleigh fading channel with complex fading coefficients having zero mean and unit variance. The fading coefficients assumed to be constant within a symbol period and change independently from one symbol to another. The frequency response of the pulse shaping filter in the transmitter is $P(f)$. The received complex envelope $z_{UV}(t)$ is applied to a matched filter, with impulse response $p(-t)$. The frequency response of this filter is $P^*(f)$, where $()^*$ denotes complex conjugate. The overall frequency response of the receiving and transmitting filters defined in the frequency domain as

$$G(f) = P(f)P^*(f) = |P(f)|^2 \tag{2}$$

where $|\cdot|$ indicates magnitude. The matched filter output signal is sampled at times $kT + \hat{\tau}_{UV}, k = 0, \pm1, \pm2...$ where $\hat{\tau}_{UV}$ is an estimate of the unknown time delay τ_{UV}. The resulting matched filter output sample $r(k;\hat{\tau}_{UV})$ has no intersymbol interference at the correct decision instants $kT + \hat{\tau}_{UV}$ as the baseband pulse at the matched filter output is a Nyquist pulse. Square root raised cosine (SRC) filter is used as the pulse shaping filter and also as the receiving filter, the overall response is therefore similar to a raised cosine filter. The impulse response of the raised cosine filter is given by:

$$g(t) = \frac{\sin\left(\pi\frac{t}{T}\right)}{\pi\frac{t}{T}} \frac{\cos\left(\pi\alpha\frac{t}{T}\right)}{\left(1 - 2\alpha\left(\frac{t}{T}\right)^2\right)} \tag{3}$$

where α is called the roll-off factor, which takes values in the range $0 \leq \alpha \leq 1$ and T is the symbol period.

During the first phase, the received signals are $r_{SR}(k;\hat{\tau}_{SR})$ and $r_{SD}(k;\hat{\tau}_{SD})$ where $P_{SD} = P_{SR} = P_1$, the subscripts SR and SD refer to "from source to relay" and "from source to destination" respectively and the rest of the parameters are defined before. During second phase, the received signal is $r_{RD}(k;\hat{\tau}_{RD})$ where $P_{RD} = P_2$, the subscript RD refers to "from relay to destination". All the channels, noise processes, and timing delays are independent to each other for cooperative transmissions. The powers of η_{SR}, η_{SD} and η_{RD} are respectively N_0^{SR}, N_0^{SD} and N_0^{RD} .

The received signals at the destination from the source in first phase and that from the relay in second phase are combined using signal-to-noise-ratio combining (SNRC) [12]. The total power for transmission is constrained in our analysis, such that

$$P_1 + P_2 = P. \tag{4}$$

More detailed description on the power constraints is provided in the subsequent section. Furthermore, the mean path loss that we consider here is proportional to the term d^{e_p} where d is the distance between the radios and e_p is the path loss exponent considered to be the same for all the wireless channels. In the numerical results that we present in later sections however we consider the distances between any two given nodes (e.g. between S and R, or S and D etc) are always the same and hence we do not consider the path loss equation in our calculations for transmit and receive power calculations.

3 Power Constraint and Cooperative Scenarios

The total power P of the overall communication is constrained in the system. For the non-cooperative systems of course the consumed power for transmission is given by

$$P_{NC} = \text{Power from source to destination} = P_1 \tag{5}$$

and for the cooperative system, the total consumed power for the transmissions is given by,

$$P_C = \text{Power from source to relay} + \text{Power from relay to destination} = P_1 + P_2 \tag{6}$$

where, we assume that the processing power difference between the non-cooperative and the cooperative scenarios at the nodes are negligible comparing to the value of P. With the above definition we can evaluate the performance of cooperative and non-cooperative systems for the constraint $P = P_{NC} = P_C, P \in R^+$, by varying the power levels P_1 and P_2 with, $P = P_1 + P_2$.

Note the when $P_2 = 0$ then we essentially have a non-cooperative system. Now let us see two different scenarios where power constraints are considered in cooperative networks.

First, we consider the scenario where transmit power could be optimized to achieve the required overall BER considering both non-cooperative and cooperative scenarios. Figure 2 depicts such a scenario, where the overall power utilized for the communication from S to D (i.e. the RAT-Radio Access Terminal) is minimized. In other words the minimum of P_{NC} and P_C (given by $\min P_{NC}, P_C$) is

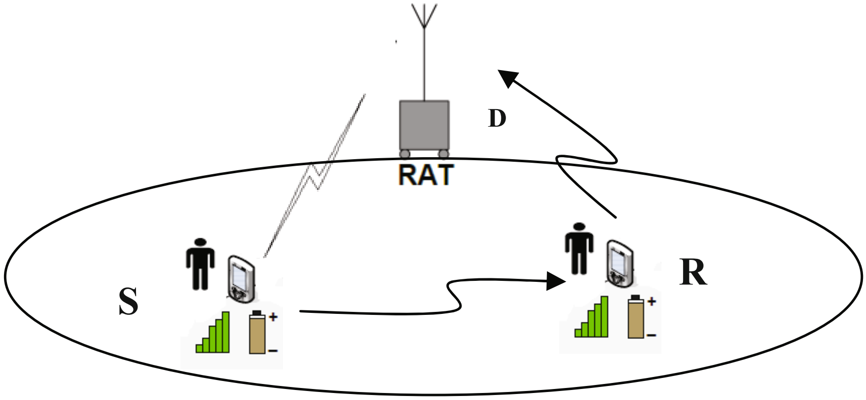

Fig. 2. Optimization of transmit power by means of cooperation

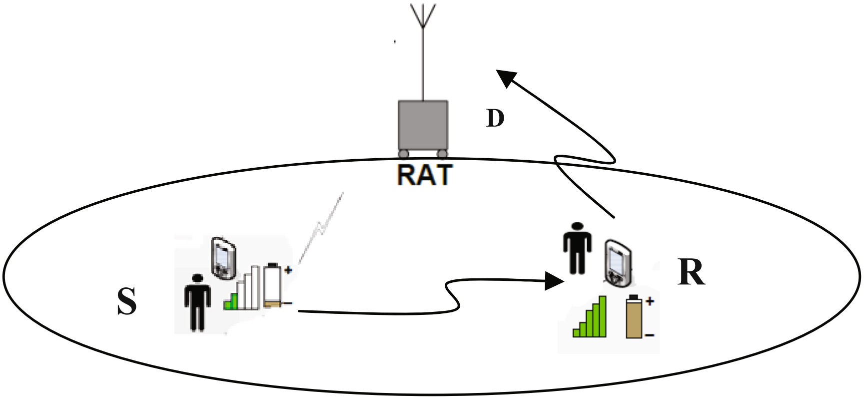

Fig. 3. Optimization of local transmit power at the selfish node by means of cooperation

chosen to obtain the required BER performance which essentially optimizes the power usage.

Second, we consider the scenario where the source node has limited power to transmit. A classical scenario for this problem is depicted in Figure 3. In the figure the source node has less power to perform its transmission (the required power is P for example to transmit to the destination directly and the available power at S is only P_1) due to a dying battery, and hence it is seeking to cooperate with the neighboring node R to transmit its data to the destination node. In this case for a given BER performance the relay node is required to allocate necessary power to relay the data to the destination.

Having the above motivation in mind, that is to optimize the transmit power consumption in the overall communication as well as at the source node S, we study the BER performance of cooperative and non-cooperative systems subjected to synchronization errors in the following sections.

4 Near ML Timing Synchronization

A non-data-aided (NDA) near Maximum Likelihood (ML) timing estimation technique as derived by the authors of this paper, is also described in [13, 14]. We use the ML principles to derive the symbol timing estimator assuming no a-priori knowledge of the received symbol sequence. Let a matrix of samples of L symbols with N samples per symbol be given as

$$\mathbf{Y}=\begin{bmatrix}\mathbf{y_0}\\ \vdots \\ \mathbf{y_k} \\ \vdots \\ \mathbf{y_{L-1}}\end{bmatrix}=\begin{bmatrix} y_0(1) & \cdots & y_0(i) & \cdots & y_0(N)\\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_k(1) & \cdots & y_k(i) & \cdots & y_k(N) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_{L-1}(1) & \cdots & y_{L-1}(i) & \cdots & y_{L-1}(N)\end{bmatrix} \tag{7}$$

where,

$$\mathbf{y_k} = [y_k(1), \cdots, y_k(i), \cdots, y_k(N)] \tag{8}$$

and,

$$y_k(i) = r_{UV}(k; \tau_{UV}) \tag{9}$$

for a specific timing delay, $\tau_{UV} = iT_s$ considering

$$\tau_{UV} \in [T_s, 2T_s, \cdots, iT_s, \cdots, NT_s]. \tag{10}$$

Here, τ_{UV} is the timing delay to be estimated and $r_{UV}(k; \tau_{UV})$ is defined in Section 2. As timing delays are related to the sample number, $y_k(\cdot)$ will be denoted by $y_k(\tau_{UV})$ and the estimator is then given by:

$$\hat{\tau}_{UV} = \arg\max_{\tau_{UV}} \sum_{k=0}^{L-1} |y_k(\tau_{UV})|. \tag{11}$$

The validity of the technique demands the constraint on number of samples to be integer multiple of symbols. The probability density function of the NDA near ML timing estimates is presented and BER performances of the estimator under AWGN channel and various fading conditions are reported in [15].

5 Cooperative Transmissions

A number of cooperative relaying techniques can be used in the relay station namely amplify-and-forward (AF), decode-and-forward (DF), etc. We consider decode-and-forward relaying where relay R processes $r_{SR}(k; \hat{\tau}_{SR})$ to demodulate and detect an estimate $\hat{c}_m$, then during second phase transmits $c_m = \hat{c}_m$. To calculate the end-to-end average SNR of a multi-hop link using DF, first the end-to-end average bit-error-rate (ABER) of the link is calculated which can then be translated to an equivalent end-to-end average SNR. To compute the end-to-end ABER, the probability that an error occurs in n hops has to be determined. Suppose $P(E)_i$ denotes the ABER of hop i, a bit error occurs only if there was an error in the previous hop and no error in the next hop, or if there was no error in the previous hop and an error occurs in the next hop [16]. This is described mathematically as

$$P_b^{(i+1)}(E) = P_b^{(i)}(E)(1 - P_b(E)_{i+1}) + (1 - P_b^{(i)}(E))P_b(E)_{i+1} \tag{12}$$

where $P_b^{(i)}(E)$ denotes the end-to-end ABER at hop i, and $P_b(E)_{i+1}$ is the average probability of a bit error occuring in the $(i+1)^{th}$ hop. We consider 2-hop transmission and the end-to-end ABER at destination for transmission using relay can be written as

$$P_b^{(D)}(E) = P_b^{(R)}(E)(1 - P_b(E)_D) + (1 - P_b^{(R)}(E))P_b(E)_D \tag{13}$$

where $P_b^{(R)}(E)$ and $P_b(E)_D$ are the BERs for the single links from source to relay and from relay to destination respectively. For a binary phase shift keying

(BPSK) modulated signal, the end-to-end average SNR for the multihop link, $\mathrm{SNR_{SRD}}$ can be calculated from the end-to-end average BER for multihop link, $P_b^{(D)}(E)$ using

$$\mathrm{SNR_{SRD}} = \frac{1}{2}[Q^{-1}(P_b^{(D)}(E))]^2. \tag{14}$$

The incoming signals coming directly from source and from relay are required to be combined at the destination. In this work the signals are combined only with the current information of the signal and channel. We consider signal-to-noise-ratio combining (SNRC) method. SNRC corresponds to Maximal Ratio Combining (MRC) for standard diversity communications. Furthermore, apart from the last hop, SNRC combining considers the channel gain of intermediate hops. We use the method discussed to estimate the end-to-end average SNR of the whole multi-hop link by (14), and weigh the received signals coming from direct link and relay by the SNRs respectively, which results in

$$r_D(k) = r_{SD}(k; \hat{\tau}_{SD}).e^{-j\angle h_{SD}^k}.\mathrm{SNR_{SD}} + r_{RD}(k; \hat{\tau}_{RD}).e^{-j\angle h_{RD}^k}.\mathrm{SNR_{SRD}} \tag{15}$$

where $\mathrm{SNR_{SD}}$ represents SNR of the direct link.

6 Numerical Results and Discussions

For the numerical results, simulation based on Monte Carlo techniques are used in the estimation of the BER. As noted in Section 2, we ignore the mean pathloss values for the wireless transmissions since we assume the same distance between the wireless nodes for our comparisons here. We adopt binary phase shift keying (BPSK) modulation scheme for Rayleigh fading channels for decode-and-forward cooperative communications using SNRC method. Roll-off-factor $\alpha = 0.6$ for the square root raised cosine filter is considered. We consider $N = 15$ samples per symbol, i.e., $T = NT_s$ where T_s is the sampling interval. The noise power spectral densities $N_0^{SR} = N_0^{SD} = N_0^{RD} = N_0$ are considered. For fair comparison, we present average BER curves as a function of P/N_0. For simplicity we consider the timing errors $\tau_{SD} = \tau_{SR} = \tau_{RD}$.

Figure 4 and Figure 5 show the average BER for cooperative communications for Rayleigh fading channels with various power allocations for $\tau_{SD} = \tau_{SR} = \tau_{RD} = 3T_s$. Figure 4 depicts the BER curves for lower values of P_1/P where as Figure 5 depicts the BER performance for higher values of P_1/P (i.e. for $P_1/P \geq 0.4$). It is observed in the figures that BER is not optimal for $3T_s$ timing error when equal power allocation is used (i.e. $P_1 = P_2 = 0.5$). We further observe that (from Figure 4) the BER performance improves when P_1/P increases but at the same time the BER is worse than the non-cooperative case at low and intermediate values of SNR. Therefore, we learn that with the above power allocations (as in Figure 4) cooperative communications show poor power efficiency compared to the non-cooperative case for a timing error of $3T_s$. However, when P_1/P is further increased (beyond $P_1/P = 0.4$) cooperative communication shows better power efficiency than the non-cooperative case as observed in

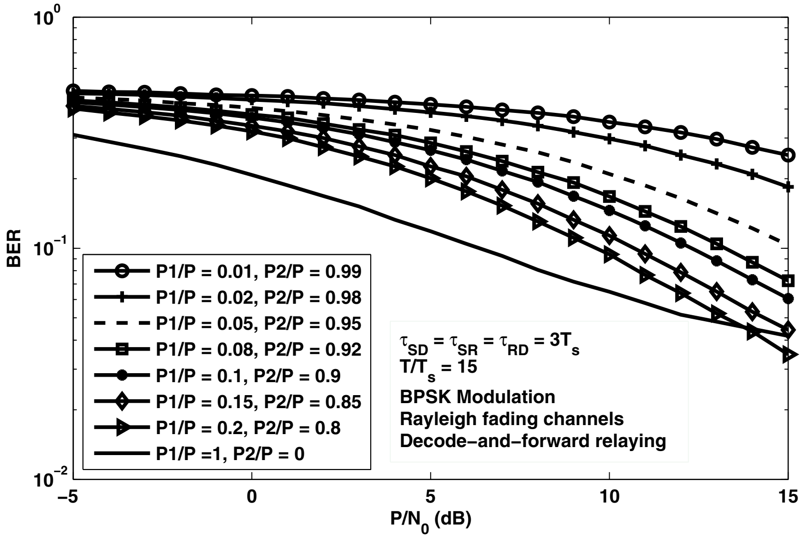

Fig. 4. BER for cooperative communications over fading channels with $3T_s$ timing error with various power allocations for lower values of P_1/P

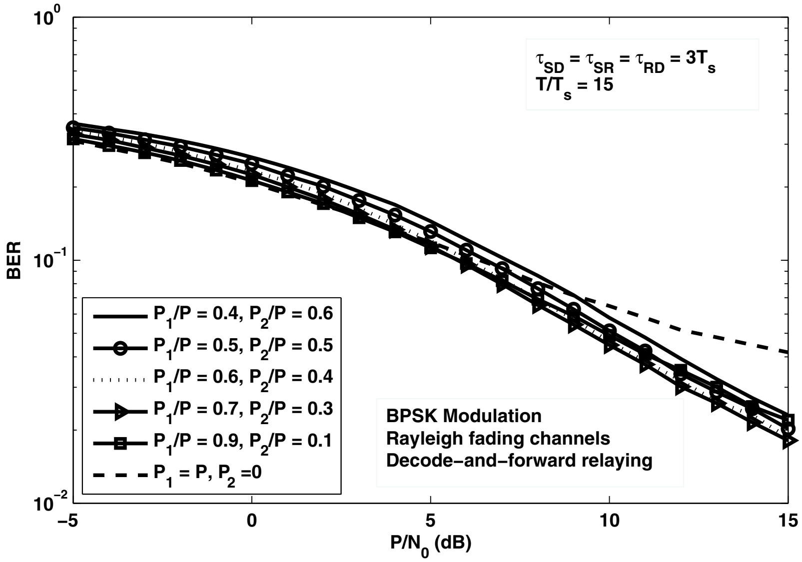

Fig. 5. BER for cooperative communications over fading channels with $3T_s$ timing error with various power allocations for higher values of P_1/P

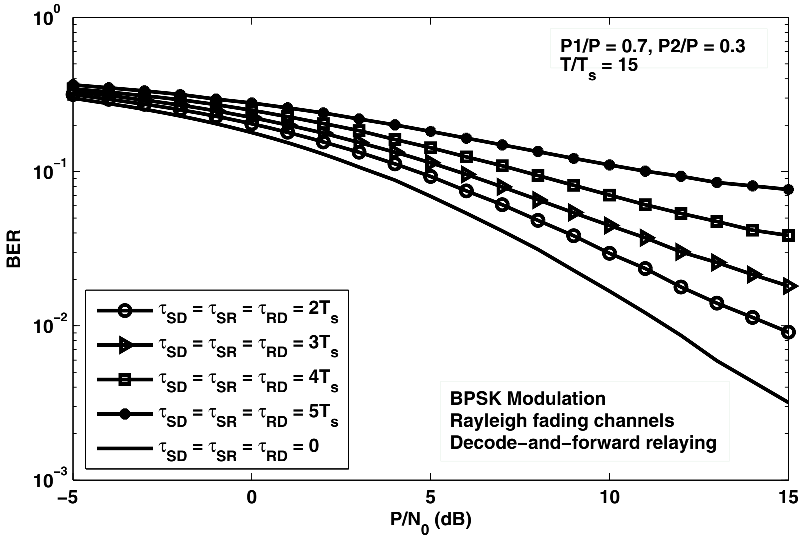

Fig. 6. BER for cooperative communications over fading channels with various timing errors

Figure 5. It should also be noted that the BER for the cooperative system starts to degrade once P_1/P goes beyond 0.7. Based on these observations we could say that $P_1/P = 0.7$ and $P_2/P = 0.3$ seems to be the best power allocation for the decode-and-forward cooperative communications over Rayleigh fading channels for $3T_s$ timing error. It is also observed in the figure that when power allocations are not such that $P_1/P = 0.7$ and $P_2/P = 0.3$ then for low values of P/N_0, the BER performance of non-cooperative system with $3T_s$ timing error is slightly better than cooperative communications for a timing error of $3T_s$.

Figure 6 demonstrates the average BER for decode-and-forward cooperative communications operating under Rayleigh fading channels with SNRC method for various timing errors for the power allocation $P_1/P = 0.7$ and $P_2/P = 0.3$. From the figure we observe that timing error has a significant effect on the performance of the cooperative communication system. We observe that with the increasing of the static timing errors, the BER performance degrades for the same power allocation. When there is $2T_s$ timing error, the performance is worse than that of with no timing error. The performance degrades further with $3T_s$, $4T_s$ and $5T_s$ timing errors. The performance degradation for $2T_s$ timing error for $P_1/P = 0.7$ and $P_2/P = 0.3$ is up to 3 dB for BER $= 9 \times 10^{-3}$. The BER performance degradation is up to 1.6 times at $P/N_0 = 8$ dB for $2T_s$ timing error for the same power allocation. The performance degradation is up to 5 dB for $3T_s$ timing error for BER $= 2 \times 10^{-2}$. The BER degradation is up to 2 times for $P/N_0 = 8$ dB for $3T_s$ timing error. For the simulation purpose, static timing error zero is assumed when timing errors are estimated and corrected using near

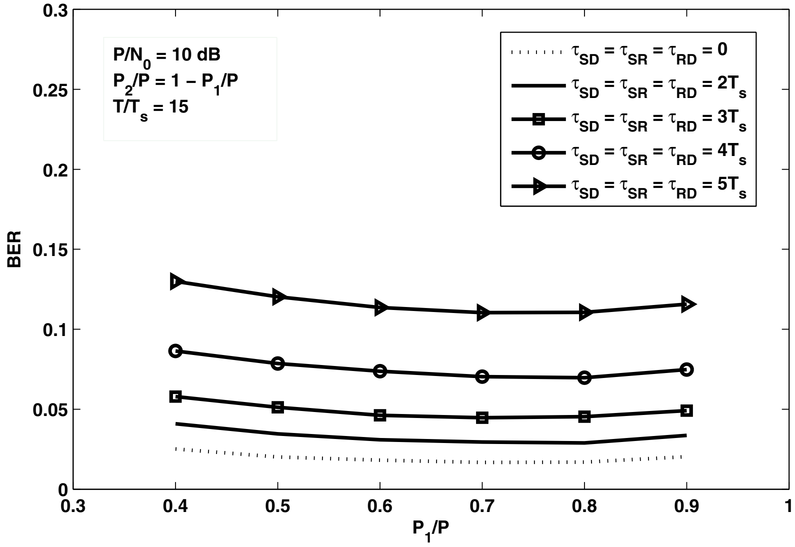

Fig. 7. BER for cooperative communications for various power allocations and timing errors

ML timing synchronization. For the timing estimation $L = 100$ symbols are considered.

Figure 7 shows the BER for cooperative communications for various power allocations and timing errors when $P/N_0 = 10$ dB. It is demonstrated in the figure that both timing errors and power allocations have effect on the BER. With the increasing of timing error, BER performance degrades for any power allocation. Again BER performance improves when P_1/P increases up to 0.7 for any timing error, then BER performance starts degrading with the increase of P_1/P. It is found that equal power allocation is not optimum for the BER performance with timing error; more power should be allocated to "source to relay" link than to "relay to destination" link; too much power allocation to "source to relay" link degrades the BER performance in presence of timing error.

7 Conclusions

In this paper, we studied the power efficiency performance of a decode-and-forward cooperative communications over Rayleigh fading channels using signal-to-noise-ratio combining technique with timing errors. Transmit power allocations at the source and the relay nodes and the timing errors at the corresponding receivers play a significant role in the BER performance of cooperative communications. In other words we can say that, in order to attain a certain level of BER performance at the receiver node, cooperation can be used to attain overall power efficiency but at the same time synchronization errors can affect the gains in power efficiency. We also observed that optimum transmit power allocation exists for the source and the relay nodes to attain maximum power efficiency for a given symbol timing error.

Based on the study presented in this paper we propose to conduct a theoretical study on the timing error versus power efficiency performance. Furthermore, we propose to study the power efficiency of cooperative systems considering dynamic timing errors (timing jitter). We also propose to use optimization techniques to identify the optimum power allocation for the source and the relay nodes considering the timing jitter at the receiver nodes.

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