On the Performance of Incremental Opportunistic Relaying with Differential Modulation over Rayleigh Fading Channels

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ABSTRACT

We propose an incremental relaying protocol in conjunction with opportunistic communication for differential modulation with an aim to make efficient use of the degrees of freedom of the channels by exploiting a imited feedback signal from the destination. In particular, whenever the direct link from the source to the destination is not favorable to decoding, the destination will request the help from the opportunistic relay (if any). The performance of the proposed system is derived in terms of average bit error probability and achievable spectral efficiency. The analytic results show that the system assisted by the opportunistic relaying can achieve full diversity at low SNR regime and exhibits a 30dB gain relative to direct transmission, assuming single-antenna terminals. We also determine the effect of power allocation on the bit error probability BEP) performance of our relaying scheme. We conclude with a discussion on the relationship between the given thresholds and channel resource savings. Monte-Carlo simulations are performed to verify the analysis.

Key Words : Bit Error Probability, Incremental Relaying, Decode-and-Forward Relaying, Rayleigh Fading, Differential Modulation

Ⅰ. Introduction

It is well known that cooperative communications are viewed as a promising technique for wireless networks to improve coverage and to provide high data rate services in a cost-effective manner since the installation of multi antennas is infeasible due to its limitations on size and energy. The key idea is to form a virtual MIMO antenna array between the source and the destination by utilizing a third terminal, a so-called relay node, which assists the direct communication. This approach provides higher spatial diversity gain than that of direct communication. Several cooperative protocols with different signal processing techniques, including amplify-and-forward(AF), decode-and-forward(DF), and coded cooperation (CC), have been well studied in the literature[1,2].

In most recent publications on the cooperative diversity networks, a distributed relay selection in which the selected criterion for choosing the best relay is the best instantaneous SNR composed of the SNR across the two-hops, called opportunistic relaying, is proposed for a two-hop AF (or DF) cooperative system that can obtain full diversity order[3-7]. Although, these protocols are very simple and do not demand any significant modification in the existing communication layers that have been designed for conventional noncooperative systems, they lead to a certain loss in the channel resource,

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especially for high rates, since the best relay among available relays repeats all the time, making inefficient use of the degrees of freedom of the channels.

To overcome such a problem and also to balance the traffic load between the source and the relay(s) in one or multi-relay cooperative networks, in [8-13], incremental relaying based on AF and DF was introduced as an efficient protocol in terms of system capacity in which it suggests the use of limited feedback from the destination, so that the relays know when to forward what they receives from the source. Such a system makes more efficient use of the channel recourses because the relays will forward the source information only if the signal-to-noise ratio (SNR) of the direct link between the source and the destination is lower than the given threshold. With an appropriate threshold decided by the required quality of the end signals, the relays may repeat rarely and the source can utilize the most of degrees of freedom.

In all above mentioned research, coherent modulation schemes are employed with the assumption that all receivers at relays and the destination have perfect channel state information (CSI). In practice, CSI can be obtained through training sequences at each cooperative node as well as at the destination. This leads to an extra computation burden and increasing hardware complexity as well as high power consumption at all receivers in the network. As a result, combinations of cooperative relaying schemes and differential modulations have recently been introduced to obviate the need for CSI[15-22]. However, to the best of the authors' knowledge, there is no published work concerning the incremental opportunistic relaying with differential modulation scheme as well as its performance in terms of bit error probability and achievable spectral efficiency over both independent identically distributed (i.i.d.) and independent but not necessarily identically distributed (i.n.d.) Rayleigh fading channels.

In this paper, motivated by all of the above, we propose an incremental opportunistic relaying with different modulation and also study its performance. By expressing the probability density function (PDF) of the instantaneous signal-to-noise radio (SNR) of the differential combiner at the destination in a tractable form, we can obtain the close-form expressions for the end-to-end bit error probability and achievable spectral efficiency of the proposed system. Although we restrict ourselves to binary different modulation, e.g. binary DPSK, due to its advantages in BER derivation, higher constellation sizes may be applied by using the same manner. In addition, a practical aspect of relay detection, i.e., without assuming that the relay can perfectly detect the cyclic redundancy check (CRC) code of received signals, is considered. To facilitate the ease of study the behavior of the system on high SNR regime, an asymptotic bound of the bit error probability is developed. It is interesting to know that the performance of the system at high SNR depends neither on number of relays nor on the quality of relaying links. Moreover, the power allocation problem between the source and the opportunistic relay is also investigated. The results show that for an incremental opportunistic network with a fixed threshold it is preferable to allocate more power to the source than to the opportunistic relay at the high SNR regime.

The rest of this paper is organized as follows. In Sect. II, we introduce the model under study and describe the proposed protocol. Section III shows the formulas allowing for evaluation of average BEP of the system. In Sect. IV, we contrast the simulations and the results yielded by theory. Finally, the paper is closed in Sect. V.

Ⅱ. System Model

We consider a wireless relay networks consisting of one source(S), N relays R_i with $i = 1,2,\ldots,N$ and one destination (D) as illustrated in Fig. 1. Each node is equipped with single antenna and operates in half-duplex mode.

It is assumed that every channel between the nodes experiences slow, flat, Rayleigh fading. For differential detection, the fading channel coefficients

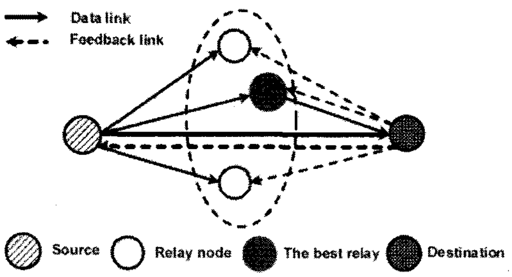

Fig. 1. Incremental Opportunistic Relaying System with Differential Modulation

are assumed static over two-symbol interval. Let h_{SD}, h_{SR_i} and h_{R_iD} be the link coefficients between the source to the destination, the source to relay i and relay i to the destination, respectively. Due to Rayleigh fading, the channel powers, denoted by $\alpha_0 = |h_{SD}|^2$, $\alpha_{1,i} = |h_{SR_i}|^2$ and $\alpha_{2,i} = |h_{R_iD}|^2$, are independent and exponential random variables with parameters λ_0, $\lambda_{1,i}$ and $\lambda_{2,i}$, respectively where $i = 1,2,...,N$. The average transmit powers for the source and the relays in two hops are denoted by ρ_1 and ρ_2, respectively. Let us define the instantaneous signal to noise (SNRs) for the $S \rightarrow D$, $S \rightarrow R_i$ and $R_i \rightarrow D$ links as $\gamma_0 = \rho_1 \alpha_0$, $\gamma_1 = \rho_1 \alpha_{1,i}$ and $\gamma_2 = \rho_2 \alpha_{2,i}$, respectively.

The rationale of the protocol is that the opportunistic relay repeating the source information will be needed if the direct link ($S \rightarrow D$) is in outage. To that effect, the one-bit feedback may be used as proposed in [2] to indicate the quality of the link between the source and the destination. For ease of analysis, we assume that the feedback channel is error free and has no latency, and the impact caused by the feedback procedure on the overall spectral efficiency of the system is negligible.

To eliminate mutual interference, the system uses orthogonal channels for transmission, either by time-division multiplexing(TDM), frequency-division multiplexing(FDM) or code-division multiplexing (CDM). To facilitate the explanation, we assume a time-division protocol with two time slots. In the first time slot, the source broadcasts the differential modulated symbols s(n) to N relays and the destination where $s(n)$ is defined as follows:

$$s(n) = s(n-1)d(n), n = 1,...,L \tag{1}$$

where L denotes number of bits within one frame, $d(n) \in \{1,-1\}$ is the information bits and the initially modulated symbol is set to 1, i.e., s(0)=1.

The received signals at the relays and the destination are written, respectively, as follows:

$$r_{SR_i}(n) = \sqrt{\rho_1} h_{SR_i} s(n) + n_{SR_i}(n) \tag{2a}$$

$$r_{SD}(n) = \sqrt{\rho_1} h_{SD} s(n) + n_{SD}(n) \tag{2b}$$

where $n_{SR_i}(n)$ and $n_{SD}(n)$ denote the noise samples modeled as zero-mean, independent, circularly symmetric complex Gaussian random variables with variance N_0.

At the end of the first phase, the destination decodes and then broadcasts a one-bit feedback message, informing the source and all relays the decoding status of the destination. The destination will broadcast the "success" message if it can decode the signal without error. Having received the feedback message, all relays will discard their signal and still keep silent, whereas the source starts transmitting with a new signal in the following time slot. Otherwise, i.e., the destination fails in decoding, the "failure message" will be broadcast to request the help from the best relay in the second time slot.

In order to choose the best relay, relay selection process is performed. In this protocol, the feedback signal plays two roles: it enables the relays keep silent in case the S−D SNR is satisfied the given threshold and also selects the best relay in case the S−D signal is not. Here we use the distributed timer based on the algorithm proposed in [4]. In particular, each cooperative node will start a timer that is inversely proportional to its received SNR across the two hops, i.e., $S \rightarrow R_i \rightarrow D$. The relay node with the shortest timer transmits first and thus becomes the transmitter of the second time slot, while other nodes discard the signals after receiving this nodes transmission. Before forwarding to the destination, the received signal at the best relay is differentially decoded as

$$\hat{d}(n) = sign\left(\Re\left\{r^{*}_{SR_b}(n-1) r_{SR_b}(n)\right\}\right) \quad (3)$$

and re-encoded via a differential encoder as

$$\hat{s} = \hat{s}(n-1)\hat{d}(n) \quad (4)$$

where R_b denotes the best relay. $\Re(.)$ denotes the real part of the argument, $(.)^*$ denotes complex conjugation and $\hat{s}(0) = 1$.

Note that, owing to the imperfect detection at the best relay, it may forward incorrectly decoded signals to the destination. Hence, similarly as in [23], the relaying channel across two hops $S \rightarrow R_i \rightarrow D$ is dominated by the weaker link, and it can be modeled as an equivalent single hop whose output SNR can be tightly approximated in the high SNR regime as follows:

$$\gamma_i \approx \min(\gamma_{1,i}; \gamma_{2,i}) \quad (5)$$

Since $\gamma_{1,i}$ and $\gamma_{2,i}$ are exponentially distributed random variables with hazard rates $\mu_{1,i} = 1/\overline{\gamma_{1,i}} = 1/(\rho_1 \lambda_{1,i})$ and $\mu_{2,i} = 1/\overline{\gamma_{2,i}} = 1/(\rho_1 \lambda_{1,i})$, respectively. From (5), it follows from the fact that the minimum of two independent exponential random variables is again an exponential random variable with a hazard rate equal to the sum of the two hazard rates[24], i.e., $\mu_i = \overline{\gamma_i}^{-1} = \overline{\gamma_{1,i}}^{-1} + \overline{\gamma_{2,i}}^{-1}$. Hence, we have

$$f_{\gamma_i}(\gamma) = \frac{1}{\overline{\gamma_i}} e^{-\gamma/\overline{\gamma_i}}; \qquad F_{\gamma_j}(\gamma) = \int_0^{\gamma} f_{\gamma_j}(\gamma) d\gamma = 1 - e^{-\gamma/\overline{\gamma_j}} \quad (6)$$

Then, the instantaneous dual hop SNR of the best relay at the destination can be given by

$$\beta = \max_{i=1,\ldots,N} \gamma_i \quad (7)$$

Under the assumption that all links are subject to independent fading, order statistics gives the cumulative distribution function (CDF) of β as

$$F_{\beta}(\gamma) = \Pr(\gamma_1 < \gamma, \ldots, \gamma_N < \gamma) = \prod_{i=1}^{N} F_{\gamma_i}(\gamma) \quad (8)$$

where $F_{\gamma_i}(\gamma) = \Pr(\gamma_i < \gamma)$ is the corresponding CDF of γ_i. Hence, the joint PDF of β, $f_{\beta}(\gamma)$, is given by differentiating (8) with respect to γ.

$$f_{\beta}(\gamma) = \frac{\partial F_{\beta}(\gamma)}{\partial \gamma} = \sum_{i=1}^{N} \left[f_{\gamma_i}(\gamma) \prod_{\substack{j=1 \\ j \neq i}}^{N} F_{\gamma_i}(\gamma) \right] \quad (9)$$

Substituting (6) into (9) gives us the desired result as[25]

$$\begin{aligned} f_{\beta}(\gamma) &= \sum_{i=1}^{N} \left[\frac{1}{\overline{\gamma_i}} e^{-\frac{\gamma}{\overline{\gamma_i}}} \prod_{\substack{j=1 \\ j \neq i}}^{N} \left(1 - e^{-\frac{\gamma}{\overline{\gamma_j}}}\right) \right] \\ &= \sum_{i=1}^{N} (-1)^{i-1} \sum_{\substack{n_1, \ldots, n_i = 1 \\ n_1 < \ldots < n_i}}^{N} \omega_i e^{-\gamma \omega_i} \end{aligned} \quad (10)$$

where $w_i = \sum_{l=1}^{i} \overline{\gamma_{i_l}}^{-1}$.

The signal received at D at the second time slot is given by

$$\begin{aligned} r_{R_b D}(n) &= \sqrt{\rho_2} h_{R_b D} \hat{s}(n) + n_{R_b D}(n) \\ &= \sqrt{\rho_2} h_{R_b D} \hat{s}(n-1) \hat{d}(n) + n_{R_b D}(n) \\ &= r_{R_b D}(n-1) \hat{d}(n) + \tilde{n}_{R_b D}(n) \end{aligned} \quad (11)$$

where $n_{R_b D}(n)$ denotes the noise sample and $\tilde{n}_{R_b D} = n_{R_b D}(n) - n_{R_b D}(n-1)\hat{d}(n)$.

Finally, the decoder at the destination combines two received signals from the best relay node and the source and then jointly differentially decodes the signals. Rather, the decoder performs a maximum likelihood (ML) detection operation on the received signals. Here, we take the imperfect decoding effect at the relay into consideration; hence, the output of combiners is modified by considering the SNR of the equivalent link as follows[16,18]:

$$\tilde{d}=sign\left(\Re\left\{\begin{array}{l} r^{*}_{SD}(n-1)r_{SD}(n) \\ +\frac{\beta}{\gamma_{R_bD}}r^{*}_{R_bD}(n-1)r_{R_bD}(n)\end{array}\right\}\right) \quad (12)$$

Ⅲ. Performance Analysis

3.1 Bit Error Probability

Using the general law of probability, the average bit error probability of the incremental opportunistic relaying system can be derived as follows:

$$\begin{aligned} P_b &= \Pr(\gamma_0 \geq \gamma_T)P_D^1 + \Pr(\gamma_0 < \gamma_T)P_D^2 \\ &= [1-\Pr(\gamma_0 < \gamma_T)]P_D^1 + \Pr(\gamma_0 < \gamma_T)P_D^2 \end{aligned} \quad (13)$$

where P_D^1 is the conditional average bit error probability of the source-destination given that $\gamma_0 \geq \gamma_{th}$. P_D^2 denotes the conditional average bit error probability that an error occurs in the cooperative transmission. Note that the first and second term in (13) account for the events of non-cooperative and cooperative transmission to the destination, respectively.

Under the assumption that γ_0 follows the exponential distribution, therefore, $\Pr(\gamma_0 < \gamma_{th})$ can be easily determined as

$$\begin{aligned} \Pr(\gamma_0 < \gamma_T) &= \int_0^{\gamma_T} f_{\gamma_0}(\gamma)d\gamma = \int_0^{\gamma_T}\frac{1}{\overline{\gamma_0}}e^{-\frac{\gamma}{\overline{\gamma_0}}}d\gamma \\ &= 1-e^{-\gamma_T/\overline{\gamma_0}} \end{aligned} \quad (14)$$

The conditional average bit error probability of the direct link over Rayleigh fading channels for binary DPSK modulation, P_D^1, is given by[26, p.827, eq. (14.4-24)]

$$P_D^1 = \int_0^{\infty}\frac{1}{2}e^{-\gamma}f_{\gamma_0|(\gamma_0 \geq \gamma_T)}(\gamma)d\gamma \quad (15)$$

where the conditional PDF of γ_0, $f_{\gamma_0|(\gamma_0 \geq \gamma_T)}(\gamma)$, can be obtained by using probability[24] as

$$f_{\gamma_0|(\gamma_0 \geq \gamma_T)}(\gamma)=\begin{cases} 0 & \gamma < \gamma_T \\ \frac{e^{\gamma_T/\overline{\gamma_0}}}{\overline{\gamma_0}}e^{-\gamma/\overline{\gamma_0}} & \gamma \geq \gamma_T \end{cases} \quad (16)$$

where $\overline{\gamma_0}=E[\gamma_0]=\rho_1\lambda_0$.

Substituting (16) into (15) and taking the integral with respect to γ, we achieve the conditional average bit error probability P_D^1 as follows:

$$\begin{aligned} P_D^1 &= \int_{\gamma_T}^{\infty}\frac{1}{2}e^{-\gamma}\frac{e^{\gamma_T/\overline{\gamma_0}}}{\overline{\gamma_0}}e^{-\frac{\gamma}{\overline{\gamma_0}}}d\gamma \\ &= e^{\gamma_T/\overline{\gamma_0}}\left[\frac{e^{-(1+\overline{\gamma_0}^{-1})\gamma_T}}{2+2\overline{\gamma_0}}\right] \end{aligned} \quad (17)$$

Next, we consider the conditional average bit error probability that an error occurs in the cooperative transmission, P_D^2. Based on the received signals from the two phases, an instantaneous SNR at the combiner output is given by

$$\gamma_{\Sigma} = \gamma_0|(\gamma_0 < \gamma_T) + \beta$$

Then the PDF of the conditional combined instantaneous SNR at the destination can be derived as[Appendix]

$$f_{\gamma_\Sigma}(\gamma)=\begin{cases} \frac{1}{\left(1-e^{-\gamma_T/\overline{\gamma_0}}\right)}\sum_{i=1}^{N}(-1)^{i-1}\sum_{\substack{n_1,\dots,n_i=1 \\ n_1<\dots<n_i}}^{N}K_1 & ,\gamma < \gamma_T \\ \frac{1}{\left(1-e^{-\gamma_T/\overline{\gamma_0}}\right)}\sum_{i=1}^{N}(-1)^{i-1}\sum_{\substack{n_1,\dots,n_i=1 \\ n_1<\dots<n_i}}^{N}K_2 & ,\gamma \geq \gamma_T \end{cases} \quad (18)$$

where K_1 and K_2 are defined as follows:

$$K_1=\begin{cases} \left[\left(\frac{\overline{\gamma_0}}{\overline{\gamma_0}-\omega_i^{-1}}\right)\frac{1}{\overline{\gamma_0}}e^{-\frac{\gamma}{\overline{\gamma_0}}}+\left(\frac{\omega_i^{-1}}{\omega_i^{-1}-\overline{\gamma_0}}\right)\omega_i e^{-\gamma\omega_i}\right] & \text{if } \overline{\gamma_0}\neq\omega_i^{-1} \\ \frac{\gamma}{\overline{\gamma_0}^2}e^{-\frac{\gamma}{\overline{\gamma_0}}} & \text{if } \overline{\gamma_0}=\omega_i^{-1} \end{cases}$$

$$K_2=\begin{cases}\left[\dfrac{1-e^{-\gamma_T\left(\frac{1}{\overline{\gamma}_0}-\omega_i\right)}}{1-\omega_i\overline{\gamma}_0}\right]\omega_i e^{-\gamma\omega_i} & \text{if } \overline{\gamma}_0\neq\omega_i^{-1}\\ \dfrac{\gamma_T}{\overline{\gamma}_0^2}e^{-\frac{\gamma}{\overline{\gamma}_0}} & \text{if } \overline{\gamma}_0=\omega_i^{-1}\end{cases}$$

Following a similar approach as for P_D^1, from (18), P_D^2 can be derived as follows [26, p. 827, eq. (14.4-24)]:

$$\begin{aligned}P_D^2&=\int_0^{\infty}\frac{1}{8}(4+\gamma)e^{-\gamma}f_{\gamma_\Sigma}(\gamma)d\gamma\\&=\int_0^{\gamma_T}\frac{1}{8}(4+\gamma)e^{-\gamma}f_{\gamma_\Sigma}(\gamma)d\gamma\\&+\int_{\gamma_T}^{+\infty}\frac{1}{8}(4+\gamma)e^{-\gamma}f_{\gamma_\Sigma}(\gamma)d\gamma\\&=\frac{I}{\left(1-e^{-\gamma_T/\overline{\gamma}_0}\right)}\end{aligned}\qquad(19)$$

where I is defined as

$$I=\begin{cases}\left[\begin{array}{l}\left(\dfrac{\omega_i^{-1}}{\omega_i^{-1}-\overline{\gamma}_0}\right)I_1\left(\omega_i^{-1},\gamma_T\right)+\\ \left(\dfrac{\overline{\gamma}_0}{\overline{\gamma}_0-\omega_i^{-1}}\right)I_1\left(\overline{\gamma}_0,\gamma_T\right)+\\ \left[\dfrac{1-e^{-\gamma_T\left(1/\overline{\gamma}_0-\omega_i\right)}}{1-\omega_i\overline{\gamma}_0}\right]I_3\left(\omega_i^{-1},\gamma_T\right)\end{array}\right] & \text{if } \overline{\gamma}_0\neq\omega_i^{-1}\\ I_2\left(\overline{\gamma}_0,\gamma_T\right)+\gamma_{th}/\overline{\gamma}_0 I_3\left(\overline{\gamma}_0,\gamma_T\right) & \text{if } \overline{\gamma}_0=\omega_i^{-1}\end{cases}$$

with $I_1(a,b)$, $I_2(a,b)$ and $I_3(a,b)$ can be solved in closed-form as follows[1)]:

$$\begin{aligned}I_1(a,b)&=\int_0^b\frac{1}{8}(4+\gamma)e^{-\gamma}\frac{1}{a}e^{-\frac{\gamma}{a}}d\gamma\\&=\frac{4+5a-(4+b+5a+ab)e^{-(1+a^{-1})b}}{8(1+a)^2}\end{aligned}$$

$$\begin{aligned}I_2(a,b)&=\int_0^b\frac{1}{8}(4+\gamma)e^{-\gamma}\frac{\gamma}{a^2}e^{-\frac{\gamma}{a}}d\gamma\\&=\frac{4a+6a^2-\begin{bmatrix}b(4+b)+\\2a\left(2+5b+b^2\right)+\\a^2\left(6+6b+b^2\right)\end{bmatrix}e^{-(1+a^{-1})b}}{8(1+a)^3}\end{aligned}$$

1) They have been confirmed by using mathematical software package MATHEMATICA.

$$\begin{aligned}I_3(a,b)&=\int_b^{+\infty}\frac{1}{8}(4+\gamma)e^{-\gamma}\frac{1}{a}e^{-\frac{\gamma}{a}}d\gamma\\&=\frac{(4+b+a(5+b))e^{-(1+a^{-1})b}}{8(1+a)^2}\end{aligned}$$

Substituting (14), (17) and (19) into (13), we can obtain a closed-form expression for the average bit error probability of the incremental opportunistic relaying cooperative system with binary DPSK over Rayleigh fading channels.

3.2 Asymptotic Analysis of Bit Error Probability P_b

Although the expression for P_b in (13) enables numerical evaluation of the system performance, it does not offer insight into the effect of the different parameters, e.g., the number of relays, the value of the given threshold, etc. that influence the system performance. Next, we aim at expressing P_b in a simple form in such a way we can see the effect of the different parameters on the system performance at high SNR regime. In particular, regarding the second term in (13), $\Pr(\gamma_0<\gamma_T)=1-\exp(-\gamma_T/\overline{\gamma}_0)$ goes to 0 as $\overline{\gamma}_0\rightarrow\infty$. Furthermore, making use the fact that the conditional average BEP P_D^2 is always less than the conditional average P_D^1 due to the use of combining technique at the destination, we can readily approximate (13) at high SNR regime as

$$\begin{aligned}P_b&\approx\left[1-\Pr\left(\gamma_0<\gamma_T\right)\right]P_D^1\\&=\frac{\exp\left[-\left(1+\overline{\gamma}_0^{\,-1}\right)\gamma_T\right]}{2\left(1+\overline{\gamma}_0\right)}\end{aligned}\qquad(20)$$

From (20), it can be seen that the performance of the proposed system at high SNR regime will converge asymptotically to that of direct transmission given that $\gamma_0\geq\gamma_T$. In addition, number of relays(N) and average channel powers of relaying links $\overline{\gamma}_i$ are not involved in evaluation of P_b. These observations leads us to a conclusion that neither number of relays nor average channel powers of the relay links does take effect the performance of the system at high SNR regime.

3.3 Achievable Spectral Efficiency

Same as the incremental protocol with one relay, the proposed protocol offers an average spectral efficiency, which is less than R but larger than $R/2$ where R denote the average spectral efficiency of direct transmission. In particular, the value of the expected spectral efficiency, denoted by $\overline{R}$, can be obtained as

$$\begin{aligned}\overline{R} &= R\Pr(\gamma_0 \geq \gamma_T) + \frac{R}{2}\Pr(\gamma_0 < \gamma_T) \\ &= R\exp\left(-\frac{\gamma_T}{\gamma_0}\right) + \frac{R}{2}\left[1-\exp\left(-\frac{\gamma_T}{\gamma_0}\right)\right] \\ &= \frac{R}{2}\left[1+\exp\left(-\frac{\gamma_T}{\gamma_0}\right)\right]\end{aligned} \quad (21)$$

Ⅳ. Numerical Results and Discussion

In this section, we validate our analysis by comparing with simulation. For brevity, the uniform power allocation is employed in order to keep the total power constraint, i.e., $\zeta=\rho_1/(\rho_1+\rho_2)=\rho_1/\rho=0.5$ where ρ is the transmit power of the source in case of direct transmission. It is worth remarking that ζ is set to 0.5 as an natural choice in practice.

Fig. 2 draws the BEP as a function of average SNR per bit when the number of cooperative relays increases. For comparison, the curve corresponding to (20) is also illustrated. As can be clearly seen from the figure, the BEP curve with an arbitrary values of γ_T is quite close to the respective BEP curve with $\gamma_T=\infty$ at low SNR regime and asymptotically converges to the limit bound given by (20) at high SNR regime. This observation leads us to conclude that the proposed protocol can achieve full diversity at low SNR regime but restricts its diversity gain at high SNR regime. However, we still obtain a certain gain at high SNR, e.g., at the target BER of 10^{-5}, the proposed protocol exhibits a 30 dB gain relative to direct transmission. In addition, it should be noted that the tightness of the derived and simulated results

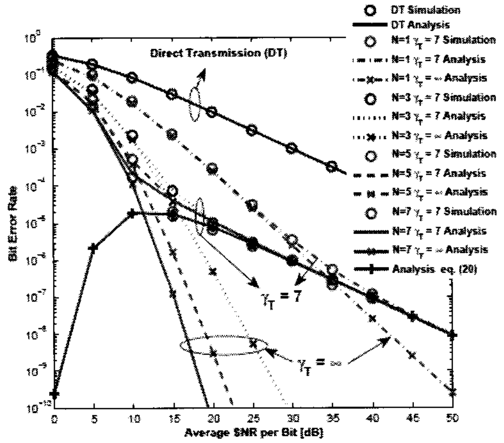

Fig. 2. Effect of increasing number of relays on the bit error probability for binary DPSK of the incremental opportunistic system. Power allocation: $\zeta=0.5$, channel setup: $\lambda_0=1$, $\lambda_{1,i}=2$ and $\lambda_{2,i}=3$ with $i=1,\ldots,N$

improves as average SNR increases; however, they slightly lose their tightness at low SNRs. This is due to the fact that the accuracy of the total SNR approximation $\gamma_{\sum}$ improves as SNR increases.

In Fig. 3, we study the effect of using different values of the threshold on the BEP of the system. We fix number of cooperative relay nodes involved in the network and vary the given threshold from 0 to ∞. The results show that the performance of the system remarkably depends on the threshold, and the

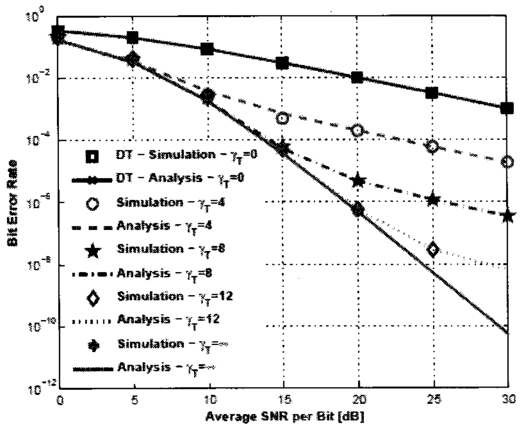

Fig. 3. Effect of increasing value of threshold on the bit error probability for binary DPSK of the incremental opportunistic system. Number of relays: N=3, power allocation: $\zeta=0.5$, channel setup: $\lambda_0=1$, $\lambda_{1,i}=2$ and $\lambda_{2,i}=3$ with $i=1,\ldots,N$

proposed protocol can achieve a good compromise between direct transmission ($\gamma_T=0$) and regular cooperative protocol with differential modulation ($\gamma_T=\infty$).

In Fig. 4, the performance of the system under both i.i.d. and i.n.d. Rayleigh fading channels is examined. For the system with $\gamma_T=0$ and $\gamma_T=\infty$, the results obtained for i.n.d. cases have the same forms with those for i.i.d. cases in all range of SNR. However, for the system with $\gamma_T=4$, the gap between two curves at high SNR is decreased. It can be explained by using the fact that at high SNRs the destination rarely requests the help from the relays(if any) resulting in the loss in diversity gain at the destination. But, it should be emphasized that the incremental relaying has a strong advantage in saving the channel resources compared to regular opportunistic relaying with differential modulation. This, of course, comes at the expense of performance loss at high SNR since regular opportunistic relaying can obtain full diversity order.

In Figs. 5-8, the BEP is depicted as a function of for both symmetric and asymmetric networks. It is obvious to see that although equal power allocation, i.e., $\zeta=0.5$, is a natural and reasonable choice in practice; it is not optimal for the proposed

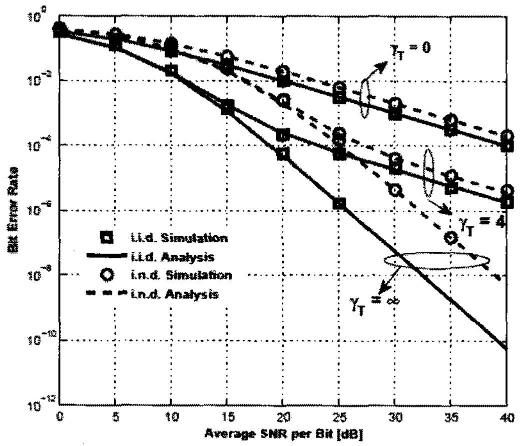

Fig. 4. BEP for binary DPSK of the incremental opportunistic system under i.i.d. channels $\lambda_0=\lambda_{1,i}$ $(=\lambda_{2,i}=1)$ and i.n.d. channels (λ_0, $\lambda_{1,i}$ and $\lambda_{2,i}$ are uniformly distributed between 0 and 1) with $i=1,\ldots,N$, the given threshold: $\gamma_T=4$ and power allocation: $\zeta=0.5$

incremental networks with differential modulation. It can be seen that the differential combination of thresholds and average SNRs results in differential optimal values for ζ. The extracted results from the figures provide some insight information on how much transmit power should be allocated to improve performance. With a fixed value of the threshold, as average SNR increases, more power should be allocated at the source, i.e., $\zeta\rightarrow 1$. On the other hand, with a fixed average SNR, as the value of threshold increases, power allocation tends to balance between the source and the opportunistic

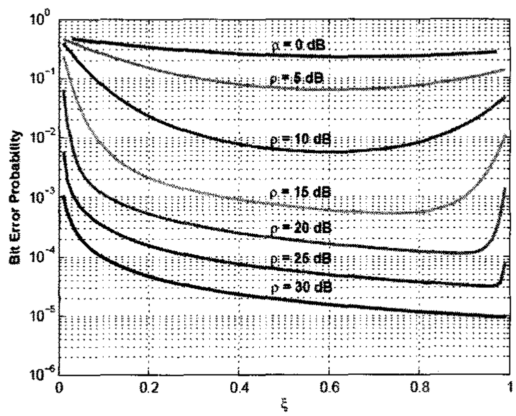

Fig. 5. BEP for binary DPSK as a function of power allocation in i.i.d. channels ($\lambda_0=\lambda_{1,i}=\lambda_{2,i}=1$ with $i=1,\ldots,N$), the given threshold: $\gamma_T=4$, number of relays: N=5

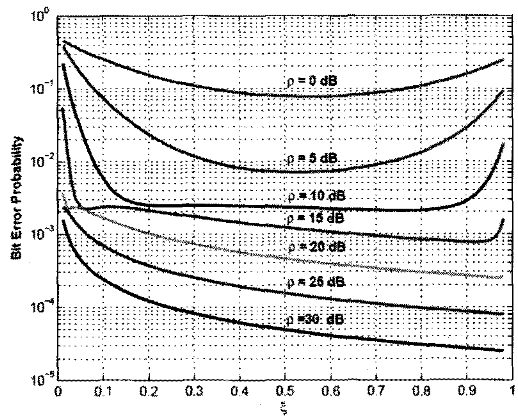

Fig. 6. BEP for binary DPSK as a function of power allocation in i.n.d. channels ($\lambda_0=1$, $\{\lambda_{1,i}\}_{i=1}^{N}=\{\lambda_{2,i}\}_{i=1}^{N}=\{2,3,4,5,6\}$), the given threshold: $\gamma_T=3$, number of relays: N=5.

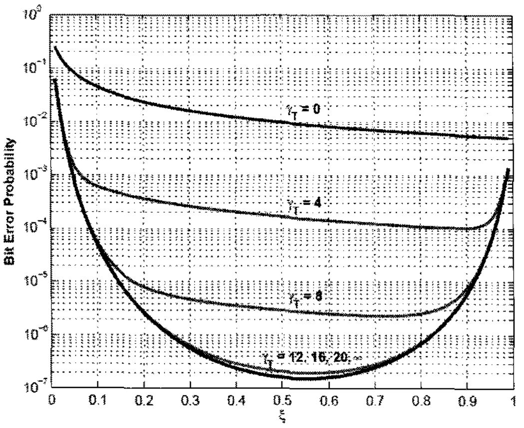

Fig. 7. BEP for binary DPSK as a function of power allocation ζ in i.i.d. channels ($\lambda_0 = \lambda_{1,i} = \lambda_{2,i} = 1$ with $i = 1, \ldots, N$, number of relays: N=5

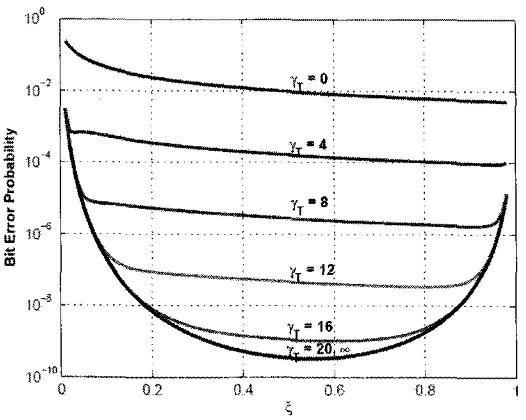

Fig. 8. BEP for binary DPSK as a function of power allocation ζ in i.n.d. channels ($\lambda_0 = 1$, $\{\lambda_{1,i}\}_{i=1}^{N} = \{\lambda_{2,i}\}_{i=1}^{N} = \{2,3,4,5,6\}$), number of relays: N=5.

relay but significantly depends on topologies of the networks.

The achievable spectral efficiency for the system is also investigated as shown in Fig. 9. Compared with regular opportunistic relaying ($\gamma_T = 0$), the advantage of the incremental opportunistic relaying is the improvement of spectral efficiency with the cost of a limited feedback from the destination as well as the performance loss in high SNR regime. As such, this scheme is suitable for adaptive systems in which the threshold can be adjusted to adapt the required quality of the end signals.

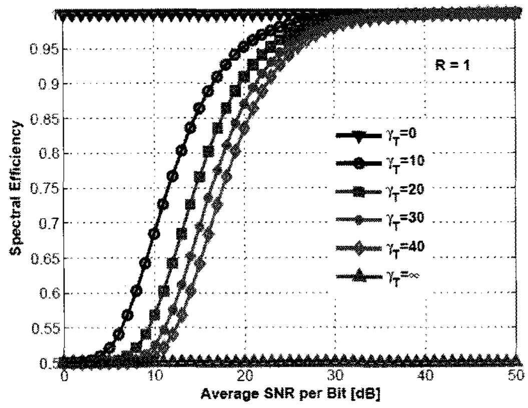

Fig. 9. Achievable spectral efficiency for the system for different values of γ_T ($R = 1, \lambda_0 = 1, \zeta = 0.5$).

V. Conclusion

We have presented the performance analysis of the incremental opportunistic relaying with binary DPSK under both i.i.d. and i.n.d. Rayleigh fading channels in terms of bit error probability and achievable spectral efficiency. By allowing the opportunistic relay to forward the source information to the destination since the direct link between the source and the destination is not good enough, the proposed protocol not only efficiently combines the received signals from the direct and the relaying links but also increases the system achievable spectral efficiency. We also provide an asymptotic bound of bit error probability, which reveals that the performance of the system depends neither on number of cooperative relays nor on the average channel powers of relaying links. Hence, the incremental relaying in conjunction with opportunistic cooperative communication for differential modulation schemes can be treated as an excellent candidate for wireless sensor networks in terms of performance-complexity trade-off.

Appendix

The purpose of this Appendix is to derive the PDF of γ_{Σ}. Under the assumption that γ_0 and β are independent, the CDF of the conditional combined signal, γ_{Σ}, is written as

$$F_{\gamma_\Sigma}(\gamma) = P\{\gamma_\Sigma \le \gamma\} \\ = P\{\gamma_0 | \gamma_0 < \gamma_T + \beta \le \gamma\} \\ = \frac{P\{\gamma_0 + \beta \le \gamma, \gamma_0 < \gamma_T\}}{\Pr(\gamma_0 < \gamma_T)} \quad (22)$$

As we can see from Fig. 10, γ can be less than, equal to or greater than γ_T, thus that gives rise to two situations that should be analyzed separately as follows:

For $\gamma \le \gamma_T$, from Fig. 10a and assuming that γ_0 and β are independent, we have

$$F_{\gamma_\Sigma}(\gamma) = \frac{\int_{\gamma_0=0}^{\gamma} f_{\gamma_0}(\gamma_0) d\gamma_0 \int_{\beta=0}^{\gamma-\gamma_0} f_\beta(\beta) d\beta}{\Pr(\gamma_0 < \gamma_T)} \quad (23)$$

For $\gamma > \gamma_T$, from Fig. 10b, we have

$$F_{\gamma_\Sigma}(\gamma) = \frac{\int_{0}^{\gamma_T} f_{\gamma_0}(\gamma_0) d\gamma_0 \int_{\gamma_T-\gamma_0}^{\gamma-\gamma_0} f_\beta(\beta) d\beta}{\Pr(\gamma_0 < \gamma_T)} \quad (24)$$

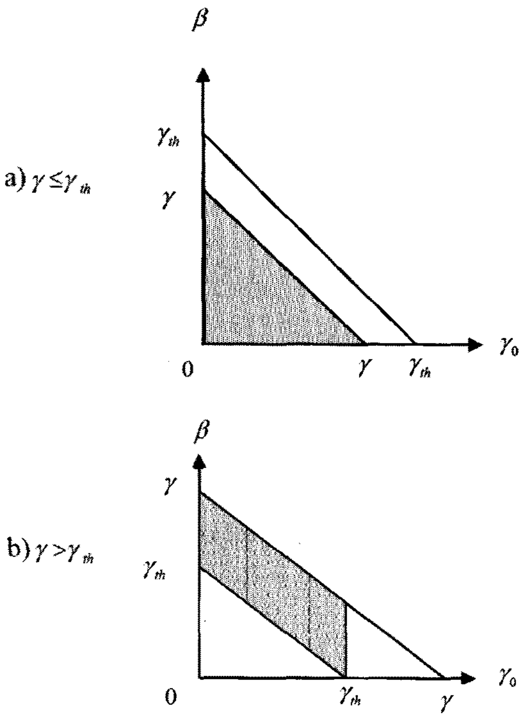

Fig. 10. Statistical distribution on γ_Σ.

Finally after differentiation the results obtained from (23) and (24), we can obtain $f_{\gamma_\Sigma}(\gamma)$ as shown in (18).

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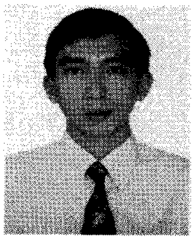

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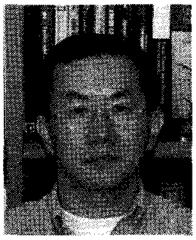

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