Long-term Fading Statistics-Based Power Allocation for Fixed Decode-and-Forward Relays

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ABSTRACT

This paper considers 2-hop wireless cooperative communications networks with fixed decode-and-forward relays. Specifically, we first derive the closed-form BER expression for theoretically evaluating the end-to-end performance of these networks. Then, based on this expression and long-term fading statistics, we propose a power allocation method for source and relay. Such a method brings about multiple advantages in term of spectral efficiency and implementation complexity over other power allocation methods based on instantaneous fading statistics. A variety of numerical results reveal that the cooperative communications scheme with the proposed power allocation significantly outperforms that with the equal power allocation and the direct transmission scheme for any position of the relay subject to the same total transmit power constraint.

Key Words : Cooperative communications, wireless network, fixed decode-and-forward, Rayleigh fading, AWGN

Ⅰ. Introduction

Signal fading due to multi-path propagation is a serious problem in wireless communications and the spatial diversity owing to the feasibility of deploying multiple antennas at both transmitter and receiver is an efficient solution to mitigate the fading[1]. However, when wireless mobiles may not be able to support multiple antennas due to size and power limitations or other constraints [2], this diversity technique is not exploited. To overcome such a restriction, a new technique, called cooperative communications (CC), was born which allows single-antenna mobiles to gain some benefits of transmit diversity [3]-[13]. Some typical CC schemes for 2-hop wireless networks including a source (S), a relay (*R*) and a destination (*D*) were proposed in [3]: fixed amplify-and-forward relaying (AF), fixed decode-and-forward relaying (DF) and selection relaying (SR). Although AF significantly reduces the signal processing at *R* because *R* only retransmits a scaled version of its received signal to *D*, it causes the noise enhancement and poses more complexity at *D* due to the demand for the channel state information (CSI) of all links in the network through which the source signals are propagated for maximum ratio combining (MRC) at *D*. DF overcomes its disadvantages by allowing *R* to completely decode, encode and forward the source information. However, DF suffers the error retransmission induced by the forwarding relay and this drawback is again corrected by SR where *R* only forwards the source information when the channel quality is favorable. One of the difficulties of SR is to determine which channel condition is favorable or which threshold is appropriate. Therefore, there is a trade-off between performance and complexity for any adopting which CC scheme. Yet, in general DF exposes the advantage in term of the net signal processing complexity at both *R* and *D* over other schemes,

※이 논문은 2007년도 정부(과학기술부)의 재원으로 한국과학재단의 지원을 받아 수행된 연구임(No. R01-2008-000-20400-0)
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논문번호 : KICS2008-08-378, 접수일자 : 2008년 8월 29일, 최종논문접수일자 : 2008년 11월 06일

thus it is considered in this paper. Wireless channel changes in time. Therefore, the power control for all entities in the network is essential to adapt such channel fluctuations so as to improve the performance of communication. Optimum power allocation methods for AF, DF and SR schemes were discussed in [4]-[7], [8]-[10] and [11]-[13], respectively and it is shown that the performance is considerably enhanced with the help of these methods. One common feature of them is that they rely on the instantaneous fading statistics. This leads to some disadvantages. The first is the loss of spectral efficiency and complexity increase because when the terminals are mobile, the requirement of accurate CSI at all respective transmitters obtained through feedback channels may mean frequent update and an extra computation burden, which is certainly undesirable. Second, CSI can not be perfectly estimated at the receivers as well as feedback to the transmitters without any error. Noisy CSI causes the power allocation inaccurately and thus affecting adversely the performance of the system. In this paper, we first derive the closed-form BER expression for theoretically evaluating the performance of DF. It is noted that there has been no exact BER expression for DF so far. Although some efforts in computing BER for SR were made in [11], the final result is only the upper bound and thus we can't obtain the BER expression for DF from that for SR in [11] by letting the threshold equal zero. Moreover, [12]-[13] derived the approximate BER formula for SR using CRC (Cyclic-Redundancy-Check) as a performance measure to decide whether *R* forwards the source data to *D* or not but in order to achieve that expression, they assume CRC code is ideal (almost impossible to exist in practice). Therefore, we can not infer the BER expression for DF from the results in [12]-[13]. Second, based on long-term fading statistics (ensemble average of path gains) and our BER expressions, we propose a power allocation method for source and relay. Such a method obviously does not require *S* and *R* to update CSI frequently since power levels of S and R are set only one time before the system operates. Consequently, our proposal overcomes the drawbacks of above mentioned methods. Although it is not an optimal solution (equivalently, it can not be comparable to the optimum methods in [4]-[13]), a variety of numerical results reveal that the cooperative communications scheme with the proposed power allocation dramatically outperforms that with the equal power allocation and the direct transmission scheme for any position of the relay subject to the same total transmit power constraint. The rest of the paper is organized as follows. Section II presents the derivation of BER expression for DF-based wireless networks. Then the proposed power allocation method is discussed in section III. Section IV demonstrates the numerical and simulated results that compare the CC scheme with our power allocation method and that with equal power allocation as well as direct transmission (without a relay). Moreover, this section also discusses thoroughly about the achieved results. Finally, the paper is closed in section V with a conclusion.

Ⅱ. BER Expression Formulation

Consider a wireless network consisting of single-antenna entities: a source (*S*), a relay (*R*) and a destination (*D*) as shown in Fig. 1. In order to mitigate the hardware implementation complexity due to the simultaneous transmission and reception at terminals, we investigate time-division approach based channel allocation without the loss of generality.

Assuming that the channels between terminals experience independent slow and frequency-flat Rayleigh fading, and are constant during one symbol period (although the analysis is illustrated on a per-symbol basis, the results also hold for block-based schemes under a block-fading assumption) that is less than the coherent time of the channel but change independently to the next. To capture the effect of path loss on BER

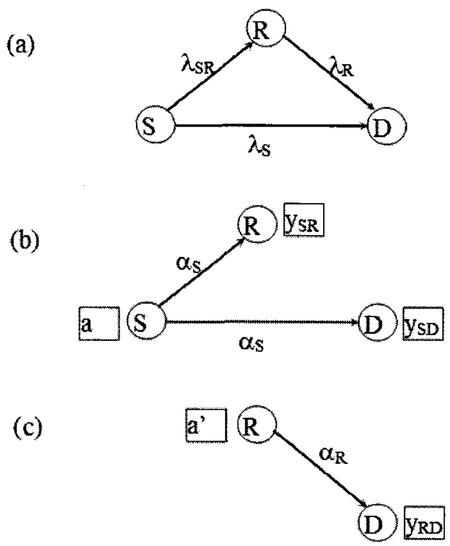

Fig. 1. DF-based cooperative signaling structure (a) Co operative network model (b) First cooperation phase: S tr ansmits data to R and D (c) Second cooperation phase: R transmits the recovered data to D. Data at the left ha nd side of each terminal is the transmitted data and that at the right hand side of each terminal is the received d ata

performance, we use the model, which is commonly discussed in the literature (e.g. [11]), where the variance of α_{ij} is given by $\lambda_{ij} = (d_{SD}/d_{ij})^{\beta}$ with d_{ij} and α_{ij} being the distance and the path gain between transmitter i and receiver j, respectively and β being the path loss exponent.

For convenience of presentation, we use discrete-time complex equivalent base-band models to express all the signals. DF scheme includes two phases of equal time duration. In the first phase, S broadcasts a BPSK-modulated symbol a (equivalently, a takes on +1 and -1 with equal probability) and so, the signals received at R and D are given by

$$y_{SR} = \alpha_{SR}\sqrt{P_S}a + n_{SR} \tag{1}$$

$$y_{SD} = \alpha_{SD}\sqrt{P_S}a + n_{SD} \tag{2}$$

where y_{ij} denotes a signal received at the terminal j from the node i, n_{ij} is a zero-mean unit-variance complex additive noise sample at the node j, P_S denotes transmit power of S.

At the end of this phase, R recovers the original data by maximum likelihood (ML) decoding as.

$$a' = sign\left(Re\left(\alpha^{*}_{SR}y_{SR}\right)\right) \tag{3}$$

Here *sign*(.) is a *signum* function and *Re*(.) is a real part.

In the second phase, R sends a' to D with power P_R. The signal arriving at D is of the form:

$$y_{RD} = \alpha_{RD}\sqrt{P_R}\,a' + n_{RD} \tag{4}$$

Now D combines the received signals from both phases based on MRC [14] and then detects the transmitted signal a as follows

$$\bar{a} = sign\left(Re\left(\sqrt{P_S}\,\alpha^{*}_{SD}y_{SD} + \sqrt{P_R}\,\alpha^{*}_{RD}y_{RD}\right)\right) \tag{5}$$

Using (2) and (4) to rewrite (5) as

$$\begin{aligned}\bar{a} &= sign\left(P_S|\alpha_{SD}|^2 a + P_R|\alpha_{RD}|^2 a' + n\right) \\ &= sign\left(\left(P_S|\alpha_{SD}|^2 a + \epsilon P_R|\alpha_{RD}|^2\right)a + n\right)\end{aligned} \tag{6}$$

Here $n = Re\left(\sqrt{P_S}\,\alpha^{*}_{SD}n_{SD} + \sqrt{P_R}\,\alpha^{*}_{RD}n_{RD}\right)$ is a Gaussian r.v. with zero-mean and variance $\left(P_S|\alpha_{SD}|^2 + P_R|\alpha_{RD}|^2\right)/2$, given channel realizations; $\epsilon = -1$ means that R made the wrong decision on the symbol a and otherwise, $\epsilon = 1$.

Based on (6), the ML detection offers the minimum error probability, conditioned on the channel realizations as

$$\begin{aligned}P_e &= \Pr\left[\bar{a} = 1 | a = -1\right] \\ &= \Pr\left[-\left(P_S|\alpha_{SD}|^2 + P_R|\alpha_{RD}|^2\right) + n > 0\right]\Pr\left[\epsilon = 1\right] + \\ &\quad \Pr\left[-\left(P_S|\alpha_{SD}|^2 - P_R|\alpha_{RD}|^2\right) + n > 0\right]\Pr\left[\epsilon = -1\right] \\ &= P_{e1}\left(1 - \Pr\left[\epsilon = -1\right]\right) + P_{e2}\Pr\left[\epsilon = -1\right]\end{aligned}$$

where P_{e1} is the probability that an error occurs in the combined transmission from S and R to D given that R decoded correctly; P_{e2} is the probability that an error occurs in the combined transmission from S and R to D given that R decoded unsuccessfully.

The average BER can be found by averaging the above over the distributions of path gains as

$$\overline{P_e}=\overline{P_{e1}}\left(1-\overline{\Pr[\epsilon=-1]}\right)+\overline{P_{e2}}\left(1-\overline{\Pr[\epsilon=-1]}\right) \quad (7)$$

where $\overline{(.)}$ stands for the ensemble average of $(.)$ Since $\Pr[\epsilon=-1]$ is the instantaneous error probability of BPSK-modulated symbol over Rayleigh fading channel *S-R* plus AWGN with zero-mean and unit-variance, its average BER is easily established as [15].

$$\overline{\Pr[\epsilon=-1]}=\frac{1}{2}\left[1-\sqrt{\frac{P_s\lambda_{SR}}{1+P_S\lambda_{SR}}}\right] \quad (8)$$

Rewrite the expression of $\overline{P_{e1}}$ in the explicit form as

$$\begin{aligned}\overline{P_{e1}}&=\overline{\Pr\left[n>\left(P_S|\alpha_{SD}|^2+P_R|\alpha_{RD}|^2\right)\right]}\\&=\overline{Q\left(\sqrt{2\left(P_S|\alpha_{SD}|^2+P_R|\alpha_{RD}|^2\right)}\right)}\end{aligned} \quad (9)$$

Here $Q(.)$ is a Q-function.

Let $x=P_S|\alpha_{SD}|^2$ and $y=P_R|\alpha_{RD}|^2$. Since α_{ij} are zero-mean complex Gaussian r.v.'s, x and y have exponential distribution; that is,

$$f_x(x)=\lambda_x e^{-\lambda_x x}U(x),\ f_y(x)=\lambda_y e^{-\lambda_y y}U(y)$$

where $\lambda_x=1/(P_S\lambda_{SD})$, $\lambda_y=1/(P_R\lambda_{RD})$, $f_x(x)$ $f_y(y)$ are pdfs of r.v.'s x and y, respectively; $U(.)$ is a unit-step function.

Also, we denotes $w = x + y$. The pdf of w, hence, is expressed as

$$\begin{aligned}f_w(w)&=\int_{-\infty}^{\infty}f_x(x)f_y(w-x)dx\\&=\begin{cases}\dfrac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}\left[e^{-\lambda_y w}-e^{-\lambda_x w}\right] & ,\lambda_x\neq\lambda_y\\ \lambda_x^2e^{-\lambda_x w}w & ,\lambda_x=\lambda_y\end{cases}\end{aligned} \quad (10)$$

and n in (6) is a Gaussian r.v. with zero-mean and variance $\left(P_S|\alpha_{SD}|^2+P_R|\alpha_{RD}|^2\right)/2=w/2$, given channel realizations.

2.1 Case of $\lambda_x=\lambda_y$

(9) is rewritten as

$$\begin{aligned}\overline{P_{e1}}&=\int_0^{\infty}Q(\sqrt{2w})\lambda_x^2we^{-\lambda_x w}dw\\&=\frac{1}{4}\left(1-\sqrt{\frac{1}{1+\lambda_x}}\right)^2\left(2+\sqrt{\frac{1}{1+\lambda_x}}\right)\end{aligned} \quad (11)$$

Also in this case, it is easy to realize that

$$\overline{P_{e2}}=\overline{\Pr\left[-\left(P_S|\alpha_{SD}|^2-P_R|\alpha_{RD}|^2\right)+n>0\right]}=0.5 \quad (12)$$

Substituting (8) and (11)-(12) into (7), we obtain $\overline{P_e}$.

2.2 Case of $\lambda_x\neq\lambda_y$

(9) is of the form

$$\begin{aligned}\overline{P_{e1}}&=\int_0^{\infty}Q(\sqrt{2w})\frac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}\left[e^{-\lambda_y w}-e^{-\lambda_x w}\right]dw\\&=\frac{\lambda_x}{2(\lambda_x-\lambda_y)}\left[1-\sqrt{\frac{1}{1+\lambda_y}}\right]-\\&\quad\frac{\lambda_y}{2(\lambda_x-\lambda_y)}\left[1-\sqrt{\frac{1}{1+\lambda_x}}\right]\end{aligned} \quad (13)$$

If we let $z=x-y$, then P_{e2} and $\overline{P_{e2}}$ is rewritten as (see Fig. 2)

$$\begin{aligned}P_{e2}&=\Pr\left[-\left(P_S|\alpha_{SD}|^2-P_R|\alpha_{RD}|^2\right)+n>0\right]\\&=\Pr[-z+n>0]\\&=Q\left(\sqrt{\frac{2z^2}{w}}\right)\Pr[z\geq 0]+\left[1-Q\left(\sqrt{\frac{2z^2}{w}}\right)\right]\Pr[z<0]\\&=P_QP_G+(1-P_Q)(1-P_G)\end{aligned}$$

and

$$\overline{P_{e2}}=\overline{P_Q}P_G+\left(1-\overline{P_Q}\right)(1-P_G) \quad (14)$$

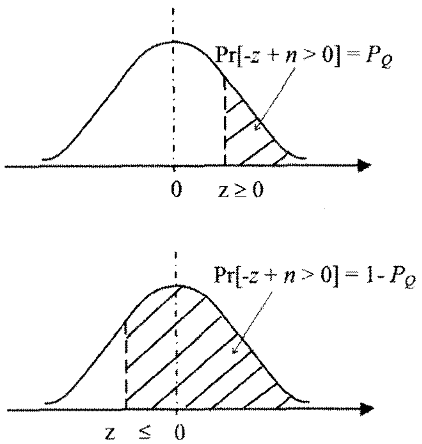

Fig. 2. Statistical distribution of n and z

Consider the case of $z\geq 0$ in the sequel, we have [16, (6-55)]

$$f_z(z)=\int_0^{\infty}f_{xy}(z+y,y)dy=\frac{\lambda_x\lambda_y}{\lambda_x+\lambda_y}e^{-\lambda_x z}$$

So

$$P_G=\Pr[z\geq 0]=\int_0^{\infty}f_z(z)dz=\frac{\lambda_y}{\lambda_x+\lambda_y} \quad (15)$$

Moreover, the pdf of $v=z^2$ is easily found as [16, (5-22)]

$$f_v(v) = \frac{1}{2\sqrt{v}} f_z(\sqrt{v}) = \frac{1}{2\sqrt{v}} \frac{\lambda_x \lambda_y}{\lambda_x + \lambda_y} e^{-\lambda_x \sqrt{v}}$$

Now we compute the pdf of $u = z^2/w = v/w$ as follows [16, (6-60)]

$$\begin{aligned} f_u(u) &= \int_0^\infty w f_v(wu) f_w(w) dw \\ &= \int_0^\infty \left[\begin{array}{l} w \dfrac{1}{2\sqrt{wu}} \dfrac{\lambda_x \lambda_y e^{-\lambda_x \sqrt{wu}}}{\lambda_x + \lambda_y} \times \\ \dfrac{\lambda_x \lambda_y}{\lambda_x - \lambda_y} \left(e^{-\lambda_y w} - e^{-\lambda_x w} \right) \end{array} \right] dw \end{aligned}$$

By changing the variable $k = \sqrt{w}$, the above is reduced to

$$f_u(u) = \int_0^\infty \left[\begin{array}{c} \dfrac{k^2}{\sqrt{u}} \dfrac{\lambda_x \lambda_y}{\lambda_x + \lambda_y} \dfrac{\lambda_x \lambda_y}{\lambda_x - \lambda_y} \times \\ \left[e^{-(\lambda_y k^2 + \lambda_x k \sqrt{u})} - e^{-(\lambda_x k^2 + \lambda_x k \sqrt{u})} \right] \end{array} \right] dk$$

Finally, P_Q and $\overline{P_Q}$ are given by

$$P_Q = Q\left(\sqrt{\frac{2z^2}{w}} \right)$$

and

$$\begin{aligned} \overline{P_Q} &= \int_0^\infty Q(\sqrt{2u}) f_u(u) du \\ &= \frac{\lambda_x^2 \lambda_y^2}{\lambda_x^2 - \lambda_y^2} \int_0^\infty \left[\begin{array}{c} Q(\sqrt{2u}) \times \\ \left[\int_0^\infty \dfrac{k^2}{\sqrt{u}} \left(\begin{array}{c} e^{-(\lambda_y k^2 + \lambda_x k \sqrt{u})} \\ - e^{-(\lambda_x k^2 + \lambda_x k \sqrt{u})} \end{array} \right) \right] dk \end{array} \right] du \\ &= \frac{\lambda_x^2 \lambda_y^2}{\lambda_x^2 - \lambda_y^2} \left[f(\lambda_y, \lambda_x) - f(\lambda_x, \lambda_x) \right] \end{aligned} \tag{16}$$

The last equality in (16) is obtained from (A4) in the Appendix. Using (15) and (16), we find (14). In addition, from (8) and (13)-(14), we calculate the BER in (7).

Ⅲ. Proposed Power Allocation Method

For fair comparison in term of total transmit power, it is essential that the total consumed energy of the cooperative system does not exceed that of corresponding direct transmission system. This is a strict and conservative constraint; allowing the relays to add additional power can then only increase the attractiveness of the cooperation. Therefore, complying this energy constraint requires

$$P_R + P_S \le P \tag{17}$$

where P is transmit power of S in case of direct transmission.

Proposed power allocation method follows the case of $\lambda_x = \lambda_y$ in section 2. Therefore, we have $\lambda_x = \lambda_y$ or

$$P_R = P_S \frac{\lambda_{SD}}{\lambda_{RD}} \tag{18}$$

Substituting (18) into (11), we obtain BER in (7) from (8) and (11)-(12) as

$$\begin{aligned} \overline{P_e} = & \frac{1}{8} \left(1 - \sqrt{\frac{P_S \lambda_{SD}}{1 + P_S \lambda_{SD}}} \right)^2 \left(2 + \sqrt{\frac{P_S \lambda_{SD}}{1 + P_S \lambda_{SD}}} \right) \\ & \times \left(1 + \sqrt{\frac{P_S \lambda_{SR}}{1 + P_S \lambda_{SR}}} \right) + \frac{1}{4} \left(1 - \sqrt{\frac{P_S \lambda_{SR}}{1 + P_S \lambda_{SR}}} \right) \end{aligned} \tag{19}$$

where P_S is constrained by (due to (17))

$$P_S \le P \left(1 + \frac{\lambda_{SD}}{\lambda_{RD}} \right)^{-1} \tag{20}$$

Since $\overline{P_e}$ in (19) is a decreasing function with respect to P_S (see Fig. 3), $\overline{P_e}$ is minimized at

$$P_S^* = P \left(1 + \frac{\lambda_{SD}}{\lambda_{RD}} \right)^{-1} \tag{21}$$

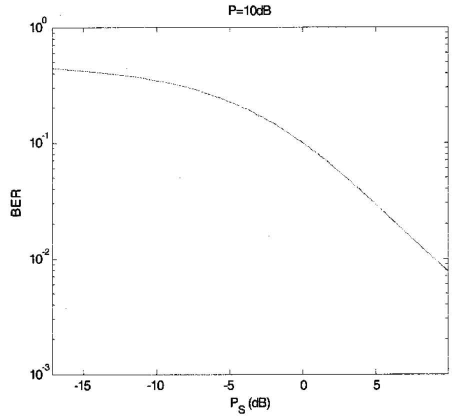

Fig. 3. BER in (19) as a function of P_S with $\lambda_{SD} = 1$, $\lambda_{RD} = 125$, $\lambda_{RD} = 125$, $\beta = 3$

Power allocation method for S and R according to (18) and (21) shows that it is extremely simple and causes no bandwidth loss. This comes from the fact that the powers of S and R are set only one time before the system operates with respect to the ensemble averages of path gains λ_{SD} and λ_{RD}, and therefore, there is no requirement of instantaneous CSI α_{ij} at the transmitters which is usually estimated at the receivers and sent through feedback channels. In addition, such a power allocation is reasonable due to following reasons. First, the power of S is required as high as possible (according to (21)) in order to help R decode successfully and thus leading to spatial diversity at D. Second, the power of R must be inversely proportional to the quality of R-D link (this is reflected in (18)) since when λ_{RD} is large (R-D link is good), there is no reason to assign more power for R to relay the source signal but instead, we reduce P_R to increase P_S so as to improve the reliability of transmission over S-R channel and as a result, the end-to-end performance of source-destination pair is enhanced.

Ⅳ. Numerical Results

We consider a network geometry where R is located on a S-D straight line, $d_{SD}=1$ and $d_{SR}=d$. For "special" case, all distances between two terminals are set to 1. Additionally, $\beta=3$ is investigated.

For notation convenience, we denote the CC scheme with proposed power allocation as S1, that with equal power allocation as S2, and direct transmission as S3. First, we verify the accuracy of BER expression in (7) by comparing with Monte-Carlo simulations. The results are depicted in Fig. 4 with equal power allocation ($P_S=P_R=P/2$). Based on the simulation conditions, we realize that except the special case which uses the expressions in case of $\lambda_x=\lambda_y$, all remaining cases must use the expressions in case of $\lambda_x \neq \lambda_y$. Also, we can see that the simulation results well match the theoretical ones. This shows that the theoretical analysis is completely exact.

Fig. 5 compares the performances of S1, S2 and S3. It demonstrates that S2 only works well (better than S3) when R is near S ($d \leq 0.9$) because at that time, R suffers less path loss caused by S-R link and thus leading to the decoding at R is more reliable. As a result, the performance is improved. In contrast, S1 always outperforms dramatically S2 and S3 for any position of R over the whole range of P. Moreover, its superiority increases with respect to the increase of total transmit power P and the decrease of d. For example, at BER of 10^{-3} and $d=0.3$, S1 provides the gains of about 4 dB and 6 dB over S2 and S3, respectively. However when the target BER is 10^{-3} and $d=0.3$, the

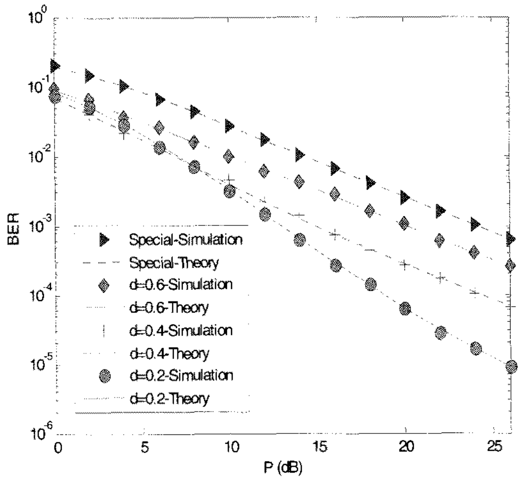

Fig. 4. BER comparison between theory and simulation with equal power allocation ($P_S=P_R$) for CC scheme

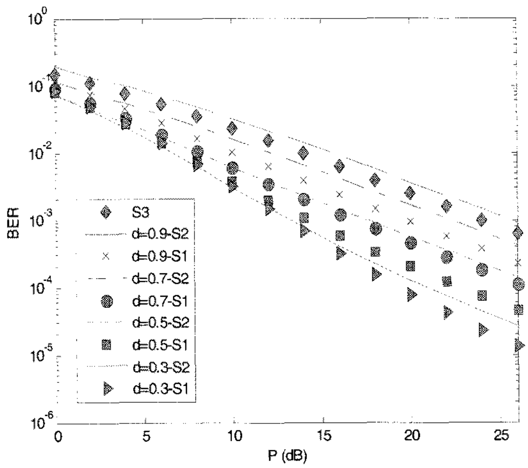

Fig. 5. BER comparison between equal and proposed power allocation

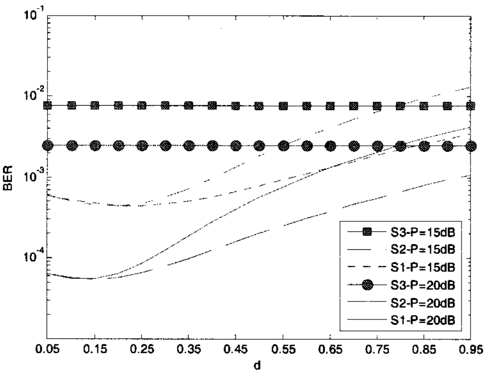

Fig. 6. BER via d

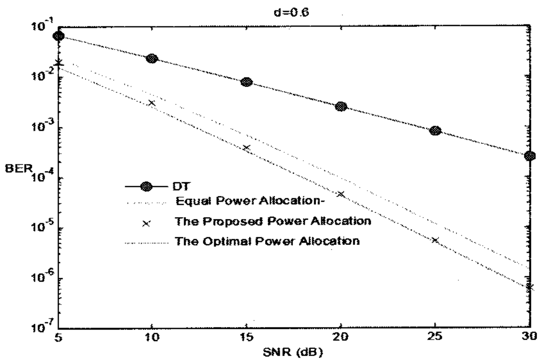

Fig. 7. BER performance with energy allocation strategies with $d=0.6$

performance gaps between S1 and S2, S3 become 4 dB and 12 dB, correspondingly.

Fig. 6 studies the influence of the relay location on the performance of communication for two different values of P of 15 dB and 20 dB. S2 is really better than S3 when d is less than 0.8 while S1 is always superior to S3 for any value of d. Fig. 6 also illustrates the optimal relay position for S1 and S2 that minimizes the error probability is approximately the same. Specifically, these positions are $d=0.21$ and 0.15 for P = 15 dB and 20 dB, correspondingly.

In Fig. 7, we further quantify the performance difference among the equal-power allocation, our proposed power allocation and the optimal power allocation. Since the proposed protocol is used, the performance loss compared to the optimal power allocation is not much. Furthermore, it can be seen that the performance of the proposed power allocation at high SNR regime will converge asymptotically to that of the optimal one. However, there is a small gap between two curses with lower SNRs due to the imperfect detection at the relay. It is obvious that the benefit of using our proposed protocol as opposed to the other is reduced hardware complexity at each node. In addition, it also reduces the computational costs and may even lead to a better performance than the optimal one, because channels with very low SNR can not be accurately estimated and contribute much noise.

V. Conclusion

We derive the closed-form BER expression for one of the simple CC schemes, DF, in this paper. Then, we proposed a power allocation method for S and R in 2-hop wireless communications networks operated over Rayleigh fading channel which is completely different from other existing methods in that only long-term fading statistics are available at the transmitters. This method brings about the considerable performance improvement over the direct transmission and the CC scheme with equal power allocation without increasing the implementation complexity as well as causing the loss of spectral efficiency. Therefore, the CC scheme with proposed power allocation is feasible and is a promising technique for the future wireless networks where there exist idle users that can serve as relays so as to take advantage of system resources efficiently.

Appendix

Applying [17, (7) on page 361 and (4) on page 880] and [18, (2) and (14)], we obtain

$$f_\epsilon(\epsilon,\lambda_1,\lambda_2)=\int_0^\infty g^2 e^{-\lambda_1 g^2-\lambda_2\sqrt{\epsilon}g}dg$$

$$=-\frac{\lambda_2\sqrt{\epsilon}}{4\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2\epsilon/2+\lambda_1}{4}e^{\frac{\lambda_2^2\epsilon}{4\lambda_1}}\left(1-\Phi\left(\sqrt{\frac{\lambda_2^2\epsilon}{4\lambda_1}}\right)\right)$$

$$=-\frac{\lambda_2\sqrt{\epsilon}}{4\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2\epsilon/2+\lambda_1}{4}e^{\frac{\lambda_2^2\epsilon}{4\lambda_1}}erfc\left(\sqrt{\frac{\lambda_2^2\epsilon}{4\lambda_1}}\right)$$

$$\cong -\frac{\lambda_2\sqrt{\epsilon}}{4\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2\epsilon/2+\lambda_1}{4}\left(\frac{1}{6}+\frac{1}{2}e^{-\frac{\lambda_2^2\epsilon}{12\lambda_1}}\right) \tag{A1}$$

$$\begin{aligned} f(\lambda_1,\lambda_2) &= \int_0^\infty Q(\sqrt{2\epsilon})\int_0^\infty \frac{g^2}{\sqrt{\epsilon}}e^{-\lambda_1 g^2-\lambda_2\sqrt{\epsilon}g}dg d\epsilon \\ &= \frac{1}{2}\int_0^\infty erfc(\sqrt{\epsilon})\frac{1}{\sqrt{\epsilon}}f_\epsilon(\epsilon,\lambda_1,\lambda_2)d\epsilon \\ &\cong \frac{1}{2}\int_0^\infty\left(\frac{1}{6}e^{-\epsilon}+\frac{1}{2}e^{-4\epsilon/3}\right)\frac{1}{\sqrt{\epsilon}}f_\epsilon(\epsilon,\lambda_1,\lambda_2)d\epsilon \end{aligned} \tag{A2}$$

where the function $\Phi(.)$ is defined in [17, (1) on page 880]. By substituting (A1) into (A2) and changing the variable $L=\sqrt{\epsilon}$, (A2) is rewritten as

$$f(\lambda_1,\lambda_2)=\frac{1}{2}\int_0^\infty\left[\begin{array}{c}\left(\frac{1}{6}e^{-L^2}+\frac{1}{2}e^{-4L^2/3}\right)\times \\ \left(-\frac{\lambda_2 L}{2\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2L^2/2+\lambda_1}{2} \\ \times\left(\frac{1}{6}+\frac{1}{2}e^{-\frac{\lambda_2^2L^2}{12\lambda_1}}\right)\right)\end{array}\right]dL \tag{A3}$$

Applying the results in [17, (2)-(3) on page 360], we can compute (A3) as

$$f(\lambda_1,\lambda_2)=\frac{1}{2}\left[\begin{array}{c}-\frac{13\lambda_2}{96\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\times \\ \left(\sqrt{\pi}\frac{\lambda_2^2+4\lambda_1}{576}+\sqrt{\frac{12\lambda_1\pi}{12\lambda_1+\lambda_2^2}}\times \right. \\ \frac{\lambda_1(\lambda_2^2+3\lambda_1)}{12(12\lambda_1+\lambda_2^2)}+ \\ \sqrt{\frac{3\pi}{4}}\frac{3\lambda_2^2+16\lambda_1}{768}+ \\ \left.\sqrt{\frac{12\lambda_1\pi}{16\lambda_1+\lambda_2^2}}\frac{\lambda_1(\lambda_2^2+4\lambda_1)}{4(16\lambda_1+\lambda_2^2)}\right)\end{array}\right] \tag{A4}$$

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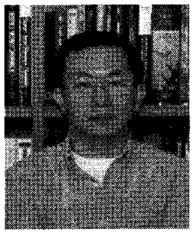

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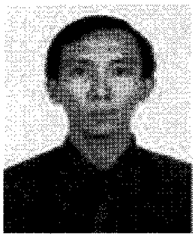

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