Exact BER Expression of 2-1-1 Relaying Scheme in Wireless Sensor Networks

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Abstract

This paper presents an energy-efficient and bandwidth-efficient 2-1-1 relaying scheme in which a sensor node(SN) assists two others in their data transmission to a clusterhead in WSNs(Wireless Sensor Networks) using LEACH (Low-Energy Adaptive Clustering Hierarchy). We derive the closed-form BER expression of this scheme which is also a general BER one for the decode-and-forward cooperative protocol and prove that the proposed scheme performs the same as the conventional relaying scheme but obtains higher channel utilization efficiency. A variety of numerical results reveal the relaying can save the network energy up to 11 dB over single-hop transmission at BER of 10^{-3}.

Key words : LEACH, Relaying Scheme, WSN.

Ⅰ. Introduction

High-energy utilization efficiency is a stringent design criterion for WSNs since each sensor node(SN) must operate for several months on a single battery[1],[2]. In addition, reliable communications over wireless channels, which is a difficult problem due to fading, is another requirement. A feasible solution is to take full advantage of idle SNs, namely relays, in the vicinity of the transmitting node to relay the original signal to its destination. This not only benefits from the path-loss reduction due to these relays usually closer to the destination, but also enables nodes to use each other's antennas to obtain an effective form of spatial diversity. Due to severe constraints on both node size and analog device power consumption, such a solution seems to be very appropriate in the WSN scenario. The ways in which the idle SNs process the received signal from a desired node are known as cooperative protocols[3]~[13].

So far, there are three basic cooperative protocols: amplify-and-forward(AF)[3],[4], decode-and-reencode(DR)[5]~[8] and decode-and-forward(DF)[9]~[13]. AF requires the inter-user Channel State Information(CSI) available at the destination, which is hard to obtain, and suffers noise enhancement at the relays that degrade the BER performance. In addition, DR using convolutional codes, turbo codes and TCM(Trellis Coded Modulation) achieves the best performance among three protocols, but complicates encoding and decoding, thus preventing implementation on SNs. DF appears to be a proper choice for cooperation in WSNs because it not only outperforms AF, but also demonstrates the lowest complexity since each receiver only needs CSI of the link to which it is listening.

For almost all cooperative protocols, transmitting nodes must also process their received signals, but current radio implementation restrictions do not allow for simultaneous transmission and reception by same transceiver since considerable attenuation over the wireless channel and insufficient electrical isolation between the transmit and receive circuitry make a node's transmitted signal dominate the signals of other nodes at its receiver input. Thus, cooperative systems usually rely on some form of orthogonality to transmit and receive signals from multiple users. Without the loss of generality, the channel allocation based on the time-division approach is normally considered as shown in Fig. 1.

Current relaying schemes use one or more intermediate nodes to assist the data transmission of an intended node. Therefore, the channel utilization efficiency(CUE) is relatively low. Specifically, we can see from Fig. 1b that CUE equals $1/N$ where N is the total number of nodes cooperating. To increase CUE, we propose a 2-1-1 relaying scheme in which a node assists two others in their data transmission by detecting the received signals separately and forming a composite signal with the real part representing the decoded information from one source node and imaginary part from the other source node. By doing so, we achieve CUE of 2/3 compared to 1/2 of a conventional one-relay scheme(see Fig. 1c). In the aspect of BER performance, we will show that they perform at the same.

Besides proposing a new relaying model, this paper derives a closed-form BER expression, which is a ge-

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neralization of DF's performance over Rayleigh-fading channels plus AWGN. The rest of this paper is organized as follows: Part 2 discusses the proposed 2-1-1 relaying scheme. Then, BER formula establishment is presented in Part 3. The Monte-Carlo simulations are also performed to verify the accuracy of the derived expressions, and the results are reported in Part 4. Finally, the paper is closed with the conclusion in Part 5.

Ⅱ. Proposed 2-1-1 Relaying Scheme

We investigate a typical communications protocol LEACH for WSNs[2]. This protocol divides a WSN into clusters, each with clusterheads. The function of clusterheads is to assign the time at which the SNs can transmit data to them based on a TDMA(Time Division Multiple Access) approach, and to aggregate data from the nodes in their cluster before sending these data to the base station. Therefore, the high-energy dissipation in communicating with the base station is spread to all SNs in the WSN.

Consider a certain cluster as shown in Fig. 2. The information sent from any SN can reach its clusterhead in the following ways.

1) *Single-hop transmission*: SN sends its data directly to the clusterhead without the help of any relay.

(a) Single-hop transmission where the whole time-slot is used for sending useful data

(b) Conventional relaying scheme where only 1/*N* of time-slot is useful

(c) Proposed scheme where 2/3 of time-slot is useful

Fig. 1. Channel allocation based on time-division approach. S denotes a transmitting node, R(or R_i) a relay, S_1 first sending node, S_2 second sending node. T_x represents the transmitting and R_x receiving.

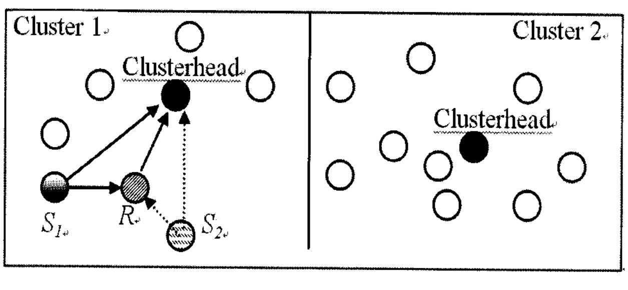

Fig. 2. Clusters of wireless sensor network.

2) *Multi-hop transmission*: data transmission has to pass through several relays before reaching the destination. The relay's role is to simply decode the data it receives from the preceding node and again encode the message prior to retransmission to the destination. It is shown that this communications scheme can only extend range or save transmit power but achieves no diversity gains(diversity order of 1)[9].

3) *Cooperative transmission*: this protocol is an extension of the multi-hop transmission protocol in which the receiver can combine the data from a desired node and its relays instead of only from the last relay. Here we distinguish two relaying schemes, namely conventional and proposed ones. Moreover, we limit the number of relays to I and only consider the DF cooperative protocol as the most feasible choice for WSNs as introduced in Part 1.

For ease of exposition, we denote the transmitting SNs as S(or S_1, S_2), their relay as R and clusterhead as D. In the conventional scheme[3]~[9], a single-hop transmission time-slot is divided into two intervals. S uses the first interval to broadcast data to D as well as to R(see Fig. 1b for the case of N=1). After decoding the received signal, R forwards the resulting signal to D. Then, the clusterhead combines the signals received in two intervals based on MRC(Maximum Ratio Combining) to make a final decision on the original data. Therefore, CEU is 1/2.

For the proposed scheme, a time-slot is divided into three intervals. The first two intervals are for S_1 and S_2 to send their own information to D and R(see Fig. 1c), respectively. Then, R detects the received signals and forms a composite signal(will be discussed clearly in next part), which is sent to D in the last interval. Thus, CEU is 2/3. Similar to the conventional scheme, D decodes the signals from each node relying on the output value of MRC. Moreover, it is straightforward to realize that the proposed scheme becomes the conventional one when only one sending node is available.

2-1 Channel Model

Assuming that the channels between SNs are independent, this is possible since the antennas of SN's are relatively far apart from one another. In addition, all channels experience fast and frequency-flat Rayleigh fading, i.e. the amplitude of path gain α_{ij} between transmitter i and receiver j is Rayleigh-distributed(equivalently, α_{ij}^2 is exponential random variable with mean λ_{ij}^2), the phase ϕ_{ij}^2 has uniform distribution in the interval[0, 2π], and they are constant during one symbol period and change independently to the next.

To capture the effect of path loss on overall performance, we use the same model as discussed in [14] where $\lambda_{ij}^2=(d_{SD}/d_{ij})^{\beta}$ with d_{ij} being the distance between transmitter i and receiver j and β being the path loss exponent. For a suburban environment, we have $\beta=3$[9] and only this case is considered in the sequel.

2-2 Signal Analysis

For convenience of presentation, we use discrete-time complex equivalent base-band models to express all the signals. The BPSK transmission is under investigation. Moreover, channel-state information is assumed to be perfectly known at all the respective receivers, but not at transmitters, and all receivers can achieve perfect timing and carrier synchronization. In addition, we restrict the analysis of one-symbol-length data frames without the loss of generality.

2-2-1 Conventional Relaying Scheme(CRS)

As briefly mentioned above, CRS consists of two phases. In the first phase, S broadcasts a BPSK-modulated symbol a and so, the signals received at R and D are given by, respectively

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

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

where y_{ij} denotes a signal received at the node j from the node i, n_{si} a zero-mean complex additive noise sample of unit variance at the node j, E_S the average bit energy of the source.

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

$$\hat{a}=\text{sign}(\text{Re}(\alpha_{SR}^{*}y_{SR})) \tag{3}$$

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

In the second phase, the relay sends $\hat{a}$ to D. The signal arriving at D is of the form

$$y_{RD}=\alpha_{RD}\sqrt{E_R}\hat{a}+n_{RD} \tag{4}$$

where E_R represents the average bit energy of the relay and n_{RD} the Gaussian noise at D.

Now, D combines the received signals from both phases based on MRC to detect the transmitted signal a

$$\bar{a}=\text{sign}(\text{Re}(\alpha_{SD}^{*}y_{SD}+\alpha_{RD}^{*}y_{RD})) \tag{5}$$

For a fair comparison, it is essential that the total consumed energy of the cooperative system does not exceed that of a 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 cooperation. Therefore, complying with this energy constraint requires $E_S=E_R=E_T/2$ where E_T is the average bit energy of SN in case of single-hop transmission.

Using (2), (4) and the fact that $E_S=E_R$ to rewrite (5), we have

$$\bar{a}=\text{sign}(\sqrt{E_S}(|\alpha_{SD}|^2a+|\alpha_{RD}|^2\hat{a})+n) \tag{6}$$

Here $n=\text{Re}(\alpha_{SD}^{*}n_{SD}+\alpha_{RD}^{*}n_{RD})$ is a Gaussian r.v. with zero-mean and variance, given channel realizations,

$$\text{Var}(n)=\frac{|\alpha_{SD}|^2+|\alpha_{RD}|^2}{2} \tag{7}$$

(7) is derived from the assumption that n_{SD} and n_{RD} are independent Gaussian r.v.'s with zero-mean and unit variance.

2-2-2 Proposed 2-1-1 Relaying Scheme(PRS)

Different from CRS in which each relay assists the data transmission for each transmitting node, PRS utilizes a 2-1-1 scheme: 2 sending nodes, 1 relay and 1 receiving node. Following the signal flow of Fig. 1c, we obtain the signals at R and D during the first phase as

$$y_{S_1R}=\alpha_{S_1R}\sqrt{E_{S_1}}a_1+n_{S_1R} \tag{8}$$

$$y_{S_1D}=\alpha_{S_1D}\sqrt{E_{S_1}}a_1+n_{S_1D} \tag{9}$$

where a_i is BPSK-modulated data symbol of S_i and E_{S_i} the average bit energy of S_i.

Similarly, the signals received at R and D in the second phase are

$$y_{S_2R}=\alpha_{S_2R}\sqrt{E_{S_2}}a_2+n_{S_2R} \tag{10}$$

$$y_{S_2D}=\alpha_{S_2D}\sqrt{E_{S_2}}a_2+n_{S_2D} \tag{11}$$

Now R decodes the signals from each SN separately to result in the recovered symbols as

$$\hat{a}_1=\text{sign}(Re(\alpha_{S_1R}^{*}y_{S_1R})) \tag{12}$$

$$\hat{a}_2=\text{sign}(Re(\alpha_{S_2R}^{*}y_{S_2R})) \tag{13}$$

Then, a pair $(\hat{a}_1, \hat{a}_2)$ is used to choose one of the 4 points in the QPSK signal constellation; that is, R will transmit the following signal to D in its own time-slot:

$$\sqrt{E_R}(\hat{a}_1+j\hat{a}_2) \tag{14}$$

where $j^2=-1$

It is apparent that D will receive the signal

$$y_{RD}=\alpha_{RD}\sqrt{E_R}(\hat{a}_1+j\hat{a}_2)+n_{RD} \tag{15}$$

Since there are two sending nodes, the total energy of the system must be $2E_T$. If SNs transmit equal power, then the following equation must be satisfied for a fair comparison among the examined schemes

$$E_R=E_{S_1}=E_{S_2}=E_T/2=E_S \tag{16}$$

The clusterhead can restore the data of S_1 and S_2 after the third phase relied on MRC

$$\overline{a_1}=\text{sign}(\text{Re}(\alpha^*_{S_1D}y_{S_1D}+\alpha^*_{RD}y_{RD})) \tag{17}$$

$$\overline{a_2}=\text{sign}(\text{Im}(\alpha^*_{S_2D}y_{S_2D}+\alpha^*_{RD}y_{RD})) \tag{18}$$

where Im(·) is the imaginary part.

Replacing (9), (11), (15), (16) into (17)~(18), we obtain the explicit forms as follows

$$\overline{a_1}=\text{sign}(\sqrt{E_S}(|\alpha_{S_1D}|^2a_1+|\alpha_{RD}|^2\hat{a}_1)+n_1) \tag{19}$$

$$\overline{a_2}=\text{sign}(\sqrt{E_S}(|\alpha_{S_2D}|^2a_2+|\alpha_{RD}|^2\hat{a}_2)+n_2) \tag{20}$$

where

$$\overline{n_1}=\text{Re}(\alpha^*_{S_1D}n_{S_1D}+\alpha^*_{RD}n_{RD}) \tag{21}$$

$$\overline{n_2}=\text{Im}(\alpha^*_{S_2D}n_{S_2D}+\alpha^*_{RD}n_{RD}) \tag{22}$$

Conditioned on the channel realizations, n_1 and n_2 are Gaussian r.v.'s with zero-mean and variances, respectively

$$\text{Var}(n_1)=\frac{|\alpha_{S_1D}|^2+|\alpha_{RD}|^2}{2} \tag{23}$$

$$\text{Var}(n_2)=\frac{|\alpha_{S_2D}|^2+|\alpha_{RD}|^2}{2} \tag{24}$$

The pairs of expressions (6)~(7), (19)~(23), (20)~(24) show that the error probabilities in detecting a, a_1 and a_2 are equal if the path gains α_{SD}, α_{S_1D}, α_{S_2D} have the same variance. So, we affirm that CRS and PRS achieve the same performance. Moreover, both schemes yield spatial diversity gain of order 2 when the quality of channels between sending nodes and relay is high since under such good S-P channel conditions, the relay will decode correctly and resend versions of the original data over an uncorrelated channel to the clusterhead. In addition, we benefit from path-loss reduction: a relay located between S and D will receive the information transmitted by S much more reliably than the clusterhead, and in turn it needs to use a dramatically smaller transmission power to reach the clusterhead.

Ⅲ. Performance Analysis

Since the expressions for use in recovering a, a_1, a_2 in (6), (19), (20) are of the same form, we just formulate BER performance of detecting a. Following the similar steps can easily derive the BER of a_1 and a_2.

The cooperative protocol used for CRS and PRS is obviously DF and so, it is extensively discussed in the literature. However, to the best of our knowledge, the performance measure for this protocol is limited to the outage probability. Although the authors in [12] made efforts in computing the BER expression, they only showed the upper bound. Thus, our goal in this paper is to derive a closed-form BER expression of the proposed relaying scheme, which is also generalized for DF protocol.

Rewritten, (6) is

$$\overline{a}=\text{sign}(\sqrt{E_S}(|\alpha_{SD}|^2+\varepsilon|\alpha_{RD}|^2)a+n) \tag{25}$$

where $\varepsilon=-1$ means that the relay made the wrong decision on the symbol a.

Then, based on (25), the ML detector offers the minimum error probability, conditioned on the channel realizations as

$$\begin{aligned}P_e&=P_r[\overline{a}=1|a=-1]\\&=\Pr[-\sqrt{E_S}(|\alpha_{SD}|^2+|\alpha_{RD}|^2)+n>0]\Pr[\varepsilon=1]+\\&\quad\Pr[-\sqrt{E_S}(|\alpha_{SD}|^2-|\alpha_{RD}|^2)+n>0]\Pr[\varepsilon=-1]\\&=P_{e1}(1-\Pr[\varepsilon=-1])+P_{e2}\Pr[\varepsilon=-1]\end{aligned}$$

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

$$\overline{P_e}=\overline{P_{e1}}(1-\overline{\Pr[\varepsilon=-1]})+\overline{P_{e2}\Pr[\varepsilon=-1]} \tag{26}$$

Since Pr[$\varepsilon=-1$] is the instantaneous error probability of BPSK signal transmission over Rayleigh fading channel S-R plus AWGN with zero-mean and unit variance, its average BER is easily established as

$$\overline{\Pr[\varepsilon=-1]}=\frac{1}{2}\left[1-\sqrt{\frac{E_S\lambda^2_{SR}}{1+E_S\lambda^2_{SR}}}\right] \tag{27}$$

where λ^2_{SR} is the variance of path gain of S-R channel.

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

$$\begin{aligned}\overline{P_{e1}}&=\overline{\Pr[n>\sqrt{E_S}(|\alpha_{SD}|^2+|\alpha_{RD}|^2)]}\\&=\overline{Q(\sqrt{2E_S}(|\alpha_{SD}|^2+|\alpha_{RD}|^2))}\end{aligned} \tag{28}$$

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

Let x= $|\alpha_{SD}|^2$ and y= $|\alpha_{RD}|^2$

Since α_{ij} are zero-mean complex Gaussian r.v.'s with variance λ^2_{ij}, x and y have exponential distribution with mean values of λ^2_{ij}; that is,

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

where $\lambda_x=1/\lambda^2_{SD}$, $\lambda_y=1/\lambda^2_{RD}$ and $x, y>=0$; $f_x(x)$, $f_y(y)$ are pdfs of r.v.'s x and y, respectively.

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

$$f_w(w)=\int_{-\infty}^{\infty} f_x(x)f_y(w-x)dx$$
$$=\begin{cases}\frac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}\left[e^{-\lambda_y w}-e^{-\lambda_x w}\right], & \lambda_x\neq\lambda_y \\ b^2 e^{-bw}w, & \lambda_x=\lambda_y=b\end{cases} \quad (29)$$

Now we establish BER expression in (26) according to two cases of (29).

3-1 Case of $\lambda_x=\lambda_y$

This is the case that both paths S-D and R-D have quality similar to the destination. Hence, we obtain from (28)

$$\overline{P_{e1}}=\int_0^{\infty} Q(\sqrt{2E_S w})b^2 w e^{-bw}dw$$

By changing the variable of the integration $m=P_S w$ and letting $\gamma=E_S/b$, the probability of error is derived as follows

$$\overline{P_{e1}}=\int_0^{\infty} Q(\sqrt{2m})\frac{1}{\gamma^2}me^{-\frac{m}{\gamma}}dx$$
$$=\frac{1}{4}\left(1-\sqrt{\frac{\gamma}{1+\gamma}}\right)^2\left(2+\sqrt{\frac{\gamma}{1+\gamma}}\right) \quad (30)$$

Also in this case, it is easy to realize that

$$\overline{P_{e2}}=\overline{\Pr[-\sqrt{E_S}(|\alpha_{SD}|^2-|\alpha_{RD}|^2)+n>0)]}=0.5 \quad (31)$$

Substituting (27), (30), (31) into (26), we obtain $\overline{P_e}$.

3-2 Case of $\lambda_x\neq\lambda_y$

The asymmetric scenario happens when fading level of one of the propagation paths to the receiver is different from the other path. In such a case, (28) is of the form

$$\overline{P_{e1}}=\int_0^{\infty} Q(\sqrt{2E_S w})\frac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}\left[e^{-\lambda_y w}-e^{-\lambda_x w}\right]dw$$
$$=\frac{\lambda_x}{2(\lambda_x-\lambda_y)}\left[1-\sqrt{\frac{1}{1+\lambda_y/E_S}}\right]$$
$$-\frac{\lambda_y}{2(\lambda_x-\lambda_y)}\left[1-\sqrt{\frac{1}{1+\lambda_x/E_S}}\right]$$
$$=\frac{1}{2(\lambda^2_{RD}-\lambda^2_{SD})}\left(\lambda^2_{RD}\left[1-\sqrt{\frac{E_S\lambda^2_{RD}}{1+E_S\lambda^2_{RD}}}\right]\right.$$
$$\left.-\lambda^2_{SD}\left[1-\sqrt{\frac{E_S\lambda^2_{SD}}{1+E_S\lambda^2_{SD}}}\right]\right) \quad (32)$$

If we let $z=x-y$, then P_{e2} and $\overline{P_{e2}}$ are written as

$$\overline{P_{e2}}=\Pr[-\sqrt{E_S}(|\alpha_{SD}|^2-|\alpha_{RD}|^2)+n>0)]$$
$$=\Pr[n>\sqrt{E_S}(|\alpha_{SD}|^2-|\alpha_{RD}|^2)]$$
$$=Q\left(\sqrt{\frac{2E_S z^2}{w}}\right)\Pr[z\geq 0]+\left[1-Q\left(\sqrt{\frac{2E_S z^2}{w}}\right)\right]\Pr[z\leq 0]$$
$$=\overline{P_Q}P_G+(1-\overline{P_Q})(1-P_G)$$

and

$$\overline{P_e}=\overline{P_Q}P_G+(1-\overline{P_Q})(1-P_G) \quad (33)$$

Consider the case of $z>=0$ in the sequel, we have [20, (6-55)]

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

So

$$P_G=\Pr[z\geq 0]=\int_0^{\infty} f_z(z)dz=\frac{\lambda_y}{\lambda_x+\lambda_y} \quad (34)$$

Moreover, the pdf of $v=z^2$ is easily found as [14, (5-22)]

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

Now we compute the pdf of $u=v/w$ as follows [14, (6-60)]

$$f_u(u)=\int_0^{\infty} wf_v(wu)f_w(w)dw$$
$$=\int_0^{\infty} w\frac{1}{2\sqrt{wu}}\frac{\lambda_x\lambda_y e^{-\lambda_x\sqrt{wu}}}{\lambda_x+\lambda_y}\frac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}\left[e^{-\lambda_y w}-e^{-\lambda_x w}\right]dw$$

By changing the variable $k=\sqrt{w}$ and using [15, (7) on page 361], the above is reduced to

$$f_u(u)=\int_0^{\infty}\frac{1}{\sqrt{u}}\frac{\lambda_x\lambda_y}{\lambda_x+\lambda_y}\frac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}k^2\cdot$$
$$\left[e^{-(\lambda_y k^2+\lambda_x k\sqrt{u})}-e^{-(\lambda_x k^2+\lambda_x k\sqrt{u})}\right]dk$$
$$=\frac{\lambda^2_x\lambda^2_y}{\lambda^2_x-\lambda^2_y}\left[\begin{array}{l}\left(\frac{1}{4\lambda_x}-\frac{\lambda_x}{4\lambda^2_y}\right)+ \\ \sqrt{\frac{\pi}{\lambda^5_y}}\frac{\lambda^2_x u+2\lambda_y}{4\sqrt{u}}\exp\left(\frac{\lambda^2_x u}{4\lambda_y}\right)Q\left(\sqrt{\frac{\lambda^2_x u}{2\lambda_y}}\right)- \\ \sqrt{\frac{\pi}{\lambda^5_x}}\frac{\lambda^2_x u+2\lambda_x}{4\sqrt{u}}\exp\left(\frac{\lambda_x u}{4}\right)Q\left(\sqrt{\frac{\lambda_x u}{2}}\right)\end{array}\right]$$

Finally, $\overline{P_Q}$ is given by

$$\overline{P_Q}=\int_0^{\infty} Q(\sqrt{2E_S u})f_u(u)du \quad (35)$$

The integral in (35) can be easily approximated as a sum [14].

Using (34), (35), we find (33). In addition, from (27), (32), (33), we calculate the BER in (26).

Ⅳ. Numerical Results

In this part, we investigate the performances of three communications schemes in a cluster as mentioned in section II. For the proposed relaying scheme, since the BER performance analysis of SNs S_1 and S_2 are similar, we only investigate the node S_1 as an example.

A simple network geometry is examined where the relay is located on a line between S_1 and D. The direct path length S_1-D is normalized to be 1. We also denote d as the distance between S_1 and R. Therefore, $d_{RD}=1-d$.

First of all, we verify the accuracy of BER expression in (26) by comparing with Monte-Carlo simulations. The results are depicted in Fig. 3. We can see that the simulation results match the analytical ones. This shows that the theoretical BER expression is completely exact.

Fig. 4 studies the influence of the relay location on the performance of cooperative protocol for two different values of average bit energy E_T of 4 dB and 12 dB. The multi-hop transmission is really better than the single-hop one only when the partner is placed in the interval [0.2 0.8] while the proposed scheme always outperforms the single-hop communications unless the distance between P and S_1 is greater than 0.8. Fig. 4 also illustrates the optimal relay position for the multi-hop transmission is at the center of S_1-D line since it presents a good trade-off between good receiver conditions for the partner and transmit power savings. Moreover, the cooperative scheme exposes its considerable superiority to comparable ones when it is closer to S and attains the best performance at roughly d=0.2.

Fig. 5 compares the optimal performances of communications schemes via the total transmit energy E_T. At the target BER of 10^{-3}, the proposed relaying scheme can save the system energy up to 8 dB and 11 dB in comparison to the multi-hop and single-hop cases, respectively. In addition, energy saving keeps increasing in proportion to the higher performance requirement, which is represented by the steeper slope of BER curve in the cooperative case than those in the other cases. This is because the cooperation benefits from diversity gains as well as from path-loss reduction.

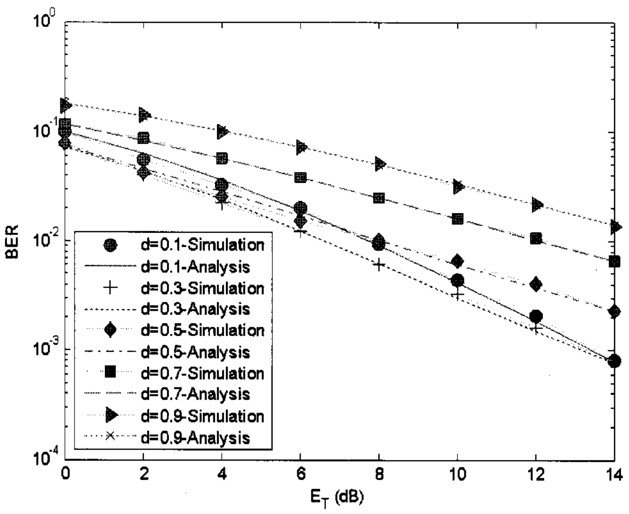

Fig. 3. BER comparison between analysis and simulation.

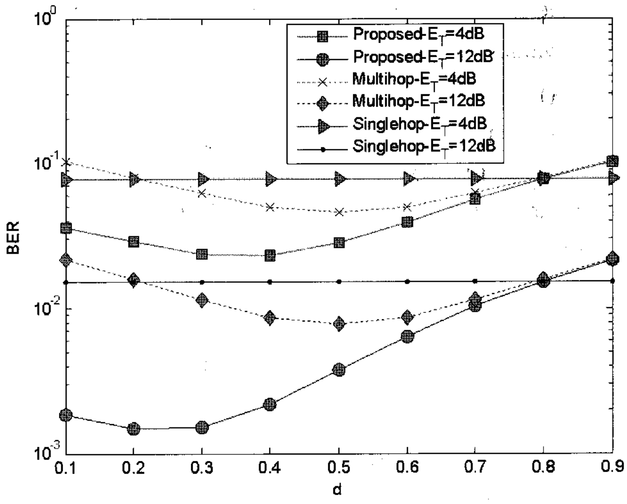

Fig. 4. BER performance versus d.

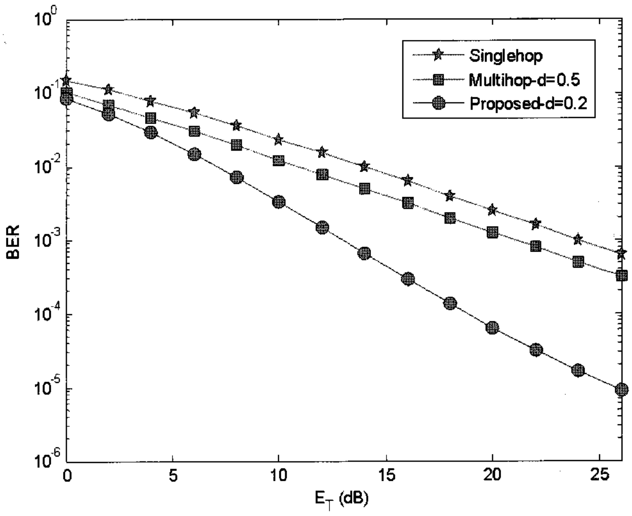

Fig. 5. BER performance of communications schemes.

V. Conclusion

The proposed relaying scheme allows an idle node to help two other SNs in data transmission to the cluster-head. A closed-form BER expression was also established to facilitate the evaluation of the performance without time-consuming computer simulations. This expression is also a generic error probability form of DF protocol. The Monte-Carlo simulations verified its validity.

The numerical results showed the suggested scheme increases the channel utilization efficiency and energy efficiency significantly without requiring additional implementation complexity for SNs. Energy saving that the cooperation achieves is equivalent to prolonging sensor network lifetime and better satisfying the critical design condition of WSNs.

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