전력 및 대역폭 효율성있는 무선센서네트워크협력 전송에 관한 연구

Ho Van Khuong[†] · 공형윤[†††] · 최정호[††] · 정휘재[††]

요 약

본 논문에서 먼저 LEACH (Low-Energy Adaptive Hierarchy)를 사용한 무선센서네트워크에서 하나의 센서 노드가 다른 두 센서노드의 클러스터 헤드를 향한 데이터 전송을 도와주는 전력 및 대역폭에 효율성있는 협력 통신 프로토콜을 제안하고, 제안한 프로토콜의 closed-form BER(Bit Error Ratio)을 유도한다. 또한 이것이 복호 후 전송 프로토콜의 일반적인 BER 임을 보이고, 제안한 시스템이 기존의 복호 후 전송 프로토콜보다 더 높은 주파수 효율을 가지면서 동일한 성능을 나타내는 것을 보인다. 많은 수학적인 결과를 통해 직접 전송인 경우 BER이 10^{-3}에서 11dB까지 네트워크의 전력이 절약되는 것을 확인할 수 있다.

키워드 : 복호 후 전송, LEACH, 협력 통신, 무선센서네트워크

Power-and-Bandwidth Efficient Cooperative Transmission Protocol in Wireless Sensor Networks

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ABSTRACT

In this paper, we first propose a power and-bandwidth efficient cooperative transmission protocol where a sensor node assists two others for their data transmission to a clusterhead in WSNs (Wireless Sensor Networks) using LEACH (Low-Energy Adaptive Clustering Hierarchy). Then we derive its closed form BER expression which is also a general BER one for the decode-and-forward protocol (DF) and prove that the proposed protocol performs the same as the conventional DF but obtains higher spectral efficiency. A variety of numerical results reveal the cooperation can save the network power up to 11dB over direct transmission at BER of 10^{-3}.

Key Words : DF, LEACH, Cooperative Transmission, WSN

1. Introduction

Efficient energy utilization 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 path-loss reduction but also enables nodes to use each other's antennas to obtain an effective form of spatial diversity without the need for physical antenna arrays. Additionally, a constraint on node size which requires each SN to be equipped with single-antenna makes such a solution very appropriate in WSN scenario. The ways the idle SNs process the signals received from a desired node are known as cooperative protocols [3]-[13].

So far, there are three basic cooperative protocols: amplify-and-forward (AF) [3], decode-and-reencode (DR) [4]-[8] and decode-and-forward (DF) [9]-[11]. AF requires inter-user CSI (Channel State Information) available at the destination which is hard to obtain, and suffers noise enhancement at the relays that degrades BER performance. In addition, DR using convolutional codes, turbo codes and TCM (Trellis Coded Modulation) achieves the best

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performance among three protocols but so complicated in encoding and decoding, thus preventing from implementing on SNs. DF appears to be a proper choice for cooperation in WSNs because it demonstrates the lowest complexity (each receiver only needs CSI of the channel it is listening).

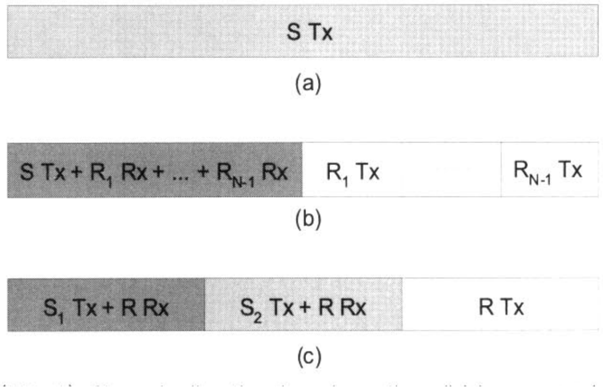
For almost cooperative protocols, transmitting nodes must also process their received signals but current radio implementation restrictions do not allow for simultaneous transmission and reception by the same transceiver. This is due to the fact that considerable attenuation over wireless channel and insufficient electrical isolation between 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 loss of generality, channel allocation based on time-division approach is normally considered as shown in (Fig. 1).

The conventional DF uses one or more intermediate nodes to assist data transmission of an intended node. Therefore, channel utilization efficiency (CUE) is relatively low. Specifically, we can see from (Fig. 1) (b) that CUE equals 1/N where N is the total number of cooperating nodes. To increase CUE, we propose a new protocol where a node assists two others for 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 ½ of conventional one-relay DF (see (Fig. 1) (c)). In the aspect of BER performance, we will show that they perform the same.

Besides proposing a new cooperative transmission protocol, this paper derives a closed-form BER expression which is a generalization of DF's performance over Rayleigh-fading channels plus AWGN (Additive White Gaussian Noise). The rest of this paper is organized as follows. Section 2 discusses the proposed protocol. Then BER formula establishment is presented in section 3. The Monte-Carlo simulations are also performed to verify the accuracy of the derived expression and the results are reported in section 4. Finally, the paper is closed with the conclusion in section 5.

2. Proposed cooperative transmission protocol

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

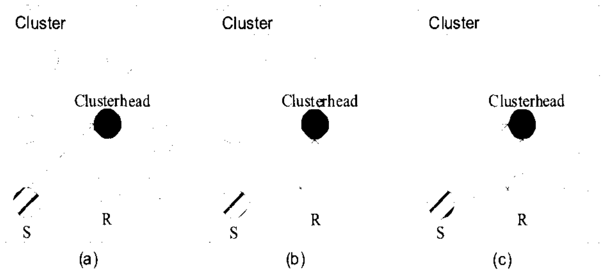


(Fig. 1) Channel allocation based on time-division approach. (a) Direct transmission where the whole time-slot is used for sending useful data. (b) Conventional DF where only 1/N of time-slot is useful. (c) Proposed protocol where 2/3 of time-slot is useful. S denotes a transmitting node, R (or R_i) a relay, S_1 first sending node, S_2 second sending node. Tx represents the transmitting and Rx receiving.

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

1) Direct transmission (see (Fig. 2) (a)): SN sends its data directly to the clusterhead without the help of any intermediate node, namely relay.
2) Multi-hop transmission (see (Fig. 2) (b)): 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 next node. The destination detects the original data only based on the signal received from the last node (nearest to the destination). It is shown that this protocol can only extend range or save transmit power but achieves no diversity gain (diversity order of 1) [12].
3) Cooperative transmission (see (Fig. 2) (c)): this protocol is an extension of the multi-hop protocol where the receiver combines the data from the

desired source node and all its relays instead of only from the last relay as for the multi-hop protocol. A wide variety of cooperative transmission protocols were proposed but a majority requires the channel estimation, thus leading to an additional increase in information processing energy. However, they can still bring many simultaneous advantages such as diversity gain, coverage extension, energy saving, etc. The maximum diversity order these protocols can achieve equals the total number of cooperating nodes.



(a) Direct transmission (b) Multi-hop (c) Cooperation

(Fig. 2) Clusters of wireless sensor networks

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 DF [9]-[11], a direct transmission time-slot is divided into two phases. S uses the first phase to broadcast data to D as well as to R (see (Fig. 1) (b) for the case of N=2). After decoding the received signal, R forwards the resulting signal to D. Then the clusterhead combines the signals received in two phases based on MRC (Maximum Ratio Combining) to make a final decision on the original data. Therefore, CUE is ½.

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

2.1 Channel model

Assuming that channels between SNs are statistically independent. This is possible since SNs are relatively far apart from each other. In addition, all channels experience slow and frequency-flat Rayleigh fading, i.e. amplitude of path gain α_{ij} between transmitter i and receiver j is Rayleigh-distributed (equivalently, $|\alpha_{ij}|^2$ is exponential random variable with mean λ_{ij}) and its phase Φ_{ij} has uniform distribution in the interval $[0, 2\pi]$ and they are constant during a data frame and change independently to the next.

To capture the effect of path loss on overall performance, we use the same model as commonly discussed in the literatre (e.g. [11], [13]) where $\lambda_{ij}=(d_{SD}/d_{ij})^{\beta}$ with d_{ij} being the distance between transmitter i and receiver j, and β being the path loss exponent.

2.2 Signal Analysis

For convenience of presentation, we use discrete-time complex equivalent base-band models to express all the signals. 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 to one-symbol-length data frames without loss of generality.

2.2.1 Conventional DF (CDF)

As briefly mentioned above, CDF 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

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

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

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

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

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

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

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

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

where P_R represents the average transmit power of R and n_{RD} zero-mean unit-variance Gaussian noise at D.

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

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

For a fair comparison, 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 cooperation. Therefore, complying with this energy constraint requires $P_S=P_R=P_T/2$ where P_T is the average transmit power of S in case of direct transmission.

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

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

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

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

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

2.2.2 Proposed protocol (PDF)

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

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

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

where a_i is BPSK-modulated data symbol of S_i and P_{S_i} the average transmit power of S_i.

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

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

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

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

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

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

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

$$\sqrt{P_R}\left(\hat{a}_1 + j\hat{a}_2\right) \tag{14}$$

where $j^2 = -1$.

It is apparent that D will receive the signal

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

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

$$P_R = P_{S_1} = P_{S_2} = P_T/2 = P_S \tag{16}$$

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

$$\bar{a}_1 = sign\left(\mathrm{Re}\left(\alpha_{S_1D}^{*} y_{S_1D} + \alpha_{RD}^{*} y_{RD}\right)\right) \tag{17}$$

$$\bar{a}_2 = sign\left(\mathrm{Im}\left(\alpha_{S_2D}^{*} y_{S_2D} + \alpha_{RD}^{*} y_{RD}\right)\right) \tag{18}$$

where Im(.) is the imaginary part.

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

$$\bar{a}_1 = sign\left(\sqrt{P_S}\left(\left|\alpha_{S_1D}\right|^2 a_1 + \left|\alpha_{RD}\right|^2 \hat{a}_1\right) + n_1\right) \tag{19}$$

$$\bar{a}_2 = sign\left(\sqrt{P_S}\left(\left|\alpha_{S_2D}\right|^2 a_2 + \left|\alpha_{RD}\right|^2 \hat{a}_2\right) + n_2\right) \tag{20}$$

where

$$n_1 = \mathrm{Re}\left(\alpha^*_{S_1D} n_{S_1D} + \alpha^*_{RD} n_{RD}\right) \tag{21}$$

$$n_2 = \mathrm{Im}\left(\alpha^*_{S_2D} n_{S_2D} + \alpha^*_{RD} n_{RD}\right) \tag{22}$$

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

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

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

The pairs of expressions (6)-(7), (19)-(23), and (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 CDF and PDF achieve the same performance. In addition, both protocols can yield spatial diversity gain of order 2 when the quality of channels between sending nodes and relay is high since under such good S-R channel conditions the relay will decode correctly and resend versions of the original data over an uncorrelated channel to the clusterhead. Moreover, we benefit from path-loss reduction : a relay located between S and D will receive information transmitted by S much more reliably than the clusterhead, and in turn it needs to use a dramatically smaller transmit power to reach the clusterhead.

3. Performance Analysis

Since the expressions for use in recovering *a*, a_1, a_2 in (6), (19), and (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 CDF and PDF is obviously DF and so, it is extensively discussed in the literature. However so far, the performance measure for this protocol is limited to the outage probability [9]. Although the authors in [11] made efforts in computing the BER expression, the result is only the upper bound. Thus, our goal in this paper is to derive a closed-form BER expression of the proposed protocol which is also generalized for DF protocol.

Rewrite (6) in the form

$$\bar{a} = sign\left(\sqrt{P_S}\left(\left|\alpha_{SD}\right|^2 + \varepsilon\left|\alpha_{RD}\right|^2\right)a + n\right) \tag{25}$$

where $\epsilon = -1$ means that the relay made the wrong decision on the symbol *a*; otherwise, $\epsilon = 1$.

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

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

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

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

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

$$\overline{\Pr[\varepsilon = -1]} = \frac{1}{2}\left[1 - \sqrt{\frac{P_S\lambda_{SR}}{1 + P_S\lambda_{SR}}}\right] \tag{27}$$

where λ_{SR} is the variance of path gain of *S-R* channel.

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

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

Here $Q(.)$ 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_{ij}, x and y have exponential distribution with mean values of λ_{ij} that is,

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

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

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

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

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 the similar quality to the destination. Hence, we obtain from (28)

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

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

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

Also in this case, it is easy to realize that

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

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

2.2 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

$$\begin{aligned}\overline{P_{e1}} &= \int_0^{\infty} Q\left(\sqrt{2P_S w}\right)\frac{\lambda_x\lambda_y}{\lambda_x-\lambda_y}\left[e^{-\lambda_y w}-e^{-\lambda_x w}\right]dw \\ &= \frac{\lambda_x}{2(\lambda_x-\lambda_y)}\left[1-\sqrt{\frac{1}{1+\lambda_y/P_S}}\right]-\frac{\lambda_y}{2(\lambda_x-\lambda_y)}\left[1-\sqrt{\frac{1}{1+\lambda_x/P_S}}\right]\end{aligned} \tag{32}$$

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

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

and

$$\overline{P_{e2}}=\overline{P_Q}P_G+\left(1-\overline{P_Q}\right)(1-P_G) \tag{33}$$

Consider the case of z ≥ 0 in the sequel, we have [14, (6-55)]

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

So

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

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

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

Now we compute the pdf of $u=z^2/w=v/w$ as follows [14, (6-60)]

$$f_u(u)=\int_0^\infty w f_v(wu) f_w(w) dw$$

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

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

$$f_u(u)=\frac{\lambda_x^2\lambda_y^2}{\lambda_x^2-\lambda_y^2}\int_0^\infty \frac{k^2}{\sqrt{u}}\left[e^{-\left(\lambda_y k^2+\lambda_x k\sqrt{u}\right)}-e^{-\left(\lambda_x k^2+\lambda_x k\sqrt{u}\right)}\right]dk$$

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

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

and

$$\overline{P_Q}=\int_0^\infty Q\left(\sqrt{2P_S u}\right) f_u(u) du$$

$$=\frac{\lambda_x^2\lambda_y^2}{\lambda_x^2-\lambda_y^2}\int_0^\infty Q\left(\sqrt{2P_S u}\right)\left(\int_0^\infty \frac{k^2}{\sqrt{u}} e^{-\left(\lambda_y k^2+\lambda_x\sqrt{u}k\right)}-\frac{k^2}{\sqrt{u}} e^{-\left(\lambda_x k^2+\lambda_x\sqrt{u}k\right)}dk\right)du$$

$$=\frac{\lambda_x^2\lambda_y^2}{\lambda_x^2-\lambda_y^2}\left[f\left(P_S,\lambda_y,\lambda_x\right)-f\left(P_S,\lambda_x,\lambda_x\right)\right] \tag{35}$$

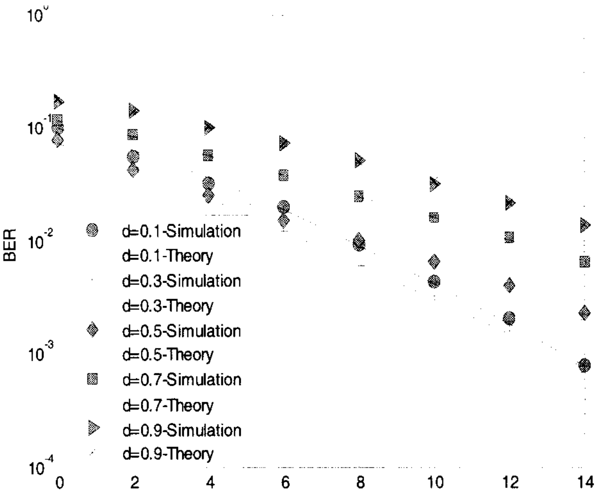
The last equality in (35) is obtained with $f(\bullet,\bullet,\bullet)$ from (A4) in Appendix.

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

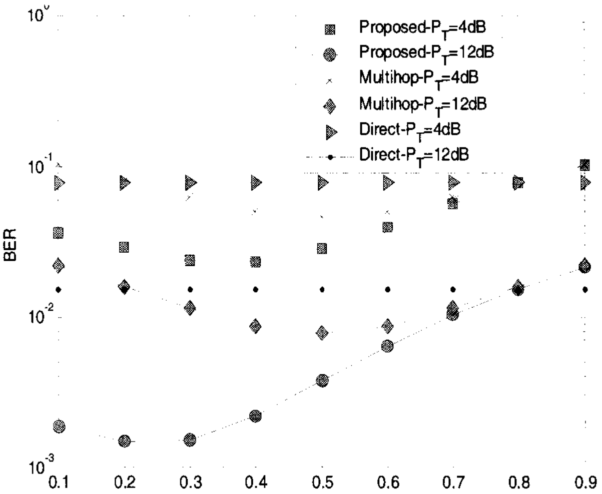
4. Numerical results

In this section, we investigate the performances of three transmission protocols in a cluster as mentioned in section 2. For the proposed protocol, since the BER performance analysis of SNs S_1 and S_2 is similar, we only investigate the node S_1 as an example. Additionally, we only consider $\beta=3$ for all simulations.

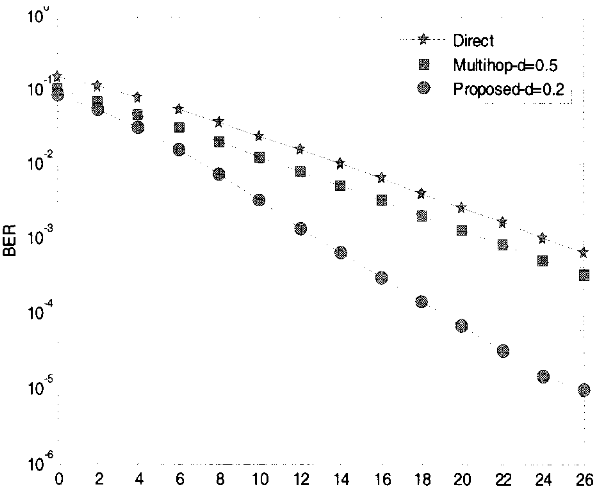
A network geometry is examined where the relay is located on a line between S_1 and D. The direct path length S_1-D is normalized to be *1*. We also denote *d* as the distance between S_1 and *R*. Therefore, $d_{RD}=1-d$.



(Fig. 3) BER comparison between theory and simulation



(Fig. 4) BER performance versus d



(Fig. 5) BERperformance of transmission protocols

First of all, we verify the accuracy of BER expression in (26) by comparison with Monte-Carlo simulations. Different values of d={0.1, 0.3, 0.5, 0.7, 0.9} are considered. (Fig. 3) depicts simulation and theoretical results. We can see that the simulation results well match the theoretical ones. This shows that the analysis is completely exact. Additionally, BER performance of the proposed cooperative transmission protocol significantly depends on the relay position.

(Fig. 4) studies the influence of the relay location on the performance of cooperative protocol for two different values of total transmit power P_T of 4dB and 12dB. It is realized that the multi-hop transmission is really better than the direct one only when the relay is placed in the interval [0.2, 0.8] while the proposed protocol always outperforms the direct transmission unless the distance between R and S_I isgreater than 0.8. (Fig. 4) also illustrates the optimal relay position for the multi-hop transmission is at the center of S_I-D line since it presents a good trade-off between good receive conditions for the relay and transmit power savings. Moreover, the cooperative protocol 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 transmission protocols via the total transmit power P_T. At the target BER of 10^{-3}, the proposed protocol can save the system power up to 8dB and 11dB in comparison to the multi-hop and direct cases, respectively. In addition, power savings keeps increasing correspondingly 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.

5. Conclusion

The proposed cooperative transmission protocol allows an idle node to help two other SNs for data transmission to a clusterhead. A closed-form BER expression was also established to facilitate in evaluating the performance without time-consuming computer simulations. This expression is also a generic error probability form for DF protocol. The Monte-Carlo simulations verified its validity. The numerical results showed the proposed protocol increases significantly the channel utilization efficiency and power efficiency without requiring additional implementation complexity for SNs. Power savings the cooperation achieves is equivalent to prolonging sensor network lifetime and better satisfying the critical design condition of WSNs.

Appendix

This Appendix calculates the function $f(\bullet,\bullet,\bullet)$ in section 3. First, applying [15, (7) on page 361 and (4) on page 880] and [16, (2) and (14)], we obtain

$$\begin{aligned} f_{\varepsilon}(\varepsilon,\lambda_1,\lambda_2) &= \int_0^{\infty} g^2 e^{-\lambda_1 g^2-\lambda_2\sqrt{\varepsilon}g}\,dg \\ &= -\frac{\lambda_2\sqrt{\varepsilon}}{4\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2\varepsilon/2+\lambda_1}{4}e^{\frac{\lambda_2^2\varepsilon}{4\lambda_1}}\left(1-\Phi\left(\sqrt{\frac{\lambda_2^2\varepsilon}{4\lambda_1}}\right)\right) \\ &= -\frac{\lambda_2\sqrt{\varepsilon}}{4\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2\varepsilon/2+\lambda_1}{4}e^{\frac{\lambda_2^2\varepsilon}{4\lambda_1}}erfc\left(\sqrt{\frac{\lambda_2^2\varepsilon}{4\lambda_1}}\right) \\ &\cong -\frac{\lambda_2\sqrt{\varepsilon}}{4\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\frac{\lambda_2^2\varepsilon/2+\lambda_1}{4}\left(\frac{1}{6}+\frac{1}{2}e^{-\frac{\lambda_2^2\varepsilon}{12\lambda_1}}\right) \end{aligned} \tag{A1}$$

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

where the function $\Phi(\bullet)$ is defined in [15, (1) on page 880].

Bysubstituting (A1) into (A2) and changing the variable $L=\sqrt{\varepsilon}$, (A2) is rewritten as

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

Applying the results in [15, (2)-(3) on page 360], we can compute (A3) as

$$f(C,\lambda_1,\lambda_2)=\frac{1}{2}\left[-\frac{13\lambda_2}{96C\lambda_1^2}+\sqrt{\frac{\pi}{\lambda_1^5}}\left(\begin{array}{l}\sqrt{\frac{\pi}{C}}\left(\frac{\lambda_2^2+4C\lambda_1}{576C}\right)+\\ \sqrt{\frac{12\lambda_1\pi}{12\lambda_1C+\lambda_2^2}}\frac{\lambda_1\left(\lambda_2^2+3\lambda_1C\right)}{12\left(12\lambda_1C+\lambda_2^2\right)}+\\ \sqrt{\frac{3\pi}{4C}}\frac{3\lambda_2^2+16C\lambda_1}{768C}+\\ \sqrt{\frac{12\lambda_1\pi}{16\lambda_1C+\lambda_2^2}}\frac{\lambda_1\left(\lambda_2^2+4\lambda_1C\right)}{4\left(16\lambda_1C+\lambda_2^2\right)}\end{array}\right)\right] \tag{A4}$$

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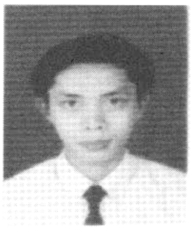

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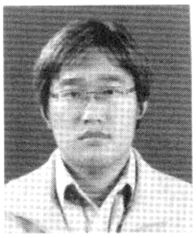

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