

Research Article

Energy-Efficiency of Cooperative Communication with Guaranteed E2E Reliability in WSNs

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This paper addresses the energy efficiency of cooperative communication in WSN. We first establish the energy model of single-hop WSN. It is found that the cooperative communication is more suitable for harsh transmission environment with long-haul distance. The energy consumption per bit is numerically minimized by finding the optimal broadcasting BER and the number of cooperative nodes. Then, we expand the conclusion to the multihop scenario where “energy hole” dominates the longevity of WSN. To mitigate the energy consumption in the hotspots, as well as to keep the promised reliability, we adjust the transmission BER of the clusters according to the hops between the sink and cluster. On one hand, the statistical reliability is met. On the other hand, the energy consumed is converted from the nearer cluster (from the sink) to the farther ones. The network lifetime is thus optimized.

1. Introduction

WSN (Wireless Sensor Network), an energy-constrained network, has nodes mainly powered by batteries which are hard to replace even if possible. Numerous applications of WSN, such as environment monitoring, always need the network to operate for years without exchange of power suppliers. The prolongation of network lifetime is hence a critical design consideration and the data transmission must be energy efficient. More specially, the sensors near the sink are likely to die earlier since they are burdened with higher data load. Their deaths lead to the dysfunction of the network with the residual energy in the outside nodes. This is the well-known “energy-hole” phenomenon, the core of many researches in the literature [1].

MIMO (multiple-input and multiple-output) explores the spatial diversity of the wireless channel which can dramatically increase the channel capacity as well as the reliability of transmission. Once the transmission distance reaches a certain threshold [2], the energy conversation performance of MIMO systems can remarkably exceed the SISO (single-input-single-output) systems under the same Signal-to-Noise Ratio (SNR). The MIMO energy-efficiency transmission scheme is particularly useful for WSN due to the limited

energy supplied. However, the direct application of multiple antennas technique on WSN is impractical for the insufficient physical size of sensor nodes. Fortunately, several individual sensors can cooperate for the data transmission in order to set up a Cooperative MIMO or MISO scheme, which are also known as Cooperative Communication (CC) [3].

CC scheme explores the energy efficiency of multiantennas technique which plays a significant role in the long-range transmission, where the transmission energy consumption dominates in the overall cost rather than that of the circuit [4]. Nonetheless, the decline of transmission energy consumption does not directly lead to the prolongation of network lifetime owing to the existence of “energy hole” [5]. The residual energy in the farther nodes may be up to 50% when the network dies [6]. Thus, the energy consumption balance is also the critical topic in the design of transmission scheme. In this paper, we first propose singleHop Algorithm for the minimization of energy consumption in single-hop scenario (see Algorithm 1). Furthermore, we generalize the conclusion to the multihop scenario and present the MultiHop Algorithm to mitigate the “energy hole” by adjusting the bit error rate (BER) at each cluster (see Algorithm 2).

Summarily, the main contributions of this paper are twofold.

Require: Network parameters, the maximum number of cooperative candidates N_{CN}^{\max} , transmission distance d and maximum BER $p_e = 1 - \delta$.

Ensure: The optimal cooperative nodes N_{CN}^* , BER of the broadcasting p_b^* and the minimum energy consumption E_{\min} .

- (1) $E_{\text{circuit}} = \infty, E_{\min} = \infty$;
- (2) **while** ($N_{CN} < N_{CN}^{\max}$ and $E_{\text{circuit}} < E_{\min}$) **do**
- (3) Compute the broadcasting radius r_b according to (9);
- (4) Calculate p_b by (15) and decide p_c by (13);
- (5) Calculate the total energy consumption E_{tot} by (17) and E_{circuit} by (12);
- (6) **if** ($E_{\min} > E_{\text{tot}}$) **then**
- (7) $E_{\min} = E_{\text{tot}}, N_{CN}^* = N_{CN}, p_b^* = p_b$;
- (8) **end if**
- (9) $N_{CN} = N_{CN} + 1$;
- (10) **end while**
- (11) Output N_{CN}^*, p_b^* and E_{\min} ;

ALGORITHM 1: SingleHop Algorithm.

Require: Network parameters and the initial energy per node E , statistical reliability δ_t .

Ensure: The optimal transmission BER sequence p_e .

- (1) Calculate the BER sequence according to Formula (31), record as $p_e^j = p_{e,1}^j, p_{e,2}^j, \dots, p_{e,j}^j, j = 1, 2, \dots, n$;
- (2) Compute the optimal N_{CN}^* and p_b^* for each cluster by SingleHop algorithm, then calculate the average energy consumption of the nodes in each cluster by (28);
- (3) **while** can **do**
- (4) Find the maximum $E_{\text{ave},a}$ at cluster a and the minimum $E_{\text{ave},b}$ at cluster b ;
- (5) Find the max decreased $\Delta p_{e,a}^j$, and inclined $\Delta p_{e,b}^j$ to ensure the reliability can be met as well as keep the energy consumption of cluster b slightly less than $E_{\text{ave},a}$;
- (6) $p_{e,a}^j = p_{e,a}^j + \Delta p_{e,j}, p_{e,b}^j = p_{e,b}^j + \Delta p_{e,b}^j$;
- (7) **end while**
- (8) Output $p_e^j = p_{e,1}^j, p_{e,2}^j, \dots, p_{e,j}^j, j = 1, 2, \dots, n$;

ALGORITHM 2: MultiHop Algorithm.

- (1) Compared to the single-input and single-output (referred to SISO henceforth) transmission, it is revealed in [2, 7] that CC can save energy when the transmission distance exceeds the certain bound. In addition to this, we find that cooperative communication is more suitable for the long-haul transmission with higher requirement of BER in the harsh communication environment (larger path-loss parameter and power density of noise). Then, we propose the SingleHop Algorithm to choose the number of the cooperative nodes and the value of broadcasting BER to optimize the total transmission energy cost.
- (2) In a multihop network, the sensors closer to the sink are more likely to be exhausted earlier due to the heavier data load. Based on the analysis of the single-hop scenario, we propose the MultiHop algorithm to prolong the lifetime of cluster-based network subject to the requirement of statistical reliability. Our strategy adjusts the transmission BER higher at the clusters farther away from the sink than the inner ones. This enables the near-sink cluster to lose the requirements

of reliability. On one hand, the overall requirement can be met. On the other hand, the energy consumption of the near-sink clusters is shifted to the farther clusters.

The rest of this paper is organized as follows. The related work is given in Section 2. Section 3 presents the analysis of the single-hop network with CC scheme and SingleHop Algorithm. The numerical and experimental results are shown in Section 4. We further evaluate the energy consumption performance in a multihop clustered network, and Multihop algorithm is presented to mitigate the “energy hole” by adjusting the transmission BER in Section 5. Section 7 concludes the paper.

2. Related Work

A certain amount of research has recently been done to investigate various cooperative communication schemes. The author of [8] analyzed the performance of cooperative ARQ (automatic re-request) in both simple and hybrid schemes. It is pointed out that the cooperative ARQ protocols perform

better than the traditional counterparts, even when the relay-destination channel is not as good as the source-destination channel, due to the spatial diversity explored by the cooperative protocols. Ikki and Ahmed investigated the capability of incremental-relaying mechanism for both decode-and-forward and amplify-and-forward relay schemes in [9]. Meanwhile, the closed-form expressions of BER and outage probability are proposed in their work. By the means of Alamouti space-time coding, Zhang et al. proposed a cooperative diversity system in [10], wherein the two users transmit data for each other, and the destination responds to the feedback at the middle of two Alamouti codes. To apply the distributed space-time codes in practice, the code distribution need to assign code matrix columns to individual cooperating nodes. Nonetheless, the basic setup in [8] and [10] includes only one intermediate relay node. As indicated in our work, more than 2 relay nodes may be demanded to optimize the transmission energy consumption.

From the perspective of energy consumption minimization, Cui et al. studied the characteristics of cooperative communication in WSN [2]. It is addressed that virtual multiple antennas are suitable for long distance transmission due to the extra circuit energy depletion. Based on this, Jayaweera studied the impact of the training overhead required in MIMO-based system and refined the conclusions obtained in [2]. However, the authors only consider the performance of cooperative transmission in comparison to the SISO systems. We generalize the object to the whole procedure of cooperative communication in cluster network (intracluster and intercluster) in our work. In [11], Li et al. analyze the energy consumption per unit transmit distance to achieve energy-efficient transmission. And the optimal transmission distance is obtained by turning the problem into a convex optimization problem. Nonetheless, the broadcasting BER is neglected in his work.

The selection of the “best relay” is applicable in case the source knows the CSI (channel state information). In [12], the relay node selection and the transmission energy allocation are both studied based on the channel estimation at the source. This is implemented by the exchange of RTS/CTS messages. However, CSIR (channel state information at the receiver), the analysis background of our paper, is more common for wireless link. Otherwise, the mature water-filling method can directly bring the optimal energy allocation scheme [13].

In [7], Zhang et al. analyzed the transmission distance in combination with the number of cooperative nodes. Then, the conclusion is extended to multihop scenario, as in our work. Hence, the optimal data transmission distance in each hop is obtained. Nevertheless, the authors merely consider the data gathering of the source node in [7]. Actually, the sensors in the network are all responsible for data collection, this is the fundamental reason for “energy hole” [14]. The global data gathering is analyzed for the rectangular scenario by Huang et al. in [15], wherein the network longevity is optimized by adjusting the cluster size. However, the authors omitted the analysis of parameters that significantly impact the network performance, especially the number of cooperative nodes and the reliability requirement. In [16], a clustered

TABLE 1: Network parameters.

P_{Ct}	Power consumption of Tx circuits	98.2 mW
P_{Cr}	Power consumption of Rx circuits	112.5 mW
R_b	Transmission bit rate	10 kbps
ρ	The density of sensors in the network	0.1 perm ²
N_0	Thermal noise PSD	-171 dbm/Hz
E_F	The energy for data fusion per bit	5 nJ/bit
C	Communication constants	3.47×10^8

TABLE 2: Notations.

N_{CN}	The number of nodes participate in the cooperative transmission
r_b	The radius of broadcasting
p_e	The bit error rate (BER) induced by cooperative communication (in single-hop scenario, this is the end to end BER)
P_g, P_b, P_c	Bit error rate in data gathering, broadcasting, and cooperative transmission phase, respectively
R_C	The radius of clusters
E_{CH}	The energy consumption of the cluster head in one round
E_{CPN}	The energy consumption of the plain nodes participate in CC in one round
E_N	The energy consumption of the plain nodes in one round
D_i	The data amount sourced from cluster i
k	Path-loss exponent

cooperative MIMO scheme based on LEACH is proposed by Yuan et al. wherein the authors concretely studied the operation process of the cluster construction. Unfortunately, the analysis of the influences of reliability and the number of cooperative nodes in cooperative communication are also ignored. In [17], Ota et al. proposed the actors’ mobility control scheme in wireless sensor and actor networks (WSAN). By reinforcement learning in Markov decision processes, the energy efficient data collection scheme is addressed.

3. Single-Hop System Description and Analysis

Table 1 presents the network parameters and the value of them. And for the convenience of readers to understand this paper, Table 2 summarizes the notations used in this paper.

3.1. System Model. We first introduce CC in a single-hop scenario, as seen in Figure 1. The relay node (particularly the cluster heads) broadcasts the data to its neighbors. The candidate nodes covered by the broadcasting would participate in the following CC phase, wherein the relay node and the cooperative nodes transmit the data simultaneously encoded by STBC [18] (space-time block coding) to the next relay node (or sink). This procedure of CC can also be seen in [19].

The energy consumption of the circuit blocks, except the power amplifier, for the transmission and reception of data packet, is summarized to constants represented by P_{Ct}

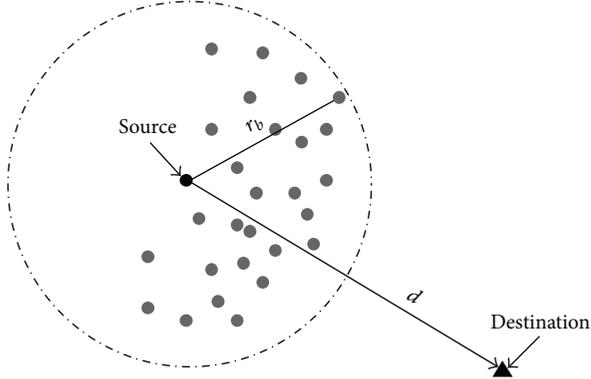


FIGURE 1: Impact of transmission range on total energy consumption.

and P_{Cr} . The power consumption of the amplifier can be approximated as follows:

$$P_{\text{Amp}} = (1 + \alpha) P_s, \quad (1)$$

where $\alpha = \xi/\eta - 1$ with ξ the peak-to-average ratio and η the drain efficiency of the RF power amplifier.

According to [15], the energy consumption of one participated node in the cooperative transmission phase can be expressed as follows:

$$P_s = C \frac{E_b R_b d^k}{N_{CN}}, \quad (2)$$

where E_b is the required energy per bit at the receiver for the demanded bit error rate (BER). R_b denotes the data rate in bit with STBC coding. N_{CN} represents the number of nodes participated in the cooperative transmission, including the relay node and candidates. C is the product of several constants defined by $C = (4\pi)^2 M_l N_f / G_T G_R \lambda^2$ [15], where G_T and G_R are the gains at the transmit and receive antennas. λ is the carrier wavelength, M_l denotes the link margin of RF amplifier, and N_f is the receiver noise figure.

Since α in (1) solely depends on the modulation scheme and the associated constellation size, and we use BPSK to modulate the signal with the same constellation size throughout this paper, for brevity, C is expanded to be

$$C = (1 + \alpha) \frac{(4\pi)^2 M_l N_f}{G_T G_R \lambda^2} \quad (3)$$

as adopted in [7].

We assume the fading of channel satisfies Rayleigh distribution. According to [15], the relationship between the BER and the received energy at the receiver can be derived to be

$$E_b \leq \frac{N_{CN} N_0}{p_e^{1/N_{CN}}}, \quad (4)$$

where N_0 denotes the single-sided thermal noise power density (PSD) at room temperature. By approximating the bound as equality as well as substituting the equality and

(3) into (1), the energy consumption of the amplifier can be expressed as in [15]:

$$P_{\text{Amp}} = C \frac{N_0 R_b d^k}{p_e^{1/N_{CN}}}. \quad (5)$$

$p_e^{1/N_{CN}}$ is the required BER at the transmitter (hereafter, referred as T-BER).

Summarily, the total energy consumption of each node for a fixed data rate can be derived as in [15]:

$$E_T(d^k, p_e, N_{CN}) = C \cdot \frac{N_0 d^k}{p_e^{1/N_{CN}}} + \frac{P_{Ct}}{R_b}. \quad (6)$$

The power needed for reception of nodes per bit is

$$E_R = \frac{P_{Cr}}{R_b}. \quad (7)$$

3.2. The Energy Consumption of CC. The broadcasting radius of the relay node is r_b . The energy consumption for the broadcasting with BER and the reception of the candidates can be derived as

$$E_b(r_b^k, p_b, N_{CN}) = E_T(r_b^k, p_b, 1) + (N_{CN} - 1) \cdot E_R. \quad (8)$$

Based on the fact that r_b is much less than the transmission distance d . The differences of BER between the candidates are omitted throughout this paper. The number of candidates covered by the broadcasting radius complies with

$$N_{CN}(r_b) = (\pi r_b^2) \rho. \quad (9)$$

After the broadcasting phase, the cooperative nodes and the relay node transmit the data to the destination with BER p_c , the total energy consumption in this phase is

$$E_{CT}(d^k, p_c, N_{CN}) = E_T(d^k, p_c, N_{CN}) + E_R. \quad (10)$$

Eventually, the energy consumption can be summarized to be

$$E_{CC} = E_b(N_{CN}, p_b) + E_{CT}(N_{CN}, p_c). \quad (11)$$

Notably, the energy consumption for the reception of the destination is included in (11). And the circuit power cost can be expressed by

$$E_{\text{circuit}} = N_{CN} E_R + (N_{CN} + 1) \cdot \frac{P_{Ct}}{R_b}. \quad (12)$$

The BER at the destination is

$$p_e = 1 - (1 - p_b)(1 - p_c) \approx p_b + p_c. \quad (13)$$

The partial derivative of E_{CC} with respect to p_b is

$$\frac{\partial E_{CC}}{\partial p_b} = \left(\frac{d^k}{(p_e - p_b)^{(1/N_{CN}+1)}} - \frac{r_b^k}{p_b^2} \right) \cdot C \cdot N_0. \quad (14)$$

The minimum E_{CC} is obtained in the following case:

$$\frac{p_b^2}{(p_e - p_b)^{(1/N_{CN}+1)}} = \frac{r_b^k}{d^k}. \quad (15)$$

It is proved that (15) has only one real solution in $p_b \in (0, p_e)$ in the Appendix. Although the closed-form solution of p_b is unsolvable, we can obtain the numerical solution to (15).

The corresponding energy consumption for SISO scheme with BER p_e is

$$E_{\text{SISO}}(d^k, p_e) = E_T(d^k, p_e, 1) + E_R. \quad (16)$$

Summarily, the total energy consumption according to the transmission scheme can be expressed by

$$E_{\text{tot}}(N_{CN}, p_e) = \begin{cases} E_{CC}, & \text{if } N_{CN} > 1, \\ E_{\text{SISO}}, & \text{if } N_{CN} = 1. \end{cases} \quad (17)$$

3.3. Cooperative Communication Energy Consumption Optimization. As shown in Section 4, the number of cooperative nodes N_{CN} and the broadcasting BER p_b have significant impact on the overall energy cost of data transmission. However, getting the optimal value of N_{CN} and p_b is very difficult due to the complexity of Formula (11). This paper proposed the algorithm of variables' selection for cooperative communication from the perspective of practice. We assume that the required reliability of CC is δ . Hence, the maximum BER is $p_e = 1 - \delta$.

It is worth noting that the circuit energy consumption increases linearly with the number of cooperative nodes, as shown in (12). In case $E_{\text{circuit}} > E_{\text{min}}$ happens, more cooperative nodes would only deteriorate the energy-efficiency performance. To reduce the calculating time, SingleHop Algorithm will finish immediately when the circuit energy consumption has exceeded the acquired minimum energy consumption. Obviously, we need to execute the algorithm only once in case the network settings and transmission distance are unchanged.

4. Numerical and Simulation Results of Single-Hop CC

The related network parameters are given in Table 1 if not specified. We use network simulator ns2 version 2.35 to conduct the simulations. For each data point in the figures, we run simulation on 20 randomly created networks and take the average.

Consistent with the results of [2, 7, 20], CC outperforms the SISO system when the transmission distance is beyond a certain threshold with low E2E BER ($p_e \approx 0.11\%$), as shown in Figure 2. And the crossover indicates where the energy saved by CC exceeds the extra circuit energy consumption in comparison with SISO system. Notably, we comprehensively consider the energy consumption of broadcasting and the reception in our model, which are omitted in [2, 7]. In addition to this, Figure 3 illustrates the proportions of the energy consumption of each operation in the total power consumed.

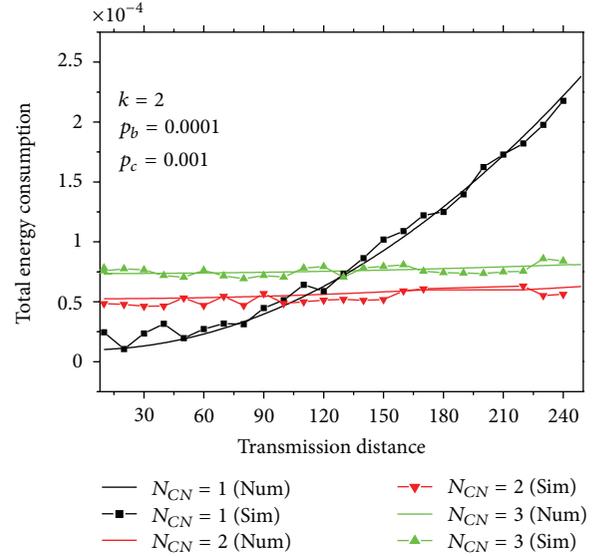


FIGURE 2: Transmission energy consumption per bit with low BER.

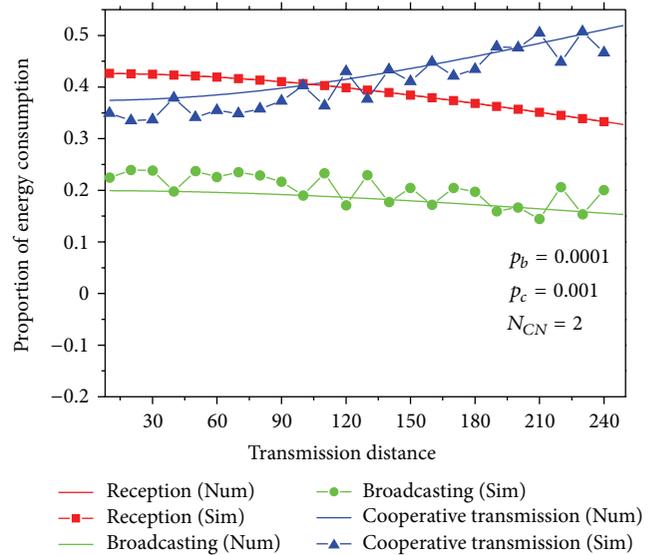


FIGURE 3: The proportional percentage of energy consumption.

Given that the energy expenditure of the data reception only depends on the number of cooperative nodes N_{CN} , the cooperative transmission takes a greater proportion as long as the transmission distance is sufficiently large ($d > 103$ m in Figure 6).

Figure 4 depicts the reason of the energy efficiency, where we plot the ratio of T-BER and the required E2E BER ($p_e^{1/N_{CN}}/p_e$) against the number of nodes participated in CC. The demanded T-BER $p_e^{1/N_{CN}}$ augments with the increasing number of cooperative nodes N_{CN} , as shown in Figure 4. The energy expenditure per node on cooperative transmission is eventually saved. Moreover, the derivative of $p_e^{1/N_{CN}}/p_e$ is with respect to p_e is $(1/N_{CN} - 1) \cdot p_e^{1/N_{CN}-1} < 0$; hence, $p_e^{1/N_{CN}}/p_e$ reversely related to the E2E BER p_e . Thus, the effect

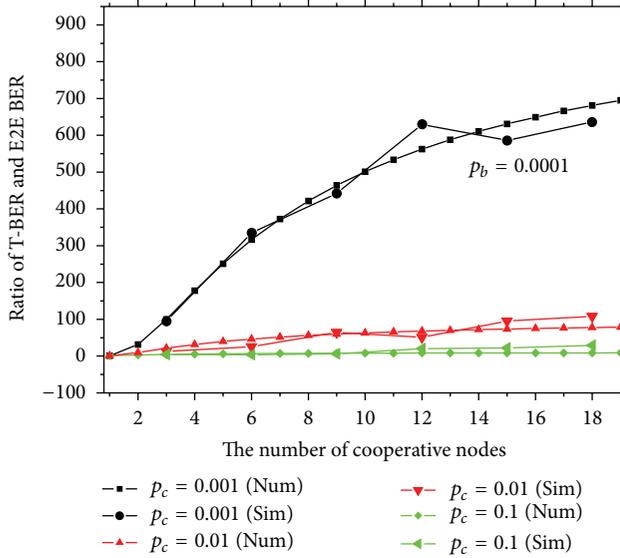


FIGURE 4: The ratio between end-to-end (E2E) BER and the T-BER.

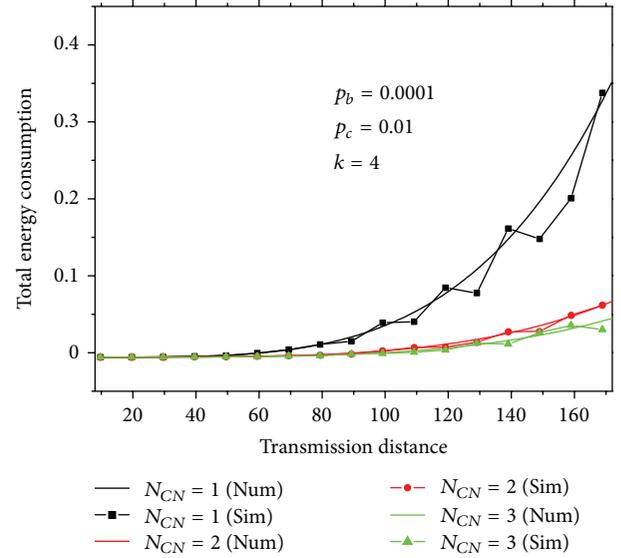


FIGURE 6: The energy consumption under multipath fading.

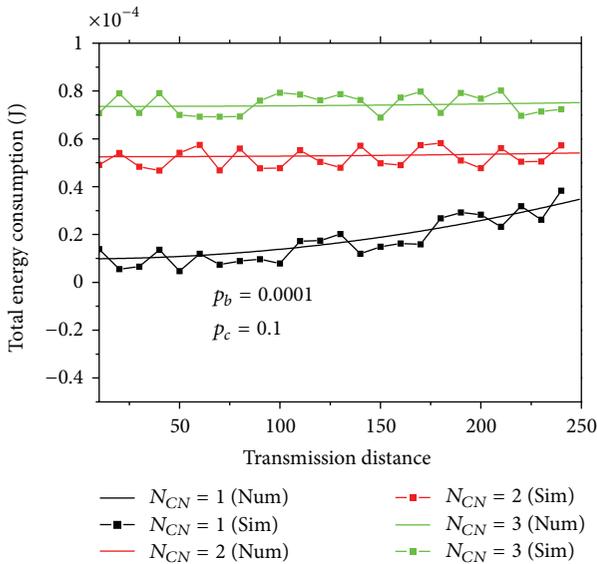


FIGURE 5: The comparison between CC and SISO scheme with high BER.

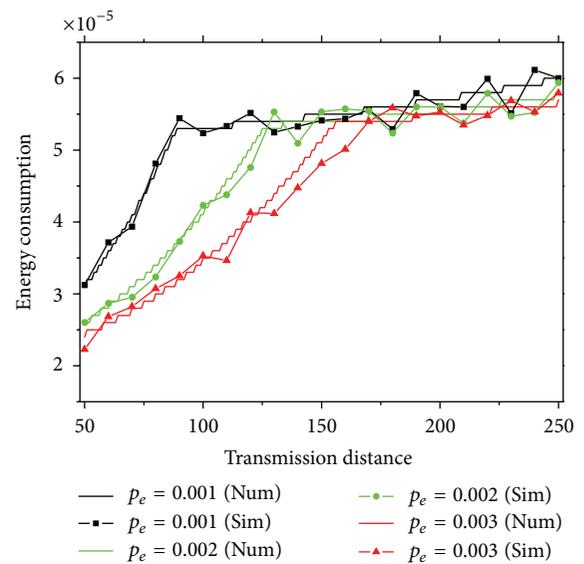


FIGURE 7: The optimal energy consumption by using SingleHop algorithm.

of CC is reduced by larger E2E BER. This explains why SISO system is always the optimal choice with low required E2E reliability ($p_e \approx 10\%$), illustrated in Figure 5.

We evaluate the performance of CC compared to SISO with path loss exponent $k = 2$ (in free space). Nevertheless, the transmitted signal would suffer the multipath fading ($k = 4$ when $d > 87$ [21]). As depicted in Figure 6, CC significantly outperforms the SISO system in multipath fading. In addition to this, the number of nodes that participate in CC relaxes the T-BER and further optimizes the energy consumption performance with amply long transmission distance. Summarily, CC is more suitable for the longer transmission in harsh propagation environment (high path-loss exponent).

The performance of SingleHop algorithm is verified in Figures 7, 8, and 9. Take $p_e = 0.1\%$ as an example. CC is chosen when the transmission distance is beyond 103 m. Afterward, the rising trend of energy consumption remarkably declined compared to the SISO scheme due to the increasing of T-BER. The optimal number of plain nodes participated in CC is shown in Figure 8. When the number of cooperative nodes exceeds 1, CC is selected as the transmission scheme. Notably, since we take the average of multiple simulations, the number of nodes participate in CC may be decimals. Figure 9 plots the optimal broadcasting BER versus the transmission distance. The broadcasting BER takes only less than 2% in the whole BER, because the broadcasting

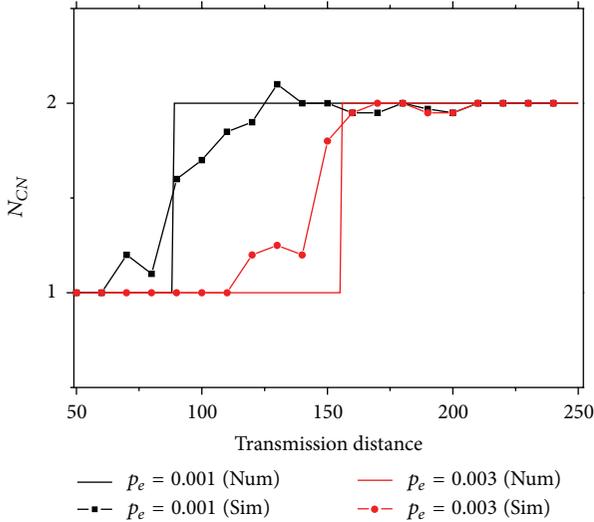


FIGURE 8: The optimal number of cooperative nodes.

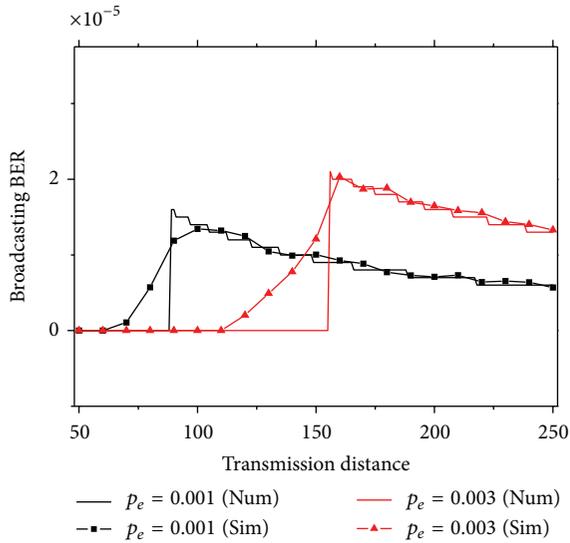


FIGURE 9: The optimal broadcasting BER obtained by SingleHop algorithm.

radius is much less than the transmission distance. As the transmit distance is growing, the reliability of broadcasting is even higher.

5. Maximization of Network Lifetime with Guaranteed E2E Reliability

In this section, we extended the conclusion of Section 3 to multihop scenario. As shown in Figure 10, nodes are densely dispersed in several circles which are far away from each other, and the clusters are linearly positioned [19]. The distance between the circles is much larger than the radius of those.

The radius of the i th clusters and the density of nodes are denoted by R_{C_i} and ρ_i , respectively. The area of cluster i

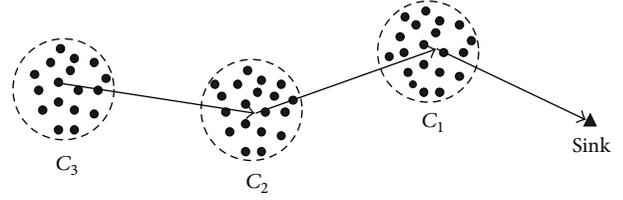


FIGURE 10: Multihop model.

can be derived to be $S_i = \pi R_{C_i}^2$. $d_{C_i-C_{i-1}}$ denotes the distance between the i th and $(i-1)$ th clusters and $d_{C_i-C_{i-1}} \gg R_{C_i}$. The channel fading satisfies Rayleigh distribution. And the path loss exponent is identical in both intra- and intercluster communication. The clusters are numbered by hops to sink.

5.1. Analysis of Energy Consumption and Bit Error Rate at Each Cluster. During the intracluster process, the plain nodes in cluster j transmit l bits data to the cluster head with BER $p_{g,j}$ in one round. Then, CH aggregates the data and chooses the transmission scheme based on SingleHop algorithm. If the cooperative communication is selected, CH broadcasts the data to the neighbors. The internal clusters are responsible for the relay of data stemming from outer clusters (C_2 and C_3 in Figure 10) in intercluster process. Notably, the notations in Section 3 are expanded in this section.

The BER in each step greatly influenced the energy consumption performance as we see in Section 3. Moreover, the overall BER consists of two parts, the BER at data gathering phase and the BER induced by the intercluster data transmission, respectively.

Here, we first investigate the relationship between BER in different phases and the required reliability. The overall reliability constraint is denoted by δ_t . δ_i^j represents the reliability for cluster i to transmit data stemmed from cluster j , and such a manner is employed in other notations. It is obtained apparently that $\delta_t = \prod_{k=1}^i \delta_k^j$.

Theorem 1. To meet the overall required statistical reliability δ_t , the approximate accuracy of the data from cluster j is given by the following formula:

$$p_{g,j} + \sum_{i=1}^j p_{e,i}^j \leq 1 - \delta_t. \quad (18)$$

Proof. At the j th cluster, (19) must hold

$$(1 - p_{g,j})(1 - p_{e,j}) \leq \delta_j^j. \quad (19)$$

Analogy to the relationship of broadcasting BER p_b and cooperative transmission BER p_c is indicated in (13). We have (19) is approximated to be $p_{g,j} + p_{e,j} \leq 1 - \delta_j^j$. Expanding this procedure to following hops, we can acquire

$$(1 - p_{g,j}) \prod_{i=1}^j (1 - p_{e,i}^j) \prod_{i=1}^j \geq \delta_i^j, \quad (20)$$

which approximates the inequality (19). \square

The nodes separately play 3 different characters in inter-cluster transmission, which are CH, cooperative nodes, and plain nodes, respectively. Based on the conclusion of Section 3, SingleHop algorithm is applied to determine the optimal value of $p_{b,i}^{j*}$, $p_{c,i}^{j*}$, and $N_{CN,i}^{j*}$. And the data load stemmed from cluster j is given by

$$D_j = (S_j \rho) \cdot l \varphi, \quad (21)$$

where φ is the fusion rate. And $E_{ag,j}$ denotes the energy consumption of data aggregation of cluster head (CH) in cluster j . Theorem 2 presents the analysis of energy consumption for each type of nodes:

Theorem 2. $E_{CH-inter,i}^{j*}$ and $E_{CN-inter,i}^{j*}$ denote the power expenditure of the cluster head and the plain nodes which participate in CC during inter-cluster transmission. The energy consumption of the CH, cooperative nodes, and the plain nodes in cluster C_i are represented by $E_{CH,i}$, $E_{CH-inter,i}$, and $E_{N,i}$

$$E_{CH,i} = \left(\sum_{j=i+1}^n D_j + \pi R_{C_i}^2 \cdot \rho \right) \cdot E_R + E_{ag,i} + \sum_{j=i}^n D_j \cdot E_{CH-inter,i}^{j*} \quad (22a)$$

$$E_{C-PN,i}^j = \begin{cases} D_j (E_R + E_{CN-inter,i}^{j*}), & \text{if } N_{CN,i}^{j*} > 1, \\ 0, & \text{if } N_{CN,i}^{j*} = 1, \end{cases} \quad (22b)$$

$$E_{N,i} = E_{g,i} (p_{g,i}). \quad (22c)$$

Proof. By CH rotation, any node in the cluster is able to be CH and the average distance between two randomly located nodes is $d_{ave,i} = 128R_{C_i}/(45\pi)$ [22]. Then, the energy consumption for each plain node can be expressed as follows:

$$E_{g,i} = E_T (d_{ave,i}^k, p_{g,i}, 1). \quad (23)$$

The energy consumption of CH for the data aggregation is

$$E_{ag,i} = D_i \cdot E_F, \quad (24)$$

where $E_F = 5 \text{ nJ/bit}$ [15] is the power consumption of data fusion per bit. Set $E_{CT,i}^{j*}$ to denote the optimal energy consumption of inter-cluster transmission, namely, the output of SingleHop algorithm:

$$E_{CT,i}^{j*} = E_{tot} (N_{CN,i}^{j*}, p_{e,i}^j). \quad (25)$$

In case CC is employed ($N_{CN,i}^{j*} > 1$), the energy consumption of CH is given by:

$$E_{CH-inter,i}^j = CN_0 \cdot \left[\frac{(d_{C_i-C_{i-1}})^k}{(p_{e,i}^j - p_{e,i}^{j*})^{1/N_{CN,i}^{j*}}} + \frac{(r_{b,i}^j)^k}{p_{b,i}^{j*}} \right] + 2 \frac{P_{Ct}}{R_b}. \quad (26)$$

The energy consumed by each plain node participated in CC is

$$E_{CN-inter,i}^j = CN_0 \frac{(d_{C_i-C_{i-1}})^k}{(p_{e,i}^j - p_{e,i}^{j*})^{1/N_{CN,i}^{j*}}} + \frac{P_{Ct}}{R_b} + E_R. \quad (27)$$

The total data amount relayed by cluster C_i is $\sum_{j=i+1}^n D_j$. Hence we obtain (22a).

The energy cost of the cooperative nodes (except CH) on the reception of the data broadcasted by CH is $\sum_{j=i+1}^n D_j \cdot E_R$. So (22b) is acquired. \square

In our paper, we assume that the CH and the cooperative nodes are selected based on the residual energy of the nodes. Therefore, it is considered that the energy consumption among the nodes are perfectly balanced, thus all nodes have approximate lifetime. Theorem 3 derives the average energy consumption of each clusters.

Theorem 3. The average energy consumption per node in the i th cluster for an entire data gathering round is presented in the following:

$$E_{ave,i} = \frac{E_{CH,i}}{N_i} + \sum_{j=i}^n E_{C-PN,i}^j \cdot \frac{N_{CN,i}^{j*} - 1}{N_{CN,i}^{j*}} + E_{N,i} \cdot \frac{N_i - 1}{N_i}, \quad (28)$$

where N_i denotes the number of nodes in C_i .

Proof. Nodes undertake the role of CH by cluster head rotation. Averagely, every node acts as CH for one time, as plain nodes for $N_i - N_{CN,i}^{j*}$ times after N_i data gathering round. In particular, the number of cooperative nodes depends on $p_{e,i}^j$, thus we consider the cooperative nodes in cluster separately according to the intercluster transmission scheme. Thus, (28) can be derived. \square

Assume that the reliability $\delta_t^j = 1 - p_{e,i}^j$ is evenly distributed along the transmission trace. To meet δ_t , $p_{e,i}^j$ should satisfy

$$p_{e,i}^j \leq \frac{1 - \delta_t - p_{g,j}}{j}. \quad (29)$$

The network longevity optimization goal can be expressed as

$$\min_{0 < i < n} \max E_{ave,i} \quad (30)$$

subject to

$$p_{g,j} + \sum_{i=1}^j p_{e,j} \leq 1 - \delta_t. \quad (31)$$

By applying this bound as equality, we obtain

$$p_{e,i}^j = \frac{(1 - \delta_t - p_{g,j})}{j}. \quad (32)$$

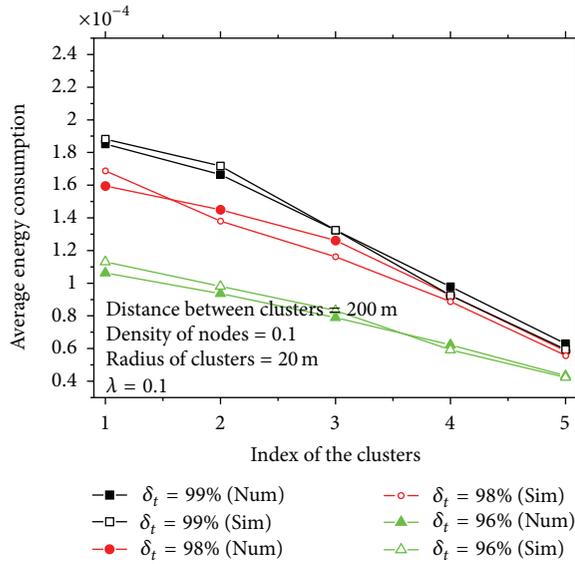


FIGURE 11: Average energy consumption of each cluster in one round.

Notably, $p_{g,j}$ is known at the cluster head of cluster j . Thus, one can overhead $p_{g,j}$ into the data packet to inform the following clusters.

Recall that $d_{C_{i-1}-C_i} \ll R_{C_i}$, the BER induced by the inter-cluster transmission takes much higher proportion than that of intracluster. In this paper, it is set $p_{g,j} = (1 - \delta_t/j) \cdot \tau$, where $0 < \tau < 1$ is a coefficient representing the proportion of p_g in the total BER. To make the analysis tractable and highlight the performance of CC in inter-cluster transmission, $\tau = 10\%$ is employed. And it is reasonable since the distance between the clusters is much larger than the radius of them. As we see in the proof of Theorem 2, the transport scheme of inter-cluster transmission depends on the required BER rather than the data amount. So we set the radius of the clusters identical to each other as $R_C = 20$ m. In addition to this, the impact of transmission distances on energy consumption is already stated in Section 3. And the distance between clusters are arranged to the same, $d_{C_i-C_{i-1}} = 200$ m.

We map the average energy consumption of each cluster in Figure 11. Obviously, cluster C_1 would die much earlier than the outside cluster because of the heavier burdened data load. This leads to the “energy hole” as well as the network paralysis [21]. Furthermore, in case the reliability of data along the transmission path is evenly distributed, the transmission scheme and broadcasting BER are also the same. Figure 12 depicts the optimal broadcasting BER for each cluster to transmit their own data. It is observed that SISO transmission is suitable for lower reliability transmission (clusters 1 and 2 when $\delta_t = 98\%$, cluster 1 when $\delta_t = 99\%$) while high-fidelity transmission prefers cooperative transmission. For instance, BER on each hop are almost (in spite the BER brought by the intra-cluster transmission) 2% and 0.4% for the clusters which are 1 hop and 5 hops to the sink according to the reliability 98%, respectively. SingleHop Algorithm selected the SISO scheme for cluster 1 and 2, where

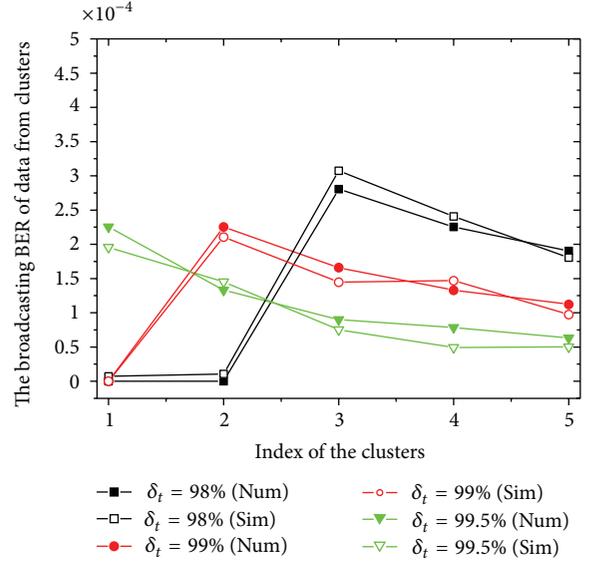


FIGURE 12: The broadcasting BER of data sourced from each cluster.

the broadcasting BER is zero, while CC is chosen for the peripheral clusters, as shown in the black lines in Figure 12.

6. Nodes Adopt the Different BER according to the Clusters They Belong to

Evidently, the cluster nearest to the sink dies much earlier than the clusters farther away which leads to “energy hole,” since the nodes in cluster 1 are burdened with larger amount of data. We notice that the reduction of power consumption at the energy hole leads to the prolongation of network lifetime. To mitigate this “energy hole” as well as maintain the statistical reliability, a strategy is proposed to convert the energy consumption at the energy hole to the farther part of the network by adjusting the transmission BER in each cluster. Based on the analysis in Theorem 3, the sum of BER along the routing path stays stable and the accuracy of the data can still reach the requirement of reliability. By means of this method, the energy consumption of the nearer clusters is reduced although the cost of the external clusters increased. As long as the maximum energy consumption declined, the network lifetime is optimized.

Through the calculation of MultiHop algorithm, Figure 13 plots the transmit BER of C_1 for the data from different clusters ($p_{e,1}^j$) compared to the originality. Since the energy expenditure of the clusters farther away from sink is lower than cluster C_1 , BER for C_1 , to transmit data is switched larger in order to balance the power cost. While to maintain the reliability, the BER of the farther cluster is relatively lower. Thus, the energy consumption of peripheral clusters increases and that of C_1 has declined as shown in Figure 14. Meanwhile, the longevity of network is improved (in case the initial energy of the nodes is $1J$, the lifetime is optimized by 9.85%).

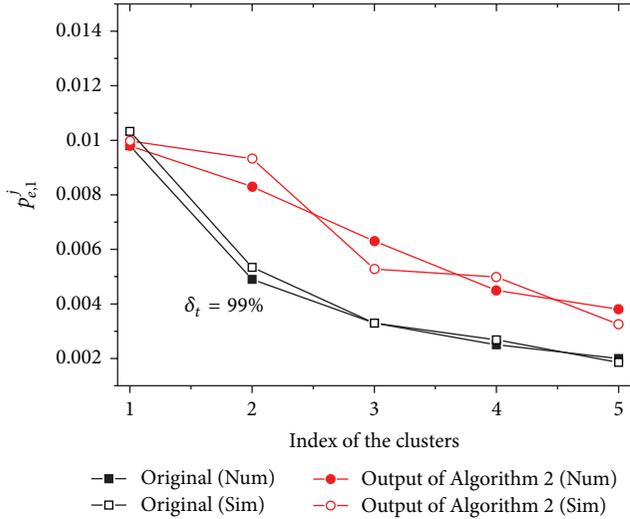
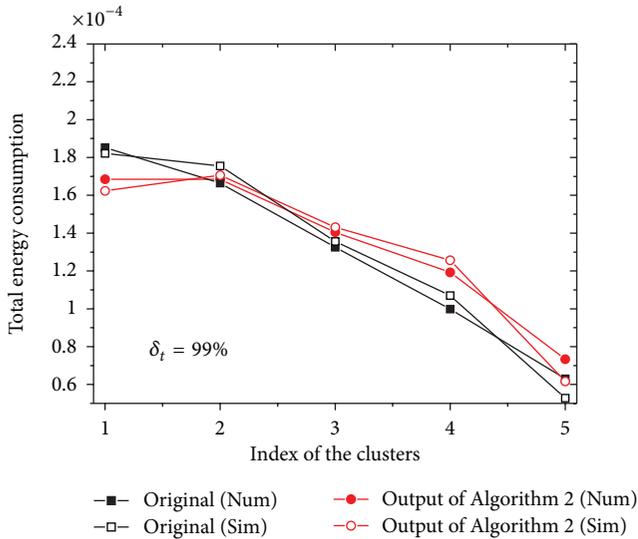
FIGURE 13: BER of transmission for cluster C_1 .

FIGURE 14: Energy consumption for one data gathering round.

7. Conclusion

In this paper, we jointly investigate the SISO and CC transmission schemes in both single-hop and multihop scenarios. The optimal number of cooperative nodes and the broadcasting BER are obtained for the energy efficiency. It is shown that cooperative communication is more suitable for the long-distance transmission in harsher environment. The conclusion of single-hop network is then expanded to multihop-clustered network where we study the energy cost of different nodes (cluster head, cooperative nodes, and plain nodes) in the cluster. Finally, we prolong the network lifetime by adjusting the transmit BER along the delivery path. An interesting extension is to precisely study the cooperative nodes selection scheme, since the probability is slightly different between nodes to be covered by broadcasting (the node at the core of the circle cluster is easier to be under the convergence).

Appendix

Suppose that $f(p_b) = p_b^2/(p_e - p_b)^{(1/N_{CN}+1)} - r_b^k/d^k$, we first prove that (15) has real solution when $p_b \in (0, p_e)$.

By $p_b = 0$, we have that $f(0) = -r_b^k/d^k < 0$. In case $p_b = p_e$, $f(p_b) = \infty - r_b^k/d^k > 0$. Since $f(p_b)$ is continuous in the domain, there must be real solutions between 0 and p_e for (15).

Take the derivative of $f(p_b)$

$$\frac{df(p_b)}{dp_b} = \frac{2p_b}{(p_e - p_b)^{(1/N_{CN}+1)}} + \frac{(1/N_{CN} + 1) \cdot p_b^2}{(p_e - p_b)^{(1/N_{CN}+2)}}. \quad (\text{A.1})$$

Note that $0 < p_b < p_e$, $N_{CN} \in \mathbb{Z}$. As a result, $df(p_b)/dp_b > 0$. Therefore, there is only one real solution for $f(p_b) = 0$.

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