Energy Efficiency of Cooperative MISO Technique in Multi-hop Wireless Sensor Networks

Zheng Huang
Department of Electrical Engineering and Computer Science
Graduate School of Engineering, Nagoya University
Nagoya, Japan 464-8603
Email: huang@katayama.nuee.nagoya-u.ac.jp

Takaya Yamazato
and Masaaki Katayama
EcoTopia Science Institute, Nagoya University
Nagoya, Japan 464-8603
Email: {yamazato, katayama}@nuee.nagoya-u.ac.jp

***Abstract*—In this paper, the energy efficiency of cooperative Multiple-Input Single-Output (MISO) technique for a multi-hop wireless sensor network is investigated and compared with other transmission schemes. Firstly, we present different schemes for data transmission of the cluster farther from base station and calculate their energy consumptions. The results show that the optimal transmission scheme varies with the inter-cluster distance in different networks. Then we explore the lifetime of the network and find that it is not always the optimal to employ the multi-hop transmission and the single-hop transmission outperform the multi-hop under a certain distance threshold. In addition, the effects of the transmission bit rate and the required bit error ratio (BER) on the distance threshold are also clarified.**

I. Introduction

A wireless sensor network (WSN) consists of large numbers of spatially distributed devices called sensor nodes which cooperate to accomplish various tasks. In general, the size of nodes is small, and their operations rely on batteries which are difficult to replenish in most applications. As a result, energy efficiency is crucial in WSN.

Many techniques have been proposed for the improvement of the energy efficiency in WSN [1], [2]. Among these techniques, cooperative transmission diversity has been considered as one of the effective ways to save energy in the fading wireless channels. Using this technique, multiple individual single-antenna nodes can cooperate on information transmission for energy-efficient communications. However, when cooperative transmission diversity is used for both diversity gain and spatial multiplexing gain, it also requires extra energy for the local cooperative data exchange and extra circuit consumption of the cooperative nodes. In [3], Cui *et al.* analyzed the energy efficiency of transmission and reception diversities, or cooperative Multiple-Input Multiple-Output (MIMO) scheme on Alamouti code for the single-hop transmission in WSN. And a closer look at the effect of increased training overhead required in cooperative MIMO systems is further considered in [4]. From their results, cooperative transmission can dramatically reduce the total energy consumption if the transmission distance is large enough. In [5], George N. Bravos *et al.* investigated the effect of circuit power consumption in cooperative MIMO. Tuan-Duc Nguyen *et al.* extended the work of [3] and showed the numbers of cooperative nodes at both the transmission and reception sides should be selected with respect to the transmission distance [6]. The above authors all focused on cooperative MIMO scheme for the single-hop transmission and analyzed the energy efficiency of the related models. However, they did not consider the energy efficiency when cooperative transmission diversity is used for the multi-hop transmission in WSN. Since multi-hop is generally considered to be one of the most effective methods for data transmission in WSN, it is of much necessity to explore the energy efficiency of cooperative transmission diversity in multi-hop WSN.

To the best of our knowledge, this paper makes the first attempt at investigating the energy efficiency of cooperative transmission diversity in the multi-hop transmission. We employ a two-cluster model for our following analysis, which is most simplified from multi-hop WSN. Furthermore, we discuss the energy efficiency of cooperative Multiple-Input Single-Output (MISO) instead of MIMO, for MISO can facilitate our analysis and extend the results easily to more general situations including MIMO. Similar to [3] and [6], we firstly calculate the energy consumptions for data transmission of the cluster farther from base station in different schemes and obtain the optimal scheme based on the inter-cluster distance. Then we focus on the lifetime of the network and employ it as the evaluation index for the energy efficiency of single-hop and multi-hop networks. Moreover, we analyze the impacts of the transmission bit rate and the required Bit Error Ratio (BER) on the energy efficiency of the network.

II. System model

In general, wireless sensor networks are composed of hundreds or thousands of sensor nodes which form hierarchical clusters. In the multi-hop transmission, the data are sent from each cluster, via other relay clusters, to the destination (e.g. base station or fusion center). In order to represent this situation, this paper uses a simple two-cluster model shown in Fig. 1. The network has a BS (Base station) and two clusters: Cluster A and Cluster B. Each cluster has N nodes and a cluster head (CH). We assume that the radius of each cluster is r, and the distance of Cluster A to Cluster B and that of Cluster B to BS both are l. It should be noted that $l \gg r$ so that the distances from any nodes of a cluster to another cluster or to BS can be considered the same.

978-1-4244-2957-8/08/$25.00 © 2008 IEEE

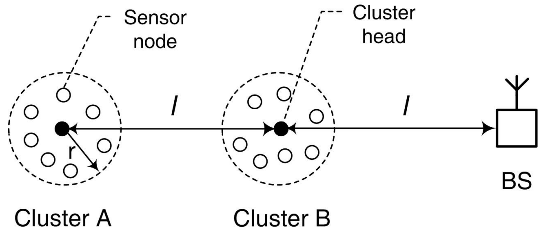

Fig. 1. System model

Data transmission can be divided into two phases: the local and the inter-cluster transmissions. In the local transmission, every node in a cluster firstly transmits their data which are collected from the targets to their CH, then the CH carries out data fusion. After that, the CH selects M_t ($M_t \geq 1$) nodes as cooperative nodes to execute cooperative transmission. Finally, the CH broadcasts the fused data to the M_t selected nodes.

In the inter-cluster transmission, the cooperative nodes use Space-Time Block Code (STBC) to encode the data, and transmit simultaneously the coded data to the next CH or BS. Since only CHs and BS are arranged to receive the inter-cluster data, the system we consider here is MISO system.

III. Calculation of energy consumption

According to our assumptions, since $l \gg r$, the energy consumption of the inter-cluster transmission will be much larger than that of the local transmission. Thus, we only consider the former in our model. And the CHs usually have higher power as compared to other nodes, so all the energy consumptions of CHs are omitted. In addition, the energy consumption of baseband signal processing circuit in each node is also omitted in order to simplify our model.

First, we calculate the power consumption of a cooperative node. Considering a general communication scheme similar to [3], the total power consumption of typical RF system can be categorized into two main parts, namely, the power consumption of the power amplifier P_{PA} which is a function of the transmission power P_{out}, and the power consumption of all other circuit blocks P_C. Let us assume that the model operates under Rayleigh fading environment with squared power path loss, then P_{out} can be calculated according to the link budget relationship [7]:

$$P_{out} = \frac{R_b N_0 (4\pi d)^2}{P_b^{1/M_t} G_T G_R \lambda^2} M_l N_f \tag{1}$$

where R_b is the transmission bit rate, d is the transmission distance, P_b is the required BER, M_t is the number of cooperative nodes in transmitter side, G_T and G_R are the transmitter and receiver antenna gains respectively, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other additive background noise or interference, N_f is the receiver noise figure defined as $N_f = N_r/N_0$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_0 is the single-sided thermal noise PSD at the room temperature with a typical value $N_0 = -171$ dBm/Hz.

Moreover, the power consumption of the power amplifier P_{PA} can be approximately calculated as

$$P_{PA} = (1+\alpha) P_{out} \tag{2}$$

where $\alpha = \xi/\eta - 1$ with ξ being the Peak to Average Ratio (PAR) and η being the drain efficiency of the RF power amplifier.

As discussed in [8], we estimate the term P_C as

$$P_C = P_{CT} + P_{CR} \tag{3}$$

where P_{CT} is the power consumption of all other circuit blocks excluding the power amplifier in transmitter side and P_{CR} is the power consumption of all circuit blocks in receiver side. In light of our previous assumptions, P_{CR} is equal to zero. For a transmitter node, P_{CT} can be further calculated by

$$P_{CT} = P_{DAC}(R_b) + P_{mix} + P_{filt} + P_{syn} \tag{4}$$

where P_{DAC}, P_{mix}, P_{filt}, P_{syn} are the power consumption values of the D/A converter, the mixer, the active filters at the transmitter side, the frequency synthesizer, respectively. It is important to note that P_{DAC} depends on the transmission bit rate R_b, and hence P_{CT} is also a function of the transmission bit rate R_b. According to the results of [8], we can demonstrate that P_{DAC} can be regarded as a constant approximately when $R_b <$ 10M bit/s.

Then, we consider the total energy consumption of cooperative transmission. Based on general physics, the energy consumption is the multiplication of the power consumption and the dissipated time. Thus, as for a bit data transmitted, the total energy consumption E_{bt} in M_t cooperative nodes can be formulated as

$$E_{bt} = (P_{PA} + P_C) M_t T_s = \frac{(P_{PA} + P_C) M_t}{R_b} \tag{5}$$

where T_s is the required time during which a bit data is transmitted.

IV. Energy consumption of data transmission from Cluster A

In certain applications of WSN, some of the clusters have data to transmit and other clusters serve only as relays. This situation will occur in the event-driven senor networks (e.g., for intrusion detection) [9]. Thus, we first consider the energy consumption of data transmission from Cluster A with respect to this situation.

A. *Different transmission methods*

Since Cluster A can use Cluster B as a relay or transmit the data directly to BS without the relay, the data from Cluster A to BS can be transmitted in different methods which induce different energy consumptions. In fact, there exist five transmission methods for data transmission from Cluster A to BS. Using the previous analysis shown in Section III, we calculate the energy consumptions per bit in these different

TABLE I
SYSTEM PARAMETERS

$f_c = 2.5$ GHz	$N_0/2 = -174$ dBm/Hz
$\alpha = 0.47$	$P_{filt} = 2.5$ mW
$G_T G_R = 5$ dBi	$P_{mix} = 30.3$ mW
$N_f = 10$ dB	$P_{syn} = 50.0$ mW
$M_l = 40$ dB	$P_{DAC} = 15.5$ mW

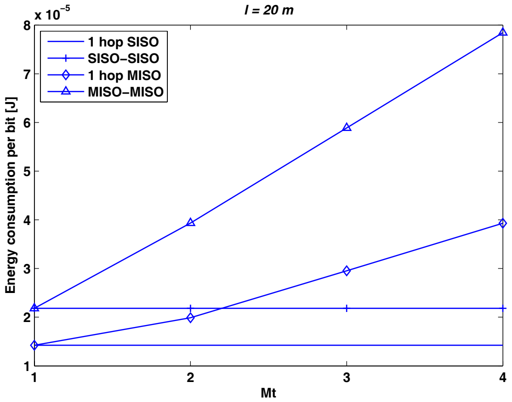

Fig. 2. Energy consumption when $l = 20$ m

methods. Firstly, in order to simplify our expressions, the product of various constants in (1) will be represented by C_{tr} which is defined as

$$C_{tr} = (1+\alpha)\frac{N_0(4\pi)^2}{G_T G_R \lambda^2} M_l N_f \tag{6}$$

Then the energy consumptions per bit in different schemes are evaluated respectively, as shown by the equations below.

a. 1 hop SISO (Single-Input Single-Output) : The data of Cluster A are transmitted directly to BS with M_t=1.

$$E_a = \frac{4l^2 C_{tr}}{P_b} + \frac{P_C}{R_b} \tag{7}$$

b. 1 hop MISO : The same with Scheme a, but M_t>1.

$$E_b = \frac{4l^2 M_t C_{tr}}{P_b^{1/M_t}} + M_t\frac{P_C}{R_b} \tag{8}$$

c. SISO-SISO : The data of Cluster A are transmitted to Cluster B, then sent to BS. In both clusters, M_t=1.

$$E_c = \frac{2l^2 C_{tr}}{P_b} + 2\frac{P_C}{R_b} \tag{9}$$

d. MISO-SISO (SISO-MISO) : The same with Scheme c. But in Cluster A (Cluster B), M_t>1; while in Cluster B (Cluster A), M_t=1,

$$E_d = \frac{l^2 C_{tr}}{P_b} + \frac{l^2 M_t C_{tr}}{P_b^{1/M_t}} + (M_t+1)\frac{P_C}{R_b} \tag{10}$$

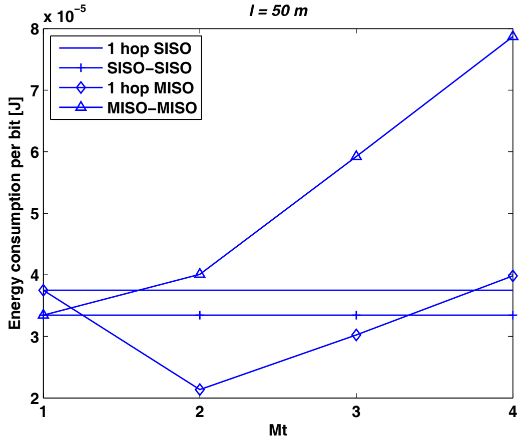

Fig. 3. Energy consumption when $l = 50$ m

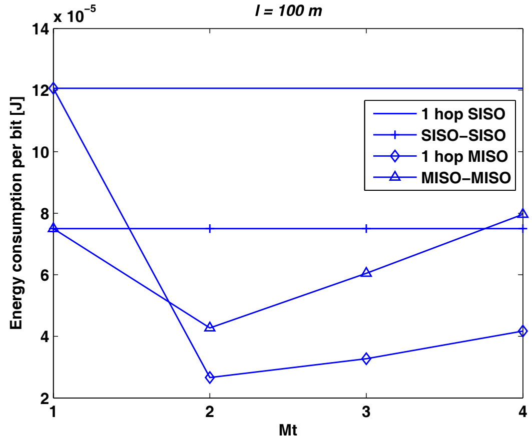

Fig. 4. Energy consumption when $l = 100$ m

e. MISO-MISO : The same with Scheme c, but in both clusters, M_t>1.

$$E_e = \frac{2l^2 M_t C_{tr}}{P_b^{1/M_t}} + 2M_t\frac{P_C}{R_b} \tag{11}$$

B. Numerical results

Next we compare the energy efficiency of different transmission methods by simulation. The simulation parameters are shown in Table I and BPSK is used as the modulation scheme during data transmission.

Since the comparison between MISO-SISO and SISO-SISO/MISO-MISO is equivalent to that between 1 hop MISO and 1 hop SISO with transmission distance l, we focus on other four methods except MISO-SISO.

We set R_b = 10k bit/s, P_b = 0.001, and change l to investigate the impact of l on the energy consumption.

Small l: Figures 2, 3 and 4 show different energy consumptions with different methods when l = 20 m, 50 m and 100 m, respectively. From these figures, it can be seen that when l is small (20 m) the best method is 1 hop SISO and the better is 1 hop MISO or SISO-SISO depending on M_t. On

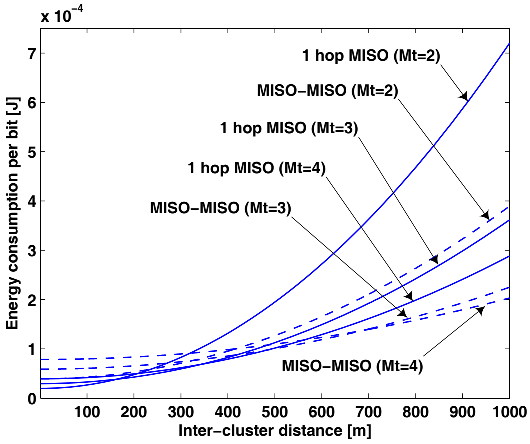

Fig. 5. Energy consumption of 1 hop MISO vs. MISO-MISO when l is large

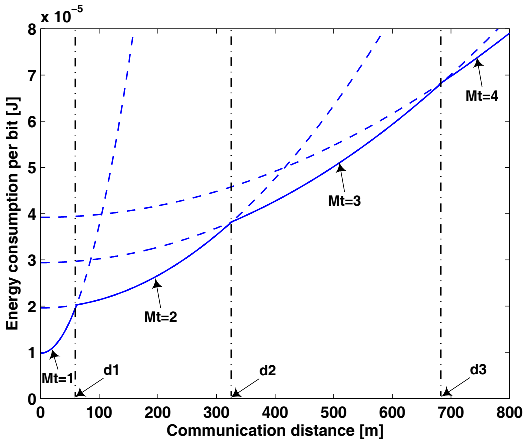

Fig. 6. Optimal M_t based on communication distance

the contrary, when l is large (50 m and 100 m), 1 hop MISO and MISO-MISO outperform 1 hop SISO and SISO-SISO.

Large l: Fig. 5 shows the performances of 1 hop MISO and MISO-MISO as functions of l with M_t as a parameter. From this figure, it is found that MISO-MISO has more energy efficiency than 1 hop MISO if l is large enough, and when M_t increases, the energy efficiency of MISO-MISO also increases. That is, multi-hop transmission with a large number of cooperative nodes is the optimal choice.

V. Evaluation of Network Lifetime

In contrast with Section IV, it is possible that all the clusters of a WSN have data to transmit in some applications, i.e., there exist periodical data transmission in every cluster (e.g., for field monitoring) [9]. Hence, we further study the energy efficiency of the network including the transmission for the data of Cluster B in the following discussion.

A. General analysis

We assume that the energy of each node is J joules. Considering the energy consumptions of both clusters, we can use lifetime as an evaluation index for energy efficiency. We

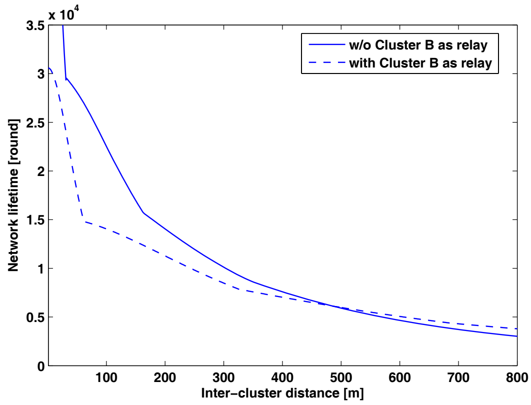

Fig. 7. Network lifetimes with or without Cluster B as relay

assume that each cluster needs to transmit T bits data to BS in every round. Hence, the definition of lifetime of a cluster is the possible total rounds K, which can be calculated as:

$$K = \frac{J(N/M_t)}{T(E_{bt}/M_t)} = \frac{JN}{TE_{bt}} \tag{12}$$

It is obvious that the lifetime of the whole network is determined by the cluster which consumes all its energy firstly.

Similar to the previous section, Cluster A can take Cluster B as a relay or not in its transmission. When Cluster A uses Cluster B as a relay, the communication distances of Cluster A to Cluster B and Cluster B to BS are both l, thus the number of cooperative nodes in Cluster A is equal to that in Cluster B, i.e. $M_{tA} = M_{tB}$. However, if Cluster A directly sends its data to BS, the communication distance of Cluster A to BS is $2l$ and M_{tA} may not be the same to M_{tB}.

From the results of the previous section, there are different optimal schemes for different communication distances. That is, the value of optimal M_t varies with the communication distance, as shown in Fig. 6. It can be seen that optimal M_t will be 2, 3 and 4 when the communication distance exceeds d_1, d_2 and d_3, respectively. Hence, we choose optimal M_{tA} and M_{tB} for the above two cases, according to different values of their communication distances.

B. Numerical results

We still use the parameters in Table I and can get the values of d_1, d_2 and d_3 in Fig. 6 are 61 m, 326 m and 687 m, respectively. Then assuming that $T = 2000$ bit, $J = 100$ joule and $N = 12$ [10], [11], the network lifetimes in cases with or without Cluster B as a relay can be calculated from the previous analysis, as shown in Fig. 7.

Fig. 7 shows that it is not always the optimal to employ a relay. When $l < 486$ m, the lifetime of network without relay is even longer than that with a relay. Thus it can be concluded that when the inter-cluster distance is under a certain threshold, the transmission energy saved in the network with a relay is not sufficient to compensate for the circuit consumption increased, so it is not of the most energy efficiency to use a relay.

TABLE II
THE DISTANCE THRESHOLD OF THE NETWORK LIFETIMES

The distance threshold [m]		P_b		
		10^{-3}	10^{-4}	10^{-5}
R_b [bit/s]	10k	486	421	236
	100k	152	133	100
	1M	49	42	32

On the other hand, we can also get the conclusion that the multi-hop networks with small communication distance are not always more energy efficient than the single-hop ones, due to the circuit consumption. Hence it is more energy efficient to choose the single-hop method with cooperative transmission in a small-scale or medium-scale WSN.

C. The impacts of R_b and P_b on the distance threshold

According to (1), (5) and (12), the lifetime K is also a function of the transmission bit rate R_b and the required BER P_b. It is obvious that in whichever cases, K has the same varying trend with R_b and P_b. And what we pay more attention to is the changes of the distance threshold which decides the more energy efficient case.

Table II shows the impacts of R_b and P_b on the distance threshold. As depicted in Fig. 7, when $R_b = 10$k bit/s and $P_b = 0.001$, the distance threshold is 486 m. When R_b increases or P_b decreases, the distance threshold will decrease correspondingly.

The results of Table II indicate that multi-hop network will outperform single-hop at a shorter inter-cluster distance with the increase of R_b or the decrease of P_b. Hence, the energy efficiency of multi-hop networks will be improved by increasing R_b or decreasing P_b.

VI. CONCLUSIONS

In this paper, we investigate the energy efficiency of different transmission schemes in a two-cluster WSN. In our model, the cluster farther from BS can use the nearer one as a relay to transmit its data. Firstly, we compare the energy consumptions for the data transmission of the farther cluster in different transmission methods. As a result, the single-hop transmission with SISO is the best candidate when the inter-cluster distance is small, and the multi-hop with SISO brings more energy efficiency with the increase of inter-cluster distance. However, if the inter-cluster distance becomes much larger, the cooperative MISO transmission will outperform SISO and the multi-hop transmission with more cooperative nodes will be the optimal choice. Then, the energy consumptions for the data transmission of both clusters are considered and we put our emphasis on the analysis of the network lifetime in two cases: with or without the nearer cluster as a relay. Our results show that because of the circuit consumption, multi-hop network will have less energy efficiency than single-hop network if the inter-cluster distance is under a certain threshold. That is, the single-hop method with cooperative transmission will be more efficient in a small-scale or medium-scale WSN. Moreover, our simulation results also clarify that the energy efficiency of multi-hop networks will be improved by increasing the transmission bit rate R_b or decreasing the required bit error ratio P_b.

REFERENCES

[1] V. Raghunathan, S. Ganeriwal, and M. Srivastava, "Emerging techniques for long lived wireless sensor networks," *IEEE Commun. Mag.*, vol. 44, no. 4, pp. 108–114, Apr. 2006.

[2] N. A. Pantazis and D. D. Vergados, "A survey on power control issues in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 9, no. 4, pp. 86–107, 2007.

[3] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.

[4] S. K. Jayaweera, "Virtual MIMO-based cooperative communication for energy-constrained wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 5, pp. 984–989, May 2006.

[5] G. N. Bravos and A. G. Kanatas, "Energy efficiency of MIMO-based sensor networks with a cooperative node selection algorithm," in *Proc. IEEE International Conference on Communications (ICC 2007)*, Glasgow, UK, Jun. 2007, pp. 3218–3223.

[6] T. D. Nguyen, O. Berder, and O. Sentieys, "Cooperative MIMO schemes optimal selection for wireless sensor networks," in *Proc. IEEE 65th Vehicular Technology Conference (VTC2007-Spring)*, Dublin, Ireland, Apr. 2007, pp. 85–89.

[7] J. G. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2000.

[8] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *IEEE Trans. Wireless Commun.*, vol. 4, no. 9, pp. 2349–2360, Sep. 2005.

[9] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless micro-sensor network models," *ACM SIGMOBILE Moblie Computing and Communications Review*, vol. 6, no. 2, pp. 28–36, Apr. 2002.

[10] X. H. Li, M. Chen, and W. Liu, "Application of STBC-encoded cooperative transmissions in wireless sensor networks," *IEEE Signal Process. Lett.*, vol. 12, no. 2, pp. 134–137, Feb. 2005.

[11] Y. Yuan, Z. He, and M. Chen, "Virtual MIMO-based cross-layer design for wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 55, no. 3, pp. 856–864, May 2006.