Cooperative MIMO and Hop Length Optimization for Cluster Oriented Wireless Sensor Networks

Yuyang Peng, Youngshin Ahn and Jaeho Choi

Abstract An energy-efficient multi-hop communications scheme based on cooperative multiple-input multiple-output technique is proposed for wireless sensor networks. The proposed method takes into account the modulation constellation size and transmission distance and effectively saves energy by optimizing hop distances with respect to the modulation constellation. Here, the equidistance hop length scheme as a conventional scheme is compared to the proposed method. In order to evaluate the performance of the proposed scheme, a qualitative analysis is taken in terms of energy efficiency. The analytical results indicate that the propose method can significantly save total energy consumption in comparison to the conventional one. The possible application of the proposed scheme can be an emergency monitoring system such as the forest fire detection; and this method can provide a longer lifetime of monitoring system.

Keywords Cooperative Communications · Sensor Networks · Multi Hop · Hop Distance · MIMO · Energy Efficiency

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1 Introduction

It is well known that saving energy is the main concern in wireless sensor networks since the size of the sensors is too small for them to have been designed with enough energy for long time operation. Recently, many approaches including multiple-input multiple-output (MIMO) communication and multi-hop schemes have been developed to improve the energy efficiency. In fact, it is difficult to implement multiple antennas at a small sensor node in a realistic environment for the MIMO approach. Therefore, cooperative MIMO schemes have been designed [1, 2], which allow single antenna nodes to achieve MIMO capability. Energy efficiency has been done to explain that the cooperative MIMO outperforms the SISO (single-input single-output) after a certain distance [3]. But the use of cooperative MIMO in a multi-hop network making the transmission more efficient is still a hot reach topic that should be sought.

In this paper, in order to take full advantage of these approaches, a new scheme is proposed which involves the joint utilization of cooperative MIMO and multi-hop techniques. Moreover, the modulation constellation size is also considered in this scheme for a more practical case. Also, it is further demonstrated that the energy efficiency performance of the proposed scheme can be improved.

The remainder of the paper is organized as follows. In Sect. 2, the fundamentals and system model are introduced. In Sect. 3, the multi-hop cooperative MIMO wireless sensor network is presented; and the quantitative analysis on the performance of the proposed scheme is presented in Sect. 4. Finally, in Sect. 5, the paper is concluded with a brief summary.

2 Fundamentals and System Model

A wireless sensor network composed of n clusters and a destination is shown in Fig. 1b where the cooperative MIMO communication technique Fig. 1a is applied to a multi-hop scheme for saving energy. In the cluster, the longest distance amongst the nodes is defined as d_{long}. The long-haul distance between the nearest nodes of different cluster is defined as d_i ($i = 1, 2, \ldots n$) which is assumed much larger than d_{long}.

In order to evaluate the performance of the proposed scheme, the energy consumption is first discussed. From [1] it is known that the total average power consumption can be categorized into two main components: the power consumption of all the power amplifiers P_{PA} and the power consumption of all the circuit blocks P_c. Considering the optimized transmission time T_{on}, the total energy consumption per bit can defined as follows:

$$E_{\mathrm{bt}} = (1+\alpha)\,\bar{E}_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c T_{on}/L \tag{1}$$

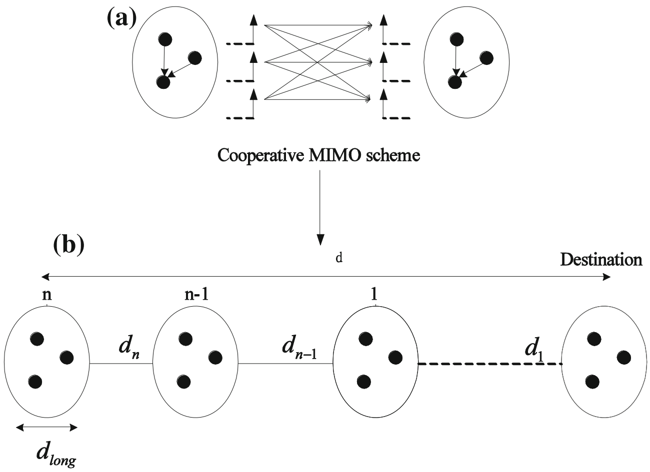

Fig. 1 An energy efficient wireless sensor network is constructed with **a** cooperative MIMO communications and **b** multi-hop techniques

where $\alpha = {}^{\xi}/_{\eta} - 1$ with ξ is the peak to average ratio (PAR); η is the drain efficiency of the RF power amplifiers; $\bar{E}_b$ is the average energy per bit required for a given bit error rate (BER); d is the transmission distance; 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 interference or background noise; and N_f is the receiver noise. It should be noted that N_f is given by $N_f = N_r/N_0$, 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 room temperature with $N_0 = -171$ dBm/Hz. Assume that the transmitter buffer length is L bits. In Eq. 1, $\bar{E}_b$ is defined by the BER and constellation size b. The average BER can be obtained as follows [4]:

$$\bar{P}_b \approx \varepsilon_H \left(\frac{4}{b} \left(1 - \frac{1}{2^{\frac{b}{2}}} \right) Q \left(\sqrt{\frac{3b}{M-1} \gamma_b} \right) \right) \tag{2}$$

for $b \geq 2$; and for $b = 1$, Eq. 1 can be simplified as follows:

$$\bar{P}_b \approx \varepsilon_H \left[Q(\sqrt{2\gamma_b}) \right] \tag{3}$$

where $\varepsilon_H[\,]$ denotes the expectation given the channel $\mathbf{H}$; γ_b is the instantaneous received signal-to-noise ratio (SNR); $Q(\,)$ is the Q-function. The Chernoff bound can be applied to obtain and the upper bound for $\bar{E}_b$ as follows:

$$\bar{E}_{\mathrm{b}} \leq \frac{2}{3} \times \left(\frac{\bar{P}_b}{\frac{4}{b}\left(1 - \frac{1}{2^{\frac{b}{2}}}\right)} \right)^{-\frac{1}{M_t M_r}} \frac{2^b - 1}{b} M_t N_0 \qquad (4)$$

By substituting Eq. 4 into Eq. 1 the total energy consumption per bit can rewritten as follows:

$$E_{\mathrm{bt}} = (1 + \alpha) \times \frac{2}{3} \times \left(\frac{\bar{P}_b}{\frac{4}{b}\left(1 - \frac{1}{2^{\frac{b}{2}}}\right)} \right)^{-\frac{1}{M_t M_r}} \times \frac{2^b - 1}{b} M_t N_0 \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{bB} \qquad (5)$$

where B is the modulation bandwidth; M_t and M_r are the number of transmitter and receiver antennas, respectively.

3 Multi-Hop Network Analysis and Calculation

In this section the cooperative MIMO and multi-hop schemes is considered jointly as shown in Fig. 1. Let d_i represent the optimal transmission distance and b_i represent the optimal constellation size. Then, for a transmission distance d_i, the energy consumption per bit of long-haul can be defined as follows:

$$E_{\mathrm{bt}}(d_i) = (1 + \alpha) \times \frac{2}{3} \left(\frac{\bar{p}_b}{\frac{4}{b_i}\left(1 - \frac{1}{2^{\frac{b_i}{2}}}\right)} \right)^{-\frac{1}{M_t M_r}} \times \frac{2^{b_i} - 1}{b_i} M_t N_0 \times \frac{(4\pi d_i)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{b_i B} \qquad (6)$$

There can be various scenarios, however, in this paper, it is assumed that two sensor nodes group together making a cluster since this assumption on the number of nodes in a cluster can reduce the complexity of the calculation. Nevertheless, it is important to note that the calculation can in principle be extended to any cluster size. For a scenario where all nodes are transmitting, the total energy consumption can be defined as follows:

$$E_{total} = E_{local} + 2\sum_{i=1}^{n} (n + 1 - i) E_{\mathrm{bt}}(d_i + 2d_{long}) N_i \qquad (7)$$

where each sensor node assumes to transmit N_i bits. E_{local} is the local energy consumption; and $2\sum_{i=1}^{n} (n + 1 - i) E_{\mathrm{bt}}(d_i + 2d_{long}) N_i$ is defined as the long-haul energy consumption. Using the cooperative communication scheme proposed in

[1, 2] the local energy consumption of the proposed scheme E_{local} can be defined as follows:

$$E_{local} = \sum_{i=1}^{n}\left[\sum_{i=1}^{M_t} N_i E_i^t + \sum_{j=1}^{M_r-1} N_s n_r E_j^r\right] \tag{8}$$

where E_i^t, E_j^r denotes the energy cost per bit for local transmission for the transmitter and receiver, respectively; N_s is the total number of symbols; n_r is the number of bits after quantizing a symbol at the receiver.

On the other hand, in order to minimize the total energy consumption, in this paper, the proposed method tries to optimize the hop distance between the clusters. Let d_i be the optimal transmission distance. First, through observation of the transmission distance in the proposed model, the constraint $\sum_{i=1}^{n} d_i = d - nd_{long}$ is set. Along with the constraint, the cost function can be defined as follows:

$$\Phi = E_{local} + 2\sum_{i=1}^{n}(n+1-i)E_{\mathrm{bt}}(d_i + 2d_{long})N_i + w(d - nd_{long} - \sum_{i=1}^{n} d_i). \tag{9}$$

To Minimize E_{total} under the constraint $\sum_{i=1}^{n} d_i = d - nd_{long}$, the partial derivatives with respect to d_i are taken and set them equal to 0 as follows:

$$\frac{\partial\Phi}{\partial d_i} = 4E \times (n+1-i)(d_i + 2d_{long}) - w = 0 \tag{10}$$

where E is $(1+\alpha) \times \frac{2}{3} \times \left(\frac{\bar{p}_b}{\frac{4}{b_i}\left(1-\frac{1}{2^{\frac{b_i}{2}}}\right)}\right)^{-\frac{1}{M_t M_r}} \times \frac{2^{b_i}-1}{b_i} M_t N_0 \times \frac{(4\pi)^2}{G_t G_r \lambda^2} M_l N_f N_i;$
and w is a Langrage's multiplier.

Solving for d_i in Eq. 10, the hop distance between the clusters can be obtained as follows:

$$d_i = \left(\frac{w}{4E(n+1-i)}\right) - 2d_{long} \tag{11}$$

where w can be obtained by using the constraint $\sum_{i=1}^{n} d_i = d - nd_{long}$. Then Eq. 11 can be rewritten as follows:

$$d_i = \frac{d + nd_{long}}{\sum_{f=1}^{n}\left(\frac{1}{n+1-f}\right)(n+1-i)} - 2d_{long}. \tag{12}$$

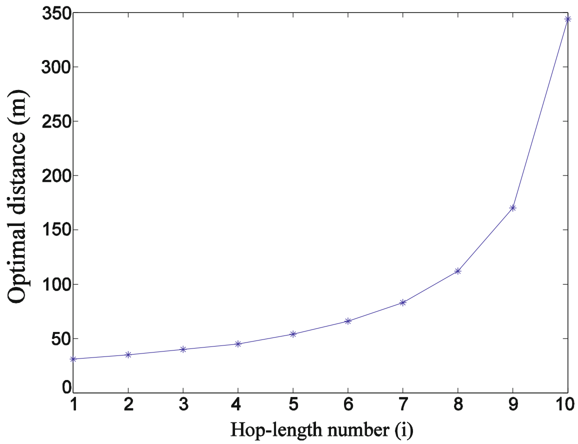

Fig. 2 Optimal distances versus hop-length numbers

4 Numerical Results

In this section, a quantitative analysis on the performance of the proposed method is presented. There are various scenarios to be considered, however, for the preliminary study, some to the parameters are set in such a way to simplify the complexity of the equations and also the computation.

Now, suppose that $n = 10$, $d = 1000$ m, and $d_{long} = 2$ m. In Fig. 2, the optimal transmission distances are obtained using Eq. 12 and the results are plotted. The figure shows that for the clusters located farther from the destination the hop distances or lengths for them also increase. The reduction of energy consumption can be obtained using this scheme instead of the equidistance scheme. In order to compare the performance of the proposed method with the equidistance scheme, one set of typical parameters are set and used as follows:

$B = 10$ kHz, $f_c = 2.5$ GHz, $P_{mix} = 30.3$ mW, $P_{filt} = 2.5$ mW, $P_{filr} = 2.5$ mW, $P_{LNA} = 20$ mW, $P_{synth} = 50$ mW, $M_l = 40$ dB, $N_f = 10$ dB, $G_tG_r = 5$ dBi and $\eta = 0.35$, $N_i = 20$ kb, $n_r = 10$.

For simplicity, Alamouti scheme [5] has been adopted in this paper. Using the brute-force simulation method proposed in [6] the optimal constellation size b is obtained for different transmission distances as listed in Table 1.

For the evaluation of the performance, an equidistance scheme is calculated in order to compare with the proposed scheme. As already referred, the proposed scheme is the use of cooperative MIMO in optimal hop-length wireless sensor network with consideration of modulation constellation size, extra training overhead requirement, and data aggregation energy. In Fig. 3 the total energy consumption per bit is plotted as a calculation aim for the proposed scheme and equidistance scheme. It can be seen that the majority of clusters in the proposed scheme have less total energy consumption per bit when compared with the equidistance scheme, i.e. the proposed scheme has a better performance. After calculating energy consumption of each cluster and adding all the values together,

Table 1 Optimal constellation size b versus different transmission distances

d(m)	10	20	40	70	100	150	200	300	350
b	8	6	5	4	3	2	2	1	1

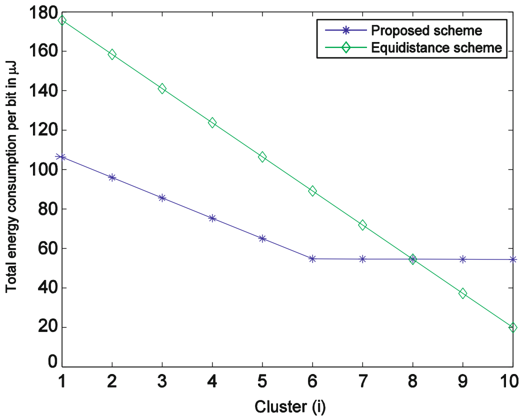

Fig. 3 Total energy consumption per bit in every cluster for different schemes ($n = 10$, $d = 1000$ m, $d_{long} = 2$ m).

the results show that the proposed scheme offers a total energy saving of about 29.5 %.

5 Conclusion

A multi-hop scheme based on a cooperative MIMO has been proposed. The feasibility of using this scheme for optimization of the performance of the wireless sensor networks is validated numerically by measurement of the total energy consumption. The results demonstrate that the proposed scheme offers a total energy saving of around 29.5 % after taking into account with modulation constellation size and transmission distance compared with the traditional scheme. Therefore it is concluded that the proposed scheme can be applied in wireless sensor networks for the reduction of energy consumption when the prime concern is to extend the network life time.

References

1. Cui S, Goldsmith A, Bahai A (2004) Energy-efficiency of MIMO and cooperative MIMO techniques in sensor network. IEEE J Select Areas Comm 22:1089–1098
2. Gai Y, Zhang L, Shan X (2007) Energy efficiency of cooperative MIMO with data aggregation in wireless sensor networks. Proceedings of IEEE Wireless Comm. Networking Conference, pp 791–796

3. Cui S, Goldsmith A, Bahai A (2003) Modulation optimization under energy constraints. Proceedings of IEEE international conference on comm, pp 2805–2811
4. Proakis J (2000) Digital Communications, 4th edn. McGraw Hill, New York
5. Alamouti S (1998) A simple transmit diversity technique for wireless communications. IEEE Jr Select Areas Comm 16:1451–1458
6. Cui S, Goldsmith A, Bahai A (2005) Energy-constrained modulation optimization. IEEE Trans Wireless Comm 4:2349–2360