An Energy-Efficient Multi-Hop Scheme Based on Cooperative MIMO for Wireless Sensor Networks

Yuyang Peng*, Seong-Beom Ahn* ***Associate Members***, Jae-Kyung Pan* ***Lifelong Member***

ABSTRACT

An energy-efficient multi-hop scheme based on cooperative MIMO (multiple-input multiple-output) technique is proposed for wireless sensor networks, taking into consideration the modulation constellation size, transmission distance, and extra training overhead requirement. The scheme saves energy by selecting the hop length. In order to evaluate the performance of the proposed scheme, a detailed analysis of the energy and delay efficiencies in the proposed scheme compared with the equidistance scheme is presented. Results from numerical experiments indicate that by use of the proposed scheme significant savings in terms of total energy consumption can be achieved.

Key Words : cooperative, MIMO, energy-efficient, multi-hop, WSN

Ⅰ. Introduction

It is well known that energy efficiency 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 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. For the minimization of energy consumption, distribution spacing under a multi-hop scheme is discussed in [3] which shows that the equidistance scheme is not the best way in wireless senor networks and an optimal spacing scheme should be sought.

In this paper, in order to take full advantage of these approaches, a scheme is proposed which involves the joint utilization of cooperative MIMO and multi-hop techniques. Moreover, the training overhead requirement 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 even with extra energy overhead training.

The remainder of the paper is organized as follows. In section 2, the necessary background information that we use and the system model are introduced. In section 3 the multi-hop cooperative MIMO wireless sensor network is analysed and in section 4 the performance of the proposed scheme is presented using numerical calculation. Finally, in section 5 the conclusion is given.

Ⅱ. Background Information and System Model

A wireless sensor network composed of n clusters and a destination is shown in Fig. 1(b) wherein the cooperative MIMO communication technique Fig. 1 (a) is applied to a multi-hop scheme for saving

※ This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (MEST)(NO. 2011-0000896).

* The Department of Electrical Engineering, Chonbuk National University, Smart Grid Research Center at CBNU (yuyang@jbnu.ac.kr, mcgrady@jbnu.ac.kr, pan@jbnu.ac.kr)

논문번호 : KICS2011-03-153, 접수일자 : 2011년 3월 22일, 최종논문접수일자 : 2011년 6월 23일

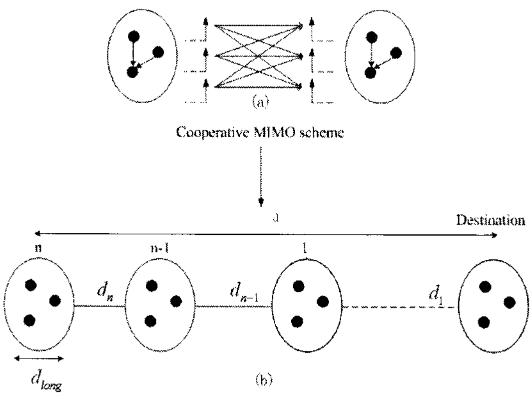


Fig. 1. An energy efficient wireless sensor network is constructed with (a) cooperative MIMO communication and (b) multi-hop techniques.

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 clusters is defined as d_i (i=1...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. Taking into consideration the optimized transmission time T_{on}, for a system the total energy consumption per bit can be expressed as

$$E_{tt} = (1+a)\overline{E_b} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c T_{on}/L \quad (1)$$

where $a=\xi/\eta-1$ with ξ being the peak to average ratio (PAR) and η being the drain efficiency of the RF power amplifiers, $\overline{E_b}$ 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 figure. 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 a value N_0= -171 dBm/Hz. It is assumed that we have L bits in transmitter buffer. In equation (1), $\overline{E_b}$ is defined by the BER and constellation size b. The average BER is given[1]

$$\overline{P_b} \approx \varepsilon_H\left(\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right) \quad (2)$$

for $b \geq 2$ and

$$\overline{P_b} \approx \varepsilon_H\left[Q\left(\sqrt{2\gamma_b}\right)\right] \quad (3)$$

for b=1. $\varepsilon_H[\ ]$ denotes the expectation with variable channel matrix **H**, γ_b is the instantaneous received signal-to-noise ratio (SNR), $Q(\ )$ is the Q-function. From (2) and (3), $\overline{E_b}$ is obtained and substituted it into (1), producing

$$E_{tt} = (1+a) \times \frac{2}{3} \times \left(\frac{\overline{P_b}}{\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)}\right)^{-\frac{1}{M_t M_r}} \times \frac{2^b-1}{b} M_l N_0 \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{bB} \quad (4)$$

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

Here for a realistic case we take into account the training overhead requirement in MIMO systems. It is supposed that the block size is equal to F symbols and there are pM_t training symbols in each block where it is assumed that p symbols are used to train each transmitter and receiver antenna pair. The energy penalty due to the training overhead requirement is defined as $\mu = \frac{R_b^{eff}}{R_b} = \frac{F-pM_t}{F}$ [4], R_b^{eff} is effective bit rate, R_b is actual bit rate, $F=\lfloor T_C R_S \rfloor$, where R_S is the symbol rate and T_C is the coherence time which is related to the Doppler shift f_m. p=1 in this paper. Then the total energy consumption per bit can be rewritten as

$$E_{tx} = \frac{1}{\mu}[(1+a)\times\frac{2}{3}\times\left(\frac{\overline{P_b}}{\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)}\right)^{-\frac{1}{M_tM_r}} \times\frac{2^b-1}{b}M_tN_0\times\frac{(4\pi d)^2}{G_tG_r\lambda^2}M_tN_f+\frac{P_c}{bB}] \quad (5)$$

Ⅲ. Multi-hop Network Analysis and Calculation

Now the cooperative MIMO and multi-hop schemes will be considered jointly as 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, optimal energy consumption of long-haul is given by

$$E_t(d_i) = \frac{1}{\mu}[(1+a)\times\frac{2}{3}\times\left(\frac{\overline{P_b}}{\frac{4}{b_i}\left(1-\frac{1}{2^{\frac{b_i}{2}}}\right)}\right)^{-\frac{1}{M_tM_r}} \times\frac{2^{b_i}-1}{b_i}M_tN_0\times\frac{(4\pi d_i)^2}{G_tG_r\lambda^2}M_tN_f+\frac{P_c}{b_iB}]N_i \quad (6)$$

where we assume that each sensor node has N_i bits to transmit.

It will be assumed that two sensor nodes in one cluster are used in order to reduce the complexity of the calculation. However it is important to note that the calculation can in principle be extended to any cluster size. For all nodes transmitting scenario, the total energy consumption can be expressed as

$$E_{total} = E_{local} + 2\sum_{i=1}^{n}(n+1-i)E_t(d_i+d_{long}) \quad (7)$$

where E_{local} is local energy consumption which represents energy consumption within the clusters and $2\sum_{i=1}^{n}(n+1-i)E_t(d_i+d_{long})$ is long-haul energy consumption which represents energy consumption in the hop-lengths. In order to totally cover the sensor nodes between two clusters, d_i+d_{long} is used here as transmission distance. Using the cooperative communication scheme proposed in [1] energy consumption for the local part includes energy consumption on the Tx and Rx side, respectively. For n clusters scenario, local energy consumption E_{local} of the proposed scheme is expressed as

$$E_{local} = \sum_{i=1}^{n}\left[\sum_{i=1}^{M_t}N_iE_i^t + \sum_{j=1}^{M_r-1}N_sn_rE_j^r\right] \quad (8)$$

where E_i^t, E_j^r denotes the energy cost per bit for local transmission on Tx and Rx side, respectively, N_s is the total number of symbols, n_r is the number of bits after quantizing a symbol in Rx side. Also the total delay for the proposed scheme can be expressed by the relationship

$$T_{total} = \sum_{i=1}^{n}\left[T_s\left(\frac{\sum_{i=1}^{M_t}N_i}{b_m}+\sum_{i=1}^{M_t}\frac{N_i}{b_i^t}+\sum_{j=1}^{M_r-1}\frac{N_sn_r}{b_j^r}\right)\right] \quad (9)$$

where b_i^t and b_j^r are the constellation sizes used during the local transmission on the Tx and Rx side, respectively and b_m is the optimal constellation size for long-haul transmission. For a fixed transmission bandwidth B, we assume the symbol period is approximately $T_s \approx (1/B)$.

For minimization of the total energy consumption, the optimal transmission distance d_i is calculated next. First, through observation of the transmission distance in the proposed model, the constraint $\sum_{i=1}^{n}d_i = d - nd_{long}$ is obtained. This yields the relationship,

$$\Phi = E_{local} + 2\sum_{i=1}^{n}(n+1-i)E_t(d_i+d_{long}) + w(d-nd_{long}-\sum_{i=1}^{n}d_i). \quad (10)$$

Minimizing E_{total} with the constraint $\sum_{i=1}^{n}d_i = d-nd_{long}$ and taking partial derivatives with respect to d_i and equating to 0, establishes the equation

$$\frac{\partial\Phi}{\partial d_i} = 4E(n+1-i)(d_i+d_{long}) - w = 0 \quad (11)$$

where E is

$$\frac{1}{\mu}(1+a)\times\frac{2}{3}\times\left(\frac{\overline{P_b}}{\frac{4}{b_i}\left(1-\frac{1}{2^{\frac{b_i}{2}}}\right)}\right)^{-\frac{1}{M_tM_r}} \times\frac{2^{b_i}-1}{b_i}M_tN_0\times\frac{(4\pi)^2}{G_tG_r\lambda^2}M_lN_f$$

as a representation only for reduction the complexity of the writing and w is a Langrage's multiplier. Solving for d_i in (11) results in

$$d_i=\frac{w}{4E(n+1-i)}-d_{long} \qquad (12)$$

where w can be obtained by the use of $\sum_{i=1}^{n}d_i=d-nd_{long}$ so that (12) becomes

$$d_i=\frac{d}{\sum_{f=1}^{n}\left(\frac{1}{n+1-f}\right)(n+1-i)}-d_{long}. \qquad (13)$$

Ⅳ. Numerical Results

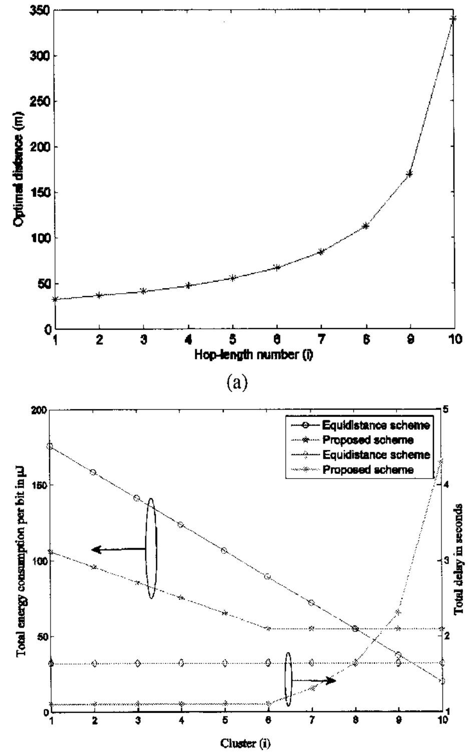
As an example of a numerical result, suppose that n=10, d=1000m, d_{long}=2m. In Fig. 2(a), the optimal transmission distance is obtained using equation (13) and plotted. As the distance to the destination increases, the hop-length also increases. The reduction of energy consumption can be obtained using this scheme instead of the equidistance scheme.

In this simulation, the following values have been assumed: 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 η=0.35, N_i=20 kb, n_r=10. For simplicity, Alamouti scheme has been adopted in this paper. Using the brute-force simulation method proposed in [5] 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 extra training overhead requirement. Regarding the equidistance scheme, cooperative MIMO is used in equidistance hop-length wireless sensor network without consideration of extra training overhead requirement. In Fig. 2 (b) the total energy consumption per bit and total time delay are 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

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



(a)

(b)

Fig. 2. (a) Optimal distance versus hop-length number. (b) Comparison of the total energy consumption per bit in the same cluster for different schemes and comparison of total delay in the same cluster for different schemes. (n=10, d=1000m, d_{long}=2m).

scheme, i.e. the proposed scheme has a better performance. After calculating energy consumption of each cluster and adding all the values together, the results show that the proposed scheme offers a total energy saving of about 29%. The delay performance comparison between the two schemes is also plotted in Fig. 2 (b). It is observed that within a certain range the delay of the proposed scheme is smaller and out that certain range the delay is larger since the long-haul transmission distance dominates the delay when the distance is long. After calculating the total delay of all the clusters, the results show that the proposed scheme offers a total delay reduction of about 1.2% when comparing with the equidistance scheme.

V. Conclusion

A multi-hop scheme based on 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 and the delay. The results demonstrate that the proposed scheme offers a total energy saving of around 29% even after taking into account with the extra training overhead requirement compared with the equidistance scheme. Concerning the delay, a certain range exists where the proposed scheme has a smaller delay. Combining the proposed scheme with monitoring equipments will provide a good performance in arbitrary deployment WSN system such as forest fire detection system.

References

〔1〕 S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor network," *IEEE J. Select. Areas Commun.*, Vol.22, No.6, pp. 1089-1098, Aug. 2004.

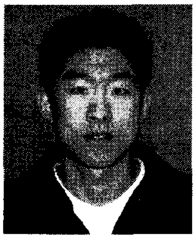
〔2〕 Y. Gai, L. Zhang, and X. Shan, "Energy efficiency of cooperative MIMO with data aggregation in wireless sensor networks," *Proc. 2007 IEEE Wireless Commun. Networking Conf. (WCNC2007)*, pp.791-796, Mar. 2007.

〔3〕 Z. Shelby, C. Pomalaze-raze, H. Karvonen, and J. Haapola, "Energy optimization in multihop wireless embedded and sensor networks." *Int. J. Wireless Inform. Networks*, Vol.12, No.1, pp. 11-21, Jan. 2005.

〔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.

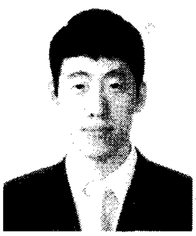
〔5〕 S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *IEEE Trans. Wireless Commun.*, Vol.4, No.5, pp.2349-2360, Sep. 2005.

팽 우 양 (Yuyang Peng) 준회원



2008년 7월 Dalian Polytechnic University 전자정보공학과 졸업
2009년 3월~현재 전북대학교 대학원 전기공학과 석사과정
<관심분야> WSN, MIMO 시스템

안 성 범 (Seong-Beom Ahn) 준회원



2010년 2월 전북대학교 전기공학과 졸업
2010년 3월~현재 전북대학교 대학원 전기공학과 석사과정
<관심분야> WSN, ZigBee 응용

반 재 경 (Jae-Kyung Pan) 종신회원

1980년 2월 연세대학교 전자공학과 졸업
1982년 2월 연세대학교 대학원 전자공학과 석사
1987년 8월 연세대학교 대학원 전자공학과 박사
1987년 5월~현재 전북대학교 전기공학과 교수
<관심분야> 광 FBG 응용, WSN, ZigBee 응용 등