An Energy Efficient Cooperative MIMO Routing Protocol for Cluster Based WSNs

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Abstract Energy efficiency and quality of service are foremost concerns in Wireless Sensor Networks (WSNs). Among the methods used to achieve these requirements there is Virtual multiple input multiple output (MIMO) technique, where sensor nodes cooperate with each other to form an antenna array. These multiple antennas can be used to improve the performance of the system (lifetime, data rate, bit error rate…) through spatial diversity or spatial multiplexing [1]. In this paper, we propose a distributed energy efficient cooperative MIMO routing protocol for cluster based WSNs (EECMIMO) which aims at reducing energy consumption in multi-hop WSNs. In EECMIMO, sensor nodes are organized into clusters and each cluster head utilizes a weighted link function to select some optimal cooperative nodes to forward or receive traffic from other neighboring clusters by utilizing a cooperative MIMO technique. Simulation results indicate that virtual MIMO based routing scheme achieves a significant reduction in energy consumption, compared to SISO one for larger distances.

Keywords Wireless sensor networks (WSNs) · Cooperative multiple input multiple output (MIMO) · Cooperative communication · Clustering algorithms

1 Introduction

The current progress in the field of wireless technology allows to develop small size sensors called nodes, communicating with each other via a radio link and are characterized by their limited resources (energy supply, limited processing, memory

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A. El Oualkadi et al. (eds.), *Proceedings of the Mediterranean Conference on Information & Communication Technologies 2015*, Lecture Notes in Electrical Engineering 381, DOI 10.1007/978-3-319-30298-0_24

storage…). Their flexibility of use makes them more utilized to form a wireless sensor network (WSN) without returning to a fixed infrastructure. Furthermore, these nodes typically deployed in inaccessible areas to control a definite phenomenon, ensure the transfer of data collected using a multi-hop routing to a BS, which is far from the monitored field.

Based on the above observations, for a WSN to accomplish its function without failure of the connection between the nodes, because of a depleting battery of one or more nodes, we need a data routing protocol which gives higher priority to the energy factor compared to other limitations, in order to provide stability of the network. At this point, many studies have been made; the most known ones are based on the MIMO technologies. However, the node cannot carry multiple antennas at the same time due to its limited physical size. Therefore, a new transmission technique called "Cooperative MIMO" has been proposed [2]. This technique is based on the cooperation principle where the existence of different nodes in the network is exploited to transmit the information from the source to a specific destination by virtually using the MIMO system [3]. The Cooperative MIMO allows to obtain the space-time diversity gain [4], the reduction of energy consumption, and the enhancement of the system capacity [5].

In this paper, we would like to investigate cooperative virtual MIMO for cluster based WSNs, with the objective of maximizing the network lifetime. We first introduce a novel approach to grouping sensors into clusters and electing cooperative MIMO links among clusters on such that intra-cluster messages are transmitted over short-range SISO links, while inter-cluster messages are transmitted over long range cooperative MIMO links [6]. Each cluster head selects one or multiple cluster members using a weighted link function to form a MIMO array together with itself. To transmit a message to a neighboring cluster, the cluster head first broadcasts the message to other members in the MIMO array. The MIMO array then negotiates the transmission scheme with the MIMO array in the neighboring cluster, encodes and sends the message over the cooperative MIMO link between them. Theoretical analyses show that, we can achieve high energy efficiency by adapting data rate and transmission made (SISO, SIMO, MISO, MIMO) [7]. Simulation results have proved that the proposed scheme can prolong the sensor network lifetime greatly, especially when the sink is far from the sensor area.

The remainder of the paper is organized as follows: In Sect. 2, the Energy Efficiency of MIMO Systems is described. Section 3 describes the proposed protocol. Section 4 describes the simulation and results. Finally, Sect. 5 concludes the paper and provides directions for future work.

2 Energy Efficiency of MIMO Systems

2.1 System Model

In our protocol we use the system model proposed in [1], the total average energy consumption of MIMO transmission in WSNs includes two parts: the power consumption of all power amplifiers P_{PA} and the power consumption of other circuit blocks P_C. The transmitted power is given by

$$P_{out} = \overline{E_b} R_b . \frac{(4\pi)^2 d_{i,j}^{k_{i,j}}}{G_t G_r \lambda^2} M_l N_f . \tag{1}$$

where $\bar{E}_b$ is the required energy per bit at the receiver for a given BER requirement, R_b is the bit rate, $d_{i,j}$ is distance between nodes i and j, $k_{i,j}$ is the path loss factor from node i to j, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin and N_f is the receiver noise figure given by $N_f = N_r/N_0$ where N_0 is the single-sided thermal noise power spectral density and Nr is the power spectral density of the total effective noise at the receiver input.

The power consumption of the power amplifiers is dependent on the transmitted power P_{out} and can be approximated as

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

where, $\alpha = \left(\frac{\xi}{\eta} - 1\right)$ with η the drain efficiency of the RF power amplifier and ξ the peak-to-average ratio. The power consumption of the circuit components is given by

$$P_c = M_t \left(P_{DAC} + P_{Mix} + P_{filt} + P_{syn}\right) + M_r \left(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} + P_{syn}\right). \tag{3}$$

$$Pc = M_t P_{ct} + M_r P_{cr} \tag{4}$$

where P_{DAC}, P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, $P_{syn,}$ M_t and M_r are the power consumption values for the DAC, the mixer, the Low Noise Amplifier (LNA), the Intermediate Frequency Amplifier (IFA), the active filters at the transmitter side, the active filters at the receiver side, the ADC, the frequency synthesizer, transmitters number and receiver s number respectively. The total energy consumption per bit according to [1] is given by

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

2.2 Variable-Rate Systems

Using MQAM modulation scheme, the constellation size b can be defined as $b = \log_2 M$ Further, we can define constellation size in terms of number of bits L, Bandwidth B, and duration radio transceiver is on T_{on}, and data rate R_b (bits/second) [1].

$$b = \frac{L}{BT_{on}} = \frac{R_b}{B} \tag{6}$$

The total energy consumption for Variable-rate Systems per bit according to [1] is given by Eq. (7), where $\overline{P_b}$ is the average bit error rate.

$$E_{bt} = \frac{2}{3}(1+\alpha)\left(\frac{\overline{P_b}}{4}\right)^{\frac{-1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t}+1}} M_t N_0 \frac{(4\pi)^2 d_{i,j}^{k_{i,j}}}{G_r G_t \lambda^2} M_l N_f + \frac{P_C}{Bb}. \tag{7}$$

Based on the Eq. (7) the optimal constellation sizes for different transmission distances are listed in Table 1.

3 The Proposed Protocol

The Clustering algorithm consists of five steps:

Step 1: **1-hop neighbor discovery**
Each node broadcasts a message including its residual energy (RE) to its 1-hop neighbors once receiving a RE message from a neighbor, a node adds an entry to its 1-hop neighbor list including the neighbor's residual energy and the estimated distance.

Step 2: **1-hop weight discovery**
The weight of each node is calculated and broadcast to 1-hop neighbor. Also as part of optimizing the energy resources of a WSN, it will be better to affect the CH role to a node with high residual energy and small average intra-cluster distance. In this regard, the weight for cluster head selection at each node i can be defined by

$$\mathrm{weight}(i) = \frac{E_i}{\frac{\sum_{j=1}^{N(i)} d_{i,j}}{N(i)}}. \tag{8}$$

Table 1 Optimized constellation size

Distance (m)	b_{SISO}	b_{MISO}	b_{MIMO}
10	5	8	10
20	4	6	8
70	2	4	5
100	2	3	5

where, N(i) is the 1-hop neighbors number of node i, $d_{i,j}$ denotes the distance between nodes i and j, and E_i is the residual energy of node i.

Step 3: **cluster formation**
In this step, sensor nodes with the high weight in their 1-hop neighborhoods elect themselves as cluster heads. The cluster head election procedure is executed on each node as every node is aware of the weights of its 1-hop neighbors. Isolated nodes declare them self as cluster heads.

Step 4: **cluster neighbor discovery**
In this step, all cluster members send a Cluster Forward (CF) message to their cluster heads, in which the updated 1-hop neighbor list is included. After receiving all the CF messages from its cluster members, a cluster head knows all the neighboring clusters.

Step 5: **cooperative MIMO link selection**
In this step, each cluster head negotiates with the cluster heads of neighboring clusters to select the optimal cooperative MIMO links, as more than one such links may exist between two neighboring clusters. In general, on one hand, the cooperative MIMO link with high energy efficiency should be selected to save transmission energy; on the other hand, a link with low residual energy should not be selected even if it has high energy efficiency to avoid exhausting the link. We define Ef (l) as the energy efficiency of a cooperative MIMO link l, which is determined by Eq. (10). We use Ei (l) to represent the residual energy of link l, which is set to the least residual energy of all nodes involved. To balance the effect of both factors, an empirical influence factor β ranging from 0 to 1 is introduced, which can be adjusted according to the type of application. Thus the weight of a cooperative MIMO link is defined as

$$\mathrm{weight}(l) = \beta\,\mathrm{Ef}(l) + (1-\beta)\mathrm{Ei}(l). \tag{9}$$

$$\mathrm{Ef}(l) = \frac{1}{E_{bt}}. \tag{10}$$

4 Simulation Results

4.1 Simulation Environment

To illustrate the value added by our proposed EECMIMO algorithm on network behavior, we evaluated the EECMIMO performances in terms of energy consumption per bit, stability, lifetime and amount of data sent to the BS in three different scenarios (SISO, MISO and MIMO). The stability period and the lifetime are defined respectively according to the following metrics: FND (first node dies) and HND (half node dies). Simulation parameters used for these evaluations are

Table 2 Simulation parameters

Parameter	Value
σ^2	N0/2 = −174dBm/Hz
k	2–5
Round number	5000
Nodes number (N)	100
Network area	100 m × 100 m
Packet length (N_B)	4000 bit
G_tG_r	5 dBi
fc	2.5 GHz
B	10 kHz
N_f	10 dB
M_l	40 dB
β	0.5
η	0.35
$\overline{P_b}$	10–3
P_{ct}	0.0844263 W
P_{cr}	0.112497827 W
N_0	−171 dBm/Hz
λ	0.12 m
ξ	$3.\frac{\sqrt{M}-1}{\sqrt{M}+1}$, $M = 2^b$

listed in Table 2. Where, the base station is located at the center of the network and in order to illustrate the effect of distance on energy consumption the base station moves in the horizontal direction.

4.2 Performance Evaluation Discussion

Firstly, we compare the energy consumption of EECMIMO using different multi-hop transmission MIMO, MISO and SISO with variable data rate according to Table 1. Figure 1 shows the graphs of energy consumption per bit with respect to the distance from the base station. Initially, the base station is placed at the center of the network. Then, the base station is moved away from the center in the horizontal direction. As shown in Fig. 1, the energy consumption of SISO has more advantage in energy saving when the transmission distance is less than 10 m, but the MIMO has more advantage in energy-saving when the distance is more than 10 m, this is because, for small distances circuit block power consumption dominates and for large distances amplifiers power dominate Further, SISO is still better than MISO until the traversed distance equals 23 m, for distance exceeding this value, the

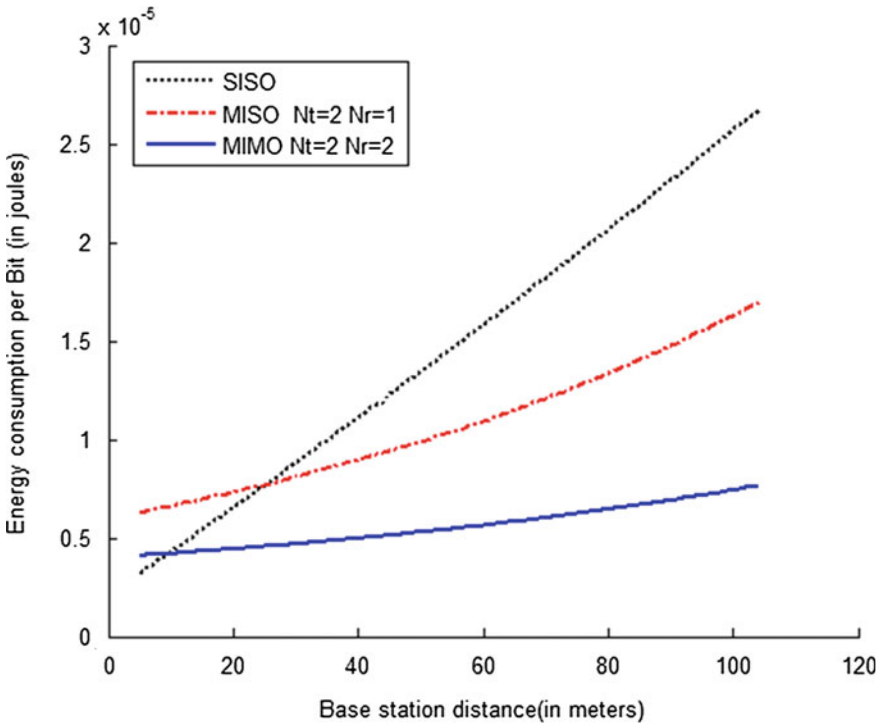

Fig. 1 Energy consumption per bit for MIMO, MISO, SISO networks according to distance

standard deviation of SISO is also higher as compared to the other techniques. MIMO performs better than MISO in all the cases. Then the EECMIMO with MIMO technique and adapted bit rate is more energy efficient routing for large communication distance.

Secondly, we consider a fixed base station initially placed at position (50, 50) and we evaluate our proposed algorithm in terms of stability, lifetime and amount of data sent to the BS. Figure 2 shows the simulation results. From Fig. 2, we can see that 2 × 2 MIMO technique exceeds the other techniques in terms of stability, lifetime and amount of data sent to the BS. Furthermore, the 2 × 2 MIMO technique has a stability period (FND) considerably larger compared to other algorithms which allows the network to operate without fault for a very long time. Table 3 summarizes the simulation results of this scenario. From the simulation results, 2 × 2 MIMO is considered as an energy efficient routing technique. In fact, the stability period is increased approximately by 47, 14 and 12 % while the network lifetime is increased nearly by 11, 12 and 10 % compared with those obtained by SISO, MISO and 3 × 3 MIMO techniques respectively.

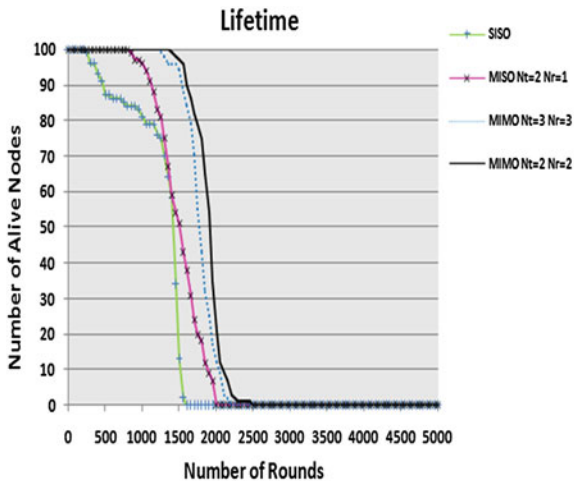

Fig. 2 Distribution of alive nodes according to the number of rounds for each MIMO technique

Table 3 Simulation Results

Protocol	FND	HND	Paquets number
SISO	282	1550	6.5×10^7
MISO 2 × 1	931	1410	3.8×10^8
MIMO 3 × 3	1070	1591	4×10^8
MIMO 2 × 2	1336	1698	4.2×10^8

5 Conclusion

In this paper, an Energy Efficient Cooperative MIMO routing protocol for cluster based WSNs, called EECMIMO in which, sensor nodes are organized into clusters such that intra-cluster messages are transmitted over short-range SISO links, while inter cluster messages are transmitted over long-range energy-efficient cooperative MIMO links. To reduce energy consumption and prolong the network lifetime, an adaptive cooperative nodes selection strategy is also designed. After that, we investigate the use of multiple transmitters and multiple receivers in virtual MIMO, considering the case of variable data rate. Further, we investigate the impact of distance on the choice of MIMO, MISO and SISO, We demonstrate that in large range applications, by optimizing the constellation size MIMO systems may outperform MISO and SISO systems. Also The MIMO 2 × 2 technique is more suitable for any application WSN since it exceeds the other techniques tested in terms of stability, lifetime and the number of packets sent to the BS. EECMIMO is designed for stationary WSNs, in future works, our algorithm can be extended to handle the mobile wireless sensor networks under the platform NS2.

References

1. Cui, S., Goldsmith, A.J., Bahai, A.: Energy efficiency of MIMO and cooperative MIMO techniques in sensor networks. IEEE J. Sel. Areas Comm. **22**, 1089–1098 (2004)
2. Nguyen T., Berder O., Sentieys O.: Cooperative MIMO schemes optimal selection for wireless sensor networks. In: IEEE 65th Vehicular Technology Conference, pp. 85–89 (2007)
3. Sendonaris, A., Erkip, E., Aazhang, B.: User cooperation diversity-part I: system description. IEEE Trans. Commun. **51**, 1927–1938 (2003)
4. Winters, J.: The diversity gain of transmit diversity in wireless systems with rayleigh fading. IEEE Trans. Veh. Technol. **47**, 119–123 (1998)
5. Belmega E.V., Lasaulce S., Debbah M.: A Survey on Energy-Efficient Communications. International Symposium on Personal, Indoor and Mobile Radio Communications Workshops, Turkey, pp. 289–294 (2010)
6. Dawei, G., Miao, Z., Yuanyuan, Y.: A multi-channel cooperative MIMO MAC protocol for clustered wireless sensor networks. J. Parallel Distrib. Comput. **74**, 3098–3114 (2014)
7. Sajid, H., Anwarul, A., Jong, H.P.: Energy efficient virtual MIMO communication for wireless sensor networks. J. Telecommunication Systems **42**, 139–149 (2009)