Abstract

Energy efficiency in data collection and transmission is always a crucial factor in wireless sensor network (WSN). Unreliability in data transmission is very common for long range communications in WSNs. Factors like fading of channel, interference and radio irregularity further pose a big challenge on the design of energy efficient data transmission protocols in WSNs. Cooperative MIMO (Multiple Input Multiple Output) communication may help to solve these problems in long range transmission. In this paper we propose a mobility aided cooperative MIMO based communication model where a few mobile sensors using Alamouti diversity schemes take part in cooperative communication. A mobile sensor can move to a specific location of the field, gather the sensed data from the nearby sensors and finally transmit cooperatively to the sink or other cooperative sensor node. We take two different types of sensors, namely Listeners and Supervisors, which are deployed together in the field, each having different kinds of responsibilities. Listeners only sense the environment and communicate the sensed data to the Supervisors. Supervisors (usually do not sense) are capable of moving and they have higher capacity in terms of battery power (also rechargeable) and communication range than the Listeners. This model of communication helps in achieving both uniform energy expenditures by the nodes and a good average lifetime for the network. By choosing some costly re-chargeable supervisors, we can avoid the problem of energy expenditure in cluster head selection as well as dynamic cooperative node selection of any Cooperative MIMO based LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol. Simulation results demonstrate the working strategy of the proposed model and show much better result in terms of network lifetime than an existing energy efficient LEACH based cooperative MIMO model.

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Keywords: WSNs; energy efficiency; cooperative MIMO; supervisor; listener; pair-wise deployment; mobility;
1. Introduction

In wireless sensor networks (WSNs), low battery power is always a critical problem. Apart from that, long range communication in WSN faces fading and also consumes a lot of energy.

In this paper, our main goal is to develop a MIMO (Multiple Input Multiple Output) based communication model for WSNs where sensors die out evenly and slowly by consuming minimum transmission energy. Here, two different types of sensors namely, listener and supervisor are deployed with two different deployment strategies (Fig 1). Listeners mainly do sensing and a pair of mobile and re-chargeable supervisors represents a cluster of the listener sensors each in long range routing. Pairing of supervisors is done in order to share the workload in a cluster and also to easily adjust the cooperative distance between two cooperative supervisors following 2x1 or 2x2 STBC (Space Time Block codes) MIMO [Paulraj, Nabar and Gore, 2003]. Rechargeable supervisors reduce the workload on listeners. The model involves mobility aided cooperative MIMO communication so we name it as MACO MIMO. This model can be used for mission critical purposes such as in battlefields; nuclear plants etc. where some regions are very critical to reach but some points can be safely reached. We can deploy listener sensors in the critical regions once in their lifetime whereas supervisor sensors can be brought by their mobility to a nearest safe place for recharging purpose.

In any LEACH (Low-Energy Adaptive Clustering Hierarchy) based cooperative MIMO model [Tang, Liang, Yue and Li, 2011], energy is consumed due to cluster formation and cluster head selection, selection of cooperative nodes, data transmission from non cluster head nodes to cluster head, data aggregation, data transmission (broadcast) from cluster head to cooperative nodes and communication from cluster head and cooperative nodes to sink. Our model overpowers an existing LEACH based cooperative MIMO model [Tang, Liang, Yue and Li, 2011] by eliminating the above mentioned causes by introducing mobility in supervisors, a centralized selection of supervisors and by making supervisors act both as a cluster head and a cooperative node. This model is based on a centralized protocol to be discussed in a subsequent section and the sink is responsible for maximum of the computations.

Fig. 1. Deployment Strategies (Strategy 1: sink at center, Strategy 2: sink at corner of the field)

The rest of the paper is organized as follows. Related work in this direction is given in section 2. Section 3 describes the model in detailed. Energy model to analyze the energy efficiency of the model is presented in section 4. Performance evaluation of the proposed model is presented in section 5. Finally, section 6 concludes the paper with some future perspectives.

2. Related Work

There are numerous investigations have been done for reducing transmit power or condensing data for transmission or the combination of the two in the topic of energy saving in WSN. In [Tang, Liang, Yue and Li, 2011] an Energy Efficient LEACH MIMO is proposed where network is partitioned into sectors with equal angle for avoiding the distribution non-uniformity of cluster heads. An energy efficient WSN coverage model with workload sharing by deploying two different types of sensors in order to enhance the network lifetime is proposed in [Medhi and Sarma, 2011]. In [Islam and Kim, 2008] cooperative sensors are selected based on the channel condition. A scheme is discussed in [Gao, Zhang, Gai and Shan, 2007], where a two-layer hierarchy is formed by clustering, and the cluster heads perform local data aggregation, balance communication loads and
transmit data back to the base station using cooperative MIMO techniques. An approach for long haul transmission is described in [Gai, Zhang and Shan, 2007] presents cooperative MIMO and data aggregation based on the model given in [Cui, Goldsmith and Bahai, 2004]. We compare our model with the Energy Efficient LEACH MIMO model mentioned in [Tang, Liang, Yue and Li, 2011].

3. Mobility Aided Cooperative MIMO (MACO MIMO)

There are some assumptions and pre-conditions like, both kinds of sensors are GPS (Global Positioning System) enabled, mobile supervisors do not follow random way-point mobility and sink knows the location of all the deployed sensors. Sink calculates the dynamic cluster size and assigns a pair of supervisors to each of the clusters. Figures 2(a), 2(b), 3(a) and 3(b) explains the steps of the proposed protocol.

Fig. 2. (a) Initial deployment (red circles are mobile supervisor sensor and brown squares are static listener sensors). (b) A pair of supervisors takes charge of one cluster and get located as queried by sink. Remaining supervisors go to sleep mode.

Fig. 3. (a) Gathering of sensed data. (b) Multi-hop communication using 2x1 and 2x2 STBC MIMO in deployment strategy 2.

1. **Initial communication between sink and supervisors**: In this phase (Fig 2(a)), sink sends a query to all the supervisors individually mentioning the supervisor’s ID, its target location and the IDs of the listeners it should take charge of in the dynamic cluster.

2. **Mobility**: After receiving the initial query of the sink, supervisors move to their target locations as assigned (Fig 2(b)). After reaching the target location, supervisors send an ACK message of the format \(< Sid, Ack >\) to the sink to inform that they have reached their position.

3. **Internal communication**: Internal communication between the listeners and the supervisors take place in order to fix up a cluster and this information gets recorded by the sink (Supervisors communicate to the sink prior to a session begins as mentioned above in step 1 and 2). A supervisor after reaching its destination, broadcast a message containing its id and selected listener’s ids \(< Lid(1 \text{ to } n), Sid >\). A listener, among several received messages find out the one containing its own id. It notes the supervisor’s id for further data communication and responds to the queries of that supervisor only. A listener waits for a signal for time \(t_{wait}\) and goes to sleep. Then after a time \(t_{sleep}\), a listener becomes active to hear for any signal again. Listener stops hearing further broadcast messages as soon as it receives the message with its id.

4. **Data gathering phase**: Each listener node in a dynamic cluster uses different time slot to transmit their raw sensor data to its assigned supervisor node with data rate \(R_b\) (same data rate for the previous two steps also) for compression. Only one between the pair of supervisors placed in a cluster is responsible for gathering data (Fig 3(a)). This selection is done alternatively for each round.

5. **Compressing phase**: As the data sensed by listener sensors in a cluster is correlated, the data gathered at the supervisor is compressed in this phase. The extent of correlation in the data from different sources is
defined by the distance between them which is to be depicted later. Supervisor is located in such a way that it comes in the communication range of all the listeners in the cluster. The supervisor which gathers data is responsible for compression.

6. Cooperative communication phase: Supervisor node after compressing data transmits it to the other supervisor in that cluster. Together they adjust the distance between them to cooperatively send the data to the sink directly (1st deployment strategy) or cooperatively communicate to the intermediate supervisors on the way to the sink (multi-hop communication in the 2nd deployment strategy) (Fig 3(b)). This model involves 2x1 and 2x2 cooperative STBC MIMO strategy [Alamouti et al., 1998] for long range communication for their efficiency in case of energy consumption of transmitter and receiver [Zuo, Gao and Fei, 2010].

4. Energy model in MACO MIMO

As shown in Fig 1, in the randomly deployed heterogeneous sensor field, there are ‘m’ number of supervisor sensors and ‘n’ number of listener sensors. We assume that each cluster consists of \((2n/m)\) listener sensor nodes (i.e. the cluster size is \(2n/m\)), and that the amount of data sensed by each listener node is \(D\) bits within a definite sensing period. \(D\) represents the size of the transmitted data by a listener. We assume that Alamouti schemes [Alamouti et al., 1998] are used to achieve diversity in the MIMO system. In this model, a square-law path loss with additive white Gauss noise (AWGN) is assumed for local communication, while for long range communication, a flat Rayleigh-fading channel with square law path loss is assumed. We take orthogonal space time block coding (STBC) in long range cooperative communication and the channel is assumed constant during the transmission of each orthogonal STBC codeword. In this model, we consider BPSK modulation scheme and amplify-and-forward (AF) cooperative protocol. In a flat Rayleigh-fading channel, i.e., the channel gain between each transmitter antenna and each receiver antenna is a scalar fading matrix [Paulraj, Nabar and Gore, 2003]. The fading is assumed constant during the transmission of each Alamouti codeword [Alamouti et al., 1998]. The related circuit and system parameters are defined in Table I.

In the energy consumption model, a general communication model which is the same as in [Cui, Goldsmith and Bahai, 2004], [Gai, Zhang and Shan, 2007] is used. The energy consumption per bit for the transmitter and the receiver can be formulated respectively as, \(E_{bt} = (P_{PA} + P_{ct}) / R_b\), \(E_{br} = P_{cr} / R_b\) where, \(P_{PA} = (1+\alpha)P_{out}\). We use the notation \(L(.)\) to define the size (length) of a message.

4.1. Energy calculation of the proposed protocol stepwise (Explained for deployment strategy 1)

4.1.1. Step1  (In receiver circuitry of supervisor nodes in order to receive sink’s query)

\[ E_1 = (m/2).Q_{ini}.E_{br} \]  \hspace{1cm} (1)

Where, \(Q_{ini} = L(S_{id}) + L(location) + (2n/m).L(L_{id})\)  \hspace{1cm} (2)

\(Q_{ini}\) : initial query, location: target location (small square region) as determined by sink, \(L_{id}\): listeners’ id.

4.1.2. Step2  (Energy consumed by supervisor sensor due to its mobility)

\[ E_2 = m.e_m.d_m \]  \hspace{1cm} (3)

Where, \(e_m\) : unit energy per unit distance (Joules/meter). \(d_m\) : distance moved by the supervisor sensors.
4.1.3. Step3  (communication between supervisors and listeners in the cluster fixing step)

\[ E_{3a} = \frac{m}{2}.E_{bt}((2n/m).L(L_{id}) + L(S_{id})). \]  (supervisor broadcasts \( L_{id}(1 \text{ to } n), S_{id} \))  \\

\[ E_{3b} = n.E_{br}((2n/m).L(L_{id}) + L(S_{id})). \]  (listener receiving their id in the n-th packet from supervisors)  \\

\[ E_3 = E_{3a} + E_{3b} = \frac{m}{2}.E_{bt}((2n/m).L(L_{id}) + L(S_{id})) + n.E_{br}((2n/m).L(L_{id}) + L(S_{id})) \]  \\

4.1.4. Step4  (Supervisors gather data from listeners)

\[ E_4 = n.D.E_{bt} + n.D.E_{br} \]  (Data gathering: supervisors Tx circuit and listeners Rx circuit)  \\

Where,

\[ E_{bt} = \frac{P_{PA-local} + P_e}{R_b} \]  \\

From the link budget relationship [Cui, Goldsmith and Bahai, 2004], [Proakis et al., 2000] when the channel only experiences a square-law path loss, we have

\[ P_{PA-local} = (1 + \alpha) \times E_{b-BER} \times R_t \times (4\pi d_{local})^2 \times M_r N_f / G_t G_r \lambda^2 \]  (power consumption of power amplifier)  \\

Where, \( R_t = \frac{b_{local} \cdot B}{G_r} \) (The transmission data rate), \( b_{local} \) (constellation size for local transmission) = 4 (16-QAM for local transmission), \( B \) the modulation bandwidth. \( \alpha = (\xi / \eta) - 1 \) with \( \xi \) the peak to average ratio (PAR) and \( \eta \) the drain efficiency of the RF power amplifier. \( E_{b-BER} \) is the energy per bit required for a given BER requirement. We assume that dynamic clusters are such that each listener can communicate to the supervisor in charge (which is within their communication range) and transmission distance of local communications \( d_{local} \) has the maximum value of the communication range of the listeners. \( N_f \) is the receiver noise figure defined as \( N_f = N_r / N_0 \) with \( N_r \) the power spectral density (PSD) of the total effective noise at the receiver input and \( N_0 \) the single sided thermal noise PSD at room temperature.

The PAR \( \xi \) depends on the modulation scheme and the associated constellation size. Multiquadrature amplitude modulation (MQAM) is used for local communications, thus we have

\[ \xi = 3.\left(\frac{2^{b_{local}/2} - 1}{2^{b_{local}/2} + 1}\right) \]  \\

In order to get \( P_{PA-local} \), \( E_{b-BER} \) required for a given BER, \( E_{b-BER} \) needs to be determined. The average BER of a SISO with MQAM when \( b_{local} = 4 \) is given by [Proakis et al., 2000],

\[ \varepsilon_{b-BER} \approx \frac{3}{4} \left( \frac{Q \left( \frac{4 E_{b-BER}}{5 N_0} \right)}{Q \left( \frac{3}{4} \right)} \right) \]  \\

Where \( Q[ \cdot ] \) is the Q-function, defined as

\[ Q(x) = \left( \frac{1}{\sqrt{2\pi}} \right) \int_{x}^{\infty} e^{-y^2/2} dy, \]

We then invert to get the required value of \( E_{b-BER} \) that yields the desired \( \varepsilon_{b-BER} \).

4.1.5. Step5  (Data compression to obtain non-redundant data)

\[ E_5 = (m/2).n.D.e_c \]  (Energy required for data compression)
Where $e_c$ denotes the energy cost per bit for data compression and $n.D = \text{total gathered data.}
\]

In this model, we take a sparse sensor network and assume that sensors must be placed apart by a distance of $d \geq 2r$, where, $r$ is the sensing radius for the listener sensor. If the sensor network is dense then we follow equation 12 to determine the compression energy, otherwise, it is not required.

4.1.6. Step6 (Long haul communication using cooperative MIMO along with intra-cluster communication)

Energy is consumed due to intra-cluster supervisor communication and inter-supervisor as well as communication between supervisors and sink using 2x1 and 2x2 Alamouti code MIMO [Alamouti et al., 1998] scheme. In the intra-cluster communication, a data gathering supervisors send a copy of the data to another cooperative supervisor present in the cluster.

\[
E_{6a} = n.D.(m/2).E_{bt} + n.D.(m/2).E_{br} \quad \text{(Intra-cluster, m/2 nodes send data to other m/2 nodes)} \quad (13)
\]
\[
E_{6b} = m.P_{PA-long}.(n.D/R_{long}) \quad \text{(Cooperative communication to the sink)} \quad (14)
\]

Where, $P_{PA-long}$ is the power consumption of the power amplifiers at the transmitting node and $R_{long}$ (transmission bit rate) = $R_S.b_{long}.B$, $R_S$ is the spatial rate of encoding scheme and $b_{long}$ (constellation size for long range transmission) = 2. We consider 4-QAM for long range communication. Here, we use a rate 1/2 orthogonal STBC, so we take $R_S=1/2$.

\[
E_6 = E_{6a} + E_{6b} = n.D.(m/2).E_{bt} + n.D.(m/2).E_{br} + m.P_{PA-long}.(n.D/R_{long}) \quad \text{(Overall in step 6)} \quad (15)
\]

The long range transmission distance, denoted as $d_{long}$, is approximately the same for each transmitting node (Since sink is placed at center as per deployment strategy 1). According to [Cui, Goldsmith and Bahai, 2004], [Proakis et al., 2000], $P_{PA-long}$ at the transmitting side due to square path loss is given by,

\[
P_{PA-long} = (1 + \alpha) \times E_{h-BER-long} \times R_{long} \times (4\pi d_{long})^2 \times M_l N_f / G_t G_r \lambda^2 \quad (16)
\]

Where, $E_{h-BER-long}$ is the average energy per bit required for a given BER requirement, $\lambda$ 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. In order to get $P_{PA-long}$, the average energy per bit required $E_{h-BER-long}$ for a given BER, $e_{h-BER-long}$ needs to be determined. The average BER of a MIMO with MQAM when $b_{long} = 2$ is given by [Paulraj, Nabar and Gore, 2003], [Proakis et al., 2000],

\[
e_{h-BER-long} = \mu_h[Q(\sqrt{2\gamma_{long}})] = \int_{0}^{\infty} Q(\sqrt{2\gamma_{long}}) f(\gamma_{long}) d\gamma_{long} \quad (17)
\]

Where, $\mu_h[ \cdot ]$ denotes the expectation with channel matrix $H$. $\gamma_{long}$ is the instantaneous received SNR for cooperative MIMO system which is given by,

\[
\gamma_{long} = E_{h-BER-long} \|H\|^2_F / mN_0 \quad (18)
\]

According to the Chernoff bound [Paulraj, Nabar and Gore, 2003] (for high SNR),

\[
e_{h-BER-long} \leq \left( \frac{E_{h-BER-long}}{mN_0} \right)^m \quad (19)
\]

We can derive an upper bound for the required energy per bit,
\[ E_{\text{long}} = \frac{t \cdot N_0}{e^{t/\log_{10} E_{\text{long}}}} \]  

(20)

Where, \( t \) denotes the number of cooperative nodes. \( t = 1 \) or \( 2 \) (depending upon Alamouti coding scheme).

Thus, overall energy consumed by the six steps of the new protocol can be obtained from equations (1), (3), (6), (7), (12) and (15). Energy consumed overall, consumed by supervisors only and by listeners only can be expressed as follows:

\[ E_{\text{total}} = E_1 + E_2 + E_3 + E_4 + E_5 + E_6 \]  

(21)

\[ E_{\text{supervisor}} = E_1 + E_2 + E_{3a} + n.D.E_{br} + E_5 + E_6 \]  

(22)

\[ E_{\text{listener}} = E_{3b} + n.D.E_{bt} \]  

(23)

Equation (21) gives the overall energy consumption for one round of operation. But, we have assumed the supervisors as rechargeable so, mainly we take into consideration the energy consumption in the listener sensors only. Long range communication up to a distance 1000m leads to a negligible consumption of transmission energy at supervisor’s end and works well up to a distance 10,000m. Energy consumption increases in a lower rate with the increasing size of cluster (Fig 5(b)). Energy is consumed in the listener’s end in step 3 and 4 only.

5. Simulation results and analysis

The simulation and performance evaluation of MACO MIMO has been carried out using MATLAB for both the deployment strategies as mentioned earlier. For simulation purpose, we take a square sensor field of size 150 x 150, 120 listener sensors and 24 supervisor sensors. Sensing range, \( r \) of listeners is approximated as 10 m. Communication range of listeners has been taken as \( R_L = 3r \) (maximum) and that of supervisor is \( R_S = 6r \). A listener sensor is assumed to have an initial energy of 2kJ (approx.) and that of a supervisor is 18kJ (approx.). Ratio of initial energies of a listener and a supervisor has been taken as 1:9 which has been derived from the results of equations (22), (23) for a specific number of rounds. This ratio has been taken in order to balance the network lifetime between listeners and supervisors, so that neither of the two types dies early.

The system parameters as given in [Zuo, Gao and Fei, 2010], [Cui, Goldsmith and Bahai, 2004], [Johansson, Bjornemo and Ahlen, 2007], [Vidhya and Dananjayan, 2010] are given in the following table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of RF power amplifier (( \eta ))</td>
<td>0.4706</td>
<td>Link margin, ( M_i )</td>
<td>40 dB</td>
</tr>
<tr>
<td>Circuit power of transmitter (( P_{o} ))</td>
<td>98.2 mW</td>
<td>Receiver noise figure, ( N_i )</td>
<td>10 dB</td>
</tr>
<tr>
<td>Circuit power of receiver(( P_{r} ))</td>
<td>112.6 mW</td>
<td>The single-sided thermal noise PSD, ( N_0 )</td>
<td>-171 dBm/Hz</td>
</tr>
<tr>
<td>Bandwidth (( B ))</td>
<td>10 kHz</td>
<td>Unit energy for compression, ( e_c )</td>
<td>5 nJ/bit/sig</td>
</tr>
<tr>
<td>Carrier wave-length (( \lambda ))</td>
<td>0.12 m</td>
<td>Constellation size (local communication) (( b_{\text{local}} ))</td>
<td>4 (16 QAM)</td>
</tr>
<tr>
<td>Transmittable data (( D ))</td>
<td>2000 bits</td>
<td>Constellation size (long communication), ( b_{\text{long}} )</td>
<td>2 (4 QAM)</td>
</tr>
<tr>
<td>Product of antenna gains, ( G_sG_r )</td>
<td>5 dBi</td>
<td>Unit energy spent due to mobility, ( e_m )</td>
<td>1 J/m</td>
</tr>
<tr>
<td>BER performance, ( b_{\text{BER}} )</td>
<td>( 10^{-3} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4. (a) Total energy consumption of both type of sensors in terms of rounds, (b) Average energy consumption per node of both types of sensors in terms of rounds.

Fig. 5. (a) Average energy consumption per supervisor node with distance, (b) Average energy consumption per listener node in terms of cluster size.

From Fig 4(a) and 4(b), we can observe the energy dissipated against the number of rounds. From this result, we see that a supervisor node should be recharged before 7000 rounds get over. Fig 5(a) shows the energy consumed with the increasing communication distance and Fig 5(b) depicts the average energy consumption with the increasing cluster size. Each simulation has been run for 10,000 rounds and values are obtained after averaging 100 simulation attempts. In our model, average life time of the network is high because of low energy consumption in listeners and also a much greater number of nodes stay alive even after several thousands of rounds of communication. Above simulation has been done in order to represent an ideal scenario for our model. A comparative simulation has also been done whose results are tabulated below.

Table 2. A comparative study between the existing model [Tang, Liang, Yue and Li, 2011] and the proposed one (Results obtained after aggregating the results of 100 comparative simulation attempts)

<table>
<thead>
<tr>
<th>Measures</th>
<th>Existing model</th>
<th>Proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors’ death rate</td>
<td>Not all the nodes evenly die out</td>
<td>Almost all the nodes die out evenly</td>
</tr>
<tr>
<td>Network lifetime</td>
<td>Runs only for 1400 rounds</td>
<td>Runs for almost 4000 rounds</td>
</tr>
</tbody>
</table>
All the parameters and initial energies are set same for both the models as per given in [Tang, Liang, Yue and Li, 2011] and simulated again. The comparative simulation results as given in Table 2 show that the proposed model is better than the existing in terms of network lifetime and the rate with which sensors die. From the simulation results, it is evident that if rechargeable mobile supervisor sensors are used then a really good mutual balancing between network life-time and wishful monitoring of a flexible network is possible.

6. Conclusion

Adding mobility in cooperative MIMO communication is the main investigation of this work. Workload division is another part where effort has been given. Our proposed model which includes workload sharing, mobility, flexibility along with cooperative communication shows a new way of getting an energy efficient cooperative MIMO communication model for a long lasting wireless sensor network. Estimations of energy consumptions of the protocol under two proposed deployment scenarios are found to be very satisfactory and simulation results validate our claims. Future work includes the optimization of the energy consumption model further by deploying an on demand coverage and a more dynamic communication model.

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