Joint rate and cooperative MIMO scheme optimization for uniform energy distribution in Wireless Sensor Networks

Irfan Ahmed a,*, Mugen Peng a, Wenbo Wang a, Syed Ismail Shah b

a Wireless Signal Processing and Network Lab, Beijing University of Posts and Telecommunications, 10-Xitucheng Road, Beijing 100876, China
b MIMO Research Lab, Iqra University, Islamabad, Pakistan

1. Introduction

On wireless fading channel transmission, multi-antenna techniques (MIMO) have shown the potential of increased channel capacity [1]. Under the same Signal to Noise Ratio (SNR), MIMO systems can be far more reliable than Single-Input–Single-Output (SISO) systems and they need less transmission energy for the same Bit Error Rate (BER) requirement. The MIMO energy-efficiency transmission scheme is particularly useful for Wireless Sensor Network (WSN) where each wireless node has to operate without battery replacement for a long time and energy consumption is the most important constraint. However, the direct application of multi-antenna technique to WSN is impractical due to the limited physical size of sensor nodes which can typically support a single antenna. Fortunately some individual sensor nodes can cooperate for the transmission and the reception in order to set up a cooperative-MIMO scheme. Power minimization strategies in different layers of the protocol stack of cooperative network have motivated intensive research interests in recent years. In particular, energy-efficient design in various aspects of communication systems, such as modulation [2], coding [3], and routing [4].

Cooperative MIMO (C-MIMO) scheme can deploy the energy-efficiency of MIMO technique which plays an important role in long range transmission where transmit energy is dominant in the total consumption. In various applications, such as area surveillance for agriculture or intelligent transportation systems, middle and long range transmissions are indeed often required because of the large covered area of the wireless sensor networks. Nonetheless, C-MIMO scheme requires extra energy for the local cooperative data exchange, extra circuit consumption of the cooperative nodes, and extra energy of the more complex digital processing [5]. Therefore, it is not practical for short range transmission in which circuit energy consumption is dominant in the total energy consumption. The energy-efficiency of C-MIMO scheme versus non multi-hop SISO scheme was shown in [6]. The result is limited to the case of 2 antennas using Alamouti Space–Time Block Code (STBC) [7]. Depending on the energy model of [2], the present paper proposes an extension of this cooperative principle to MIMO systems with 3–8 antennas using Tarokh orthogonal STBC [8]. An energy-efficient antenna subset selection that depends on the cluster load is performed followed by an iterative rate selection algorithm that selects the transmission rate for uniform cluster energy consumption.

The rest of the paper is organized as follows. In Section 2, we explain the problem statement. The advantages and drawbacks of C-MIMO schemes are introduced in Section 3. The structure of Orthogonal STBC (O-STBC) of Alamouti and Tarokh and their application to the C-MIMO scheme are presented. The transmission–reception cluster energy model and the energy calculation for cooperative MIMO system are explored in Section 4. Joint
optimization of rate and C-MIMO schemes is presented in Section 5. In order to prove the expediency of adaptive rate C-MIMO (ARC-MIMO) in achieving uniform cluster energy consumptions in a typical Wireless Sensor Network, simulation results are given in Section 6, followed by conclusions in Section 7.

2. Problem statement

In a typical cluster based multi-hop Wireless Sensor Network shown in Fig. 1, data flow from the source cluster (through a number of transit clusters) to the base station. In this way, the transit clusters not only forward their own data but also they relay the data of other clusters in the network. This additional load causes superfluous energy consumption in the transit clusters, especially in the clusters near the base station, which may result in complete demise of sensor network before the tentative time.

3. Cooperative MIMO and Space–Time Block Codes for wireless sensor networks

3.1. Cooperative MIMO scheme

For data transmission from source node $S$ to destination node $D$ over distance $d$, instead of SISO direct transmission which is not practical for long range, we can create a C-MIMO transmission, to reduce the transmit energy. In the transmission side, node $S$ can cooperate with its neighbors and exchange its data (the distance between cooperating nodes $dc << d$). MIMO techniques (STBC, Space-Time Trellis Code (STTC), Spatial Multiplexing, etc.) are then employed to transmit their data simultaneously to the destination node (or multi-destination cooperative nodes) like a multi-antenna diversity system (each cooperative node plays role of one antenna of MIMO system). In the reception side the cooperative neighbors of destination node $D$ receive the MIMO modulated symbols and, respectively, retransmit them to the destination node $D$ for joint MIMO signals combination.

However, if the C-MIMO scheme can exploit the energy-efficient transmission of MIMO technique, the local data transmission at TX and RX sides of C-MIMO scheme costs an extra transmission energy due to the extra circuit consumption of the cooperative nodes and the more complex MIMO digital signal processing. For short range transmission, this extra energy consumption can be greater than the transmission energy saved by using C-MIMO (or MISO) instead of SISO technique. Another C-MIMO trade-off is the delay of the cooperative local data transmission. Nevertheless, transmission delay is a less important design criterion than energy consumption and in comparison to multi-hop technique.

3.2. Application of STBC

Among MIMO diversity coding techniques (Space–Time Block or Trellis Codes, Spatial Multiplexing), STBC is the most practical for WSN [9]. The simplicity of ST coding and combination is very interesting due to the calculation limitation of the sensor node (decoding algorithm of STBC is only based on linear processing).

The diversity Alamouti code [7] is used, for systems with 2 transmission antennas, whereas the orthogonal STBC for complex symbol signals developed by Tarokh [8] is used for systems with 3–8 transmission antennas.

Due to the diversity of transmission and reception, BER performance of MIMO STBC can easily outperform SISO system under the same Signal-to-Noise Ratio $E_b/N_0$. In other words, with the same BER requirement, MIMO system requires less energy for the transmission than SISO system.

We assume that we have perfect synchronization, perfect channel estimation and Maximum Likelihood detection in the receiver.

3.3. A note on time synchronization

In principle, the RTS/CTS transmission between source and destination exists in many medium access control (MAC) protocols. The reception of the CTS packet triggers at each relay the initiation of the timing process, within an uncertainty interval that depends on different propagation times[10]. Since source CH and receiver CH have direct communication link, therefore, an explicit time synchronization protocol among the cooperative nodes is not required [10].

4. Cluster energy consumption model

First we consider energy consumption in a cluster that employs cooperative communications for data transmission/reception as shown in Fig. 2. We will calculate the total energy consumption in cluster $j$. There are two main components of cluster energy,
energy consumption during reception from the neighbors and the energy consumption during data transmission to the next hop.

\[ \text{Data in cluster } j' = \sum_{i=1}^{N} l_i \times FF \times (\text{Data sensed in cluster } j) \times FF \]

(1)

where \(l_i\) is sensed data in neighbor \(i\), and FF is the fusion factor [11]. Cluster \(j'\) has to forward the data of \(N\) number of neighbor clusters in addition to its own data. The load (sensed data) on neighbors can be expressed as

\[ \{l_1, l_2, l_3, \ldots, l_N\} = C_i(j), \quad i = 1, 2, \ldots, N \]

(2)

where \(C_i(j)\) is the average sense data per cluster in the network such that the neighbor \(j'\) carries the load of total \(n_i\) clusters (including itself).

Energy consumption in cluster \(j'\)

\[
\begin{align*}
\text{Energy consumption in cluster } j' &= E_{\text{RCV, coop}} \{N \sum_{i=1}^{N} l_i\} + E_{\text{TRANS, nodes}} \{\text{(Data sensed in cluster } j) \times FF\} \\
&+ E_{\text{RCV, CH}} \{\text{(Data sensed in cluster } j) \times FF\} \\
&+ E_{\text{TRANS, coop}} \{N \sum_{i=1}^{N} l_i\} + E_{\text{RCV, CH, CH}} \{\text{(Data sensed in cluster } j) \times FF\} \\
&+ E_{\text{TRANS, CH, CH}} \{N \sum_{i=1}^{N} l_i\} + E_{\text{TRANS, CH, CH}} \{\text{(Data sensed in cluster } j) \times FF\} \\
&+ E_{\text{TRANS, CH, CH}} \{N \sum_{i=1}^{N} l_i\} + E_{\text{TRANS, CH, CH}} \{\text{(Data sensed in cluster } j) \times FF\}
\end{align*}
\]

(3)

where \(E_{\text{RCV, coop}}\) is the energy consumption for cooperative reception in cluster \(j'\) (for each neighbor \(i\) in cluster \(j'\) has different receive number of nodes, which are determined by that neighbor \(i\)’s). \(E_{\text{RCV, CH}}\) is the receive energy consumption of cluster head (CH) for its own cluster data. \(E_{\text{TRANS, nodes}}\) is sensor nodes transmission energy in cluster \(j'\). \(E_{\text{TRANS, coop}}\) is cooperative transmission energy. \(E_{\text{TRANS, CH, CH}}\) is receive overhead during transmission from cooperative nodes to CH. \(E_{\text{TRANS, CH, CH}}\) is receive overhead energy consumption in the receive circuit of CH during the data collection from the cooperative nodes, similarly \(E_{\text{TRANS, CH, CH}}\) and \(E_{\text{TRANS, CH, CH}}\) are the transmission side overheads. \(n_i\) is the number of cooperative nodes (in transmission mode \(n_{\text{CH}} = n_i - 1\) and in receive mode \(n_{\text{RCV}} = n_i - 1\)).

Cooperative communication is a hybrid type of communication which includes both direct transmission and MIMO transmission.

4.1. Energy consumption in direct communications

The total power consumption of typical RF transmission system consists of two components: the transmission power \(P_{\text{in}}\) of the power amplifier and the circuit power \(P_{\text{circuit}}\) of all RF circuit blocks. \(P_{\text{in}}\) is dependent on the transmit power \(P_{\text{out}}\). If the channel is \(l\)-law path loss, it can be calculated as follows:

\[ P_{\text{out}} = E_b R_b d^\alpha K \]

(4)

where \(K\) is a constant depends upon transmit and receive antenna gains, carrier frequency, link margin and power spectral density (PSD) of the total effective noise at receiver input [2], \(E_b\) is average received bit energy, \(R_b\) is transmission rate in bits per second and ‘\(d\’\) is the transmission distance.

\[ P_{\text{in}} = (1 + 2)P_{\text{out}} \]

(5)

where \(\alpha = \xi / \eta - 1\) with \(\xi\) the drain efficiency of the RF power amplifier and \(\eta\) the Peak-to-Average Ratio (PAR) which depends on the modulation scheme and the associated constellation size. Therefore the total transmission power is given by \(P_{\text{TX, total}} = P_{\text{in}} + P_{\text{circuit}}\), and the transmission energy per bit can be expressed as

\[ E_{\text{TRANS}} = E_b d^\alpha K (1 + 2) + P_{\text{circuit}} / R_b \]

(6)

At the receiver side the total power consumption \(P_{\text{RX, circuit}}\) is due to the RF receive circuit blocks. Hence the energy per bit at the receiver node is given by

\[ E_{\text{RCV}} = P_{\text{circuit}} / R_b \]

(7)

4.2. Energy consumption in cooperative MIMO communications

The extra energy of the local cooperative data exchange is dependent on the number of cooperative antennas and the local inter-node distance \(d_i\) between two cooperating nodes at both TX and RX sides. \(d_i\) is expected to vary from 1 m to 10 m depending on the geographical configuration of the network. We assume that average distance between transmit cluster and the receive cluster is ‘\(d\’\) and there are \(n_i\) and \(n_R\) nodes to cooperate at TX and RX sides, respectively.

The following equation gives the relation between bit energy and the symbol error rate (SER) in M-ary PSK modulation [12], [5.2–61] as

\[ P_m \approx N_0 Q\left(\sqrt{2b \eta_b \sin^2 \pi / M}\right)^{-n_t/n_e} \]

(8)

where \(\eta_b\) is the post processed SNR at receive CH and \(N_0\) is the number of nearest neighbors in the underlying constellation. Assuming each entry in \(H\) (channel gain matrix) is independent zero mean, circularly-symmetric, complex Gaussian (ZMCG) random variable with unit variance. In high SNR regime the average BER is upper bounded as [13]

\[ v = \left[\frac{n_t}{n_e}\right] \leq N_0 \left(\frac{E_b}{N_0} \frac{1}{n_t} \sin^2 \pi / M\right)^{-n_e/n_t} \]

(9)

Using above equation with (6), we have the expression for energy consumption per bit for cooperative transmission as

\[ E_{\text{TRANS, coop}} = \left(\frac{1}{b} \frac{P_{\text{in}}}{N_0} \frac{1}{n_t} (1 + 2) K d^\alpha + P_{\text{circuit}} / R_b\right) \times \eta_f \]

(10)

where \(K' = N_0 K\) and \(N_0\) is PSD of thermal noise.

On the receiver side the cooperative reception energy per bit is simply given as

\[ E_{\text{RCV, coop}} = (P_{\text{RS, circuit}} / R_b) \times n_R \]

(11)

Remember that cluster \(j'\) receives data from \(N\) neighbors of neighbors and for each neighbor it has different number of receive cooperative nodes, so \(n_R\) varies accordingly in (3).

Now we move towards the overheads that occur during cooperative transmission, the source CH first decodes the information according to appropriate STBC code book [7 or 8] and sends it to all cooperative nodes.

(i) Transmission overhead in sending data from CH to all cooperative nodes.

\[ E_{\text{TRANS, CH, CH}} = \left(1 + 2 \frac{N_0}{N_0} \frac{K d^\alpha}{\sin^2 \pi / M} + P_{\text{circuit}} / R_b\right) \times n_f \]

(12)

(ii) Transmission overhead in receiving data by \(n_f - 1\) cooperative nodes from CH.

\[ E_{\text{TRANS, CH, CH}} = (P_{\text{RX, circuit}} / R_b) (n_f - 1) \]

(13)
Therefore total energy consumption in cooperative transmission is
\[ E_{\text{TRANS,coop,total}} = E_{\text{TRANS,coop}} + E_{\text{TRANS,OH,trans}} + E_{\text{TRANS,OH,rcv}} \]  
(14)

In the RX side, the \( n_R - 1 \) cooperative nodes firstly receive the MIMO modulated symbols (assuming full rate STBC), multiply with respective estimated channel coefficient and then retransmit their symbols respectively to the CH, where the combiner and maximum likelihood detector recover the original information.

(i) Cooperative receive overhead for sending back data to CH for combining and detection is given as
\[ E_{\text{RCV,OH,trans}} = E_{\text{TRANS,OH,trans}} \times (n_R - 1) \]  
(15)

(ii) Cooperative receive overhead during the collection of data by CH is given by
\[ E_{\text{RCV,OH,rcv}} = E_{\text{RCV}} \]  
(16)

Therefore total energy consumption in cooperative reception becomes
\[ E_{\text{RCV,coop,total}} = E_{\text{RCV,coop}} + E_{\text{RCV,OH,trans}} + E_{\text{RCV,OH,rcv}} \]  
(17)

4.3. Key points for uniform energy distributions

The per bit cooperative transmission energy dependence on the number of transmit and receive nodes for a desired BER requirement is shown in Fig. 3. This is a clue for the solution for non-uniform energy consumption.

Fig. 4 shows how \( E_{\text{TRANS,coop,total}} \) depends on the constellation size \( b \) for various C-MIMO schemes. It is clear from Fig. 4 that there is an optimal constellation size for each C-MIMO scheme for which the total transmission energy per bit is minimized.

Signal bandwidth is another parameter which can play an important role in achieving uniform energy distribution in a cluster based network. Fig. 5 depicts the variation of cooperative transmission energy over a range of signal bandwidth for various constellation sizes.

5. Joint optimization of rate and C-MIMO scheme

In this section, we provide analysis of optimal uniform cluster energy scheduling strategy based on joint optimization of rate and C-MIMO scheme selection. Our objective is to minimize the cluster energy consumption subject to given range of transmit and receive cooperative nodes and available transmission rates:

\( \min \ E_{\text{Cluster,j}} \)  \( j = 1 \ldots N \),

\( \text{s.t.} \)  \( n_T \leq a_j \),  \( n_R \leq a_j, \ i = 1 \ldots N \),

\( E_{\text{Cluster,j}} + E_{\text{edge}} \leq E_{\text{Cluster,j}} \leq E_{\text{edge}} + E \),

\( b_1 \leq R_b \leq b_2 \)  \( j = 1 \ldots N \),

where \( N \) is the total number of clusters in a network, \( a_i \) is the number of transmit cooperative nodes, \( b_i \) is receive cooperative nodes for \( i \)-th downstream cluster, \( c \) is a small acceptable tolerance range and \( b_1, b_2 \) are lower and upper limits for transmission rate in bits per second, respectively.

It can be easily seen from (10) that cooperative transmission gives us leverage to reduce the energy per bit by increasing the number of transmit and receive cooperative nodes for a required BER performance. Total cooperative transmission energy per bit and total receive energy per bit for \( \text{SER} = 10^{-3}, d = 50 \text{ m}, d_c = 5 \text{ m}, P_{r_{\text{elec}}} = 98.2 \text{ mW}, P_{r_{\text{elec}}} = 112.6 \text{ mW} \) are presented in Table 1.
By assuming same average sensed data in each cluster, the normalized load of each cluster becomes \(1/N\). A cluster which carries load of \(N_i \leq N\), \((N_i = \{n i = 1 \ldots N\})\) clusters (including it) adjusts the transmit energy consumption per bit using (18) as follows:

\[
E_{\text{TRANS,coop}} + E_{\text{RCV,coop}} = \frac{CN}{P}
\]  

(19)

where \(C\) is a constant defined by the energy consumption of a cluster which carry only its own data. The receive energy consumption \(E_{\text{RCV,coop}}\) is determined by the neighbor clusters for which the said cluster is the immediate next hop.

\[
E_{\text{RCV,coop}} = \frac{P_{tx,elect}}{R_b} \sum_{i=1}^{N_i} C_n R_i(1) \sum_{i=1}^{N_i} 1 \frac{1}{C_{i-1} + C_i}, \quad C_0 = 0
\]

(20)

Now after getting \(E_{\text{TRANS,coop}}\) from (19) we can easily obtained the number of transmit cooperative nodes of said cluster and the number of receive cooperative nodes of next hop cluster from the look up Table 1. As for a practical example we consider energy consumption in five hop long-haul C-MIMO communication shown in Fig. 6.

### Algorithm

1. Estimate the incoming neighbors set \(N_i \leq N\) from routing table
2. Each incoming neighbor \(i, i \in N_i\) informs the cluster \(j\) about its total load \(l_j = \sum C_j\); is
3. Select \(n_i\) on the basis of \(E_{\text{cluster,ab}} \times l_j \approx C\)
4. Look up Table 1 gives appropriate values of \(n_i\) for cluster \(j\) and \(n_k\) for upstream neighbor cluster \(k\).
5. for \((i \leq N_i; i + +)\), \(N_d\) is total no.of clusters in a routing path
   - calculate \(E_{\text{local,GM}}\)
   - calculate \(E_{\text{TRANS,coop}}\)
   - calculate \(E_{\text{RCV,coop}}\)
   - if \((i = 1)\), since cooperative receive energy is zero in 1st cluster
     \(E_{\text{cluster}}(i) = E_{\text{TRANS}}(i) + E_{\text{local,GM}}\)
   - else
     \(E_{\text{cluster}}(i) = E_{\text{TRANS}}(i) + E_{\text{RCV}}(i - 1) + E_{\text{local,GM}}\)
   - if \((i \geq 2)\)
     \(q = 0\;
   \)
   - While \((E_{\text{cluster}}(i) - E_{\text{cluster}}(1) > e)\)
     \(b + + \)
     \(R_b = R_b + q\)
     \(q = q + 10 \text{ kbps}\)
   - calculate \(E_{\text{cluster}}(i)\)
   - end While
   - end if \((i \geq 2)\)
   - end if \((i = 1)\)

### Table 1

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<th>(n_b)</th>
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<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>12.5</td>
<td>10.9</td>
<td>10.1</td>
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<td>4.4</td>
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<td>8.8</td>
<td>11</td>
</tr>
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</table>

### 6. Simulation results

The simulations were performed in MATLAB® from The MathWorks. Simulation scenario is shown in Fig. 6. When one or more sensor nodes sensed data, they send it to the CH. Then the CH forwards it to the BS by multi-hop transmission. The neighboring clusters as well as the clusters in the routing path also induce their sense data; such that the load gradually increases as we move towards the BS.

For simulations we set the following parameters: sense data per node is 10 bytes, average distance for cooperative communications between clusters \(d = 50\) m, average distance between cooperative node and CH \(d_c = 5\) m, required \(SER = 10^{-3}\), \(P_{tx,elect} = 98.2\) mW, \(P_{tx,elect} = 112.6\) mW. \(F = 0.9, \alpha = 0.47[3]\), path loss exponent \(l = 3\), modulation scheme is BPSK \((N_e = 1, b = 1)\), transmission rate \(R_b = 100\) kbps unless otherwise specified.

![Fig. 6. Simulation scenario.](image-url)

![Fig. 7. Cluster energy consumption along the routing path with SISO transmission. One node has sensed data per cluster.](image-url)
1.5
1.5
4.5
4
2.5
2.5
5
2
4
3
5
2
3
43x315 clusters are shown in Fig. 8. We have used same transmit and the same sensed data per cluster.

BS consumed about 15 times more energy than the edge cluster for ter (cluster 1 in Fig. 6) and the cluster near the BS. Cluster near the ent clusters without cooperative communications. One can see that edge cluster which carries only its own sensed data as a random variable to get more realistic results.

Cluster energy consumptions with flat C-MIMO schemes in all clusters are shown in Fig. 8. We have used same transmit and receive cooperative nodes pairs in each cluster to cluster long-haul transmission. Though the cooperative communication reduces energy consumption per cluster but it does not renders the uniform energy consumption.

In Fig. 9 cluster energy consumption under various load conditions for the proposed ARC-MIMO selection scheme is shown. Due to the adaptive selection of transmission rate and cooperative MIMO schemes and hence the energy consumption per bit, each cluster has leverage to control its total energy consumption. It can be seen that edge cluster which carries only its own sensed data and the cluster near the base station which carries the load of 15 other clusters in addition to its own sensed data have approximately the same energy consumption. Rates (R1, R2) and C-MIMO schemes for each hop are shown in Fig. 9. It can be seen from Table 1 that transmission energy is monotonically decreasing with the number of receive nodes and receive circuit energy is monotonically increasing with the number of receive nodes (or antennas). Since BS has no energy constraint, therefore we can select large number of receive antennas on BS in the last hop (1 × 5 in our example). It significantly alleviates the maximum load carrying cluster, in our case, cluster 5, as shown in Table 2.

7. Conclusions

In this paper, we propose a solution for non-uniform energy consumption in the cluster based multi-hop WSN through adaptive selection of transmission rate and C-MIMO schemes. We have shown that the multi-hop C-MIMO in transit clusters results in reduced energy consumption as compared to the non-cooperative case, and ARC-MIMO transmission provides uniform energy consumption within a tolerance range ε in all the clusters. The proposed ARC-MIMO communication architecture can also offer substantial energy saving in Wireless Sensor Networks provided that the system is designed judiciously. These include careful consideration of transmission distance requirements and joint rate and number of cooperative nodes optimization. The conclusions drawn in this paper only apply to the dense WSN where appropriate number of close cooperative nodes (dc ≪ d) are available.

This work can be further extended by introducing transit cluster sensed data as a random variable to get more realistic results.

References


