Analysis of Cooperative STBC MIMO Transmissions in WSN using Threshold Based MAC Protocol

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ABSTRACT
Sensor networks require robust and efficient communication protocols to maximise the network lifetime. Radio irregularity, channel fading and interference results in larger energy consumption and latency for packet transmission over wireless channel. Cooperative multi-input multi-output (MIMO) schemes can combat the fading effects in wireless sensor network (WSN) and can significantly improve the communication performance. More over, the traffic offered to the sensor network is highly dynamic and an inefficiently designed medium access control (MAC) protocol however, may diminish the performance gains of MIMO operation. Hence, this paper proposes a distributed threshold based MAC protocol for cooperative MIMO transmissions using space time block codes (STBC) to maintain stability even under higher traffic loads. The protocol uses a thresholding scheme that is updated dynamically based on the queue length at the sending node to achieve lesser energy consumption and minimise packet latency ensuring the stability of transmission queues at the nodes. STBC techniques are applied for MIMO data transmission to utilise the inherent spatial diversity in wireless systems. Simulation results are provided to evaluate the performance of the proposed MAC protocol and are compared with fixed group size cooperative MIMO MAC protocols with and without STBC coding. Results show that the proposed protocol outperforms cooperative MIMO MAC protocols that use fixed group sizes. STBC technique for the proposed MAC protocol provides significant energy savings and minimises the packet delay by leveraging MIMO diversity gains.

General Terms
Multi-input multi-output, Medium access control, Space time block code, Wireless sensor network.

Keywords
Cooperative transmission, Energy efficiency, Diversity gain, Packet delay, Thresholding scheme.

1. INTRODUCTION
Wireless sensor network (WSN) comprises of hundreds to thousands of small nodes employed in a wide range of data gathering applications such as military, environmental monitoring and other fields [1]. Due to limited energy and difficulty in recharging a large number of sensor nodes, energy efficiency and maximising network lifetime have been the most important design goals for the network. However, channel fading and radio interference pose a big challenge in design of energy efficient communication protocols for WSN.

To reduce the fading effects in wireless channel, multi-input multi-output (MIMO) scheme is utilised for sensor network [2,3]. In physical layer, multiple antenna techniques have been shown to be very effective in improving the performance of wireless systems in the form of diversity gain, array gain and multiplexing gain. Many schemes proposed in previous researches [4] show that diversity can be leveraged in the network, link or physical layers to provide reliable transmission with low power, reduce energy consumption and extend battery lifetime. However, applying multiple antenna techniques directly to sensor network is impractical because of the limited size of a sensor node usually supports a single antenna. Cooperative MIMO schemes have thus been proposed [3,5] for WSNs to improve the communication performance.

Cooperative transmission and reception from antennas in a group of sensor nodes can be used to construct a system fundamentally equivalent to a MIMO system for WSN [5]. Normally, MIMO technique needs to estimate all channels between the source and destination. If cooperative transmission from multiple sensor nodes are allowed, the amount of channel estimation at the receiver can be reduced and hence can save the energy of sensor nodes [4,5]. The traffic offered by the sensor network is highly dynamic and results from collision when nodes transmit data at the same time. Thus an inefficiently designed medium access control (MAC) protocol will increase the energy spent in exchanging the cooperative control messages and diminishes the performance gains of MIMO system.

The fundamental task of a MAC protocol [6] is to schedule the transmissions from nodes sharing the same channel and prevent collisions. Due to energy constraints in WSNs, protocols for sensor network must have the additional requirement to be energy efficient. Most current MAC protocols for WSNs use sleep-wake cycles to reduce the energy wastage during idle listening. However, sleep-wake cycles may be inappropriate for time critical applications because of long packet delays and provides inherent instability at high traffic loads.

MAC protocols can be classified as either contention based or collision free. The most popular contention based MAC protocol is SMAC [6]. In SMAC each node follows a sleep-wake cycle to reduce the energy consumption. For collision free MAC, centralised architectures are widely used [7]. However, the use of centralised architecture [7-11] for cooperative MIMO MAC transmission leads to energy wastage and introduce additional coordination delays.

To minimise the energy wastage and provide stability at high traffic loads, distributed system architecture [12,13] for cooperative MIMO MAC transmission [14] is utilised. In this protocol, the source and destination nodes cooperate with their neighbouring nodes while transmitting and receiving data. The MIMO transmission system achieves lower overall energy consumption than point to point communications [2]. However, the number of nodes in the sending and receiving groups is fixed and is difficult to set the right numbers for the groups to achieve the minimum energy consumption, delay and increases the likelihood that the queue length at the sender becomes unstable under heavy traffic conditions [12,13].

To address these issues and facilitate cooperative MIMO transmissions with a high degree of performance improvement, a new MAC protocol is suggested for scheduling cooperative MIMO transmissions in distributed WSNs. The proposed MAC protocol dynamically selects the cooperative group size based on the thresholding scheme. The cooperative threshold is updated by the receiver based on the queue length at the source and the number of neighbours recruited at the sending node.

This threshold is essential to maintain maximum throughput and increase the network lifetime. If the desired threshold is achieved, the destination node calculates the size of sending and receiving groups that has minimum energy consumption to proceed with MIMO data transmission. The proposed MIMO MAC protocol utilises space time block code (STBC) scheme [15-17] and provides significant diversity gain to enhance the system performance. This protocol outperforms fixed group size cooperative MIMO MAC scheme in terms of energy and delay.

The remainder of the paper is organised as follows. Section 2 presents the proposed cooperative MIMO MAC model. In section 3 the mathematical model to analyse the performance of the proposed MAC protocol is presented. Simulation results are discussed in section 4 to evaluate energy consumption and delay of the proposed MAC scheme utilising STBC coding and conclusions are drawn in section 5.

2. COOPERATIVE MIMO SYSTEM MODEL

The cooperative MIMO system model comprises of a small-scale wireless sensor network which consists of many clusters, each with a cluster head of its own. The sink node controls all the cluster heads in the WSN [1]. The cluster heads are selected based on their energy level. After some fixed number of runs, the sink node reselects the cluster head for each cluster since frequent transmissions of data to the sink node drains its energy. The cluster head invokes an algorithm for selecting cooperative nodes for the relay of data to other cluster heads occasionally within the cluster.

The selection of cooperative node is dependent on the distance between the cluster head and the cooperative node and also on the energy level. In cooperative MIMO systems, transmit and receive diversity are achieved in a distributed manner by the sending and receiving group/cluster [12-13]. In the sending group, transmitted signals from multiple sending nodes are combined before arriving at the receiver. The proposed cooperative MIMO communication strategy consists of the following steps and is shown in Figure 1.

i) Broadcasting

The source node broadcasts its data using low transmission power to the selected source cluster members and destination as shown in Figure 1a. The selection of cluster members is based on the space time block coding requirement. The source node specifies the order for selected cooperative nodes so that each cooperative node will choose one of the rows of the STBC [15-17] code for cooperative MIMO data transmission.

ii) STBC MIMO transmission

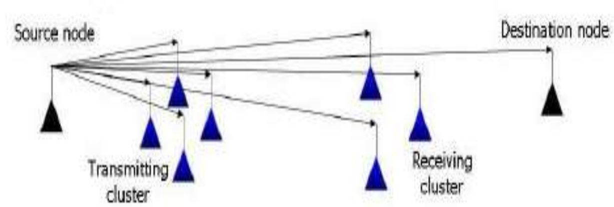
As shown in Figure 1b, the cooperative nodes in sending group will use the corresponding row of STBC code, assigned in step 1, to change the permutation of data bits. Then, all nodes in the sending group, including the source node, will transmit space-time block coded data to the receiving group. Multiple nodes in the sending and receiving group form cooperative system to achieve MIMO diversity.

iii) Data collection and combining

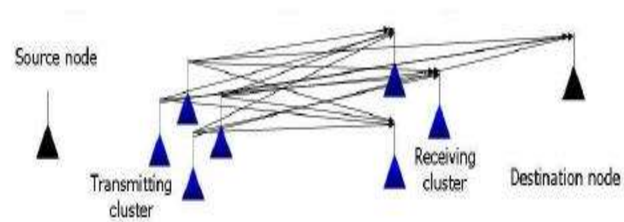
After receiving data from the sending group as shown in Figure 1c, each node in the receiving group uses the channel state information to decode the space-time block coded data. After decoding the STBC, cooperative nodes in receiving group relay their copies to the destination node. The destination receives signal copies from the cooperative nodes and detects them as soft symbols. It then uses code combining and chooses the most possible codeword based on the received soft symbols.

iv) Neighbouring traffic

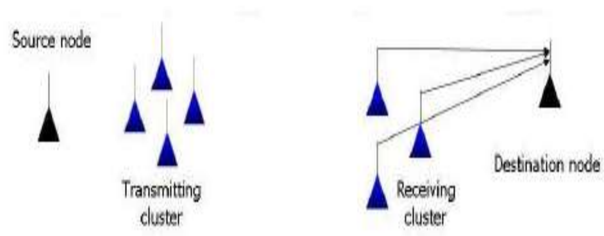
The cooperative nodes do not always respond immediately to the recruiting message sent by the source node. This condition arises when the nodes are busy with data transmissions of other source nodes. The source node under this condition may choose to wait for the busy node or proceed with the available nodes.



(a). Broadcasting



(b). MIMO transmission



(c). Data collection and combining

Figure 1. Proposed cooperative scheme

2.1 Proposed Cooperative MIMO MAC Protocol

The proposed cooperative MIMO MAC protocol for coordinating transmissions from multiple nodes is discussed below. Consider the operation of source node that forwards a packet to destination as shown in Figure 2. When a node has data to send, it first senses the channel to ensure that it is idle. If the channel is sensed to be busy, the node initialises a backoff timer and waits for the idle channel. If the backoff timer has decremented to zero, the source node first broadcasts recruiting message at low transmission power to its local neighbours for cooperative transmission [6,14].

When the replies are received from the neighbours, the source node transmits a request-to-send (RTS) message to destination at normal power. It then waits for the clear-to-send (CTS) reply from destination node to reserve the channel for data transmission. The RTS message contains information on the current queue length at the sender based on the network traffic and the number of neighbours it has recruited. This information is used by the receiver to update the cooperative threshold.

The source node receives a negative CTS (NCTS) packet from the destination node if the receiver is unable to update the cooperative threshold. During this process, the source node will backoff, recruit the cooperative nodes and attempt for retransmission. When the source does not receive the CTS packet within the specified time interval, the node automatically attempts for retransmission.

Once the CTS packet is received, the source node proceeds with the data transmission. Each CTS packet contains the optimum size of the cooperative group at the sending end. The source node broadcasts the data packet at low power to the nodes in its group and synchronises them. Each node in the source-cluster transmits the data cooperatively using STBC coding [4,5,7,8] and waits for an acknowledgement (ACK) from the destination node. If no ACK is received, the retransmission process begins starting from neighbour recruitment.

2.2. Proposed Thresholding Scheme

The destination node uses the RTS information i.e., queue length and available cooperative node at the sender to calculate the threshold. The methodology to determine the threshold for the proposed MAC protocol is described below as shown in Figure 3. Consider the source and destination cluster sizes available for cooperation to be M and N respectively. For each possible choice of M, N, the expected packet error rate (PER), $P_e(M,N)$ is first evaluated using STBC coding [16].

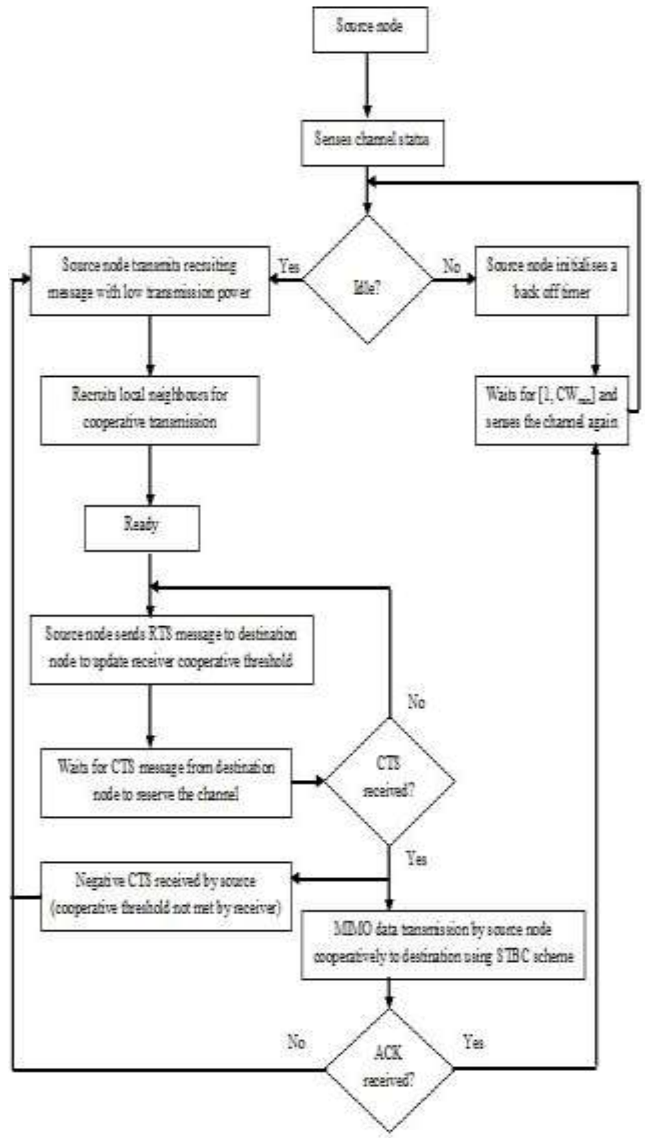


Figure 2. Flow chart of cooperative threshold based MAC protocol for source node

Let the number of unique PER values obtained for the possible choices of cluster sizes are denoted by K. The K successful packet transmission probabilities i.e., $\varphi(i) = \varphi(1), \varphi(2),\ldots, \varphi(K)$ are listed and their corresponding cluster sizes are derived. When the current queue length at the sender is Q, threshold i, i.e., $\varphi(i)$ in terms of the desired successful packet transmission, is chosen if $(K-i)\xi < Q \leq (K-i+1)\xi$, where ξ is a positive integer. The threshold is set at 1 for $Q > K\xi$. For threshold i choosen, the possible set of S = (M, N) cluster sizes is obtained for which the packet delivery rate is greater than $\varphi(i)$.

The destination node does an exhaustive search of the possible group sizes of M, N of $\varphi(i)$ and selects the combination that has the lowest energy consumption subject to the threshold. The cooperative group size M, N corresponding to this energy consumption is dynamically selected as sending and receiving group for data transmission.

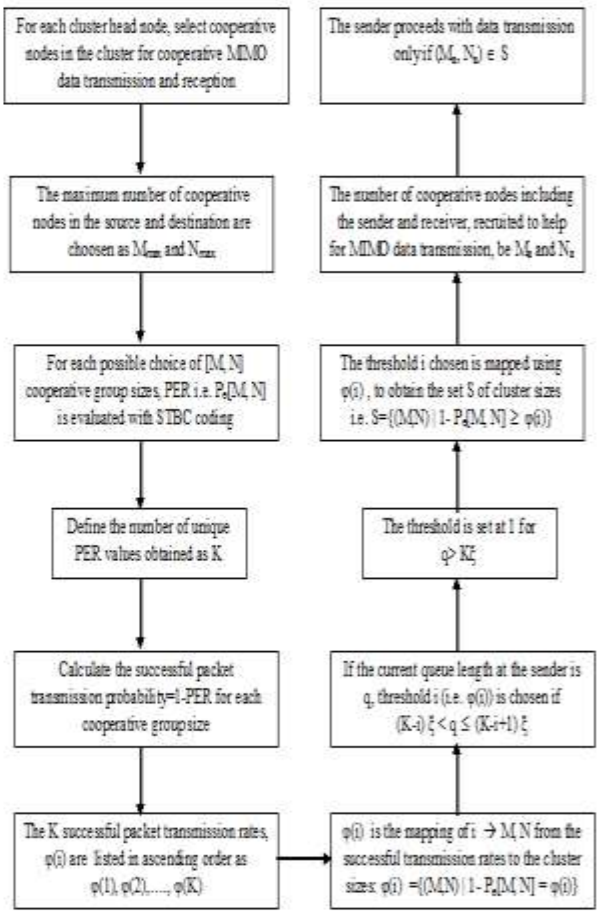


Figure 3. Flowchart of thresholding scheme for the proposed MAC protocol

3. ANALYSIS OF COOPERATIVE MIMO MAC PROTOCOL

A mathematical model to evaluate error probability, packet delay and energy consumption for the proposed cooperative MIMO MAC transmission scheme is described below. The bit error rate is assumed to be 0 in the first step (broadcasting) since a node can be in the sending group only if it receives the data packet correctly. Thus the bit error rate performance for transmission of data from transmit cooperative nodes to receive cooperative nodes and the bit error rate performance after code combining in the destination node have to be considered. The bit error probability is used to analyse the system energy consumption and the delay incurred in the transmission of data from the source to the destination.

3.1. Bit Error Probability

The system is assumed to transmit quadrature phase shift keying (QPSK) signals [2] through Rayleigh fading channel with additive white Gaussian noise (AWGN) noise.

The relationship between the packet error probability p_p and bit error probability p_b [3,12] is given by

$$p_p = 1 - (1 - p_b)^L \quad (1)$$

where

L is the frame length in bits

Data transmission errors are generated from two factors in cooperative MIMO i.e. from the sending group to the receiving group and from cooperative receiving nodes to the destination. Since the cooperative sending nodes will not forward the data packet when it is corrupted, the error from the source to its neighbours will not be considered.

3.2. Energy Consumption Analysis

Consider a scenario with M senders and N receivers involved in cooperative MIMO transmission. The energy consumed for each transmission can be divided into two parts: the energy spent on channel reservation, recruiting and the energy spent on data transmission.

The energy spent for RTS/CTS exchange as well as the recruitment process is given by

$$E_{wait} = E_{rts} + E_{cts} + E_{recruit} \quad (2)$$

where

E_{rts} is the energy consumed in sending RTS packet
E_{cts} is the energy consumed in sending CTS packet
$E_{recruit}$ is the energy consumed on recruiting neighbouring nodes

When all the neighbouring nodes reply to the recruiting messages and that recruiting messages and their replies require energies of source and destination E_{rec_s} and E_{rec_d} respectively, then

$$E_{recruit} = 2E_{rec\_s} + (M_{max} + N_{max})E_{rec\_d} \quad (3)$$

The energy consumed for an unsuccessful transmission attempt and for a successful transmission from sending to the receiving group using STBC MIMO MAC are calculated to analyse the overall energy consumption in a hop [2,13].

The energy consumption for an unsuccessful transmission attempt is

$$Eu_{coop} = E_{wait} + E_{br} + E_{bs} + ME_{data} + (N-1)E_{col} \quad (4)$$

and the energy consumption for a successful attempt is

$$ES_{coop} = E_{wait} + E_{br} + E_{bs} + ME_{data} + (N-1)E_{col} + E_{ack} \quad (5)$$

where

E_{bs} is the energy spent by the source node to send the data to its cooperative neighbours

E_{br} is the energy spent by the destination node to send the notification messages to the recruited neighbours

E_{data} is the energy spent for data transmission between sending and receiving group

E_{ack} is the energy spent by destination node in sending ACK to the source

E_{col} is the energy spent while the destination collects the message from cooperating receivers

The total energy consumption for every one-hop data transmission in cooperative MIMO system [18] depends on the choosen threshold i or φ(i) and is given by

$$E_M(i) = \frac{p_M}{(1-p_M)} Eu_{coop} + Es_{coop}$$

(6)

where

p_M is the packet error probability obtained considering uncoded or STBC scheme.

Based on the above analysis, the destination node in the proposed protocol determines the sending and receiving group sizes. With the given number of nodes available at the sending and receiving groups, the destination node determines an exhaustive search of the possible sizes of M, N and selects the combination that has lower energy consumption, subject to the threshold for MIMO data transmission.

3.3. Packet Transmission Delay

Each packet transmission in cooperative MIMO system requires more steps as shown in Figure 2 which may increase the packet delays. However, the reduction in the packet error probability with cooperative MIMO MAC reduces the occurrence of retransmissions which in turn reduces the packet delays in comparison to point to point MAC protocols [6,11,18].

The total expected packet delay for cooperative MIMO MAC can be evaluated similar to energy consumption equations described above and is given by

$$T_{dM}(i) = \frac{p_M}{(1-p_M)} Tu_{coop} + Ts_{coop} \quad (7)$$

For the dynamically selected group size with thresholding scheme, the delays are evaluated taking into account uncoded or STBC error probability.

4. SIMULATION RESULTS

The analysis of cooperative MIMO MAC protocol is carried out using MATLAB. The parameters considered for simulation is summarised in Table 1.

The performance of proposed threshold based cooperative MIMO MAC protocol with STBC and uncoded schemes are evaluated in terms of energy consumption and packet delay from source to the destination node for the traffic conditions in the network.

4.1. Performance Analysis of Uncoded MIMO Scheme

The energy consumption for diversity orders (2-4) for the uncoded system for fixed group size MAC protocol is shown in Figure 4. At lower SNRs, the higher order MIMO configuration with diversity order 4x4 performs better and has lesser energy consumption of about 70% when compared to lower order system.

Table 1. Simulation parameters

Parameter	**Value**
Total frames per packet	10 frames
Total bytes per packet	410 bytes
Time for transmitting RTS	35.3 ms
Time for transmitting CTS	30.5 ms
Time for transmitting ACK	32 ms
Time for transmitting data	0.006 s
Energy consumed for transmission of RTS, CTS and ACK	0.027J
Energy consumed for transmission of data	0.2J
Modulation type	QPSK
Channel	Rayleigh fading channel

However as the SNR increases beyond 5 dB, the lesser cooperative sending and receiving group sizes consume lower energy of about 5% when compared with higher cooperative group size taking into account the neighbouring traffic conditions of the network. This reduction in energy consumption with the lesser number of nodes is due to lesser number of attempts needed to recruit their neighbours for cooperative MIMO data transmission.

It is also observed from the Figure 5 that the proposed scheme outperforms fixed group size MIMO scheme by changing the cooperative threshold according to the queue length at the sender. The dynamic group size selected using cooperative threshold scheme varies as it selects the group size that has minimum energy expended on recruiting and time spent on waiting for the required number of nodes in retransmission.

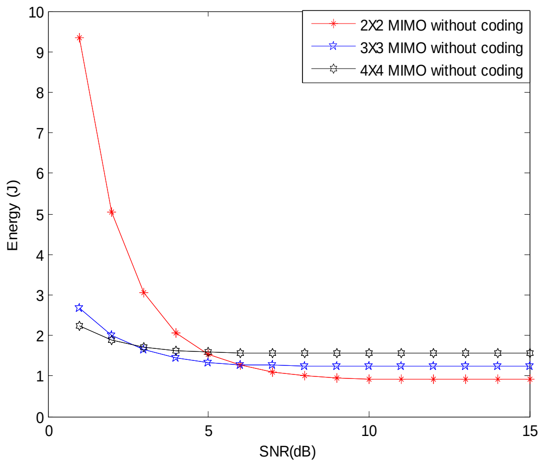


Figure 4. Energy consumption of uncoded scheme for fixed group size MIMO configurations

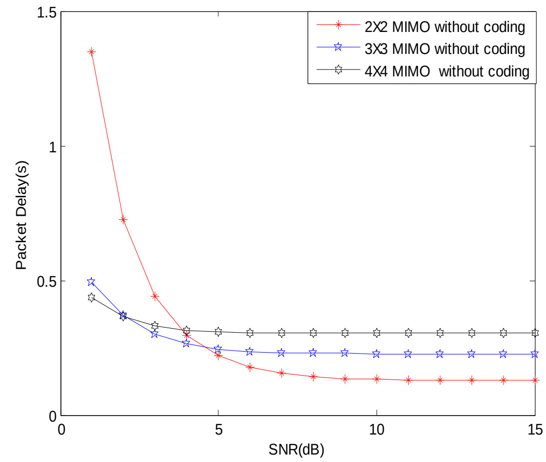


Figure 6. Packet delay of uncoded scheme for fixed group size MIMO configurations

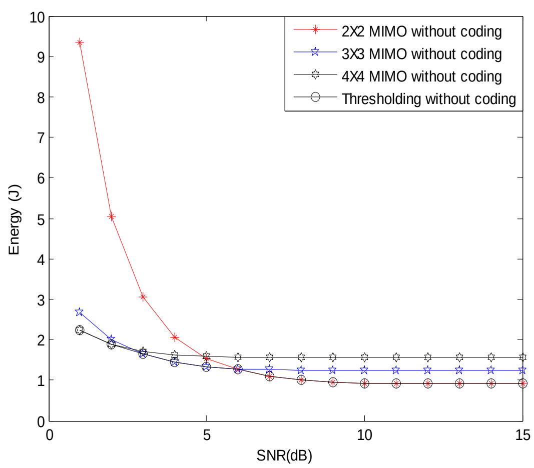


Figure 5. Energy consumption of uncoded scheme for fixed group size MIMO configurations and cooperative threshold

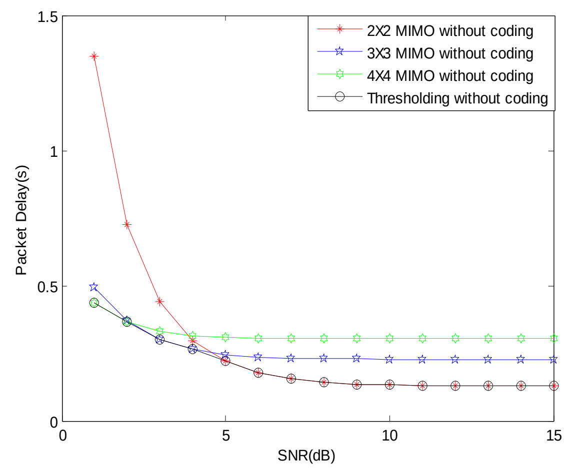


Figure 7. Packet delay of uncoded scheme for fixed group size MIMO configurations and cooperative threshold

Using thresholding policy the dynamic cooperative group size selected is 4 for SNR upto 3 dB, 3 upto SNR 6 dB and 4 above 6 dB. This is because of lesser channel contention with lesser diversity orders. As the SNR increases, the energy consumption decreases this is due to the lesser error rates achieved due to the diversity gain of MIMO systems.

The delay incurred for various fixed transmit and receive group sizes are plotted in Figure 6. The delay keeps reducing with the increase in diversity gain due to increase in the number of receiving cooperative nodes at low SNRs of about 10% approximately.

The decrease in delay is due to less SER and fewer retransmissions in the system. It is clear that the proposed scheme shown in Figure 7 chooses dynamic group size similar to characteristics shown in Figure 5 based on cooperative threshold as it utilises lesser recruiting time to recruit the neighbours for data transmission.

4.2. Performance Analysis of STBC MIMO Scheme

Similar graphs as that of uncoded schemes are obtained as shown in Figure 8 and Figure 10 for energy consumption and delay with STBC coding technique for various fixed sending and receiving group size with and without thresholding scheme. For STBC coding 4x4 is the group size selected as it incurs lesser energy and delay values at low SNRs. The reduction in energy consumption and delay for 4x4 group size MIMO configurations are 15% and 10% respectively when compared with 2x2 MIMO configurations. This is due to the diversity gain exploited by the use of STBC coding techniques. Figure 9 and Figure 11 illustrates the performances of STBC scheme with cooperative threshold in terms of energy and delay. It is vivid from the results that using thresholding policy the dynamic cooperative group size selected is 4 for SNR upto 2 dB, 3 upto SNR 5 dB and 4 above 5 dB. This is because of lesser energy and time spent on nodes in packet transmission.

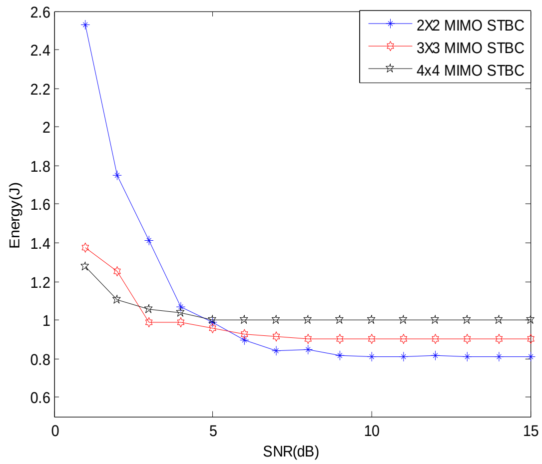


Figure 8. Energy consumption using STBC scheme for various MIMO configurations

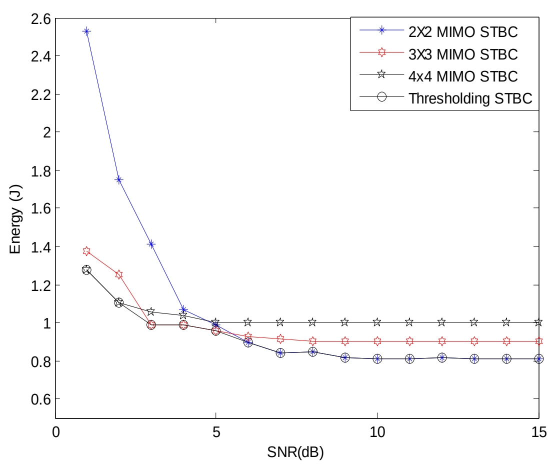


Figure 9. Energy consumption using STBC scheme for various MIMO configurations and cooperative threshold

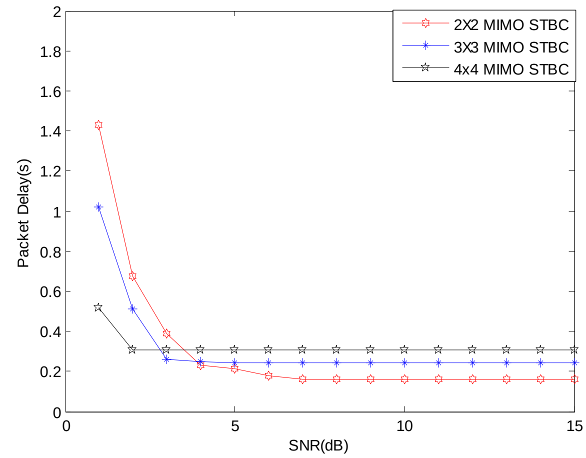


Figure 10. Packet delay using STBC scheme for various MIMO configurations

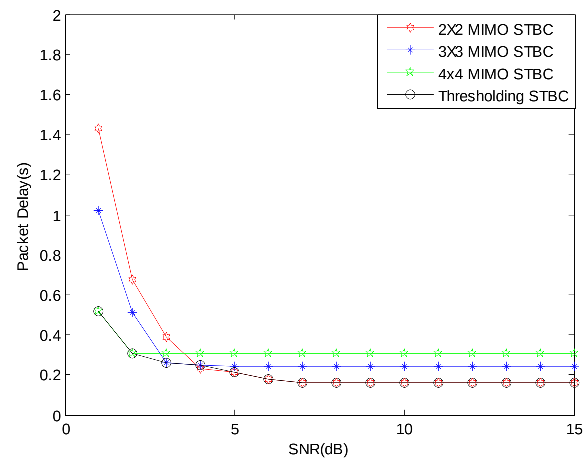


Figure 11. Packet delay using STBC scheme for various MIMO configurations and cooperative threshold

4.3. Performance Comparison of Uncoded MIMO and STBC MIMO Scheme

The performance of uncoded system and STBC MIMO with cooperative threshold is shown in Figure 12 and Figure 13. In case of uncoded system the energy consumption is larger than STBC coding by about 10%. Furthermore, the packet delay of uncoded scheme is 4% more than the coded scheme. This is due to higher SER value with uncoded scheme. The use of coding technique reduces the error in data transmission leading to the significant reduction in energy consumption and delay.

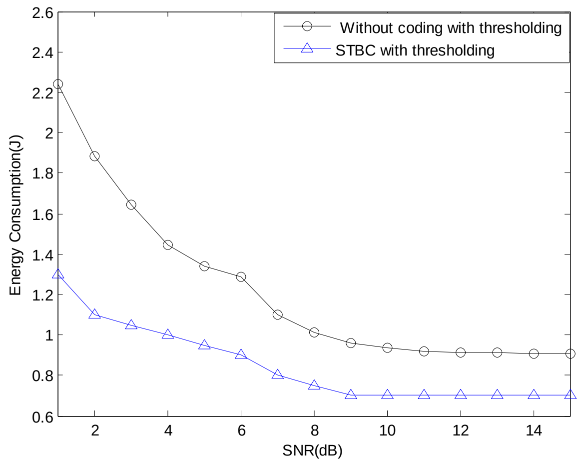


Figure 12. Comparison of energy performance of uncoded scheme and STBC coding with cooperative threshold

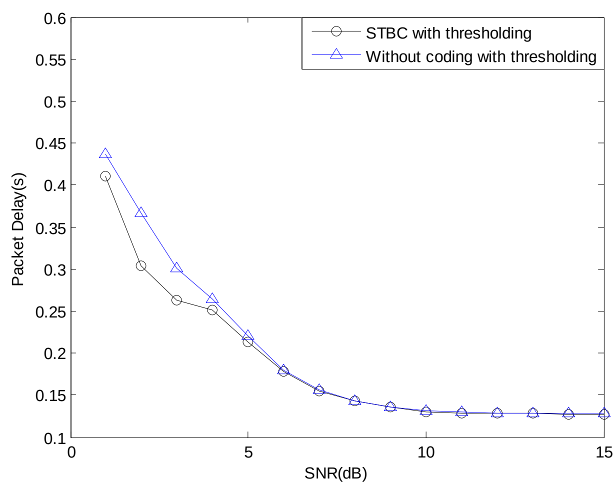


Figure 13. Comparison of delay performance of uncoded scheme and STBC coding with cooperative threshold

5. CONCLUSION

A new cooperative MIMO MAC protocol is proposed in this work to overcome the reduction in throughput of the WSN due to the fading effects of wireless medium. The cooperative MIMO transmission adopted along with the threshold based MAC protocol improves the reliability of the link between the source and destination and enables transmission of data packets with shorter delay and less energy consumption even in extreme fading conditions prevailing in the wireless channel. The performance of the cooperative MIMO MAC system is evaluated for uncoded scheme and STBC system in terms of energy and delay for various orders of diversity. Till the value of SNR reaches 5 dB, the total energy consumed and delay decreases as the order of diversity increases beyond which however the lowest diversity order (2x2) has the minimum energy and delay due to lesser number of nodes to be recruited and used for data transmission as well as reception. The MAC protocol implemented with the thresholding policy hence dynamically chooses the cluster size corresponding to the least energy and delay for the given channel fading conditions determined by the value of SNR at the instant.

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