Cooperative MIMO MAC Protocol using STTC in Wireless Sensor Networks

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Abstract: - Sensor networks require robust and energy 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 transmission of data using multi-input multi-output (MIMO) scheme is used to combat channel fading and improve the communication performance of distributed wireless systems. However, an inefficiently designed medium access control (MAC) protocol may diminish the performance gains of MIMO operation. Hence this paper develops a distributed MAC protocol for packet transmissions using fixed group size cooperative MIMO utilising space time trellis code (STTC) to achieve high energy savings and lesser delay. Further, to ensure the stability of transmission queue at the sender, this paper also proposes a threshold based MAC protocol for MIMO transmission. The protocol uses thresholding scheme that updates dynamically the cooperative group size based on the queue length at the sending node. The performance of the fixed group size MIMO MAC protocol using STTC technique is evaluated for various orders of diversity in terms of transmission error probability, energy consumption and delay. Simulation results are also provided to evaluate the performance of threshold based MAC protocol. Results show that 4X4 cooperative group size is dynamically selected as the cooperative group size as it provides minimum energy and delay. Cooperative transmission using STTC technique provides significant performance improvement than uncoded scheme due to the exploitation of MIMO diversity gain.

Key-Words: - cooperative MIMO, diversity gain, energy efficiency, MAC, STTC, thresholding scheme, wireless sensor network

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 [1-3]. 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 [4,5]. Applying multiple antenna technique directly to sensor network is impractical because of the limited size of sensor node usually supports a single antenna. 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. Normally, a MIMO system needs to estimate all channels between source and destination. If cooperative transmissions 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 [6,7]. The complexity in coordinating the actions of sensor nodes limits the practical use of MIMO in WSN. Also, an inefficiently designed medium access control (MAC) protocol will increase the energy spent in exchanging the cooperative control messages, and diminish the performance of MIMO system.

Most recently developed MAC protocols for WSN use sleep-wake cycles to reduce the energy wastage during idle listening [8-10]. However these sleep-wake schemes are not suitable for time sensitive applications. Also, the use of centralised architecture [11-13] for cooperative MIMO MAC transmissions leads to energy wastage on cluster maintenance and introduces additional coordination delays. To minimise the energy wastage, the distributed system architecture [14,15] for cooperative MIMO MAC transmission is utilised. In this protocol, the source and destination nodes cooperate with their neighbouring nodes while transmitting and receiving data. Existing MIMO MAC protocols use only simple modulation techniques for transmission without using space time coding schemes. Hence the paper proposes a cooperative fixed group size MIMO MAC protocol utilising space time trellis coding (STTC) [16-18] scheme to provide significant coding and diversity gain to enhance the system performance. However, when the number of nodes in the sending and receiving groups is fixed, it is difficult to set the right numbers for the groups to achieve the minimum energy consumption and delay and increases the likelihood that the queue length at the sender becomes unstable.

To facilitate cooperative MIMO transmissions with a high degree of performance improvement, a threshold based MAC protocol is also suggested. The proposed threshold based 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 performance of the proposed STTC MIMO MAC protocol is evaluated in terms of energy and delay and is compared with uncoded scheme.

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

2 Proposed Cooperative MIMO MAC Protocol System Model

In cooperative MIMO systems, transmit and receive diversity are achieved in a distributed manner by the sending and receiving group. The cooperative MIMO transmission model is shown in Fig.1. The sending and receiving groups include multiple sending nodes and receiving nodes, each equipped with single antenna. In the sending group, transmitted signals from multiple sending nodes are combined before arriving at the receiver. Space time trellis coding and decoding is used at the sending and receiving group to separate the received signals and exploit the diversity gain [16,17].

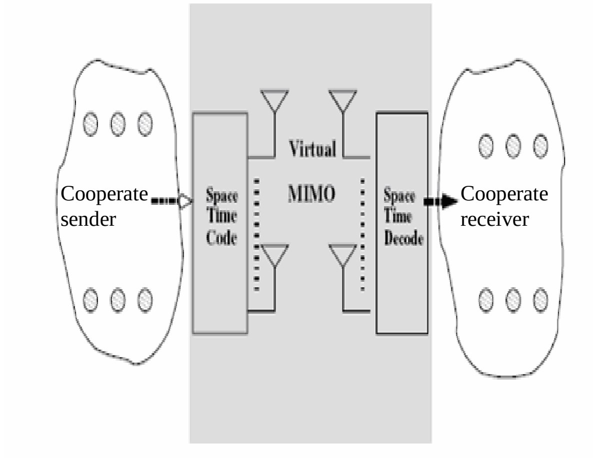

Fig.1. Cooperative MIMO system model

2.1 Fixed Cooperative group size MIMO MAC model using STTC scheme

At the beginning of each data transmission, the source node sends a recruiting request-to-send (RRTS) message to its neighbours to solicit help for the transmission of data packets. The RRTS message is transmitted at a power level lower than that required for normal transmission to ensure that only the near by nodes are recruited. The available neighbours will reply with a sequential clear-to-send (SCTS) message for the purpose of reducing the collision with each other.

After recruiting the sending group, the source node sends MIMO RTS (MRTS) control messages to the destination node to establish data transmission link. The destination node recruits receiving group nodes using the same recruiting procedure as that of the source node using RRTS and SCTS messages. After the destination node gets the SCTS reply, it sends broadcast messages to the selected receiving neighbours to recruit them and help in receiving STTC encoded MIMO data from the sending group. If the receiving group does not have enough nodes, the MIMO CTS (MCTS) control message will notify the source node to retransmit [8,9].

Once the MCTS is received, the source node encodes information bits with STTC. The number of nodes required for STTC encoding is selected. The source node specifies the order for selected cooperative nodes so that each node will choose the corresponding row in space time trellis code matrix for cooperative MIMO data transmission [16,17]. All nodes in the sending group, including the source node, will transmit space-time coded data to the receiving group. Multiple nodes in the sending and receiving group form cooperative MIMO diversity.

After receiving the MIMO data from the sending group, each node in the receiving group uses the channel state information to decode the space time trellis coded data. After decoding STTC, the 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. The destination uses code combining and chooses the most possible codeword based on the received soft symbols.

If the original data is decoded correctly, the destination node will send back an acknowledgement (ACK) message to the source node. Otherwise, no ACK is sent and the source nodes will timeout and initiate backoff mechanism before attempting retransmission and the whole procedure is repeated.

The algorithm for cooperative MIMO MAC data transmission is described below:

STATE: LISTEN node listens to the channel after it wakes-up

if Packet ready to be send *then*

node is the source
STATE: RTS node sends RTS packet and receives CTS packet
if CTS not received *then*
repeat *STATE: RTS*
end if
STATE: SLEEP sets timer to wake-up and goes to sleep
STATE: BSDATA broadcasts BS data to transmitting group followed by data packet with low power
STATE: DATA sends MIMO data using STTC when the sending timer expires
if receive ACK packet *then*
go to *STATE: LISTEN*
else
go to *STATE: RTS*
end if
endif
if receive RTS packet then

node is the destination
STATE: SLEEP receives RTS packet and sets timer to wake-up
STATE: CTS sends CTS packet
STATE: BR sends broadcast recruiting packet to its neighbours with low power
STATE: SLEEP sets timer to wake-up and goes to sleep
if STTC MIMO data packet is received *then*
go to *STATE: COLLECTION*
else
go to *STATE: LISTEN*
end if
STATE:COLLECTION set timer to wait for receiving group nodes to send data packet
if packet not received correctly then
go to *STATE: LISTEN*
end if
STATE: ACK node sends ACK packet
go to *STATE: LISTEN*
end if

if receive BSDATA *then*

Cooperative sending node
STATE: COOPERATIVE_SENDING nodes transmit data packet when sending timer expires
go to *STATE: LISTEN* listens for channel activity
end if

if receive BR *then*

Cooperative receiving node
STATE:COOPERATIVE_RECEIVING set expiration timer
if STTC MIMO data packet received *then*
go to *STATE: COLLECTION*
else
go to *STATE: SLEEP* after timeout
end if
STATE: COLLECTION sends data to destination node
go to *STATE: SLEEP*
end if

2.2 Threshold based MIMO MAC model using STTC scheme

Consider the operation of source node that forwards a data packet to destination. 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.

When the replies are received from the neighbours, the source node transmits a RTS message to destination at normal power. It then waits for the 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 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 STTC coding and waits for an ACK from the destination node. If no ACK is received the retransmission process begins starting from neighbour recruitment.

The operation of the destination node is as shown in Fig.2. The destination node on receiving the RTS packet, seeks for an idle channel. If the channel is idle, the destination node sends a recruiting packet at low power to recruit its neighbours. On receiving replies from nodes willing to cooperate for reception, the destination node uses the RTS packet to calculate the threshold.

If the cooperative threshold as required is not met, a NCTS packet is sent to source node to cancel the transmission. On the other hand, if the threshold is met, the destination node broadcasts a low power message to the cooperative receiving group to help in the reception. It then sends a CTS packet with the required cooperative group size to source node.

The destination node waits for data transmission from the source cluster. Next, it waits for each node in the destination cluster to sequentially forward its copy of the received data packet. Finally it decodes the packet by combining all copies of the received packet and replies with an ACK packet to the source if the packet is decoded correctly. Otherwise, the destination node does nothing and the source node will eventually timeout.

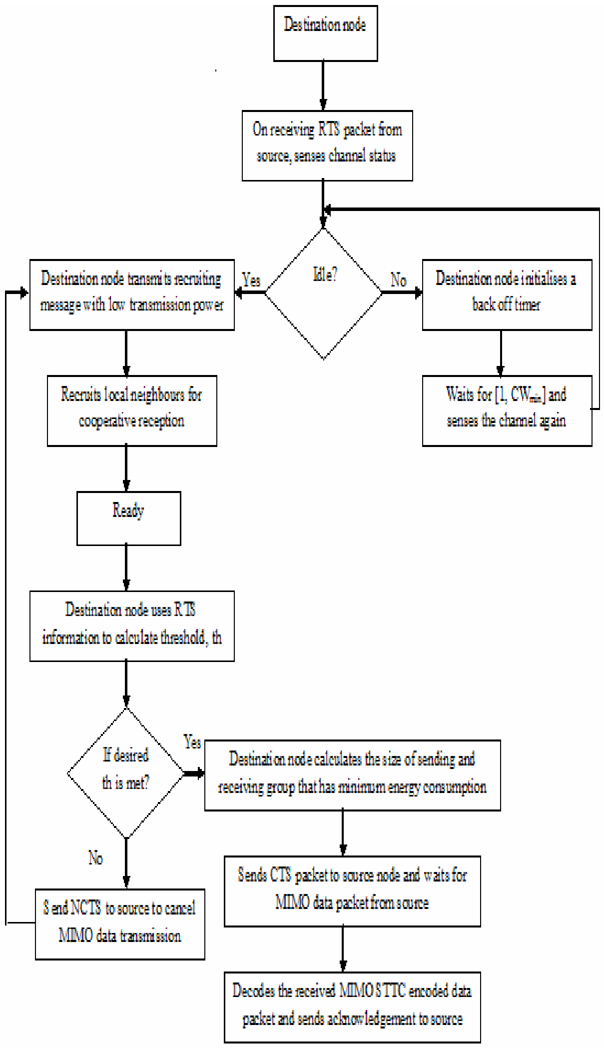

Fig.2. Flow chart of cooperative threshold based MAC protocol for destination node

The methodology to determine the threshold for the proposed MAC protocol is shown in Fig.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 STTC coding [16,17].

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., $\varphi(i)$ = $\varphi(1)$, $\varphi(2)$,…., $\varphi(K)$ 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)ξ < Q ≤ (K-i+1)ξ, where ξ is a positive integer. The threshold is set at 1 for Q > Kξ. For threshold i choosen, the possible set of S = (M, N) cluster sizes is obtained for which the packet delivery rate is greater than φ(i).

The destination node does an exhaustive search of the possible group sizes of M, N of φ(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.

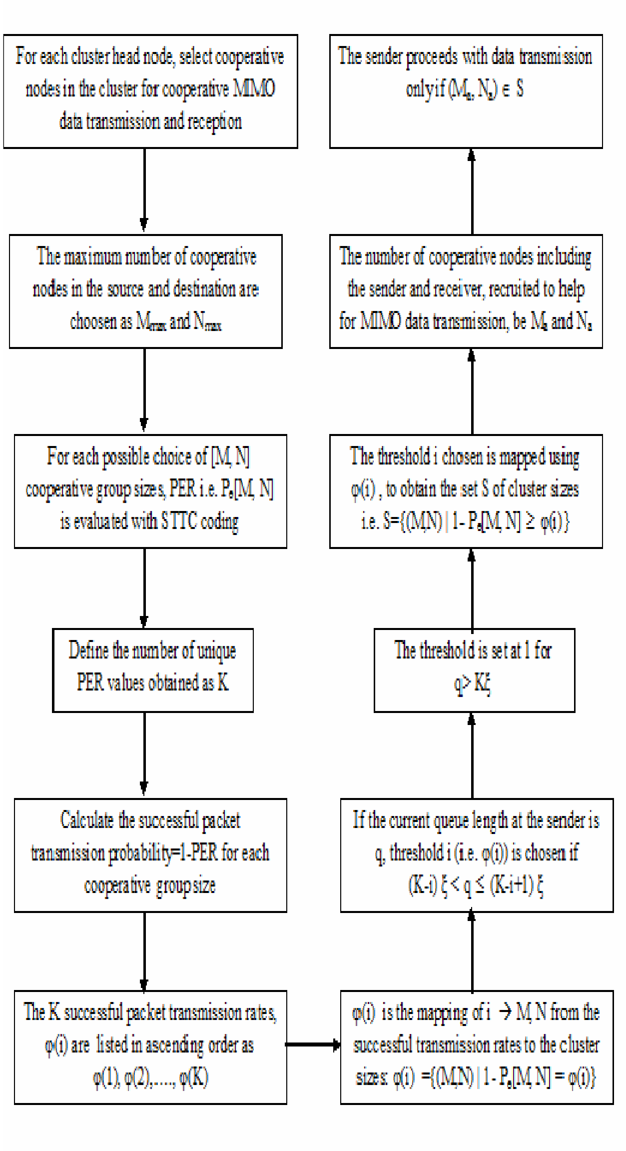

Fig.3. Flowchart of thresholding scheme for the proposed MAC protocol

3 Performance Analysis of the Proposed 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 initially during 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 node to the destination.

3.1 Error Probability

The system is assumed to transmit quadrature phase shift keying (QPSK) signals 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 [18,19] is given by

$$p_p = 1 - (1 - p_b)^L \tag{1}$$

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 does not forward the data packet when it is corrupted, the error from the source to its neighbours is not considered.

3.2 Energy Consumption Analysis

Consider a scenario with M senders and N receivers involved in cooperative MIMO transmission. The energy consumed for an unsuccessful transmission attempt and for a successful transmission from sending group to the receiving group using STTC MIMO MAC scheme are calculated to analyse the total energy consumption in a single hop [4,9].

The energy consumption for an unsuccessful transmission attempt is

$$Eu_{coop} = E_{mrts} + E_{mcts} + 2E_{rrts} + (M-1)E_{scts} + (N-1)E_{scts} + E_{br} + E_{data} + (N-1)E_{col} \quad (2)$$

and the energy consumption for a successful attempt is given by

$$Es_{coop} = E_{mrts} + E_{mcts} + 2E_{rrts} + (M-1)E_{scts} + (N-1)E_{scts} + E_{br} + E_{data} + (N-1)E_{col} + E_{ack} \quad (3)$$

where
E_{mrts} is the energy consumed in sending MIMO RTS
E_{mcts} is the energy consumed in sending MIMO CTS
E_{ack} is the energy consumed in sending ACK
E_{rrts} is the energy consumed in sending RRTS
E_{scts} is the energy consumed in sending SCTS
E_{col} is the energy consumed in data collection by the receiving group
E_{br} is the energy consumption of broadcasting data to the cooperative nodes in sending group
E_{data} is the energy consumption for data transmission between the sending group and receiving group

The MRTS and MCTS messages are control messages between source and destination and require higher transmission power for long distance transmission. The RRTS and SCTS are control messages between source/destination and their neighbours. Compared to the MIMO RTS and CTS, RRTS and SCTS can be transmitted with less power due to short-distance transmission. In the receiving group, each neighbouring node will transmit its signal back to the destination with energy E_{col} and there are N−1 cooperative nodes in the receiving group, excluding the destination node.

The total energy consumption for every one-hop transmission in cooperative MIMO STTC system is given by

$$E_M = \frac{p_M}{(1-p_M)} Eu_{coop} + Es_{coop} \quad (4)$$

where
p_M is the error probability obtained with STTC coding or uncoded scheme

3.3 Packet Transmission Delay

Each packet transmission in cooperative MIMO requires more steps which may increase the packet delays. However, the reduction in the packet error probability with cooperative MIMO MAC scheme reduces the occurrence of retransmissions which in turn reduces the packet delays.

The duration of transmission attempt that is successful with cooperative MIMO transmission is given by

$$Ts_{coop} = T_{rts} + T_{Br} + T_{cts} + T_{Bs} + T_{data} + T_{col} + T_{ack} \quad (5)$$

and the duration for an unsuccessful attempt is

$$Tu_{coop} = T_{rts} + T_{Br} + T_{cts} + T_{Bs} + T_{data} + T_{col} + T_{wait} \quad (6)$$

where
T_{rts} is the transmission time for the RTS
T_{cts} is the transmission time for the CTS
T_{ack} is the transmission time for the ACK
T_{data} is the transmission time for the data
T_{wait} is the duration for which sender waits for an ACK
T_{Br} is the transmission time of a recruitment message sent by the destination node
T_{Bs} is the transmission time required for the source node to send the data packet to its cooperating nodes
T_{col} is the time required by the cooperating receiving nodes to send the data to the destination.

The total packet delay for every one-hop transmission in cooperative MIMO system is given by

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

4 Simulation Results

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

The performance of the proposed fixed group size cooperative MIMO MAC protocol with STTC coding scheme is evaluated in terms of symbol error rate (SER), energy consumption and delay incurred in transmission of data packets from source to the destination node. The dynamic group size selected using the proposed threshoding scheme is determined based on the queue length at the sender. The performances of dynamic thresholding scheme are evaluated and compared with STTC and uncoded scheme.

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	0.027 J
Energy consumed for transmission of data	0.2 J
Modulation type	QPSK
Channel	Rayleigh fading channel with AWGN floor

4.1 Error Performance

The performance of the STTC system in terms of SER for various fixed cooperative sending and receiving group sizes is illustrated in Fig.4. The symbol error rate reduces considerably as the size of sending and receiving group increases. Cooperative 2x2 MIMO system requires 20 dB more signal power when compared with 4x4 MIMO system to achieve SER of 10^{-3}. This reduction in SER for larger group size is due to the exploitation of STTC coding gain and diversity gain.

4.2 Energy Analysis without Cooperative Threshold scheme

The energy consumption of different fixed cooperative node sizes at transmit and receive cluster using STTC scheme is evaluated in Fig.5. The performance of asymmetric MIMO configurations 2x3 and 3x2 are analysed and it is found that their energy consumption is midway between the values of 2x2 and 3x3 MIMO configurations. The power consumed per successful transmission is different for each case because of different SERs obtained in the system. 4x4 MIMO configuration produces 60% lesser energy consumption when compared to the 2x2 lower order system.

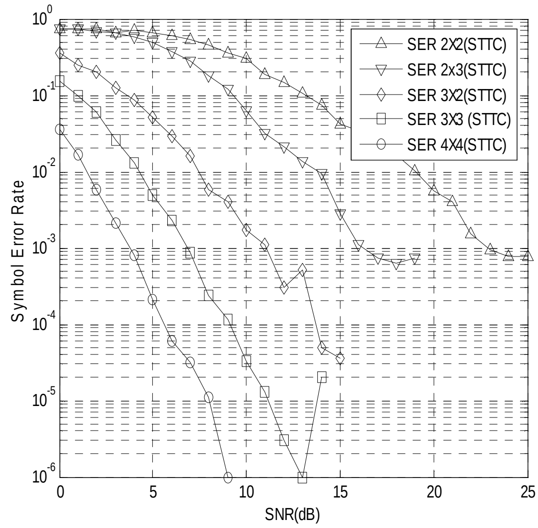

Fig.4. SER of STTC scheme for different diversity orders

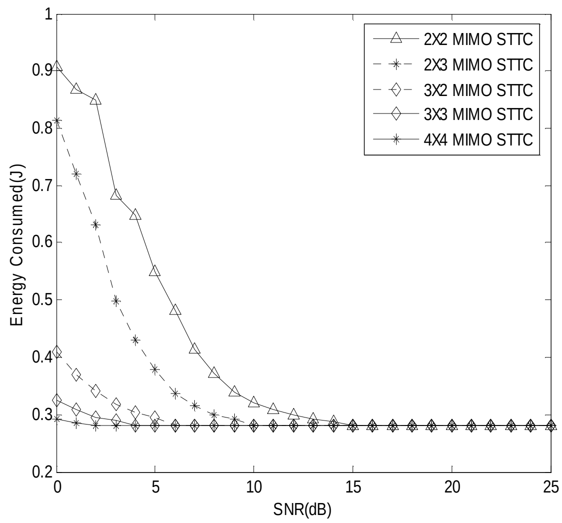

Fig.5. Energy analysis of STTC based cooperative MIMO MAC protocol

4.3 Delay Analysis without Cooperative Threshold scheme

Fig.6 illustrates the delay analysis of STTC based fixed group size cooperative MIMO MAC protocol for various orders of diversity. The delay incurred in the transmission of data reduces with the increase in the number of cooperative nodes both at transmit and receiver clusters by exploitation of the STTC coding gain. It is evident from the results that 4x4 STTC based cooperative MIMO MAC scheme incurs less delay of about 0.18 seconds over 2x2

MIMO configuration.

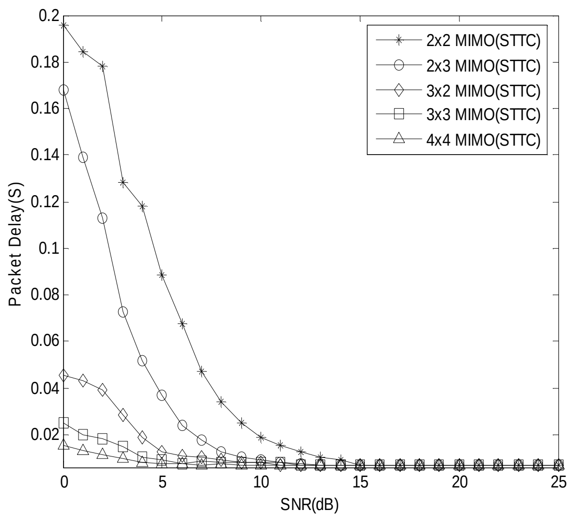

Fig.6. Delay analysis of STTC based cooperative MIMO MAC

4.4 Energy Analysis with cooperative Threshold scheme

The energy analysis of the proposed threshold based MAC protocol is shown in Fig.7. From the graph it is evident that by changing the cooperative threshold according to the queue length randomly generated at the sender, the dynamic group size selected for data transmission is 4x4 MIMO configuration.

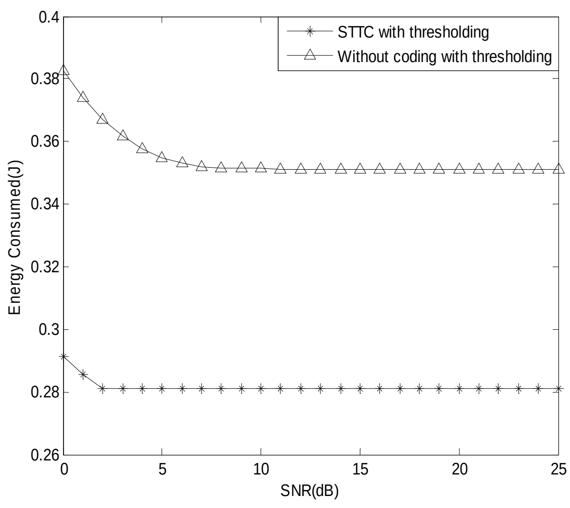

Fig.7. Energy analysis of uncoded scheme and STTC with threshold based MAC

Further more, the performance of uncoded system and STTC MIMO with cooperative threshold is shown in Fig.7. In case of uncoded system the energy consumption is larger than STTC by about 9%. This is due to high SER of the uncoded system. The use of coding technique reduces the error in data transmission leading to significant reduction in energy consumption.

4.5 Delay Analysis with Cooperative Threshold scheme

Fig.8 portrays the delay performance of the threshold based MAC protocol. It is vivid that the dynamic group size selected is 4x4 MIMO configuration with cooperative threshold. It minimises the time spent on waiting for the required number of nodes in retransmission. Futher more, it is observed that the packet delay of uncoded scheme is 32% more than the STTC scheme. The decrease in delay is due to less SER due to diversity gain and lesser retransmissions with STTC system.

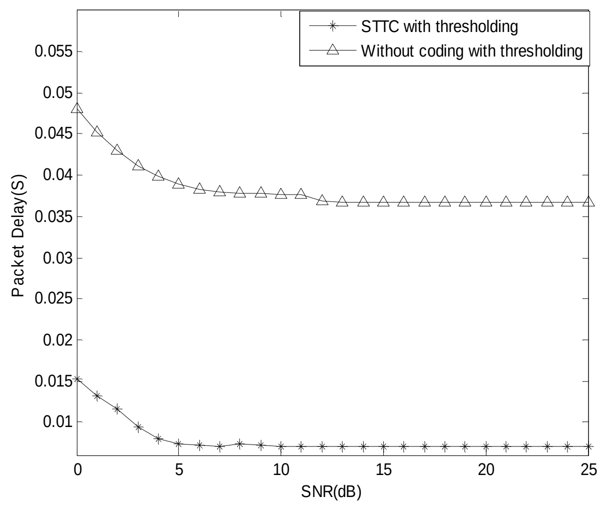

Fig.8. Delay analysis of uncoded scheme and STTC with threshold based MAC

5 Conclusion

A cooperative MIMO MAC protocol utilising STTC technique has been proposed to combat fading in wireless channels and maximise the sensor network lifetime. The performance of the proposed system is analysed in terms of SER, energy and delay for various orders of diversity for fixed group size cooperative MIMO. Results prove that as the diversity order increases, the system performance increases. Cooperative 4x4 MIMO systems provide 60% less energy consumption and 80% lesser delay than 2x2 MIMO scheme. This results from the reduction in SER and diversity gain of higher order MIMO configuration.

To further ensure the stability of transmission queue at the sender a threshold based MAC protocol was explored in WSN. The dynamic group size obtained with cooperative the cooperative threshold is 4x4. Simulation results show that STTC performs better and consumes 9% less energy for packet transmissions than uncoded scheme with cooperative threshold The delay incurred in data transmission with uncodded scheme is 32% more than MIMO MAC protocol utilising STTC. The significant reduction in delay and energy results from the diversity gain and lesser error probability rates achieved with the coded MIMO systems.

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