A MAC Protocol for Cooperative MIMO Transmissions in Sensor Networks

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***Abstract*— Cooperative MIMO can achieve higher energy saving and lower delay in distributed systems by allowing nodes to transmit and receive information jointly. In this paper, we develop a new MAC protocol for enabling packet transmissions using cooperative MIMO. The paper also develops analytical models for evaluating the packet error probability, energy consumption and packet delays associated with the proposed MAC protocol. The analysis is validated against simulation results using the NS-2 simulator. Our results show that the proposed MAC protocol has lower delays and lower energy consumption as compared to regular point to point MAC protocols.**

I. INTRODUCTION

Wireless sensor networks (WSNs) typically consist of a large number of energy constrained sensor nodes with limited on board battery resources which are difficult to recharge or replace. Protocols for WSNs are thus required to be energy efficient. Multi Input Multi Output (MIMO) systems [1] have been studied intensively in recent years due to their potential to dramatically increase the channel capacity and reduce transmission energy in wireless fading channels. Sensor nodes using MIMO techniques would require lower transmission power to achieve the same bit error rate (BER) as point to point communications. However, using multi-antenna techniques directly in sensor networks is impractical because of the limited size of a sensor, which can only support a single antenna. If cooperative transmissions from multiple nodes are allowed, the transmissions and receptions from antennas at different nodes can be used to construct a system fundamentally equivalent a traditional MIMO system. Cooperative MIMO schemes have been proposed for WSNs to improve communication performance in [2]. In the cooperative MIMO scheme, multiple single-antenna nodes cooperate on message transmission and reception for energy efficient communications.

While cooperative MIMO has the ability to improve the performance of WSNs, the distributed operation of sensors is a big obstacle in achieving the cooperative transmissions and receptions. The complexity of coordinating the actions of distributed nodes limits the practical use of cooperative MIMO in WSNs. Further, the energy and time spent in setting up the collaborative transmissions may diminish the performance gains of MIMO operation if the MAC protocol is inefficiently designed. To address these issues and make cooperative MIMO transmissions feasible with a high degree of improvement over point to point communications, this paper proposes a new MAC protocol. The protocol is applicable for scheduling cooperative MIMO transmissions in both wireless ad-hoc networks and distributed WSNs.

The contribution of this paper is that we develop a new protocol to facilitate cooperative MIMO transmissions and develop extensive analytic models to evaluate its performance. In this new MAC protocol, the transmission is separated into multiple steps and the source and destination nodes cooperate with neighboring nodes while transmitting and receiving. The performance of the protocol in terms of its transmission error probability, the energy consumption, delay performance and channel capacity are also analyzed. We show that the proposed cooperative MIMO MAC protocol can outperform point to point communications at low transmission powers. Our analysis has been verified by extensive simulations.

The rest of the paper is organized as follows. Section II describes the related work and section III presents the proposed MAC protocol. Analytic models to evaluate the proposed MAC protocol are presented in section IV. Validating simulation results and comparison with point to point communications are presented in Section V. Section VI concludes our paper.

II. RELATED WORK

The fundamental task of MAC protocols is to schedule transmissions from stations sharing the same channel and prevent collisions. MAC protocols for WSNs, because of energy constraints, also need to consider energy efficiency. Most current MAC protocols for WSNs use sleep-wake cycles to reduce the energy consumption because idle listening in wireless nodes is a major source of energy wastage [8]. However, sleep-wake schemes may not be appropriate for some applications because of the long packet delays when data arrive during a node's sleep state.

Current point to point communications use two major types of MAC protocols: contention based and collision free. In WSNs, the most popular contention based MAC protocol is SMAC [3]. In SMAC each node follows a sleep-wake cycle. In the wakeup state, each node first synchronizes with its neighbor nodes and then exchanges any information that it may have. The sleep state is used to reduce the energy consumption. For the collision free MACs, the LEACH architecture is widely used [4]. In such mechanisms, sensor nodes in a geographical region select a node amongst them as the cluster head and all other nodes are leaf nodes, and can only communicate with the cluster head in their cluster. Inside each cluster, cluster heads use TDMA to communicate with leaf nodes. Lower energy consumption can be further achieved by using sleep periods after the intra-cluster data transmission [5].

Cooperative MIMO needs several nodes to cooperate with each other for each data packet transmission. Thus the MAC

Algorithm 1 Cooperative MIMO MAC Protocol

```
STATE: IDLE: node is idle and listen to the channel
if Packet ready to send then
    go to algorithm 2
end if
if receive RTS packet then
    go to algorithm 3
end if
if receive BCASTdata packet then
    go to algorithm 4
end if
if receive BCASTrecv packet then
    go to algorithm 5
end if
```

protocol needs to consider the state of multiple distributed nodes. Although SMAC is distributed and uses the CSMA/CA mechanism [7], it is unable to coordinate cooperative transmissions of the same data from multiple nodes. Clustering architectures such as LEACH [4] may also be extended for the cooperative MIMO operation in [6]. However the centralized architecture leads to energy wastage in cluster maintenance and also introduces additional coordination delays when a packet needs to be cooperatively transmitted by one node in the cluster.

In contrast to existing literature, we propose a distributed MAC protocol for cooperative MIMO transmissions. The protocol is easy to deploy and is shown to perform better than traditional point to point protocols.

III. PROTOCOL DESCRIPTION

The MAC protocol proposed in this paper combines the distributed implementation of CSMA/CA type MAC protocols with the cooperation advantage of cluster based MAC protocols. The RTS/CTS mechanism is used to establish the connection between the source and destination nodes and clustered communications are used to transmit data. We do not use the sleep state in our MAC protocol to ensure that cooperative nodes are available when a node has to transmit or receive and also to satisfy the delay requirements of time critical applications.

The basic structure of the proposed protocol is given in Algorithm 1. A node may respond to four types of events. In case the node gets a data packet to send (i.e. it is the source node), its operation is shown in Algorithm 2. The node starts by sending a RTS packet to the destination after sensing the channel is idle. If a CTS packet is received, the source first transmits a copy of the data packet at low power so that nodes around it also have the data and synchronizes them (using a sending timer) to cooperatively send this data packet together at a later time. If an ACK is not received for the data packet, the whole process is repeated.

The operation of the destination node is shown in Algorithm 3. On receiving the RTS packet, if the channel is idle, it first broadcasts a low power message to recruit its neighbors to help in the reception. It then sends a CTS packet to the source node and waits for the data packet.

Algorithm 2 Node is the source

```
STATE: RTS node sends RTS packet
if CTS not received then
    repeat STATE: RTS
end if
STATE: BCASTdata send data to transmitting group with low power; set sending timer
STATE: Data send MIMO data when the timer expires
if receive ACK packet then
    go to STATE:IDLE
else
    go to STATE:RTS
end if
```

Algorithm 3 Node is the destination

```
STATE: BCASTrecv broadcast recruiting packet with low power
STATE: CTS send CTS packet
if MISO data received then
    go to STATE: Collection
else
    go to STATE: IDLE
end if
STATE: Collection set timer to wait for receiving group nodes to send packet
if packet not received correctly then
    go to STATE: IDLE
end if
STATE: ACK send ACK packet
go to STATE: IDLE
```

Idle nodes on the sender's side who receive a copy of the data packet and synchronization message participate in the cooperative MIMO transmission as outlined in Algorithm 4. The sending group comprising of these nodes and the source node transmit together when the sending timer expires. This cooperative transmission from multiple nodes can be treated as multiple transmitting antennas at each receiving node and an equivalent MISO system can be constructed. Each node in the cooperative receiving group receives the data packet and forwards it to the destination after a random backoff, completing the MIMO operation as shown in Algorithm 5. The destination does the final decoding of the packet based on all the received copies of the message from its cooperative nodes.

IV. PERFORMANCE ANALYSIS OF COOPERATIVE MIMO MAC PROTOCOL

In this section we first develop a model for evaluating the packet error rates with cooperative MIMO transmissions and then present models to evaluate the packet delay, energy consumption and channel capacity.

A. Bit Error Rate

In this section, we develop the BER, p_b, in cooperative MIMO networks. The packet error probability, p_p, can be

Algorithm 4 Cooperative sending node

```
STATE: Cooperative Sending nodes transmit data packet when sending timer expires
go to STATE: IDLE
```

Algorithm 5 Cooperative receiving nodes

```
STATE: Cooperative Receiving set expiration timer
if MISO data packet received then
    go to STATE: Collection
else
    go to STATE: IDLE after expiration timeout
end if
STATE: Collection send data to destination after random backoff
go to STATE: IDLE
```

easily derived from the BER. If no FEC codes are used, the relationship between p_p and p_b is given by

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

where L is the frame length in bits. In regular point to point communications, the data errors are generated at the path from the source to the destination. However, data transmission errors will be generated from two factors in cooperative MIMO: 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 if it is corrupted, the error from the source to its neighbors will not be considered.

Theoretical BER in a wireless channel is a function of the signal to noise ration (SNR) which is given by

$$SNR = \frac{P_r}{P_N} = \frac{E_b R_b}{N_0 B} \tag{2}$$

where P_r is the reception power, P_N is the noise power, E_b is the reception power per bit, N_0 is the noise power density, R_b is the data transmission rate, and B is the bandwidth. Higher transmission power will increase the reception power P_r, so as to increase E_b. In the contention based MAC protocol 802.11b, $R_b = 2Mbps$, and $B = 2MHz$, so $SNR = \frac{E_b}{N_0} \times 1bps/Hz$.

In our model, the error is generated from two steps: from sending group to the nodes in receiving group and from the receiving nodes to the destination node. In cooperative MIMO, the cooperative sending nodes use the same amount of power. Since space-time codes are not used, each sensor node will send the same data packet to each node in the receiving group at the same time. A combination of these transmissions will be detected at each receiving node which can be considered as a MISO scenario. The error rate for cooperative sending to the receiving node $p_{e_{M\_1}}$ will be related to the power summation from multiple signal transmission paths. Because different fading characteristics may occur in different signal transmission paths, each sending node will have a different effect on the receiving node. In addition to the $p_{e_{M\_1}}$ in each route, the error from one receiving node to the destination $p_{e_{pp}(dst)}$ will also contribute the overall route error. The error rate in each route is given by

$$p_e = p_{e_{M\_1}} + p_{e_{pp}(dst)} - p_{e_{pp}(dst)} p_{e_{M\_1}(recv)} \tag{3}$$

The data packet flows arrive at the destination node from multiple routes. We use a simple decision rule at the destination node when multiple data packets are received: the decision will be made according to the most reception routes giving the same results. For example, in a scenario with three receiving routes in the receiving group, if more than one node gives the same reception, this reception will be taken as the right reception. In case of a tie, the destination node will take its own reception as the right reception. If each receiving node in the receiving group has the same BER, the BER in the destination node after the reception from the N nodes forming the reception group is:

$$p_{e_{M\_N}} = \sum_{i=N/2}^{N} \binom{N}{i} p_e^i (1 - p_e)^{N-i} \tag{4}$$

The error rate function depends on the modulation, channel coding scheme and channel model. To illustrate the derivation process, we consider the case of BPSK modulation under Rayleigh fading channel without using space time or channel codes. Other modulation and coding schemes or channel models will show the same trend. In the Rayleigh fading channel with BPSK modulation, the BER for a receiving node is

$$\hat{p_e}(\gamma_b) = Q(\sqrt{2\gamma_b}) \tag{5}$$

where γ_b is the SNR at specific time. In point to point communications it is given by

$$\gamma_{bpp} = \frac{P_t \lambda^2}{d^\alpha N_0} \tag{6}$$

where P_t is the transmission power and d and λ are the distance and fading gain from the sending node to the receiving node. The path loss constant α is between 2 and 4. The PDF of γ_{bpp} is

$$p(\gamma_{bpp}) = \frac{1}{\bar{\gamma_{bpp}}} \exp^{-\frac{\gamma_{bpp}}{\bar{\gamma_{bpp}}}} \tag{7}$$

and if we assume $E[\lambda^2] = 1$, then the value of $\bar{\gamma_{bpp}}$ is

$$\bar{\gamma_{bpp}} = E[\lambda^2] \frac{P_t}{N_0 d^\alpha} = \frac{P_t}{N_0 d^\alpha} \tag{8}$$

The mean value of the BER is then

$$p_{bpp} = E[Q(\sqrt{2\gamma_{bpp}})] \tag{9}$$

Using the Chernoff bound

$$\begin{aligned} Q(\sqrt{2\gamma_{bpp}}) &= p(x \geq \sqrt{2\gamma_{bpp}}) \leq e^{-\gamma_{bpp}} \\ E[Q(\sqrt{2\gamma_{bpp}})] &\leq E[e^{-\gamma_{bpp}}] \end{aligned} \tag{10}$$

The moment generating function of γ_{bpp} is

$$\Phi(S) = E[e^{\gamma_{bpp}S}] = \frac{1}{S\bar{\gamma}_{bpp}}$$

$$p_{bpp} \leq E[e^{-\gamma_{bpp}}] = \Phi(-1) = \frac{1}{1+\frac{P_t}{N_0 d^{\alpha}}} \tag{11}$$

If there are M nodes in the sending group that send the same message, the BER at each node in the receiving group can be obtained from Eqn. (5), and the SNR is given by

$$\gamma_{bM} = \sum_{i=1}^{M} \lambda_{ij}^2 \frac{P_t}{N_0 d_{ij}^{\alpha}} = \sum_{i=1}^{M} \gamma_{ij} \tag{12}$$

where λ_{ij}, d_{ij} and γ_{ij} are fading gain, distance and SNR from node i in sending group to the node j in receiving group. Assuming $E[\lambda_{ij}^2] = 1$, the PDF of γ_{ij} is

$$p(\gamma_{ij}) = \frac{1}{\bar{\gamma}_{ij}} \exp^{-\frac{\gamma_{ij}}{\bar{\gamma}_{ij}}} \tag{13}$$

$$\bar{\gamma}_{ij} = E[\lambda_{ij}^2]\frac{P_t}{N_0 d_{ij}^{\alpha}} = \frac{P_t}{N_0 d_{ij}^{\alpha}} \tag{14}$$

The moment generating function of γ_{bM} is given by

$$\begin{aligned} \Phi(S) = E[e^{\gamma_{bM}S}] &= \prod_{i=1}^{M} \frac{1}{S\bar{\gamma}_{ij}} \\ p_{b_{M\_1}} \leq E[e^{-\gamma_b}] &= \Phi(-1) = \prod_{i=1}^{M} \frac{1}{1+\frac{P_t}{N_0 d_{ij}^{\alpha}}} \end{aligned} \tag{15}$$

When nodes in the receiving group get a data packet, they will forward it to the destination node. The BER in this path can be modeled as a point to point transmission, which is given by Eqn. (11). Using the result of Eqn. (3), the overall error rate bound in each route consisting of the transmission from the nodes in the sending group to the destination node through one of the nodes in the receiving group is given by

$$\begin{aligned} p_e &= \prod_{i=1}^{M} \frac{1}{1+\frac{P_t(mimo)}{N_0 d_{ij}^{\alpha}}} + \frac{1}{1+\frac{P_t(dst)}{N_0 d_{jD}^{\alpha}}} \\ &\quad - \prod_{i=1}^{M} \frac{1}{1+\frac{P_t(mimo)}{N_0 d_{ij}^{\alpha}}} \frac{1}{1+\frac{P_t(dst)}{N_0 d_{jD}^{\alpha}}} \end{aligned} \tag{16}$$

where d_{jD} is the distance from node j in receiving group to the destination node, and the transmission power is $P_t dst$.

Using the value of p_e from Eqn. (16) in Eqn. (4), we obtain the overall BER at the destination node. In Figure 1, we compare the BER of various systems. The corresponding packet error probabilities can be easily obtained from Eqn. 1. The total transmission power of the cooperative MIMO system was kept the same as the point to point system. Thus if the transmission power in the 1×1 system is P_t, the transmission power of each node in the 2×2 and 4×4 system was $\frac{P_t}{2}$, and $\frac{P_t}{4}$ respectively.

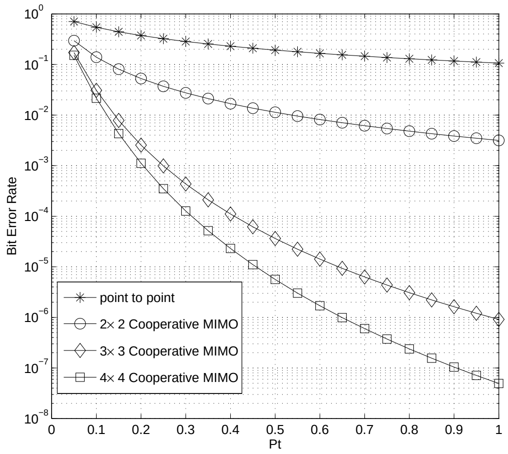

Fig. 1. Bit error rate with different transmission power

B. Energy Consumption

Compared to a regular point to point CSMA/CA based MAC protocol, cooperative MIMO MAC requires more steps to complete a successful packet transmission. But it achieves a higher successful packet transmission probability for a given transmission power. In the other words, in order to get the same successful packet transmission probability, cooperative MIMO will require less power. In this section, we compare the energy consumption of these two kinds of MAC protocols.

The energy consumed by a sensor node for communications consists of two parts: energy spent on running the circuits P_c and the transmission energy P_t. While the same energy is spent on running the circuits irrespective of whether the node is transmitting, receiving or idle listening [8], the transmission energy is spent only during packet transmissions. While comparing the energy consumption of point to point with cooperative MIMO systems we can thus ignore the circuit power and only compare the transmission energy consumed by the nodes. This is because the circuit power of the nodes in the point to point system that are not transmitting is the same as that of nodes transmitting in the MIMO system.

MAC layer reliability ensures that if a corrupted packet is received, it is retransmitted. For the regular CSMA/CA protocol, the energy consumed for an unsuccessful transmission attempt is $E_{u\_p} = E_{rts} + E_{cts} + E_{data\_pp}$, and that for a successful attempt is $E_{s\_p} = E_{rts} + E_{cts} + E_{data\_pp} + E_{ack}$. Here E_{rts}, E_{cts}, E_{ack} and E_{data_pp} are the energy consumed while sending RTS, CTS, ACK and point to point data. p_{pp} denotes the packet error probability which can be obtained from the previous section. The expected energy consumption is

$$\begin{aligned} E_{pp} &= (1-p_{pp})E_{s\_p} + p_{pp}(1-p_{pp})(E_{u\_p}+E_{s\_p}) \\ &\quad + {p_{pp}}^2(1-p_{pp})(2E_{u\_p}+E_{s\_p}) + \cdots \\ &= \frac{p_{pp}}{1-p_{pp}}E_{u\_p} + E_{s\_p} \end{aligned} \tag{17}$$

where we have considered CSMA/CA without collisions as is likely in sensor networks where loads are typically low.

Consider a scenario with M senders and N receivers involved in a cooperative MIMO transmission. The energy consumption in a transmission attempt that is successful is $E_{s\_M} = E_{rts} + E_{B_R} + E_{cts} + E_{B_S} + ME_{data\_M} + (N-1)E_{col} + E_{ack}$. In case the transmission is unsuccessful, the energy consumed is $E_{u\_M} = E_{rts} + E_{B_R} + E_{cts} + E_{B_S} + ME_{data\_M} + (N-1)E_{col}$. While E_{rts}, E_{cts}, E_{ack} here have the same meanings as in the point to point case, E_{data_M} is the transmission power for transmitting data. E_{B_R} is the energy which the destination sends the recruiting message to its neighbors and E_{B_S} is the energy which the source sends the data message to its cooperative neighbors. Finally, E_{col} is the energy spent while the destination collects the message from cooperating receivers. With p_M denoting the packet error probability, the energy consumption of the cooperative MIMO MAC for a packet transmission is similar to Eqn. (17), and is

$$E_M = \frac{p_M}{1-p_M} E_{u\_M} + E_{s\_M} \tag{18}$$

C. Packet Transmission Delay

As noted earlier, 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 reduces the incidence of retransmissions which in turn reduce the packet delays in comparison to point to point MAC protocols.

For point to point communications, T_{rts}, T_{cts}, T_{data} and T_{ack} are the transmission time for the RTS, CTS, data and ACK packets. The time associated with a successful transmission attempt is $T_{s\_p} = T_{rts} + T_{cts} + T_{data} + T_{ack}$, and the time for an unsuccessful attempt is $T_{u\_p} = T_{rts} + T_{cts} + T_{data} + T_{wait}$, where T_{wait} is the duration for which the sender waits for an ACK. The packet delay is then

$$\begin{aligned} T_{dpp} &= (1-p_{pp})T_{s\_p} + p_{pp}(1-p_{pp})(T_{u\_p} + T_{s\_p}) \\ &\quad + {p_{pp}}^2(1-p_{pp})(2T_{u\_p} + T_{s\_p}) + \cdots \\ &= \frac{p_{pp}}{1-p_{pp}} T_{u\_p} + T_{s\_p} \end{aligned} \tag{19}$$

For the cooperative MIMO MAC, in addition to T_{rts}, T_{cts}, T_{data} and T_{ack} as above, T_{B_R} is the transmission time of a recruitment message sent by the destination node, T_{B_S} is the transmission time required for the source node to send the data packet to its cooperating nodes and T_{col} is the time required by the cooperating receiving nodes to send the data to the destination. The duration of a transmission attempt that is successful is then $T_{s\_M} = T_{rts} + T_{B_R} + T_{cts} + T_{B_S} + T_{data} + T_{col} + T_{ack}$, and the duration of an unsuccessful attempt is $T_{u\_M} = T_{rts} + T_{B_R} + T_{cts} + T_{B_S} + T_{data} + T_{col} + T_{wait}$. The expected packet delay is similar to Eqn. (19), and given by

$$T_{d\_M} = \frac{p_M}{1-p_M} T_{u\_M} + T_{s\_M} \tag{20}$$

D. Capacity Analysis

The standard expression for the Shannon capacity is

$$C = Wlog_2\left(1 + \frac{S}{N}\right) \tag{21}$$

where C is the channel capacity, W is the bandwidth, and $\frac{S}{N}$ is the SNR at the receiving node. In the point to point case, the channel capacity is then given by

$$C_{pp} = Wlog_2\left(1 + \frac{P_t}{WN_0}\frac{\lambda^2}{d^\alpha}\right) \tag{22}$$

where P_t is the transmission power and d and λ are the distance and fading gain, respectively.

We calculate the channel capacity of our cooperative MIMO MAC in three steps. First, the channel capacity for the broadcast to form the sending group can be obtained by using the SIMO channel model approximation. If there are M nodes in the sending group with d_{Si} and ${\lambda_i}^2$ being the distance and the fading gain from the source to node i in the sending group, $1 \leq i \leq M-1$, the capacity of this step is

$$C_1 = Wlog_2\left(1 + \frac{P_{t(src)}}{WN_0(M-1)}\sum_{i=1}^{M-1}\frac{{\lambda_i}^2}{d_{Si}^\alpha}\right) \tag{23}$$

In the cooperative transmission step, all sending group members transmit at the same time. Each channel is assumed to be independent. So for each receiving node j in a cooperative receiving group with N nodes, the channel is MISO. Since the overall transmission power is the same as in point to point communications, the channel capacity is

$$C_{2j} = Wlog_2\left(1 + \frac{P_t}{WN_0M}\sum_{i=1}^{M}\frac{{\lambda_{ij}}^2}{d_{ij}^\alpha}\right) \tag{24}$$

where d_{ij} and λ_{ij} are the distance and fading gain from sending node i to receiving node j. The capacity in the second phase is then

$$C_2 = \sum_{j=1}^{N} C_{2j} \tag{25}$$

In the third phase, data is collected from the cooperative receiving nodes by the destination node. The channel capacity for each path from node j to the destination is

$$C_{3j} = Wlog_2\left(1 + \frac{P_{t(dst)}\lambda_{jD}^2}{WN_0(N-1)d_{jD}^\alpha}\right) \tag{26}$$

Since each cooperative receiving node returns the message to the destination separately, the capacity in the third phase is

$$C_3 = \frac{1}{\sum_{j=1}^{N-1}\frac{1}{C_{3j}}} \tag{27}$$

Combining the three steps, the channel capacity is

$$C_{CoMIMO} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} \tag{28}$$

The channel capacity comparisons between the cooperative MIMO MAC and point to point MAC is shown in Figure 2. At low powers, cooperative MIMO achieves much higher capacity as compared to the point to point case.

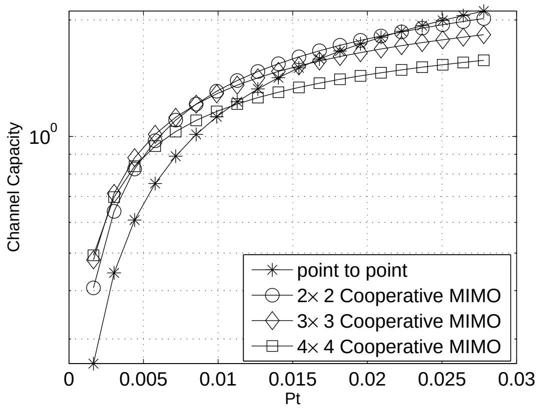

Fig. 2. Channel capacity comparison in different networks

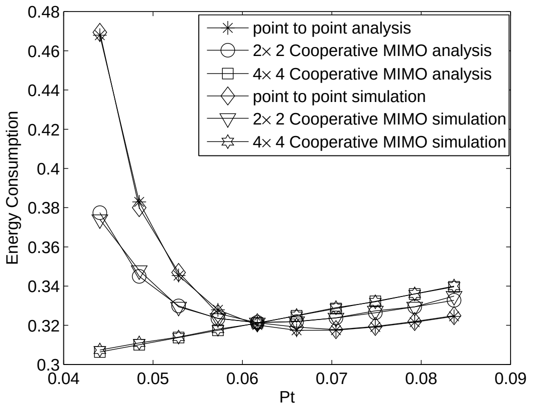

Fig. 3. Energy consumption comparison in different networks

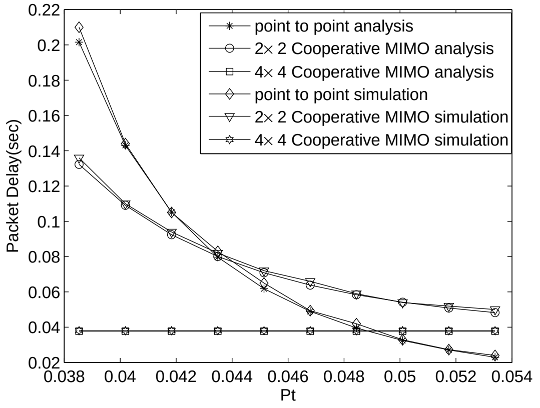

Fig. 4. Packet delay comparison in different networks

V. SIMULATION RESULTS

In this section, we validate our analytic results using NS-2 simulations and compare the performance of the proposed MAC protocol with point to point communications. Different transmission powers result in different packet error probabilities, and thus different retransmission rates. In order to compare the performance fairly, we set the overall transmission powers of both protocols to be the same. So if the transmission power of each sending node in a 1×1 network is P_t, the transmission power of each sending node in 2×2 and 4×4 networks will be $P_t/2$ and $P_t/4$ respectively. Since collisions also affect the performance of contention based MAC protocols, we will only compare the performance without retransmissions resulting from collisions.

Figure 3 shows the energy consumed by cooperative MIMO and point to point communications for a simulation of 6000 seconds. The packet arrival rate was kept at 0.32 packets per second in order to eliminate the effect of collisions. We observe that the proposed MAC protocol leads to significant energy saving at low transmission powers. This advantage is nullified if the transmission power is increased since considerable energy is now spent on establishing the cooperative mechanism. However, sensor nodes are expected to operate with as low energy as possible and in these scenarios, the proposed MAC protocol is superior to point to point communications.

Figure 4 compares the delays associated with the protocols when the packet size is kept at $1024 bits$. Defaults NS-2 values were used for CSMA/CA (using 802.11) with $T_{rts} = 3.53e-004sec$, $T_{cts} = 3.05e-004sec$, $T_{ack} = 3.2e-004sec$, $T_{data} = 0.006sec$ and $T_{wait} = 0.07sec$. We also set $T_{B_R} = 6.9000e-004sec$, $T_{B_S} = 0.0077sec$, and $T_{col} = 0.0223sec$ in our new MAC protocol. We note that the cooperative MIMO MAC has lower delays when low transmission power is used.

VI. CONCLUSION

This paper presents a new cooperative MIMO MAC protocol for sensor networks. We also develop an analytic model to evaluate the associated packet error probability or retransmission rates. These result are then used to evaluate the energy consumption, delays and channel capacity associated with the proposed MAC protocol. Simulation results are used to validate our analysis and to show that the proposed MAC protocol for cooperative MIMO achieves lower energy consumption and packet delays over traditional point to point communications at low transmission power regimes.

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