Cooperative Communication to Improve Reliability and Efficient Neighborhood Wakeup in Wireless Sensor Networks

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***Abstract*—To maximize lifetime of Wireless Sensor Networks, medium access control protocols usually trade off reliability for energy efficiency. Channel errors, collisions, idle listening, and overhearing further aggravate the problem. Our work investigates opportunities to improve reliability in Wireless Sensor Networks under such constraints. We consider a multi-hop data gathering network in which sensor nodes are deployed around a sink. Nodes periodically sense data and forward it to next hop nodes. For such a network, a Medium Access Control protocol, called CPS-MAC, is proposed. This protocol uses cooperative communication to improve reliability by using overhearing to its advantage. In conventional protocols, overhearing causes nodes to receive packets which are not meant for them. Therefore, these packets are discarded and considered a waste of energy. On the contrary, CPS-MAC intentionally wakes up next 1-hop and 2-hop neighbors to improve their chances of overhearing a packet. The overheard packets are buffered and then relayed to the next hop neighbor, combating channel fading by a cooperative spatial diversity gain. By combining multiple copies of the same packet, next hop neighbor is more likely to recover the original packet. Design challenges such as efficiently waking up neighborhood nodes, minimizing energy overhead, and partner selection are addressed. Simulation results show that CPS-MAC significantly decreases packet error rate without expending additional energy.**

***Keywords*—Wireless Sensor Networks; Media Access Control; Cooperative Communication; Reliability.**

I. INTRODUCTION

Wireless sensor networks (WSN) are used in a wide range of applications, such as target tracking, habitat sensing and fire detection. WSN are particularly useful in situation where an infrastructure network is not present or not feasible. In such conditions, sensor nodes can be deployed around a sink to create a multi-hop data gathering network as shown in Figure 1. The nodes coordinate locally to forward each other packets. The packets travels in a hop-by-hop fashion towards the sink.

As sensor nodes are battery powered, they operate under strict energy constraints. Common WSN protocols such as S-Mac, T-MAC and CSMA-MPS trade off performance for energy efficiency [18], [22]. The nodes use low transmission powers and switch the transceiver between sleep and awake states. Fading and the broadcast nature of the wireless channel results in channel errors, collisions, and overhearing due to which these networks drop a significant proportion of packets.

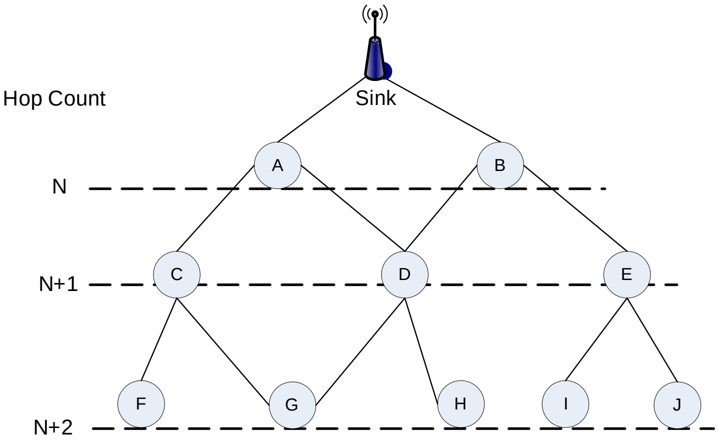

Fig. 1. Data gathering network

Signal fading can be the most severe among these impairments. In a wireless channel, random scattering from reflectors with different attenuation coefficients results in multiple copies of a transmitted signal arriving (and interfering) at a receiver with different gains, phase shifts, and delays. These multiple signal replicas can add together in a constructive or destructive way, amplifying or attenuating the received signals amplitude. Destructive interference results in fading, which causes temporary failure of communication, as the amplitude of the received signal may be low to the extent that the receiver may not be able to distinguish it from thermal noise.

Under such conditions, ensuring reliable communication while conserving energy is a challenging problem. This has motivated us to design Cooperative Preamble Sampling Medium Access Control (CPS-MAC) protocol which can improve reliability without expending additional energy. Our protocol takes advantage of overhearing. Overhearing means that a node will receive all messages in its reception range including those that are intended for other nodes. Considered problematic, specially in dense WSN, these packets are usually discarded and this wastes energy.

We suggest using cooperative communication (CC) [3] to take advantage of these overhead packets. In CC, nodes cooperate to improve the overall performance of the network.

Since a transmission in the wireless channel is overheard by neighboring nodes, these nodes can process the overheard packets and re-transmit them [4]. Figure 2 elaborates a 3-node CC scenario. We refer to this as a cooperative triangle, which consists of a source, partner, and destination node. Destination node here refers to the next-hop node in the cooperative triangle and is used in the same context throughout this paper.

We exemplify a possible realization of a cooperative communication scheme as follows (for alternatives, see [8], [12]–[14]). The source broadcasts a message to the destination in a first phase. Due to the broadcast nature of the wireless channel, the partner station can overhear the source transmission, decode it, and if received correctly, forwards it to the destination in a second phase. We refer to this two phase scheme as one transmission cycle. By combining different copies of the same transmission by source and partner stations, the destination can improve its ability to decode the original packet and exploit spatial diversity and robustness against channel variations due to fading.

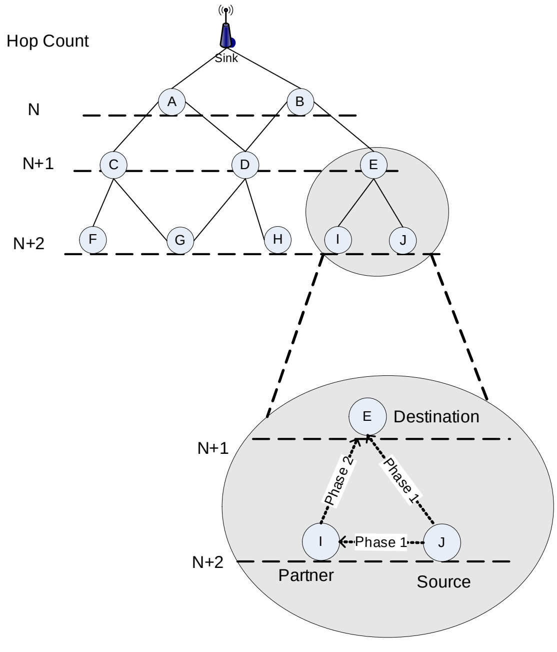

Fig. 2. Cooperative Communication

We propose to realize this concept at the Medium Access Control (MAC) layer, which is responsible for radio usage and scheduling transmission efficiently. Although CC has already been investigated at the MAC layer for traditional wireless networks such as wireless LANs (WLAN) based on the IEEE802.11 standard [8], [9], [13]–[15], integrating CC into MAC layer for WSN has received little attention. It is important to mention here that MAC protocols for WSN differ significantly from MAC protocols for WLAN. In WLAN optimization of performance parameters such as throughput, latency, and fairness is a primary concern. In WSN energy conservation and extending lifetime is essential. Details can be found in Section II.

We briefly outline the challenges faced in developing CC based MAC protocols for WSN, along with solutions proposed in CPS-MAC.

1) MAC protocols such as X-MAC try to conserve energy by maximizing the sleep duration of the nodes [17]. CC on the other hand increases energy expenditure by requiring nodes to be awake more often. In such a situation, improving reliability and conserving energy may seem counter intuitive. CPS-MAC compensates for the additional energy expenditure by reducing the time needed to wake up neighboring nodes and by achieving lower packet error rates.
2) Application of CC in densely deployed WSN can result in multiple nodes overhearing and forwarding a packet and flooding part of the network. In such situations, it could be practical to limit the number of nodes taking part in CC and avoid redundant transmission and energy wastage. For this CPS-MAC includes an addressing scheme which allows source node to select partner and destination prior to transmission. For this, CPS-MAC includes an addressing scheme which attempts to limit one transmission cycle to three nodes and minimizing the number of nodes unnecessarily overhearing the transmission.
3) Under ordinary conditions data would travel in a hop-by-hop fashion during each transmission. Narayanan et al. [10] and Zhu et al. [11] have shown that two-hop forwarding leads to higher total network throughput. Therefore, CPS-MAC attempts to deliver a packet over multiple hops in a single transmission cycle as shown in Figure 3. Notice here that Figure 3 differs from Figure 2. This multi-hop transfer in a single transmission cycle consumes less energy then several single-hop transfers. The protocol uses hop count parameter for this purpose and is explained in section III in detail.

Details of CPS-MAC are presented in Section III.

II. BACKGROUND

A. Medium Access Control in Wireless Sensor Networks

MAC protocols in WSN conserve energy by duty cycling radio which is the main source of energy consumption. Several MAC protocols for WSN have been proposed in recent years, which optimize duty cycle depending upon underlying application requirement and traffic behavior [22]. They can be divided into two main categories namely schedule-based and contention-based.

The schedule-based approach requires nodes to synchronize at some common time of reference such that they can wake up collectively prior to transferring. This approach may seem attractive at first glance because idle-listening and overhearing simply do not occur. However, the need to synchronize sleeping schedules and the control packet overhead make them less feasible. Ideally, a MAC protocol in WSN does not impose a high overhead for exchanging control information. Otherwise, a significant amount of energy will be consumed for it.

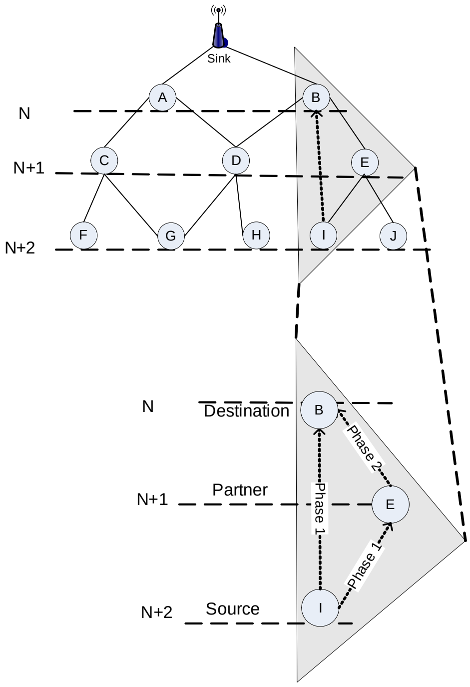

Fig. 3. Cooperation over multiple hops

Contention-based schemes on the other hand does not require synchronization of sleep schedules and are more flexible to handling variable traffic loads [1]. However in such schemes, nodes who wish to transmit must content for the channel and the winner transmits at the risk of collision. Accordingly, these protocols contain mechanism to avoid or to minimize the probability of collisions.

Preamble sampling is one such protocol which is specifically designed for WSN [16] and is particularly useful when the traffic generation is non-periodic. Figure 4 shows the working of the protocol. Nodes switch between sleep and listen (awake) states. When a sender has data to send, it wakes up the receiver by sending a preamble which is longer than the sleep duration of the receiver node. When a receiver node wakes up and switches its radio to listen state, it hears the preamble, uses it to synchronize with the source, and stays awake for incoming transmission. Then, the source initiates the transmission at the end of the preamble. After the transmission is complete, nodes resume duty cycling. As the cost (energy) of waking up is transfered from receiver to sender, and there are more receivers than senders, a lot of energy is saved.

To shorten the preamble length and further minimize energy consumption at both sender and receiver, an improvement to Preamble Sampling was proposed in [17] and [18]. This scheme is known as Minimum Preamble Sampling (MPS) and is shown in Figure 5. Here one long preamble is divided into a series of short preambles interleaved with listening intervals. We refer to these listening intervals as inter-preamble spacing. If a receiving node wakes up and hears the short preamble, it sends an acknowledgment (ACK) packet to the sender during the inter-preamble spacing. Upon receiving the ACK, the sender initiates the data transmissions.

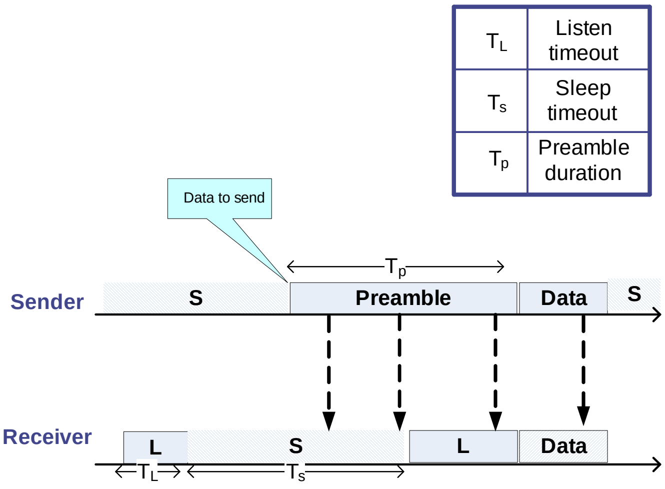

Fig. 4. Preamble Sampling

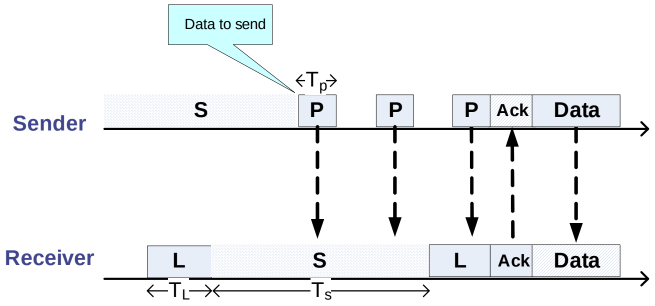

Fig. 5. Minimum Preamble Sampling

B. Medium Access Control Protocols for Cooperative Communication

A significant amount of work has been done on developing CC protocols in wireless networks to combat the effects of channel fading. The initial work focused on physical layer schemes [2], [6]. However, in order to realize the full potential of cooperative communication, it is imperative that the layer directly above the physical layer, namely the medium access control (MAC) layer, must be able to schedule transmissions effectively and efficiently. This has led researchers to investigate the support of cooperative communication in various forms at higher protocol layers including MAC layer [7]. A MAC protocol called CoopMAC illustrates how the legacy IEEE 802.11 distributed coordination function (DCF) [9] can be modified to use cooperative communication thus achieving both higher throughput and lower interference [8]. More cooperative communication protocols based on IEEE 802.11 were proposed in [12], [13], [14] and [15]. However, protocols based on IEEE 802.11 are not feasible in WSN as they have strict energy constraint and limited processing power.

Analyzing the effects of cooperation in legacy MAC protocols for WSN has received little attention. Mainaud et al.

[19] has recently proposed a cooperative MAC protocol for WSN based on preamble sampling. The primary focus of the work is to define a relay node among the neighboring nodes and relaying decision at the link. However, the work does not analyze the effect on energy consumption, a primary concern in WSN.

Motivated by the previous work, we have designed CPS-MAC.The difference between CPS-MAC and prior work is that CPS-MAC addresses a number of design challenges such as addressing scheme, energy efficient wake up, and a scheduling scheme which uses CC. These schemes are integrated together into a low-overhead practical MAC protocol.

III. PROTOCOL DESIGN FOR CPS-MAC

We consider an ad hoc multi-hop data gathering network where sensor nodes are deployed around a sink as shown in Figure 6. Each node defines its distance from the sink using hop count which is defined as the number of intermediate hops between the node and the sink [20]. The sensor nodes periodically sense the data, wake up the neighboring nodes, and broadcast the data. Neighboring nodes receive the data and the one which is closer to the sink forward it to the next-hop nodes. Data eventually reaches the sink which is responsible for collecting, processing, analyzing, and forwarding the data to a base station.

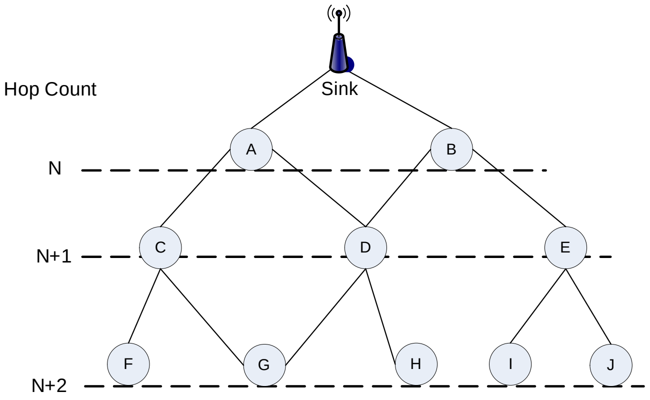

Fig. 6. Data Gathering Network

Once the sensor nodes are physically deployed around the sink, CPS-MAC works as follows.

A. Initialization Phase

In order to make routing decision and address nodes, CPS-MAC uses hop count value and neighborhood information. Hop count is the minimum number of non-cooperative transmissions required to reach the sink from a given node [20]. In order to setup this field, we use a flooding algorithm. An example of such an algorithm is the Cost Field Establishment Algorithm (CFEA) [21]. It is executed during the startup phase of the network and whenever the network topology changes. No CC is used during this phase. Consider the hierarchy shown in Fig 6. Initially, the sink sets its hop count to 0 and nodes set their hop count to ∞. The sink initiates the algorithm by broadcasting an advertisement (ADV) packet. The content of an ADV packet is shown in Figure 7 which would contain nodes hop count, its own addresses, and address of its 1-hop parent nodes. The address of 1-hop parents are needed for addressing and will be explained in the next section.

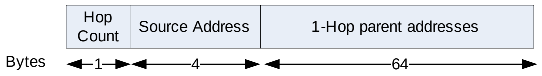

Fig. 7. Advertisement (ADV) Packet

The message propagates down from the parent node to the siblings. We use the term parent and sibling because nodes in the network are deployed in a hierarchy. Whenever a node receives an ADV message, it determines if it leads to a smaller hop count to the sink. If it does, the node resets its hop count and stores the source address as its 1-hop parent and the remaining addresses as 2-hop parent. Then, the node (re-)transmits its own ADV packet.

The 1-hop and 2-hop parent node addresses are stored in a routing table called CoopTable. It additionally stores the addresses of 1-hop sibling nodes. These addresses are obtained by simply overhearing ADV packets on the media and analyzing the hop count value. This is feasible because nodes do not sleep during the initialization phase and can receive all ADV packets in their reception range. Eventually, every node may calculate the optimal hop count to the sink through flooding. Then, the initialization phase stops and nodes start their normal operation; for example, the node D in the hierarchy above would have a CoopTable as follows:

TABLE I
NODE D: COOPTABLE PARENT NODES

1 hop Parent (Hop Count-1)	2 Hop Parent (Hop Count-2)
A	Sink
B	Sink

TABLE II
NODE D: COOPTABLE SIBLING NODES

1 Hop Sibling (Hop Count+1)
G
H

The following section explains how the CoopTable is used to address nodes and select partner nodes for cooperation.

B. Addressing Scheme

A broadcast transmission from a node to the sink over multiple hops can result in multiple nodes forwarding the same packet along different paths and flooding the network. Though it increases the chances of a packet eventually reaching the sink, nodes have to pay the price of energy expenditure and processing overhead. The problem becomes more complicated

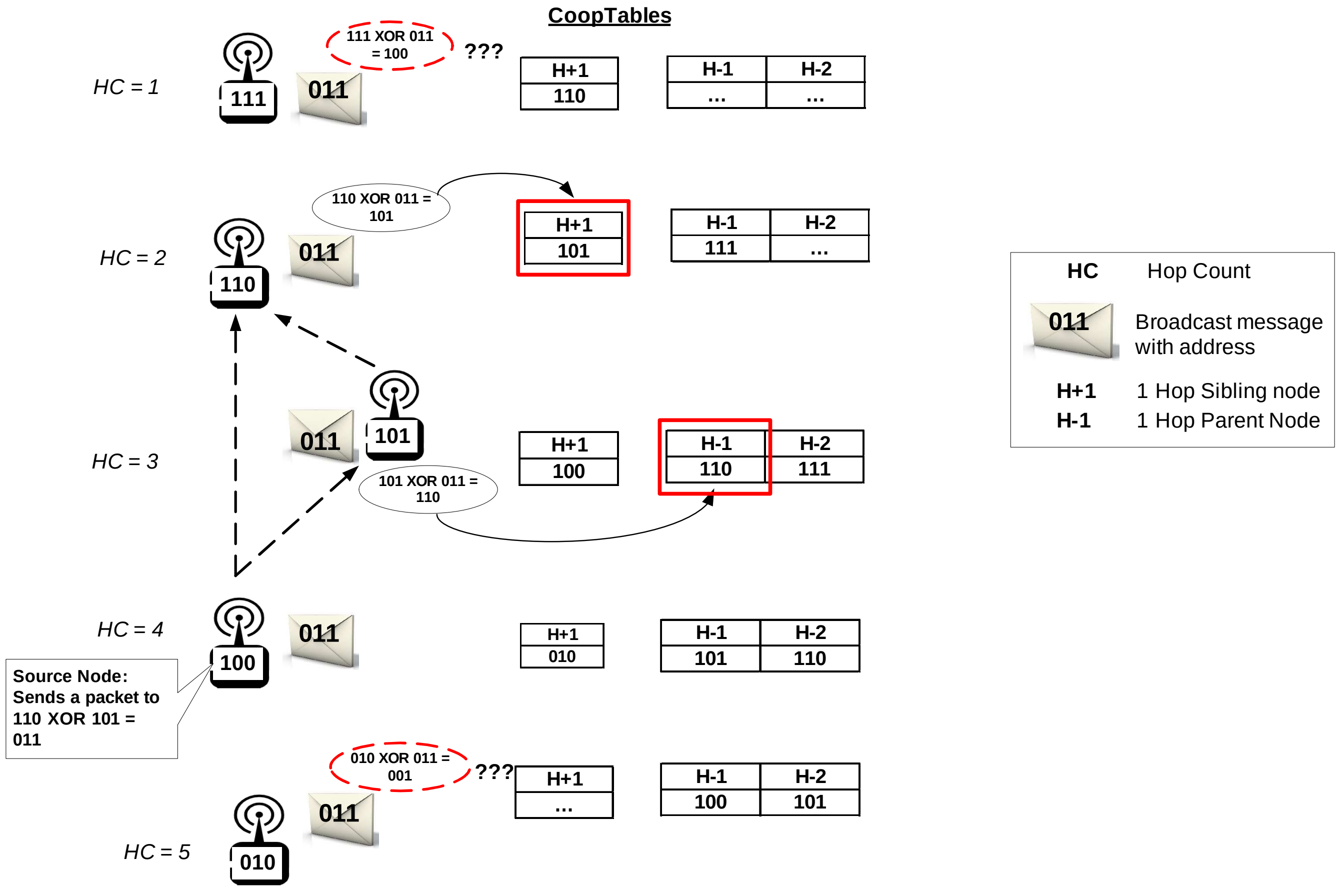

Fig. 8. Addressing Scheme

when we use cooperative communication because it involves a partner node in addition to the source-destination pair. In order to minimize this overhead and limit the cooperative communication to 3 nodes (source-partner-destination) in each transmission cycle, we use the CoopTable mentioned in Section III-A. When a node has data to send, it will select both partner (1-hop parent) and destination (2-hop parent) addresses from the CoopTable. However, instead of adding them as two separate addresses, the node will perform an XOR between them and send it as a single address. Recall from the previous section that every node stores addressing information about its 1-hop and subsequent 2-hop parents and 1-hop siblings in the CoopTable. If multiple partner\destination pairs are possible, the source cycles between them to divide the overhead. Nodes also include their hop count value in the packet. Once the packet is sent, every node that receives it extracts the address, performs an XOR with its own address, and looks up the result in its CoopTable. Nodes also calculate the hop count difference with the source node and then use the following rules to determine its role (partner /destination) in transmission.

1) If the result matches the address of a sibling node and the hop count difference with the source node is 2, the node acts as destination.
2) If the result matches the address of a parent node and the hop count difference is 1 with the source node, the node acts as partner.
3) If either the result does not matches an entry in the lookup table or if the hop count difference is greater than 2, the node takes no action.

For example, in Fig 8, the node with Identifier (ID) 100 sends a packet to node 101 and 110. The XOR of their address is 011, which is included in the data packet. Assuming that all nodes in the neighborhood correctly receive the packet, they decode the address using XOR with their own address. The lookup in the CoopTable for the node 110 and 101 matches the above mentioned rules and they define their roles as destination and partner respectively. The node 111 and 010 are not able to find the resulting address in the CoopTable and therefore do not take part in Cooperation. In this scheme, there is a probability that the result from the XOR operation might result in collision, i.e., the resulting address can map to a value in the CoopTable even though the node was not addressed, especially when the number of bits used for node identifiers is small. However, the probability significantly reduces when the identifier is large (e.g. 48, bit MAC address).

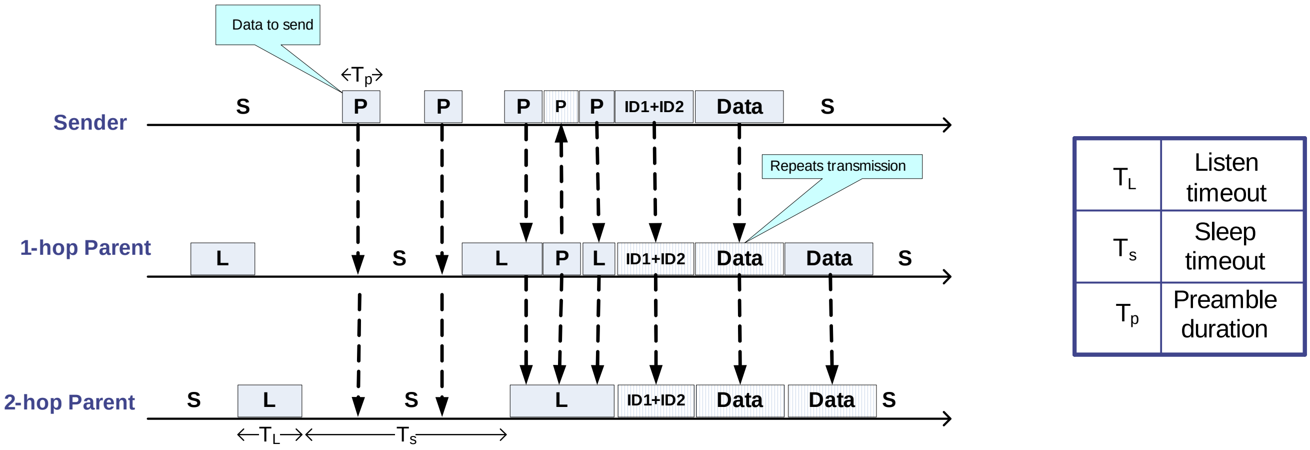

Fig. 9. CPS-MAC

C. *Medium Access Control Layer*

We propose a MAC protocol that uses cooperative communication to increase the probability of correct transmission while reducing energy consumption. Usually a broadcast transmission can be received by nodes which are multiple hops away from the source but they are discarded as they suffer from bit errors due to fading and attenuation. Our motivation is to utilize even these corrupt packets. The idea is to form cooperative triangles in the network where each triangle consists of source, partner, and destination as shown in Figure 3. Nodes cooperate in this triangle to deliver multiple copies of the packet to the destination where packet combining [4] is used to recover the original packet. However, for such a scheme to work, it becomes challenging to wake up nodes which are multiple hops away before initiating a data transmission. To solve this, we propose a wake up scheme which is based on minimum preamble sampling explained in Section II-A [16].

Figure 9 elaborates the working of the protocol. When a source node has data to send, it transmits a strobed preamble packet containing synchronization bits and the node's hop count value at the end. The strobed preamble is repeated until the source receives an acknowledgment (ACK) preamble from a neighboring node. When a neighboring node wakes up and receives the preamble, it analyzes the hop count value. If the receiver is not a parent node, it discards the preamble and immediately returns to sleep state as it cannot help the source to forward its data to the sink. 1-hop parent nodes that receive the preamble contend for the media and the successful node sends an ACK preamble. As no addressing is used in preamble, any 1-hop parent node can send the ACK preamble. This ACK preamble serves two purposes. First, it will act as wakeup preamble sequence for the next-hop parent. Second, the source will know that nodes in 1-hop neighborhood are awake. After receiving the acknowledgment preamble, the source sends the address packet. Nodes analyze the address packet as explained in Section III-B. If a node cannot define its role, it will return to sleep state to conserve energy. After this, the source broadcasts the data packet. The transmission is heard by both partner and destination yet it is unlikely to be received correctly by both nodes at once. After receiving the packet, the partner uses decode and forward (DAF) [4] to decide if it should again broadcast the packet. In DAF, the partner decodes a received packet to check for bit errors and erroneous packets are discarded. Only if the packet is received correctly, the partner again broadcasts the received packet to the destination. Thus, the destination receives two copies of the same data packet. The two packets are combined using maximum ratio combining (MRC) [4] to recover the original data. In its simplest form, MRC is modeled by adding the instantaneous signal-to-noise ratio (SNR) of the two packet received from source and partner. This accumulation of the instantaneous SNR increases the rate at which the destination can reliably decode the packet. After the transmission, nodes may return to sleep or listen state. The recipient of the data packet will schedule a transmission for further propagation of the data packet towards the sink.

IV. RESULTS

In this section, we present simulation results for CPS-MAC. Simulations are conducted using Mobility Framework for the OMNET++ discrete event simulator [23]. Our purpose is to show how the protocol behaves and reacts to typical WSN conditions such as fading channels, extended periods of low data flow, and their effect on power consumption. This gives us a good understanding of how deployment on real sensor nodes would perform.

The performance of CPS-MAC is compared with MPS-based MAC protocol mentioned below. This means that the nodes use MPS for waking up neighboring nodes prior to data transmission. For comparison purpose, we have implemented the following network configuration.

1) Direct-MPS: This scenario consists of two nodes, source and destination. The source transmits directly to the destination and uses MPS to wake up the destination node.

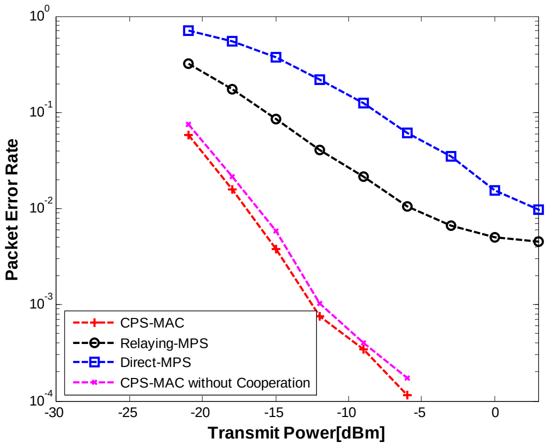

Fig. 10. Packet Error Rate

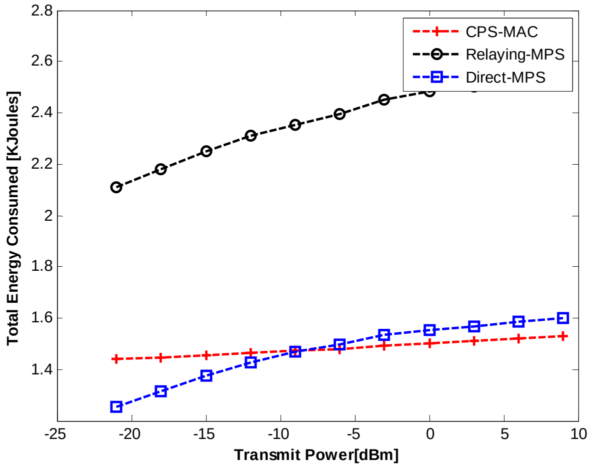

Fig. 11. Total Energy Consumed

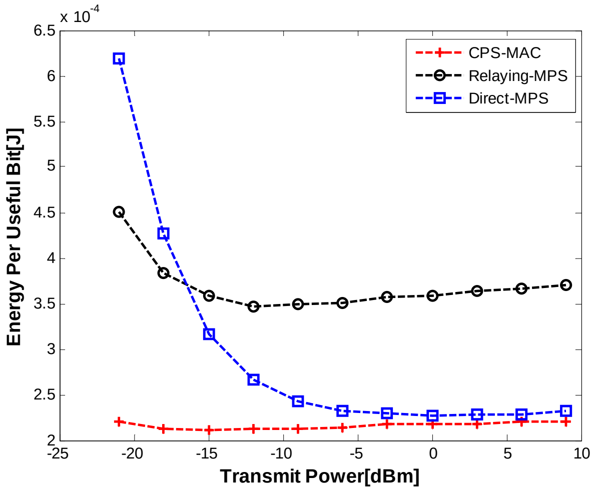

Fig. 12. Energy Per useful bit

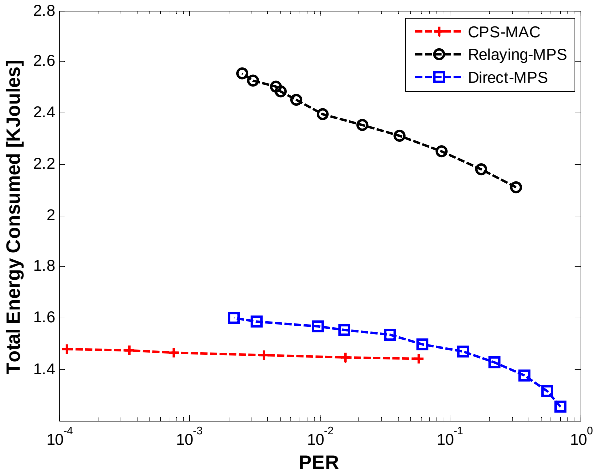

Fig. 13. Total Energy Consumed vs Packet Error Rate tradeoff

2) Relaying-MPS: In this scenario, an intermediate node is introduced between source and destination. The source first wakes up the relay using MPS and transmits the packet. The relay node then wakes up destination and forwards the packet, if correctly received from the source. If a node receives correct packets from both the source and relay, it discards the duplicate packet. This is done by keeping a sequence number of correctly received packets in a table.
3) CPS-MAC: This scenario uses our proposed protocol for a 3 node scenario as shown in Figure 3. We use cooperation to exploit both the source-destination and source-partner-destination channels.
4) CPS-MAC without cooperation: This scenario is similar to the previous one (CPS-MAC) however, cooperation for data packets is disabled. This gives us an idea of how many packets are lost in the absence of cooperation.

Figure 10 shows the Packet Error Rate(PER) for varying transmission power. CPS-MAC here achieves better PER as compared to direct and relaying MPS protocols. We have evaluated CPS-MAC performance both with and without CC. This performance improvement over MPS based protocol is attributed to the CPS-MAC wake up scheme. Repeating the preamble from the partner node increases the chances of the destination node waking up prior to data transmission. This process is similar to CC but here, preamble packet is repeated at the partner station instead of data packet. Thus, the destination would receive multiple copies of the preamble packet, increasing its chances of overhearing the preamble. CPS-MAC-without-cooperation shows the performance of CPS-MAC in the absence of cooperation. The difference in PER between CPS-MAC and CPS-MAC-without-cooperation represents the diversity gain achieved by CC and MRC for data packets. The total energy consumed by the whole network for the entire simulation duration is shows in Figure 11. The energy consumption of CPS-MAC is comparable to direct-MPS and significantly less then relaying-MPS. This is because CPS-MAC is able to wake up the 2-hop destination nodes in a single transmission cycle using repeated preambles from 1-

hop partner node. As the amount of time for waking up the node is significantly larger than the data transmission phase, size and number of preambles is a primary factor contributing to the energy expenditure. By reducing both the number of preambles sent and the time needed to wake up the nodes, CPS-MAC is able to reduce the energy utilization, making it comparable to direct-MPS.

Figure 12 shows the energy consumed per useful bit (EPUB) for the three configurations. The EPUB metric takes into account the energy consumption of all the nodes in the topology. For high transmission power, EPUB for CPS-MAC and direct-MPS is almost the same. However, at low transmission power, the improved PER pays off and CPS-MAC achieves significantly lower EPUB. Figure 13 shows the trade-off between total energy consumption and PER. For a given PER value, CPS-MAC consumes less energy then both Direct-MPS and Relaying-MPS. One thing to notice here is that the Direct-MPS is more energy efficient at very low transmission power, however, the high PER value makes it infeasible for applications where better reliability is desired.

V. CONCLUSION AND FUTURE WORK

This work has shown the possible benefits of using cooperative communication to increase the reliability and reduce energy consumption in WSN. We propose CPS-MAC, which improves reliability by using overhearing to its advantage. The improvement is realized by forming cooperative triangle in densely deployed WSN, where channel errors, collisions, idle listening, and overhearing significantly effect the performance. In duty cycling MAC protocols for WSN, the wakeup scheme has a big effect on the packet error rate at the destination. Repeating the preamble in a cooperative manner significantly increases the probability of destination waking up prior to data transmission. Results show that destination is better able to receive and decode packets under this scheme as compared to conventional MPS protocols.

By using CC for data packets, CPS-MAC delivers multiple copies of packet to the destination. Packet combining using MRC further helps CPS-MAC in combining and decoding erroneous packets and reducing the PER. By reducing the number of preambles and time needed to wake up the nodes and transferring data over multiple hops, the network can achieve significant reduction in energy expenditure. This behavior is important in preamble sampling MAC protocols as energy used in sending and receiving preambles is the dominant factor in such protocols. Simulation results show that energy expenditure of CPS-MAC is comparable to direct-MPS protocol and outperforms relaying-MPS.

We are currently planning the performance evaluation of CPS-MAC in a larger WSN configuration. For such a network, in addition to energy utilization, additional paramters such as end-to-end latency and network throughput would also be evaluated.

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