Energy Efficient MAC Protocol with Localization scheme for Wireless Sensor Networks using Directional Antennas

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***Abstract*—We propose a MAC protocol for Wireless Sensor Networks (WSN) that along with being energy efficient, also helps nodes synchronize and localize. In this work, we present a Sensor-MAC (SMAC) using different beam patterns of the sink nodes which coordinates MAC layer wakeup/sleep schedules of the sensor nodes. Our MAC protocol uses directional antennas and schedules the nodes such as to extend their battery lifetime. We show how the nodes can use directional antennas with SMAC and still be able to synchronize with each other. We further propose a technique to help the nodes in the network localize with the help of their neighbors.**

I. Introduction

Wireless Sensor Networks (WSN) attract increasing interest in many application domains. There is a great interest for such networks in commercial applications, military applications as well as in environments where the presence of an infrastructure network is impossible or not affordable. In many applications sensed data must be collected and delivered to designated gateway nodes (sinks) connected to the application subscriber serving as fusion centres, but also distributing control information and application requirements to the sensor nodes.

As larger networks are considered the data delivery entails the use of multi-hop links where the MAC protocol plays a dominant role in assuring fair communications, employing contention resolution and carrier sense techniques but, at the same time, avoiding energy waste with unnecessary retransmissions.

Directional and smart antenna technology offer a variety of potential benefits for WSN. In particular, it can concentrate energy in a specific direction and can communicate within a restricted area. Therefore it improves spatial reuse of the wireless channel. Furthermore, the directional transmission increases the signal energy towards the direction of the receiver resulting in the increase of the transmission range. Thus, the number of routing hops must be fewer than that of omnidirectional antennas in multi-hop networks. These two benefits lead to a considerable increase of throughput and capacity [1] [2].

In multi-hop sensor networks, the connectivity from a sensor node to the sink is crucial. Sensor nodes located around the sink participate in relaying data more often than other sensor nodes far from the sink. Hence, the sink's neighbor sensor nodes tend to deplete their energy more quickly than other nodes [3].

Furthermore, In any Wireless sensor networks (WSNs), the location information of node plays crucial role in understanding the application context. There are three significant advantages of knowing the location information of sensor nodes. First, location information is required to identify the location of an event of interest. Second, location awareness facilitates numerous application services. Third, location information can assist in various system functionalities. Hence, with these advantages and much more, localization should be considered as an implicit feature of a sensor network [4], [5], [6].

Considering all these areas of research, we propose a simple but efficient MAC protocol that uses directional antennas at the sink to divide the network into different sectors. Each sector has it's own wakeup/sleep schedule that is being decided by the Sink. Sink broadcasts it's wakeup/sleep schedule for each sector to it's neighbors. These neighbors further forwards these schedule to multi-hop neighbors. To further improve network lifetime, our proposed MAC protocol uses directional antennas at the sensor nodes. We have proposed a synchronization scheme for wireless sensor nodes that use directional antennas. Using the same scheme and with the help of directional antenna, a localization scheme has also been proposed.

The rest of the paper is organized as follows. In section II, we present related work. Section III describes the preliminaries like Network Topology, Antenna Model, SMAC Protocol and SLS. Section IV describes the MAC protocol including the scheduling scheme, synchronization scheme and localization scheme. Section V includes the simulation results. Section VI talks about future work and how this paper needs to be improved. Section VII concludes our work.

II. Related Work

[7] proposed a MAC protocol called SWAMP in which two types of access modes (i.e., OC-mode and EC-mode), are used. It includes a method of obtaining the neighbors location information called NHDI by using usual control frames and additional control frame called SOF to perform

a wider transmission range for communication. This method although has more overheads compared with other directional MAC protocols.

[8] uses a scheduling schemes like ours to divide the network into sectors. However the paper does not use directional antennas at the sensor nodes and does not address the challenges that comes with using directional antennas. [9] designed a directional MAC protocol (MMAC) using multihop RTSs to establish links between distant nodes and transmitting CTS, DATA, and ACK over a single hop afterward. This method need longer setup time for data transmission, even though simulation results show that it has other performance improvement.

III. Preliminaries

A. Network Topology

We assume a sensor network model as depicted in Figure 1. Due to limited transmission range, the data from sensor nodes are delivered to the sink in a hop-by-hop manner. The nodes are characterized into two types, Single-hop Neighbors and Multi-hop Neighbors. Single-hop Neighbors are the nodes that can directly communicate with the sink whereas Multi-hop neighbors need to communicate to the sink in a hop-by-hop manner. Our network may contain more than one sink and the data might reach the sink through multiple hops. The nodes are randomly distributed around the sink. Both the sink and the sensor nodes have directional antennas that can point to any direction.

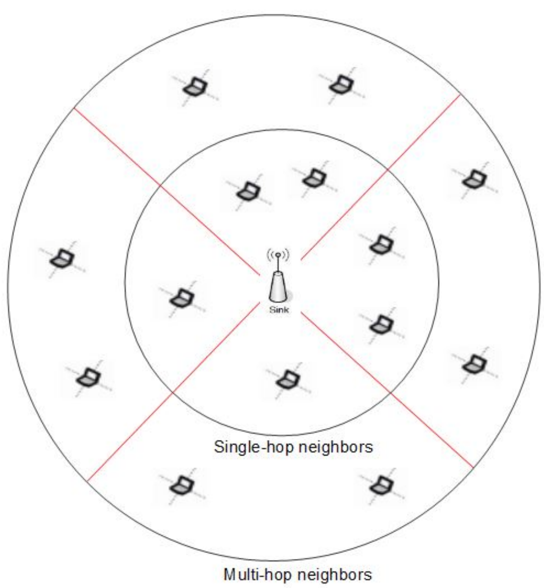

Fig. 1. Single-hop Neighbors and Multi-hop Neighbors.

B. Antenna Model

According to beam pattern, antenna models are classified into two types: omni-directional antenna and directional antenna. In omni-antenna, signal electromagnetic energy is spreaded over a large region of space, while only a small portion is received by an intended receiver. Directional antenna can concentrate electromagnetic energy into a certain direction while cancel the energy in other directions, resulting in an amplified signal in a certain direction.

In this work, we use directional antenna in both sensor nodes and anchor nodes. Because directional antennas consume less power and they are easy to localize. In addition, in our paper, we use two dimensional cone plus circle model assuming all STAs are in the same plane. The antenna gain of the main lobe and the side lobe are different with the gain of the main lobe being considerably higher than the gain of the side lobe.

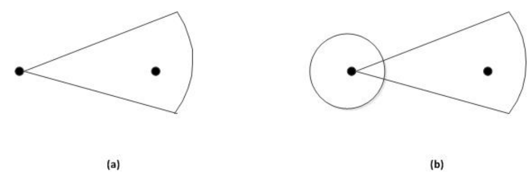

Fig. 2. Antenna Models. (a) Flat-top model (b) Cone plus circle model

C. SMAC

SMAC [10] is a low power RTS-CTS protocol for wireless sensor networks. It reduces energy consumption by periodically putting nodes to sleep to avoid idle listening and overhearing. The length of the sleep period dictates the duty cycle of SMAC. At the beginning of each active period, nodes exchange synchronization information. Following the SYNC period, data may be transferred for the remainder of the active period using RTS-CTS. In SMAC, nodes keep track of their neighbor's wakeup/sleep schedule using the SYNC period. A node can follow more than one schedule in SMAC. So a node that is following one schedule would have a different duty cycle than the node following two schedules.

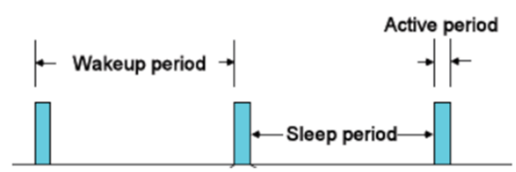

Fig. 3. SMAC structure.

D. SLS

Sector Level Sweep (SLS) is the technique sensor nodes using directional antennas would use to broadcast their SYNC packets. A node uses SLS to one by one scan each of it's sector and send a packet in that direction using directional beam. This way that nodes broadcasts the packet in each direction. Along with the data, the SLS packet also contains the sector ID which is the sector number from which the packet was transmitted. This way each node that receives one or more SYNC packets knows the sector of the transmitter with strongest received signal strength. This information can be later feedback to the transmitter to help in future transmissions between these nodes.

IV. MAC Protocol

A. SMAC using directional antennas and sectoring

Our Protocol divides all the single-hop neighbors into different sectors and gives each sector their own awake-sleep schedule. Number of sectors depend upon the beamwidth of the anchor node. When the anchor node antenna is pointing in one sector, all single-hop neighbors in that sector are able to communicate with the sink. Thus the single-hop neighbors in that sector must know the beam-forming schedule of the sink node so they can wakeup only when the sink's antenna is beamforming to their sector.

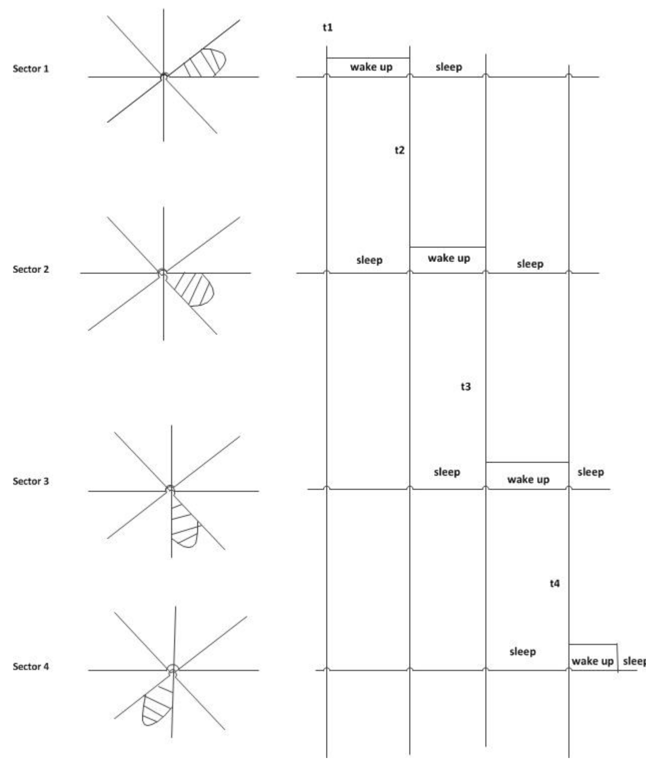

Fig. 4. Wakeup/sleep schedule according to beam patterns.

Each node transmits using directional beam where as while listening, each node listens in an Omni-direction. This way while listening a node can receive packets from any direction.

We propose that each of the single-hop neighbors that are in the same sector follow the same schedule. We make the sink broadcast it's schedule in each sector as shown in Fig. 4. The nodes that receive this schedule are single-hop neighbors to the sink. These nodes will follow only one schedule. If a single-hop neighbor receives more than one schedule from the sink due to overlapping or side nodes, it would choose the schedule with the strongest received strength. The single-hop neighbors save this schedule in their schedule table. The schedule entry consists the ID of the sink, the schedule of wakeup and sleep. After receiving the schedule, the single-hop nodes also update their routing table so they can communicate directly to the sink.

After receiving the schedule, the single-hop nodes broadcast their schedule using a sector level sweep. All the multi-hop neighbors that receive this sector level sweep would start following this schedule. If a multi-hop neighbors receives more than one schedule, it would follow all of them as specified in SMAC.

This scenario is shown in Fig. 5. at time t0, each node has its own schedule. At time tl, the sink is beamforming to node 1 and broadcasts it's schedule in that direction. Node 1 knows that it is a single-hop neighbor and changes its own schedule to it's sector's schedule. At time t2, node 1 broadcasts a sector level sweep (that contains it's schedule) to its neighbors. At time t3, the sink is beamforming to node 2 and broadcasts it's schedule again. Node 2 also knows that it is a one-hop relay node and changes its own schedule to it's sector's schedule. After that, node 2 broadcasts a sector level sweep to its neighbors. Node 3 will now follow multiple schedules, each of which is rebroadcast from node 1 and 2.

When the multi-hop neighbors receive multiple schedule messages (SLS) from other single-hop neighbors, the nodes also add different schedules to their schedule tables and know that they can communicate with single-hop neighbors of different beam patterns.

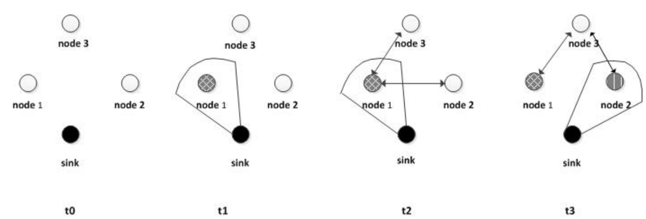

Fig. 5. Node's schedules

B. Synchronization

The listen/sleep scheme requires synchronization among neighboring nodes. Although the long listen time can tolerate fairly large clock drift, neighboring nodes still need to periodically update each other their schedules to prevent long-time clock drift. Updating schedules is accomplished by sending a SYNC packet through SLS. The SYNC packet includes the address of the sender and the time of its next sleep. The next-sleep time is relative to the moment that the sender finishes transmitting the SYNC packet, which is approximately when receivers get the packet (since propagation delays are short). Receivers will adjust their timers immediately after they receive the SYNC packet. A node will go to sleep when the timer fires.

Just like in the original SMAC protocol [10], we divide receiver listen interval into two parts. The first part is for receiving SYNC packets, and the second one is for receiving RTS packets. Each part is further divided into many time slots for senders to perform carrier sense. Each node periodically broadcasts SYNC packets to its neighbors even if it has no followers. This allows new nodes to join an existing neighborhood. The new node follows the same procedure in the above subsection to choose its schedule. It should be noted that since we are using directional antennas, SYNC packets would be send using SLS.

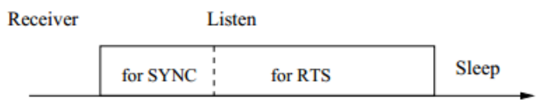

Fig. 6. Awake time of a receiver.

C. Localization

SYNC packets apart from synchronizing nodes and transferring schedules to new nodes, also serves as a localization scheme to help nodes find their location. Usually wireless sensor nodes are not equipped with a GPS which is only found at the sink. Assuming the sink already knows it's location through GPS or predetermined location installment, all the other sensor nodes can localize themselves to the sink node using the SYNC packets.

As explained before, each SYNC packet is transmitted using SLS with each packet containing the sector ID from which it was transmitted. Since every node periodically transmits a SYNC packet, depending on the frequency of SYNC packets, each node would eventually know the best sector ID of all it's neighbors. This information is included in the SYNC packet so that a node can inform it's neighbors their best sector ID. This way each node would know the direction of each of its neighbors. This information would not just help in transmitting packets directionally but would also help in approximating the node's location. A node using the transmission power and the received signal strength can easily know the distance between itself and it's neighbors. Using the distance and direction to it's neighbor a node can localize itself with respect to that neighbor.

The single-hop neighbors will find their location with respect to the sink. Hop-by-hop, each Multi-hop neighbor would learn it's location with respect to their neighbors using SYNC packets. This localization would keep getting refined with each periodic SYNC packet transmission and reception.

V. Simulation Results

We deployed twenty 20 single-hop nodes around our sink. Each of these single-hop nodes are either transmitting or receiving packets. They either generate or receive 10 to 20 frames of 50 bytes each in an interval of 1 s. The wireless link bandwidth that we used for our simulation is 250 Kbps. We calculated the time it took for these nodes to drain their batteries. We define the lifetime of our network as the time it takes for all the single-hop nodes to drain their batteries. The following equations are used to calculate the total energy consumption of a node.

$$E_{tx} = T_{start}P_{start} + \frac{n}{R * R_{code}}(P_{txElec} + \alpha_{amp} + \beta_{amp}P_{tx}) \quad (1)$$

$$E_{rx} = T_{start}P_{start} + \frac{n}{R * R_{code}}P_{rxElec} + E_{decBits}(R) \quad (2)$$

$$E_{total} = E_{tx} + E_{rx} + E_{idle} \quad (3)$$

Where T_{start} and P_{start} is the time and power consumed leaving the idle state, n is the number of bits, R is the nominal rate, R_{code} is the coding rate, P_{txElec} is the power consumed by the transmitting electronics, α_{amp} and β_{amp} depends on the antenna model, P_{tx} is the radiated power, P_{rxElec} is the power consumed by receiving electronics and $E_{decBits}$ is the energy to decode bits.

Table I shows the simulation parameters used our simulations.

TABLE I
SIMULATION PARAMETERS

T_{start}	466 us
P_{start}	58.7 mW
R	250 Kbps
P_{txElec}	200 mW
P_{rxElec}	200 mW
α_{amp}	174 mW
β_{amp}	5
$SINR_{thr}$	5.5 dB
Noise	-85 dBm

We simulate our protocol and compare it's lifetime with a network using Omni0directional antenna at the sensor nodes. We also simulate different beamwidth directional antennas at the sink. The results of the simulations are shown in Fig. 7. We note that with an Omni-directional antenna at the sink, i.e. a 360 degree beamwidth, the network lifetime is the minimum. As the beamwidth decreases, the number of sectors increases and hence the sleep time increases. This in return increases the network lifetime.

We also notice in the simulations result that directional antennas at the sensors give us a slightly longer lifetime.

VI. Future Work

In the future we want to simulate the accuracy with which the location of a node could be approximated using our localization scheme. We would also like to simulate the effect on localization of nodes mobility and frequency of SYNC packets.

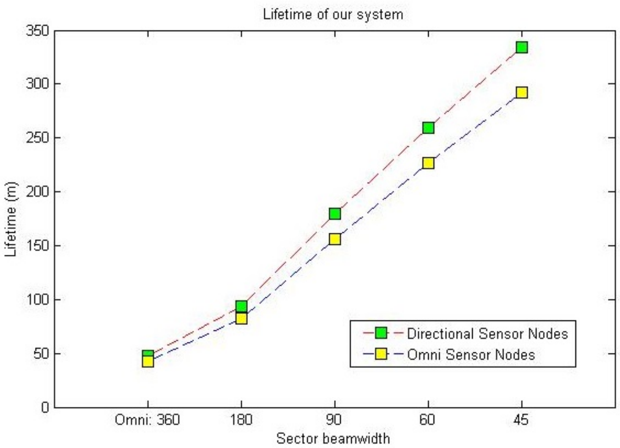

Fig. 7. Lifetime of our Network.

VII. Conclusion

In multi-hop sensor networks, sensor nodes located around the sink relay more traffic than other nodes far from the sink. Those relaying sensor nodes tend to die soon, which causes sink isolation that determines network lifetime. To solve this problem, we propose a MAC protocol that uses directional antenna at the sink and the sensor nodes to extend network lifetime. Our MAC protocol upgrades the traditional SMAC protocol to utilize it using directional antennas. This not just increases the network lifetime, but also helps the nodes in synchronization and localization.

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