Directional Antenna at Sink (DAaS) to prolong network lifetime in Wireless Sensor Networks

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***Abstract*: We investigate the effect of a directional antenna in wireless sensor networks from the perspective of network lifetime extension. Previous studies on wireless sensor networks have assumed only an omni-directional antenna model, since a directional antenna has been considered inappropriate for sensors due to size and cost constraints. In this sense, we propose to mount the directional antenna only on a designated gateway node, so called a sink, which has more energy and computational power to handle a large volume of data. With a directional antenna, the sink's communication range is extended and hence the number of neighbor nodes in the communication range increases. Since these neighbor nodes relay data toward the sink, they tend to deplete their energy more quickly than other nodes. Directional Antenna at Sink (DAaS) prolongs the network lifetime by increasing the number of neighbor nodes of the sink. To realize DAaS, we propose a sink beam pattern scheduling algorithm, which coordinates MAC layer wakeup/sleep schedules of the sink and the neighbor nodes according to the directional antenna's beam pattern schedule. The above scheduling algorithm minimizes the duty-cycle and hence saves more energy of the sink's neighbor nodes. Through extensive simulation experiments, we observe significant improvement of network lifetime with DAaS as the number of beam patterns increases.**

1. Introduction

Wireless sensor networks consist of small, low-powered sensors deployed over an area of interest to monitor their environment and deliver sensory data to a user. Sensor networks have some unique characteristics compared to ad hoc wireless networks, for example, limited resource, large and dense deployment, dynamic topology, etc. One important characteristic of sensor networks is the highly limited battery energy of sensor nodes. Therefore, energy efficiency in the wireless sensor networks is critical and a number of approaches have been proposed to prolong the network lifetime; most of them focus on reducing sensor node's energy consumption [1]. This paper introduces a novel means of prolonging the network lifetime, employing a directional antenna system to a gateway.

Sensed data must be delivered to a subscriber. Compared to the size of interested area, the communication range of a sensor node is usually limited because of its energy constraint. That is why we need a designated gateway node that connects the sensor network to the subscriber (i.e., the application user located outside the sensor network). This node is called a *sink*. The sink distributes control information to sensor nodes and gathers the sensed data.

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 [4]. If all sensor nodes in the communication range of the sink die, then the sink will become isolated. If the isolated sink is the only one in the network, the network lifetime is ended, although other sensor nodes are still alive and able to sense the interested events. Therefore, in order to defer sink isolation and extend the network lifetime, the number of sensor nodes in the communication range of the sink must be increased.

Traditionally, all the nodes in the wireless sensor networks are assumed to be equipped with omni-directional antennas due to its simplicity and low cost. However, a directional antenna provides significant enhancement over an omni-directional antenna in terms of the sensitivity of signal and energy consumption. In particular, the use of directional antennas extends communication range with the same amount of energy for transmission and reception by narrowing beamwidth. But, sensor nodes have small size and low-cost requirements which exclude using directional antennas. Thus, we propose to equip only the sink with a directional antenna.

This paper suggests a new scheme, named directional antenna at sink (DAaS), which efficiently extends the sensor network lifetime by using a directional antenna only at the sink. We adopt a switched-beam antenna model and SMAC protocol [13], the latter of which allows sensor nodes to wakeup and sleep periodically according to wakeup/sleep schedules. In DAaS, the sink determines its wakeup schedule by considering beam pattern sweeping and broadcasts its schedule to its relaying sensor nodes. Sensor nodes in the communication range of the sink set their wakeup/sleep schedules according to the beam pattern sweeping schedule of the sink. Therefore, DAaS extends the network lifetime in two aspects: 1) the extended communication range increases the number of relaying nodes, and 2) the sink's neighbor sensor nodes have low duty-cycles (the portion of wakeup time) because they wake up only when the directional antenna is scheduled to reach them. In order to coordinate MAC layer wakeup/sleep schedules of the sink and the neighbor nodes, we propose a sink beam pattern scheduling algorithm. Simulation results show that the sensor network lifetime with a directional antenna at the sink is prolonged significantly.

The remainder of this paper is organized as follows. In the next section, we present related work. Section 3 introduces the antenna, network and energy model of this paper. Section 4 gives a detailed description of the proposed DAaS and sink beam pattern scheduling algorithm. In Sections 5 and 6, simulation results and concluding remarks are given, respectively.

2. Related Work

Most of previous studies on energy management have been focused on reducing node's energy consumption by means of energy aware routing [11], energy efficient MAC [12] and energy efficient topology management [2]. While most papers assume an omni-directional antenna model for wireless sensor networks, some paper propose to employ a directional antenna for wireless sensor networks. In [5], the authors present how to implement a directional antenna in a sensor node transceiver but do not consider the effects on network operations. The authors of [10] propose and analyze a MAC protocol design taking account of a directional antenna while the study on energy consumption is absent.

On the other hand, there have been many works on directional antennas in wireless ad hoc networks. In particular, [8] deals with several issues of using directional antennas for ad hoc network and argues that there are many possible practical usages. However, previous researches on wireless ad hoc networks using directional antennas have assumed equal transmission range when using directional and omni-directional beamforms. And they are not applicable to wireless sensor nodes due to the low-cost requirements of sensor networks.

3. Preliminaries

3.1. Antenna Model

Antenna models are classified into two types: omni-directional and directional. An omni-directional antenna transmits and receives data in all directions (360°). On the other hand, a directional antenna transmits and receives data only in one direction. In this paper, we adopt an omni-directional antenna for sensor nodes and a directional antenna for a sink. The directional antenna for the sink is associated with predefined beam patterns (e.g. number of beam patterns, beamwidth). To simplify a directional antenna model, we use the switched abstract antenna model presented in [3]. If the number of beam patterns is *N*, each pattern covers 360°/*N* degrees and has a conical shape. Since we use the switched beam antenna, beam patterns are not overlapping.

Figure 1 shows a few beam patterns. Figure 1 (a) illustrates the omni-directional antenna beam pattern. Figure 1 (b) presents a directional beam pattern of the abstract antenna model. This beam pattern will sweep to cover all directions according to predetermined time schedule. In Figure 1 (c), the actual antenna's beam pattern has several lobes: a main lobe and side lobes. While adopting a directional antenna for a sink, we assume that the power radiated in side lobes is negligible and consider the conical main lobe for each beam pattern for simplicity.

According to [6], the directional antenna gain (G_θ) of the main lobe is defined as

$$G_\theta = \frac{360^o}{\theta} \tag{1}$$

where θ is a beamwidth in azimuth for each beam pattern and G_θ is applied to both transmitter and receiver gains

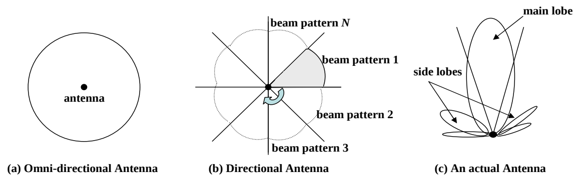

Figure 1: Antenna beam patterns.

of a directional antenna with a beamwidth θ. Note that θ is 360° in the case of omni-directional antenna.

We use the following equation, from [9], to compute the maximum communication range.

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{d^\alpha}(\frac{\lambda}{4\pi})^2 \geq \Omega \tag{2}$$

where P_t and P_r are the transmit and received powers, respectively. λ is the wavelength. G_t and G_r are the transmit antenna and receive antenna gains, respectively. Ω is the minimum receiver sensitivity threshold value and α is the path loss factor that normally ranges $2 \leq \alpha \leq 4$.

Therefore, using equation (2), the communication range *d* is given by

$$d = \left(\frac{P_t \cdot G_t \cdot G_r}{P_r}(\frac{\lambda}{4\pi})^2\right)^{\frac{1}{\alpha}} \tag{3}$$

If the sink is equipped with a directional antenna and beamwidth is θ, the communication range d_θ between the sink and a sensor node is derived from (1) and (3);

$$d_\theta = (\frac{360^o}{\theta})^{\frac{1}{\alpha}} \times d_{omni} \tag{4}$$

where d_{omni} is the communication range between the sink and a sensor node when both are using omni-directional antennas. In the case of α=2, for example, d_{60° = 2.45 x d_{omni}.

3.2. Network Model

The network model in this paper is illustrated in Figure 2. Due to limited transmission range, the data from sensor nodes are delivered to the sink in a hop-by-hop fashion. We define a *relay zone* in which sensor nodes can directly communicate with the sink in one-hop. We call the nodes in the relay zone *one-hop relay nodes*. Sensed data from source nodes are transmitted to *one-hop relay nodes* on a multi-hop path in order to reach the sink. In Figure 2, we can see that the one-hop relay nodes are likely to deliver more traffic and hence deplete their battery more rapidly than other nodes far from the sink. If all one-hop relay nodes die eventually, the sink will be isolated and the network lifetime is ended although other sensor nodes are still alive and able to sense the interested events. Indeed, the network lifetime highly depends on the number of sensor nodes deployed in the relay zone.

The number of sensor nodes is determined by node density β that is defined as the number of nodes per unit area. Let *N* be the number of sensor nodes deployed in whole network area. Let *R* be the size of the sensor networks

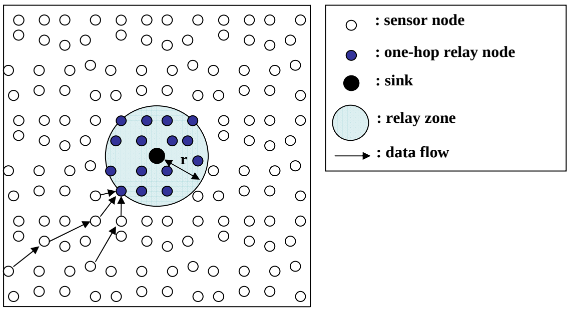

Figure 2: Illustration of relay zone and one-hop relay nodes.

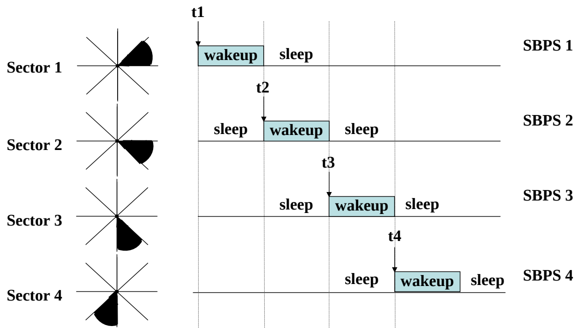

Figure 3: Wakeup/sleep schedule according to beam patterns.

$$\beta = \frac{N}{R} \tag{5}$$

The number of one-hop relay nodes N_r can be found as

$$N_r \approx \beta \times \pi r^2 \tag{6}$$

where *r* is the transmission range of the sink.

3.3. Energy Consumption Model

The network's lifetime is defined as the time until the sink is isolated, which highly depends on the energy consumption model. In sensor networks, the energy consumption of a node is incurred by three behaviors: transmitting and receiving data, staying in idle state.

The total energy cost, *E*, used by a node is given by

$$E = E(tx) + E(rx) + E(idle) \tag{7}$$

We ignore the computing and sensing energy cost in this paper. We assume that the sensor nodes have a limited battery energy and the sink has unlimited energy source. For example, sensor node *k* has energy $E_k(0)$ at time 0. The remaining energy at sensor node *k* at time *t* is

$$E_k(t) = E_k(0) - \int_o^t E_k(\tau)d\tau \tag{8}$$

where $E_k(\tau)$ is the total energy cost used at node *k* at time τ.

4. Directional Antenna at Sink (DAaS)

4.1. Overview

We divide a one-hop relay zone of a sink into *n sectors* where *n* is 360°/θ and θ is the predefined beamwidth of the sink's directional antenna. For example, when the beamwidth of the sink's directional antenna is 45°, as shown Figure 1 (b), there are *eight sectors* in the one-hop relay zone. The sink's directional antenna rotates its beam pattern among its sectors on a sector-by-sector basis. When the antenna beam pattern is formed to *sector i (i=1,2,3,⋯,n)*, all one-hop relay nodes located in *sector i* can communicate with the sink. Thus, the one-hop relay nodes in *sector i* must know the beam-forming schedule so that they can wakeup only when the sink's antenna is beamforming to *sector i*. Figure 3 shows an illustrative wakeup/sleep schedule of four out of eight beam patterns.

A wakeup/sleep protocol, such as SMAC, maintains global network connectivity by keeping track of neighbor nodes' different schedules. Thus, a node might have to follow more than one schedule to communicate with all of its neighbors. Hence, the duty-cycle of such a node may be higher than those of other nodes. If one-hop relay nodes of a sink are enforced to follow only one wakeup/sleep schedule, they save more energy by minimizing duty-cycles. To this end, we propose that the sink broadcasts a *sink beam pattern schedule (SBPS)*, for each sector, which allows all the one-hop relay nodes in each sector to follow only one schedule.

4.2. Sink Beam Pattern Scheduling Algorithm

At first, the sink broadcasts its wakeup/sleep schedule, *SBPS*, to the one-hop relay nodes for each sector one-by-one. The *SBPS* for each sector has a different wakeup/sleep time schedule as illustrated in Figure 3. The nodes that received the *SBPS* message from the sink deem themselves as one-hop relay nodes and store the *SBPS* in their schedule tables. The schedule table entry contains the ID of the sink, the schedule of wakeup and sleep. Upon receiving a *SBPS*, one-hop relay nodes delete other schedules and follow only a single *SBPS*. With the assumption of spatially non-overlapping beam patterns, each one-hop relay node follows only one *SBPS* broadcast by the sink. If beam patterns are overlapping (e.g. due to side lobes), the one-hop relay node will follow the *SBPS* with the strongest received signal strength.

Upon receiving a *SBPS*, one-hop relay nodes also update their routing tables so that they can forward packets to the sink directly. Then, the one-hop relay node broadcasts its schedule in a new SCHEDULE message to its neighbor nodes. Note that a node that hears multiple SCHEDULE messages will follow all of them as specified in SMAC.

In Figure 4, there are three nodes and one sink. Note that nodes 1 and 2 are one-hop relay nodes. At time t0, each node has its own schedule. At time t1, the sink is beamforming to node 1 and broadcasts *SBPS 1*. Node 1 knows that it is a one-hop relay node and changes its own schedule to *SBPS 1*. Right after that, at time t2, node 1 broadcasts a SCHEDULE (that contains *SBPS 1*) to its neighbors: node 2 and 3. Node 2 and 3 change their own schedules to *SBPS 1*. At time t3, the sink is

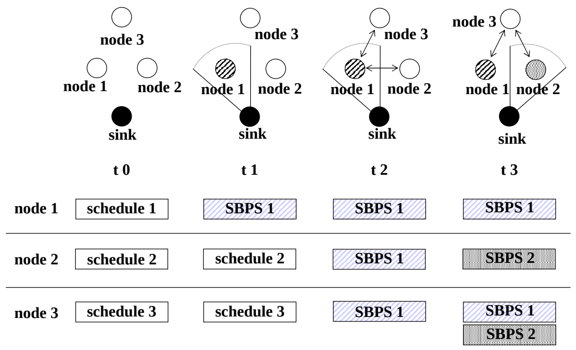

Figure 4: Each node's schedule table with time stamp.

beamforming to node 2 and broadcasts *SBPS 2*. Node 2 also knows that it is a one-hop relay node and changes its own schedule to new schedule, *SBPS 2*. After that, node 2 broadcasts a SCHEDULE (that contains *SBPS 2*) to its neighbors. Node 3 will follow multiple schedules, each of which is rebroadcast from a *SBPS*. When the nodes receive multiple SCHEDULE messages from other one-hop relay nodes, the nodes also add different schedules to their schedule tables and know that they can communicate with one-hop relay nodes of different beam patterns.

5. Simulation Results

In this section, we evaluate DAaS in terms of 1) Network lifetime, 2) The ratio of dead nodes at lifetime, 3) End-to-end hop distance and 4) End-to-end delay. Total 144 sensor nodes are deployed uniformly in an area of 120m x 120m and the sink is placed in the center of the sensor network. In simulation experiments, we consider only one sink and 12, 16, 20 source nodes (among 144 sensor nodes) deployed along the edge of the area. Obviously, all source nodes are outside of the sink's direct communication range. They transmit a burst of 50 frames of 80 bytes and the interval between bursts is 10 minutes. The wireless link bandwidth is 250 Kbps as specified in IEEE 802.15.4.

Every node in the network is stationary. Each sensor node is equipped with an omni-directional antenna while the sink is equipped with a directional antenna with flat-top antenna pattern. The sink's directional beamwidth, θ, is set to one of omni-directional (360°), 90°, 60°, and 45°. And the sink-to-sensor communication range d_θ is determined by Equation (4) where the inter-sensor communication range d_{omni} has two options of 10m, 15m.

The sink is assumed to have an infinite power source and sensor nodes have a finite battery power. The receiver sensitivity threshold is assumed to be 0 dB. As a path loss factor, $\alpha = 2$ is used. The routing and MAC model used are AODV [7], SMAC, respectively.

Each plot of the following graphs has a legend of a pair of numbers: d_{omni} and the number of sources. We define the network lifetime as the time from the beginning of the network operation until all the one-hop relay nodes of a sink become dead although the other nodes except one-hop relay nodes still alive. In other words, when the sink is isolated, the network lifetime is ended

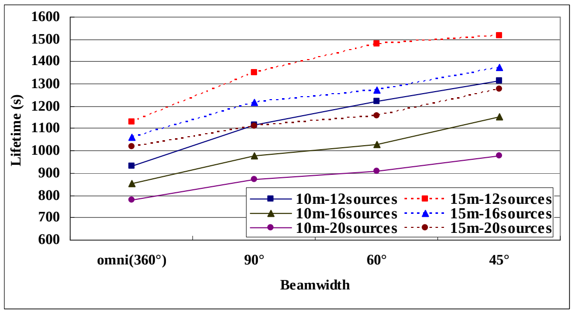

Figure 5: Network lifetime.

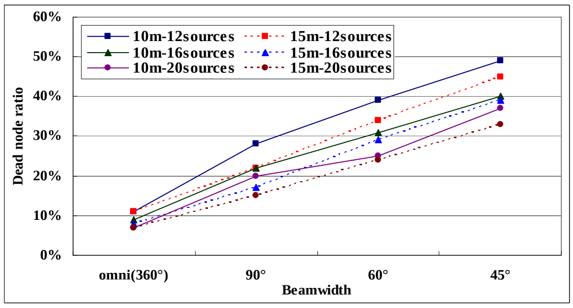

Figure 6: Dead node ratio.

because any data from sources couldn't be delivered to the sink any more. In Figure 5, the network lifetime with a directional antenna increases as the number of beam patterns increases. We also observe that one-hop relay nodes become dead more rapidly when more source nodes generate data traffic that one-hop relay nodes have to forward. Another interesting observation is that the communication range d_{omni} greatly affects the network lifetime.

We measure a dead node ratio as the ratio of dead nodes to all deployed nodes when the sink isolation happens, i.e., network lifetime is ended. If only a small portion of sensor nodes are dead and many sensor nodes are still alive when the network is ended, sensor nodes in this network are underutilized. In contrast, high dead node ratio implies that sensor nodes are efficiently utilized.

Figure 6 shows that the use of a directional antenna greatly improves the dead node ratio: it shows up to 5 times improvement compared to the omni-directional antenna's 10% dead node ratio. The communication range has a small effect on the dead node ratio.

Figures 7 and 8 show that the source-to-sink hop distance and delay decreases as a narrower beam pattern is used. In Figure 8, hop distance is substantially reduced as the communication range d_{omni}. This phenomenon explains why the longer communication range d_{omni} extends network lifetime. Comparing the two graphs of hop distance and delay, we observe the hop distance and delay is correlated: if hop distance is high, delay is also high. We observe an interesting thing when sensor node's transmission range is changed from 10m to 15m. With this change, the hop distance is drastically decreased while the delay is dropped by a small margin. This happens because more intensive data traffic from many sources causes longer queuing time at each relay node.

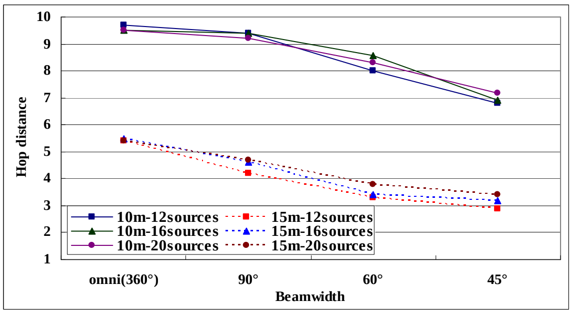

Figure 7: Hop distance.

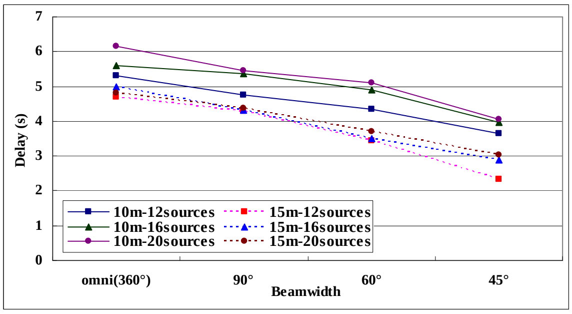

Figure 8: Delay.

6. 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 Directional Antenna at a Sink (DAaS) scheme. Mounting a directional antenna at the sink increases the sink's communication range, which extends the network lifetime. In order to effectively schedule wakeup/sleep operations of relaying nodes according to the antenna beam sweeping schedule, sink beam pattern scheduling algorithm is proposed. We showed how DAaS prolongs the network lifetime and improves dead node ratio and reduces end-to-end hop distance and delay. For the future work, we investigate the effects of transmission/reception power control on the network lifetime. By using power control, we can efficiently utilize relay nodes of sink.

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