Power Efficient System for Sensor Networks

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Abstract

We propose a power efficient system architecture that exploits the characteristics of sensor networks in order to decrease the power consumption in the network. The primary characteristic of sensor networks is that the destination of all the data packets in the network is a central data collector and this central data collector, which is usually denoted as access point(AP), has unlimited transmission power and energy whereas the sensor nodes have one battery energy to remain alive for several years. Our system uses the AP to directly synchronize and explicitly schedule the nodes' transmissions over Time Division Multiple Access(TDMA) time slots. Simulations performed in TOSSIM, a simulation environment for TinyOS, show that the battery lifetime of the network with this scheme can be increased to 1-2 years from 10 days that can be obtained from a general random access network.

1. Introduction

Wireless sensor networks is an emerging research area with potential applications in environmental monitoring, surveillance, military, health and security. Such a network consists of a group of nodes, called sensor nodes, each with one or more sensors, an embedded processor, and a low-power radio. Typically, these nodes are linked by a wireless medium to perform distributed sensing tasks.

The basic feature of a sensor network that is different from traditional wireless ad hoc networks is that data traffic flow is from the sensor nodes to an access point (AP) that collects the data, rather than many independent point-to-point flows. Another important sensor network characteristic is that traffic generation at each node either has to be periodic or can be made periodic for robustness of the system. For instance, monitoring each spot in parking lot in order to lead the cars to empty spaces requires periodic packet generation at each sensor node. On the other hand, the sensor network deployed for fire detection needs packet generation only when there is a fire. However, if the network is not functional due to node failures, the AP will interpret this as having no fire. The periodic update of the fire condition by periodic generation of packets in the sensor nodes justifies the robust operation of the system.

The energy limitation of the sensor nodes due to their small size and long lifetime requirements imposes constraints on the protocol design. The primary source of energy consumption is the radio. Collision causes a packet to be corrupted by another packet. Since this packet is discarded, the energy consumption per successful transmission will increase. Idle listening occurs when the node consumes power listening to the channel for possible traffic even when there is no packet to be received on the channel. Overhearing occurs when a node consumes energy to receive a packet that is not destined to itself. Finally, control packets should be minimized to eliminate the energy consumption related to them. Since listening to the channel or receiving a packet may cost almost as much power as transmitting a packet (listening and receiving power requirement is half of the transmitting power for the sensor nodes developed in UC Berkeley [1]), sensor nodes must only be awake to receive the packets destined to themselves or to transmit, and sleep otherwise in order to conserve power.

We propose a system for sensor networks with the goal of achieving power efficiency in a robust and adaptive way. We combine the characteristics of cellular networks with those of ad hoc networks, based on the assumption that the AP has no energy constraint whereas the sensor nodes have limited energy. A mobile node is only a single hop away from the nearest AP in a cellular system whereas the nodes communicate over multiple hops in a short-range wireless ad hoc network. Our protocol uses the cellular idea in transmitting packets from the AP to sensor nodes and the ad hoc network idea while each node transmits its data packet to the AP. In the case when it is not possible for the AP to reach all the sensor nodes in the network in one hop, more than one AP can be assigned to the network so that together they cover all the nodes in the network.

We describe the previous work on increasing the lifetime of sensor networks in Section 2. We give our system description in Section 3 and then simulation results in Section

4. We then conclude in Section 5.

2. Previous Work

Current MAC protocols for sensor networks can be divided into contention-based and TDMA protocols. We start with the review of previously proposed contention-based protocols and then continue with TDMA-based protocols.

The first class of protocols are contention based protocols. Our protocol uses a version of contention based protocol in order to provide topology information to AP. The MAC protocols in this class that provide power efficiency are based on exploiting the absence of traffic in listening state by putting the radio in sleep mode. These protocols differ from each other according to the radio wake-up algorithm. In [2], a separate wake-up radio is used to power down the normal data radio as long as there is no packet transmission or reception, based on the assumption that the listen mode of the wake-up radio is ultra low power. If a neighbor node wants to transmit a packet, it first sends a wake-up beacon over a wake-up channel to trigger the power up of the normal radio and then sends the data packet over the data radio. This protocol is successful in avoiding overhearing and idle listening problems in the data radio, but it is unable to solve the collision problem. Moreover, the difference in the transmission range between data and wake-up radio may pose significant problems.

The protocol in [3], called S-MAC (sensor-MAC), prevents overhearing by in-channel signaling, using the RTS (Request To Send) and CTS (Clear To Send) packets as in IEEE 802.11 [4]. When an interfering node hears a RTS and/or CTS packet, it goes into sleep mode. This protocol avoids idle listening through periodic listen and sleep modes, the schedules of which are known by neighboring nodes. The problem with this protocol is that it uses RTS/CTS packets to avoid contention and extra synchronization packets, which increases the energy consumption through control packets.

STEM (Sparse Topology and Energy Management) [5] protocol trades energy savings for latency through listen/sleep modes as in [3] but by using a separate radio. When a node wants to send a packet, it polls the target node by sending wake-up messages over a paging channel. Upon receiving a wake-up message, the target node turns on its primary radio for regular data transmissions. The purpose of using a separate paging channel is to prevent polling messages from colliding with ongoing data transmissions. This scheme is effective only for scenarios where the network spend most of its time waiting for events to happen. Otherwise, the polling through a stream of wake-up messages, collisions and overhearing may cancel out the energy savings obtained by sleep modes.

The second class of MAC protocols are TDMA-based protocols. The scheduling part of our protocol belongs to this class. The advantages of a TDMA based scheme are elimination of overhearing, collision and idle listening. However, the currently proposed TDMA protocols are based on performing TDMA scheduling in real communication clusters [6, 7]. The overhead of forming these clusters, and inter-cluster communication and interference may eliminate the efficiency of TDMA. Cluster problem can be solved by performing TDMA scheduling for all the nodes in the network by the usage of a simple high power AP.

These approaches all have the advantage of accommodating random access. However, they achieve power savings up to a factor of four, at a considerable increase in hardware or control complexity.

3. System Description

Our system consists of access points and sensor nodes that are in the transmission range of at least one access point. Each access point (AP) is used to coordinate a fraction of sensor nodes. The access point is assumed to be able to reach all the sensor nodes in its network in one hop since it is supposed to have a lot of energy and transmission power. However, it can also decrease its transmission range so as to help the sensor nodes determine their next hop in their route to AP. The path from the sensor nodes to AP is over multiple hops since sensor nodes have limited energy in the tree topology mentioned in [14].

The hardware of the sensor nodes is assumed to support adjusting the transmission power, which already exists in UCB Mica motes [1]. The transmissions in our system are performed over three ranges. The longest transmission range belongs to the coordination packets of AP. The access point uses this range in order to reach all the sensor nodes in one hop and to directly control their transmissions. The shortest transmission range is used in the transmission of the data packets from sensor nodes to AP. This range must be chosen to be the lowest possible range that assures the connectivity of the network. The medium transmission range is used in the tree construction so as to learn the interferers of each sensor node, which are defined to be the nodes whose signal level too weak to be decoded but strong enough to interfere with another signal.

The sensor network belonging to a particular AP can operate in one of three phases: the topology learning phase, the topology collection phase, and the scheduling phase. During the topology learning phase, every node identifies its neighbors, interferers and parent in the tree containing AP as root and the shortest paths from each node to AP. In the topology collection phase, each node sends its neighbor, interferer, and parent information to AP so that AP has complete topology information at the end of this phase. During the scheduling phase, each node transmits according to the schedule announced by AP at the beginning of the phase and sleeps during the slots that it is not transmitting or receiving any packet.

3.1. Topology Learning Phase

The topology learning phase is the phase during which each node identifies its interferers, neighbors and parent. The phase begins when the access node transmits a *topology learning* packet over the longest range in one hop to all sensor nodes that it is willing to coordinate. This packet includes the *current time* so that each node updates its time and synchronizes with each other and the *incoming packet time* so that every node will stop transmitting and listen for the next broadcast message of AP at this future time. Following this coordination packet, AP floods the *tree construction* packet over the medium range. This packet contains the *number of hops* field so as to avoid the loops that packets experience and to choose the parent node in the tree. At the end of this phase, each sensor node decides the parent to be the node over the smallest number of hops to AP, the neighbors and interferers as the nodes with the received signal level above and below some *interfering threshold* respectively.

In this phase, a random access scheme has to be used since no node has any topology information. The random access scheme and its parameters should be chosen so that the nodes learn about all of their neighbors and interferers with high probability so that scheduling phase can be successful. The nodes listen to the radio for a random amount of time before transmitting and then transmit if the channel is idle. We have added a random delay before carrier sensing in order to further reduce the number of collisions.

3.2. Topology Collection Phase

The topology collection phase is the period at the end of which AP receives the complete topology information. The topology collection phase starts with the coordination packet of the AP named *topology collection* packet that is transmitted by the access point over the longest range at the time announced in the *incoming packet time* field of the *topology learning* packet. This packet contains *current time* field for synchronization and *incoming packet time* field for the next coordination packet broadcast time.

Following the coordination packet, each node transmits its *topology* packet containing its parent, neighbor, and interferer information to AP. Here again, CSMA scheme with some random delay before the transmission is used. However, this random access scheme alone is not expected to be successful since each collision will eliminate the topology information of at least 2 nodes. In this case, using implicit acknowledgement, which is the packet transmitted from the parent of the node to the parent of its parent, can be used in detecting collisions and therefore retransmitting.

3.3. Scheduling Phase

The scheduling phase is the phase during which each node is explicitly scheduled by AP based on the complete topology information obtained in topology collection phase. The scheduling frame is divided into time slots. We assume that the packet generated at each node has constant length and can be transmitted during one time slot. At the beginning of this phase, AP performs the scheduling of the sensor nodes in the network and announces the schedule of how all the traffic will be carried during the *scheduling frame* by broadcasting the *schedule* packet over the longest range. The schedule packet, includes the transmitter information corresponding to each time slot in addition to *current time* and *incoming packet time* fields. At the beginning of the scheduling frame, each node samples the sensor and generates one packet, which is then carried to AP according to the schedule.

For this phase, any scheduling algorithm that guarantees that the packets generated at each sensor node reach AP by the end of the phase will be appropriate. If the application requires real-time delay guarantee, then the algorithm given in [13] can be used to guarantee a delay proportional to the number of nodes in the network.

The system performance is expected to improve as the proportion of the number of scheduling phases to the total number of topology learning and collection phases increases. If the percentage of successfully scheduled nodes decreases below some threshold, which is pre-determined depending on the application, for the latest scheduling frames, the topology learning phase will follow the scheduling phase.

Our system can also deal with unsuccessful transmissions via redundancy instead of restarting topology learning phase. When the degree of redundancy is n, n nodes are placed in a specific area in place of a single node, which would be the case when there is no redundant node in the network. We call these *n* nodes a *redundancy group*. After the determination of redundancy groups, only one node from each redundancy group is scheduled in each scheduling phase. If one of the nodes is not able to send its topology information to AP during the topology update phase or the topology information of a node is not correct, one of its redundant nodes will be scheduled. Redundant nodes also increase the overall lifetime of the system by putting their radio in sleep mode when they are not scheduled.

4. Simulation

The simulation environment is TOSSIM [8], a discrete event simulator for TinyOS [1], the operating system for the Berkeley sensor node. TinyOS and TOSSIM are not described here. The advantage of TOSSIM is that TOSSIM simulation compiles directly from the TinyOS code used to implement the protocol.

In the simulations the nodes are randomly distributed in a circular area of radius 100 units. The transmission rate is 50 kbps. The transmission range is chosen to be the minimum range providing connectivity [9, 10]. The results discussed below are averages of 10 Monte Carlo simulations. Variations around the averages are presented in [13].

The goal of the simulations is to perform a comparison of the power consumption of the best possible random access strategy and our power efficient system. The best possible random access strategy is obtained so as to guarantee a high percentage of the packets to reach AP by adjusting backoff and listening window sizes in CSMA. We then try to further increase the lifetime of the sensor network by adjustment of packet generation rates and redundancy level.

4.1. Comparison of Power Consumption

The operations requiring power in a sensor node are transmission and reception of a packet, listening to the channel, sampling, and running the microprocessor.

Power comparison of a random access scheme and our system is performed by estimating the lifetime of the sensor network with data rate 50 kbps. It is assumed that a clock interrupt is received every 1 msec and the sensor is sampled only once during one packet generation period, 30 sec. The lifetime calculation is performed based on the assumption that sensor nodes run on a pair of AA batteries, which can supply 2200 mAh at 3V. We get an estimate of the average lifetime without performing the actual lifetime estimate taking into account network connectivity as in [12]

Figure 1 gives the lifetime estimates for random access scheme and our system. The difference between these two schemes is observed to be significant. The lifetime of the network operating on random access is around ten days whereas that operating on our system is around two years. As the number of nodes increases, there is not much change in the lifetime of random access scheme whereas there is a decrease in the lifetime in our system.

To understand the reason for this drastic difference and the behavior of the plot with respect to the number of the nodes, the distribution of consumed power in a particular node among transmitting, receiving, listening, sampling, and clock interrupt handling is given in Figure 2.

As can be seen from the distribution of the energy, the primary cause of the huge difference in lifetime estimates

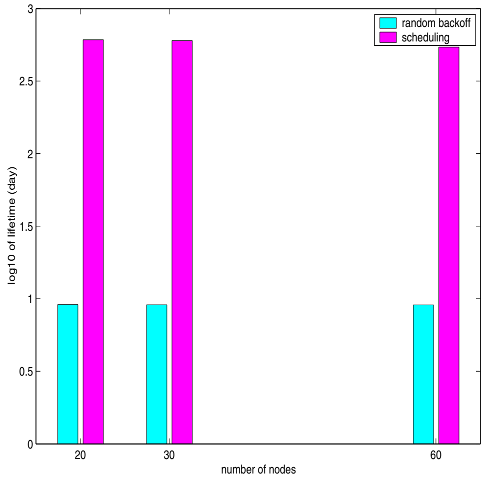

Figure 1. Comparison of the average lifetime of a sensor network operating on random access scheme and our system for different number of nodes with packet generation period 30 sec and data rate 50kbps.

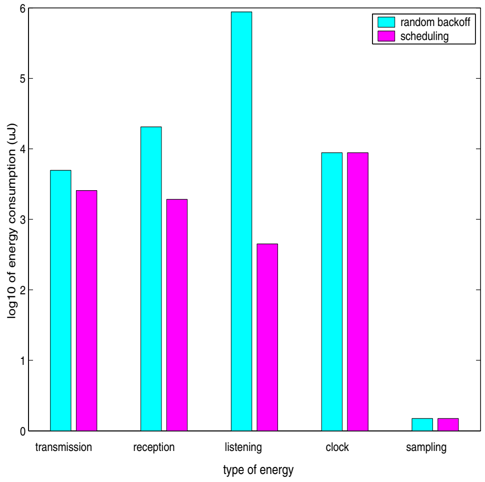

Figure 2. Distribution of power consumption in different tasks for random access scheme and our system with packet generation period 30 sec and data rate 50kbps.

is the energy consumed in listening. This was expected since listening power in receive mode is on the order of mW while it is on the order of μW in sleep mode. If the length of packet generation period increases, the difference is expected to increase even more since the time spent in listening to the channel increases.

Other reasons for the difference in lifetime estimates are the different amount of energy spent in transmission and reception. The average transmit energy difference results from the larger number of messages transmitted in the random access scheme. In random access scheme, retransmissions occur in case of collision whereas there is no retransmission in our system since every transmission is scheduled beforehand. The average receive energy difference results from the "overhearing effect". In random access scheme, when one node transmits a message, all the neighboring nodes receive this packet whereas only the parent of that node receives the packet in our system.

The reason for the almost constant lifetime of random access scheme with respect to the number of nodes is the dominating effect of listening energy. As the number of nodes increases, the additional burden on the nodes will be the increase in the number of packets transmitted and received. However, since this is only a small percentage of the consumed energy, the lifetime stays almost constant. For the scheduling scheme, the lifetime decreases as the number of nodes increases due to the increase in the number of received and transmitted messages.

Some applications may require sampling the sensors more than once between the packet generations to be able to detect events. For instance, sampling once every 30 sec may be good enough for the detection of the cars in a parking lot whereas sampling at 5-10 kHz is necessary for the detection of moving cars in traffic light application. Sampling at 5-10 kHz increases the energy consumed in sampling by a factor of 150000-30000 compared to the case of sampling once every 30 sec, which will cause the sampling energy to dominate as can be seen from the energy distribution graph in Figure 2. Therefore, sensors consuming much lower power are needed for this kind of applications [11].

4.2. Further Improvements in the Performance of Proposed Scheme

We can increase the lifetime of the system even more depending on the application using the above simulation results. If the application does not require generating packets frequently all the time, we can save power by increasing the packet generation period. Also, we can place redundant nodes in the network in order to divide the work that each one has to perform so as to increase their lifetime.

Increasing Packet Generation Period

The savings achieved by putting the radio in sleep mode instead of actively listening to the channel depend on the length of listening duration of the nodes. Figure 3 explores this effect. As the length of packet generation period increases, the lifetime of our system increases whereas there is no change in the lifetime of the random access scheme. Therefore, for the applications that do not require frequent sampling, for example applications that just require a summary of what has happened in the last 2-3 minutes or parking lot at night, the lifetime of the network can be increased even more by increasing the packet generation period. The reason of the increase in lifetime with respect to packet generation period with a slope less than 1 is the energy consumed in clock interrupt handling, which consumes high percentage of the energy as can be seen in Figure 2.

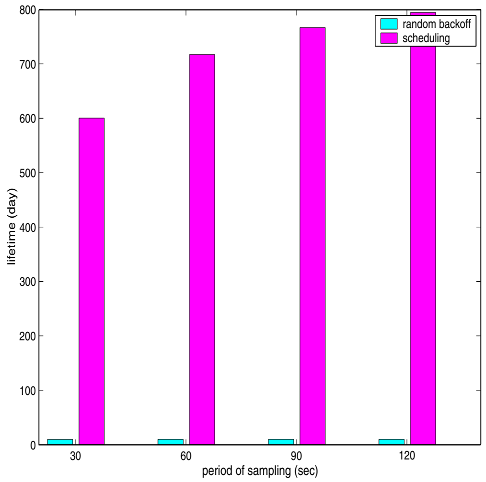

Figure 3. Lifetime estimate of our system for different sampling rates.

Increasing Redundancy in the Network

The lifetime of the nodes in our system can be increased even more by placing redundant nodes in the network. Here, we performed the simulations by placing n nodes (instead of one) in a specific area, all of which have the same topology information, for redundancy level n.

Since clock interrupt handling consumes a lot of power, we assume that the nodes that are not scheduled decreases their clocking rate and increases back in the last part of the packet generation period. In this case, if all the nodes in one redundant group can send their sampling data back, then they will be scheduled $1/N$-th of the time otherwise they will be scheduled 1/number of successful nodes in the group-th of the time.

Figure 4 shows that increasing the redundancy level in the network by a factor of 3 or 4 can increase the lifetime of the network to 5 or 6 years.

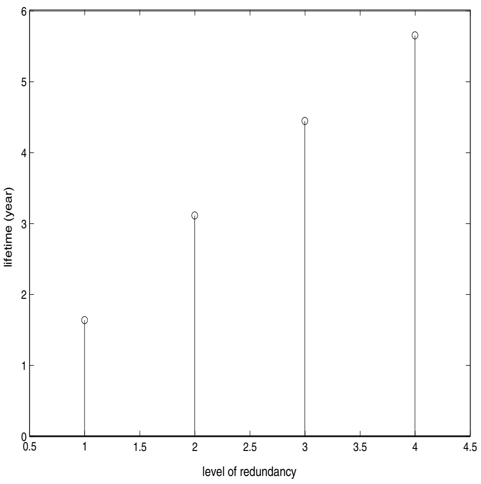

Figure 4. Lifetime estimate of our system for different redundancy levels.

5. Conclusion and Future Work

We proposed a power efficient system for sensor networks. The basic assumption of the system is that sensor nodes are transmission power and energy limited whereas the access point (AP), which is the destination of all sensor data packets in the network, is not so limited. AP can then reach all the nodes in the network in one hop by increasing its transmission power level. This helps the nodes to be synchronized easily and to be directly scheduled by AP after a topology update phase assuming static networks, which is true in most of the applications such as parking lot, traffic light. Based on simulations, we observed that our system consumes much less power compared to the random access schemes. This scheme can be explored further by scheduling the nodes with different packet generation rates, by determining redundant groups based on the location and sampling results of the nodes, and by building power saving mechanisms at physical layer and routing layer to build a more power efficient system.

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