Analysis of Energy Conservation in Sensor Networks

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Abstract. In this paper we use the Erlang theory to quantitatively analyse the trade-offs between energy conservation and quality of service in an ad-hoc wireless sensor network. Nodes can be either sleeping, where no transmission or reception can occur, or awake where traffic is processed. Increasing the proportion of time spent in the sleeping state will decrease throughput and increase packet loss and delivery delay. However there is a complex relationship between sleeping time and energy consumption. Increasing the sleeping time does not always lead to an increase in the energy saved. We identify the energy consumption profile for various levels of sensor network activity and derive an optimum energy saving curve that provides a basis for the design of extended-life ad hoc wireless sensor networks.

Keywords: sensor networks, ad hoc networks, energy efficient design, QoS, Erlang formula

1. Introduction

Recent advances in micro-electro-mechanical systems (MEMS) technology, wireless communications and digital electronics have enabled the development of low-cost, low-power, multifunctional smart sensor nodes [1]. Smart sensor nodes are autonomous devices equipped with heavily integrated sensing, processing, and wireless communication capabilities [17,3]. When these nodes are networked together in an ad-hoc fashion, they form a sensor network. The nodes gather data via their sensors, process it locally or coordinate amongst neighbors and forward the information to the user or, in general, a data sink. Due to the node’s limited transmission range, this forwarding mostly involves using multi-hop paths through other nodes [3]. A node in the network has essentially two different tasks: (1) sensing its environment and processing the information for onward transmission, and (2) forwarding traffic from other sensors as an intermediate relay in the multi-hop path.

The major design challenge for this type of network is to increase the operational lifetime of the sensors as much as possible [1,7]. Indeed, sensor nodes are miniature devices and operate on a tiny, non-replaceable battery. Energy efficiency is therefore the critical design constraint. Research can address two different perspectives of the energy problem: (1) an increase in battery capacity and (2) a decrease in the amount of energy consumed at the wireless terminal. The focus of battery technology research has been to increase battery power capacity while restricting the weight of the battery. However, unlike other areas of computer technology such as microchip design, battery technology has not experienced significant (compared to Moore’s Law) advancement in the past 30 years. Therefore, unless a breakthrough occurs in battery technology, a goal of research should be to decrease the energy consumed in the wireless terminal [8].

In terms of energy consumption, the wireless exchange of data between nodes strongly dominates other node functions such as sensing and processing [4,13]. Moreover, actual radios consume power not only when sending and receiving data, but also when listening. Energy models have been developed [13,18] which show that the energy consumption ratio of listen:receive:send is about 1:1:1.5. With this model, node listening time dominates energy consumption in light or moderate traffic scenarios. Significant energy savings are only obtainable by putting the node into a sleep mode when there is no traffic [7,10,15].

Given the importance of energy conservation in sensor networks we now describe a simple model that allows us to investigate (a) the relationship between energy consumption and network traffic and (b) the trade off between energy consumption and network performance. Our asynchronous queuing model looks rather like pure ALOHA with random periods of sleep although the local connectivity of nodes in a sensor network is quite different to the global connectivity of nodes in a simple ALOHA network. Recently, there has been some research on slotted ALOHA medium access control protocols for sensor networks [16,20,25]. The performance analysis of the pure ALOHA algorithm provides a base level of performance for judging the effectiveness of the slotted ALOHA algorithm. Similarly, our simple model also provides a benchmark against which the performance of more complex sleep synchronisation protocols can be judged.

2. Description of sensor node

We consider a network of wireless sensor nodes where each node consists of a transmitter and receiver together with some sensing device. For our purposes the sensing device is a source of information flow local to the sensor node. We will assume that the sensor node is kept as simple as possible in order to
enable mass deployment. Thus, we assume that a single antenna is available and that the node can transmit or receive but not both simultaneously. Each sensor node will accept information from other nodes for onward transmission. There will also be special ‘sink’ nodes in the network where information terminates, these will not be explicitly modelled here as we are only interested in the relationships between local and transit traffic and how these affect the performance of the network. Since nodes will have limited computational and memory resources we will explicitly model the queuing of packets in the node.

The four possible states of the nodes are shown in figure 1. A node is said to be ‘active’ when it is transmitting or receiving information and ‘idle’ when it is listening (i.e. listening but not actually receiving data) or asleep (i.e. not listening to the outside world). These four states have different levels of energy consumption, as we will discuss in the next section. Transitions between these states can occur naturally, such as the change from listening to receiving when data arrives from a neighbouring node, or as a result of some internal decision, such as the scheduling algorithm used to decide when to change from listening to sleeping and vice versa.

3. Energy-conserving algorithm

To reach our low energy target, we can let radios sleep most of the time and yet let them awaken precisely when they need to transmit or receive data. Unfortunately, current radio technology does not easily allow a radio to be awakened upon request. Hence, a radio must wake up periodically, see if anyone wants to talk to it, and, if not, go back to sleep. The simple energy-conserving algorithm that we will analyse will now be described.

Nodes are in one of the following states: sleeping, listening, sending or receiving. The state transition diagram is shown in figure 1. We use the term idle to describe the sleeping and listening states and the term active to describe the sending or receiving states.

Initially nodes start out in the sleeping state. When sleeping, the radio is off and therefore not consuming power. (Although the radio is off, sensors or other low power parts of the node may be on.) In this state the radio remains turned off for time $T_s$ and then undergoes a transition to listening. If, however, while a node is sleeping data to be transmitted is generated then it changes to the active transmit state and starts sending the data. During the listening state if neighboring nodes try to transfer packets via the node, or if data needs to be sent, the node changes to the appropriate active state. Otherwise it returns to the sleeping state after time $T_s$. When in an active state a node either sends or receives data. After all data transmission has finished, the node changes to an idle state and begins alternately sleeping and listening according to some pre-defined pattern.

The algorithm that turns off the radio is targeted to improve power consumption. However turning off the radio has implications for network performance such as reduced throughput, added latency and possibly more packet loss compared to the communication protocols without sleeping patterns. Here our objective is to characterize the trade-off and enable optimal control of the sleep/listen pattern in future networks.

We must point out that here we do not consider the synchronization of sleep schedule among the nodes as discussed in [14] where they listen at the same time and go to sleep at the same time. Though synchronization might reduce the additional latency it will increase the chance of overhearing traffic when a node picks up packets that are destined to other nodes and it will also increase the control packet overhead (synchronization packets). These are two additional sources of energy consumption and also increase the complexity of the algorithm. It should be noticed that the randomly occurring sensor information traffic is a potential interruption to the synchronization and to avoid this would require storage of information in the queue until the next waking period. This might well increase the required queue lengths in the nodes. So we consider the simplest algorithm in which each node chooses its own sleep schedule independently. This asynchronous algorithm may in some cases increase the probability of network connection. This is because long-range synchronization involves some network overhead. Methods based on local synchronization can lead to islands of synchronization where nodes within an island are synchronised but different islands are not [9,21]. This is illustrated in figure 2 where a node in island 1 wants to transmit data to a node in island 5. Recall that in a sensor network the

Figure 1. State diagram of the model sensor node.

Figure 2. Illustration of a partially synchronised network. Each island, labeled 1–5, consists of a set of nodes that have achieved local synchronisation. Since the islands are unsynchronised with each other, this leads to a lower probability of a network path between island 1 and island 5 compared to the asynchronous case.