POWER MINIMIZATION BY SEPARATION OF CONTROL AND DATA RADIOS

SHORT PAPER

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ABSTRACT

Wireless sensor networks (WSNs) are networked embedded systems where each unit generally consists of the following six components: sensors, memory, power supply, processor, communication unit, and actuators. WSNs will provide the bridge between the Internet and the physical world due to their ability to observing and controlling the physical world in real-time. Since most of the current WSNs use batteries as their energy source, energy consumption is the main design and operational constraint of sensor networks. Specifically, energy consumed by communication equipment is the dominating component of energy consumption.

In order to address this problem, we propose a new conceptual approach to minimize the communication and Therefore, the overall energy consumption by separating the traditionally used radio in sensor nodes into two radios: control radio and data radio. Control radio is used for frequent, low volume, short packet communication and to coordinate operation of data radios. Data radio is used for high latency, high volume, and large packet sensor data transmission. The preliminary studies show the high potential effectiveness of the approach.

1. INTRODUCTION

Wireless sensor networks (WSNs) are embedded wireless networked systems where each individual unit is equipped with sensors, actuators, memory, processor, communication unit, and power supply. WSNs have recently attracted a great deal of research and development attention mainly due to their potential to provide efficient and effective interface between the physical world and the computational world. Furthermore, they have high potential economic impact in many fields, including military, education, monitoring, retail, and science. At the same time, sensor networks pose numerous new researches and development challenges, including low power, low cost, small size, error and fault resiliency, flexibility, security and privacy, and a need for new types of I/O operations.

There is a wide consensus that one of most stringent bottlenecks in design and operation of WSNs is energy consumption. Although, there have been a number of proposal for sensor nodes equipped with solar panel and environmental vibration energy converters, most sensor network systems use battery as the source of energy. Due to the persistent technological battery limitations, most often the sensor nodes must operate on an extremely frugal energy budget. In majority of sensor network applications and architectures, communication cost dominates the energy budget. In typical applications, the ratio of communication to computation energy can be often as high as 100+ times [8]. Therefore, there is a strong need for reducing radio related power consumption.

Sensor networks can be configured in many architectural ways. Two most often discussed are: cell-based and ad-hoc. In a cell-based architecture, each cell consists a base station that all terminals within the cell communicate to. The base stations communicate among themselves across cells. On the other hand, in an ad-hoc (multihop) network architecture, there are no base stations that serve as the intermediate mediums. A node communicates to other nodes by discovering a path to the destination node and forward the message on to the path. Depending on the requirements of a targeted application, one or another communication architecture could be advantageous, it appears that in essentially all scenarios, communication cost is dominating the energy consumption, at least for current state-of-the-art technologies.

Numerous approaches have been proposed for power minimization, mainly using sophisticated optimization and sometimes technological techniques. We propose a new conceptual architectural approach for minimizing the communication energy consumption for sensor nodes by separating the radio into two separate units: control radio and data radio. The data radio is responsible for high volume sensor data communication. It uses large packets and can operate on higher power if there is a need to minimize the number of hops and therefore, a number of data radios that have been in active listening mode. In general, this radio is power-hungry radio, which has meaning that it consumes a lot of energy when it is operating or even simply being awake. So, it must be often and for long periods of time in the off/sleep mode in order to save energy.

On the other hand, the control radio is a frequently used, low volume radio. This radio is responsible for control functions such as reporting energy and buffer space status of each node, handshaking functions, and coordination of the communication operations (e.g. deciding when, how many data sample, and from whom to whom needs to be sent or received by others) and therefore wake/sleep control of the data radios when it is necessary.

Our primary objective in this paper is to introduce a new concept of minimizing the energy consumption of sensor nodes by separation of control radio and data radio. We also conducted a simple study that compares the power consumptions between our approach and the traditional approach.

The reminder of the paper is organized in the following way. We first summarize the related work done previously regarding sensor network in general. Then the two idea sources along with the new approach are discussed in Section 3. Finally, preliminary study that confirms the validity of the key idea is presented in Section 4. The advantages and limitations are discussed in Section 5.

2. RELATED WORK

The related previous efforts can be summarized along the following lines of research: sensor networks, power minimization, low power sensor networks, radio communication and energy consumption, and the separation of data and control in engineering systems.

Recently, sensor networks emerged as a premier high-impact research topic. A number of high profile applications for wireless sensor networks have been proposed [Ten00, Est00]. WSN pose a number of demanding new technical problems, including the need for new DSP algorithms [Pot00], low power design, operating systems [Hil00], and localized algorithms.

Low power has been the focus of intensive research and development efforts for more than a decade [2]. A great variety of modeling and optimization techniques have been proposed. The emphasis was mainly of exploiting optimization and technological aspects; relatively few new architectural concepts have been introduced for power minimization.
A number of approaches have been proposed for power minimization in sensor networks [5, 10]. In addition, several studies on energy consumption in sensor nodes have been conducted [8, 9]. It has been identified that energy is the main constraint, and communication is the dominant component of power consumption. Therefore, in order to minimize the power consumption of sensor nodes in general, minimizing the communication cost is the natural thing to do [how to minimize radios].

Separation of data and control is well proven idea that has been applied in a number of domains, including general-purpose processors [6] and network processors [7]. For example, in general-purpose processors, data path and control part are separated in order to enforce separation of concern design paradigm. In addition, instruction and data memory is separated in all Harvard-type architectures.

3. CONTROL AND DATA RADIOS: PRELIMINARIES, CONCEPTS AND TRADE-OFFS

In this section, we first briefly survey technological trends that emphasize that batteries are likely to stay of the main WSN constraint. Next, we explain the motivation for developing the two-radio architecture. After a brief description of the new architecture, we present the simulation study, which indicates that the approach indeed has high energy saving potentials. Finally, we discuss the advantages and overheads due to the separation of data and control radio.

As Figure 1 indicates, the capacity growth in batteries does not follow the Moore's Law. It only has a growth rate of 2-3% per year, which is incomparable to the much faster exponential growth of processors, hard disks and memories. This fact confirms that energy consumption is indeed the bottleneck of sensor networks' performance and lifetime.

The impetus for new architecture has been provided by two main sources: the nature of sensor network traffic and models of radio consumption and long standing idea of separation of design constraints. Although, the first large-scale well-documented experimental studies of the sensor network traffic are still not available, it is apparent that the traffic will have two components: control and data. Control data is usually very short and requires low latency response and therefore transmission. On the other hand, sensor data will be often of much high volume, often in response to a relatively rare event, and many application latency constraints will not be strict. Another important observation is that radios consume significantly less energy in sleep mode than in active modes [8].

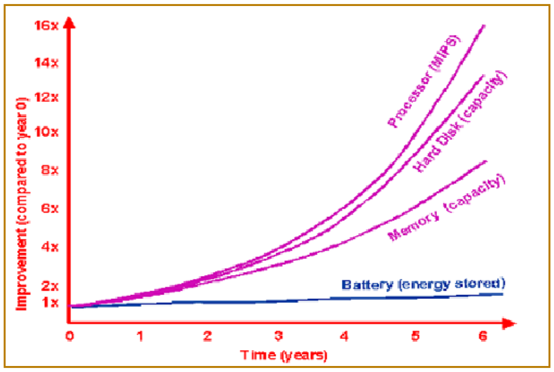

Figure1. Technological Trends: Battery capacity has by far the slowest growth rate

In addition to the already-discussed separation of data and control planes in processors, the two-radio idea has been proposed. Specifically, in a recent patent, Motorola proposed the idea of incorporating two radios in a single sensor node: one is high power, high bandwidth; and the other one is low power. The first radio is responsible for carrying out the communication operations such as transmitting and receiving data to/from other nodes. This radio is high-power, meaning that it is a main energy consumer once it is operating. However, it is often in the sleep/off mode unless there are absolute needs for it to be awakened. A low power-consuming radio, in the Motorola scheme, is often operating and its only responsibility is to wake up the communication radio when it is necessary to transmit data. The control/data radio idea is the logical next step in exploring the two-radio concept in a sense.

Therefore, we propose a new approach that in a sense provides a further push for the state-of-the-art of how to employ the two-radio strategy, which has significant advantages. We also adopt the two-radio approach: one is high power, high bandwidth and one is small bandwidth (symbol rate) and low power. In our approach, the second radio is not just responsible for waking the high power radio, but also for conducting all control related tasks. These tasks are characterized by low symbol rate and high frequency of occurrence. For example, information about the current sleep policy, estimated bandwidth needs, storage buffer occupancy, and the detection of rare events are all being conducted using the low power radio. On the other hand, data radio is only responsible for transmitting and receiving high volume sensor data. It is used in bursts and often only for a relative short period of time. Since the awaking radio is very energy consuming, significant savings can be achieved.

4. SIMULATION

In order to evaluate the potential of the control/data radio scheme, we conducted the following simulation. We assumed traffic that consists of a given percentage of short and long packets. Total number of packets was set to 1000. Short packets have length 10 bits, and long packets have length 1000 bits. Furthermore, following [8], we assumed that the ratio of cost of sending bit using short packet format varies from 1 to 10 times of the energy cost of sending long packets. Note, that for the sake of clarity, we did not take into account sleep times and wake-up costs. This additional consideration would favor the two-radio scheme additionally.

Figure 2 shows the energy consumptions of the simulation using the traditional one radio and our two-radio approach. The X-axes shows the radio of energy consumption per bit of control radio and data radio. For example, X = 2 means that control radio spends two units of energy transmitting one bit verses data radio that spends one unit of energy transmitting per bit. The Y-axis indicated the traffic mix, i.e. various percentages of packets are short (10 bits/pkt). For example, Y is 20% means that 20% of all the packets transmitted are only 10 bits long, the rest of 80% are considered long packets (1000bits/pkt). Finally, the Z-axis indicates the savings in energy consumption using two-radio scheme with respect to the energy consumption of using only one radio. Specifically, we used data from the radio that spend less energy for a given traffic mix and packet cost scenario. As we can observe from the figure, applying two-radio scheme reduces energy consumption significantly.

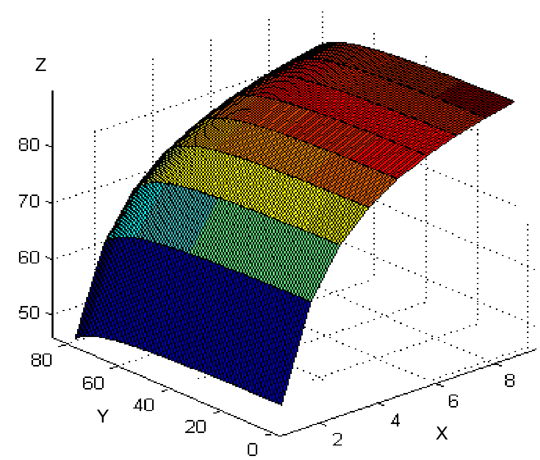

Figure2. Energy consumption vs. various radio sizes and packet sizes

Specifically, we see that the energy consumption is reduced by 50% to 80% (i.e. by factor between 2 and 4 times) due to usage of the control/data two-radio scheme.

It is interesting to note that while the traffic mix has very limited impact on the power reduction, the packet length and the cost of transmitting one bit has very high impact. Future simulation studies will consider much more comprehensive models of energy consumption in radios and properties of the traffic and are necessary for complete validation of the approach. Nevertheless, this simulation indeed indicates that there is high potential for energy reduction and lifetime enhancement of sensor networks using the new two-radio scheme.

5. ADVANTAGES AND TRADE-OFFS

The advantage of separating data and control streams and radios in wireless networks is not only lower power consumption, but also a better fault tolerance. Fault tolerance is increased because, if needed, the control radio can be used to carry out sensor data and the data radio can be used to carry out control data in the situation where one of the radios breaks down. The key design trade-off of this new approach is how to design each radio and how to properly size and configure them. In addition, there is a need to develop a new sleep policy and power (signal strength) management scheme for the sensor networks that use these new two-radio sensor nodes. We are currently implementing simulation models to evaluate and quantify the potential benefits of new scheme.

6. CONCLUSION

Energy consumption is the major bottleneck of sensor network performance and lifetime; and communication is the main component of energy consumption. Therefore, minimizing power consumption of radios is the right target to significantly reduce the energy consumption of sensor nodes. Inspired by the nature of sensor network communication traffic and by well-proved idea of control/data separation in general purpose processors and network processors, we significantly enhanced the effectiveness of the basic idea of separation of wireless radios in order to achieve a lower energy consumption level. The data radio is only awake when there are relatively large amount of data needs to be transmitted or received. It is in off/sleep mode most of the time in order to reduce the energy consumption. The control radio is in the operating mode much more often and handless short low latency burst control traffic. The simulation and preliminary studies indicate that control/data radio separation is indeed an effective method to reduce the energy consumption.

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