Techniques for Minimizing Power Consumption in Low Data-Rate Wireless Sensor Networks

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***Abstract*— Wireless sensor networks can enable numerous embedded computing applications. One of the primary benefits of wireless sensor networks is their independence from the wiring costs and constraints. However, if the batteries must be replaced often (every week or every month), not only will the initial cost savings be lost, but also many remote sensing applications may become impractical. Therefore, long battery life (in the order of years) is essential; power efficiency is a critical requirement for wireless sensor networks.**

We have devised several novel techniques for minimizing power consumption in wireless sensor networks. Based on these techniques, we have developed a highly power-efficient sensor networking platform called the i-Bean Network. In this paper, we describe these techniques in detail and the associated tradeoffs.

I. Introduction

Wireless sensor networks have immediate utility in a variety of industrial, medical, consumer and military applications. We studied several such applications and classified them based on their modes of acquiring and propagating sensor data. We find the following three classes to be the most common:

1) **Periodic Sampling** - For applications where a certain condition or process needs to be monitored constantly, such as temperature in a conditioned space or pressure in a process pipeline, sensor data is acquired from a number of remote points and forwarded to a data collection center on a periodical basis.
2) **Event Driven** - There are many cases that require monitoring one or more crucial variables and transmit only when a certain threshold is reached. Common examples include fire alarms, door and window sensors, or instruments that are used intermittently.
3) **Store-and-Forward** - In many applications sensor data can be captured and stored or even processed by a remote node before it is transmitted to the central base station. For example, a temperature sensor that periodically senses and records the cargo temperature during transit for several days, and when the cargo gets to its loading dock for unloading, the device can detect the presence of a network and transmit all the accumulated temperature data to the network base station.

The critical requirements of these applications are:

1) **Long Battery Life** - In many applications, sensors are placed in locations that are not conveniently accessible. Moreover, if the batteries must be replaced often (every week or every month), not only will the primary benefit (freedom from wiring costraints and costs) of wireless networks be lost, but also many remote sensing applications may become impractical. Therefore, long battery life (several years) is essential in wireless sensor networks. The energy efficiency of sensor networks is a critical issue and discussed in length by Goldsmith et al [1] and Min et al [2].
2) **Small Form Factor** - It is obvious that devices must be small enough to be embedded in their operating environment. This requirement affects the choice of batteries - even AA batteries are too bulky to power the sensor node, so using coin cell batteries is the only option in many situations.
3) **Low-data Rate** - Since the sampling rate (rate at which variables such as temperature are sensed) is usually small, the number of bits transmitted per second by individual nodes is low.
4) **Low Cost** - Since the number of sensor nodes in a system can be large (e.g., a large scale industrial automation application can use several hundred sensors), the cost of individual nodes must be minimal to be of practical use.
5) **Centralized Archictecture** - Most of these applications consist of a sophisticated central node and several simple end nodes. For instance, several different types of sensors in a building are controlled by a single building automation controller.

We have developed an ultra-low power sensor networking platform called the i-Bean Network to support such low data-rate sensing applications. We have devised several techniques for minimizing power consumption in the i-Bean Network.

This paper discusses these techniques in detail. The rest of the paper is structured as follows: Section II reviews works related to the research reported in this paper. Section III introduces the different components of the i-Bean Network. Section IV presents the techniques for minimizing power consumption. Section V concludes the paper with preliminary results.

II. Previous Work

As predicted by D. Estrin [3], energy concerns of wireless sensor networks have inspired several energy efficient protocols, processors, designs and algorithms. In this section, we present some of the key developments.

The WINS [4] and PicoRadio [5] projects are attempting to develop integrated circuits that contain sensing, signal processing and radio elements.

Shih et al present μAmps a sensor node that exposes the underlying parameters of the physical harware to the system designer. All layers of the node, including the algorithms, the operating system, and network protocols, can adapt to minimize energy usage. Guo et al [6] present a transmission scheme that balance energy consumption amongst nodes by considering transmission distance (between the nodes and the base station) and data density.

TRAMA [7], T-MAC [8], and S-MAC [9] are energy efficient MAC protocols. TRAMA reduces energy consumption by ensuring that communications are collision free and by placing nodes in sleep mode when they are not communicating. T-MAC uses an adaptive duty cycle, where the active part of it is dynamically ended. This reduces the amount of energy wasted on idle listening. S-MAC uses three techniques to reduce energy consumption: 1. Nodes periodically sleep 2. Neighboring nodes form virtual clusters synchronize their sleep schedules, so that the entire neighborhood is not asleep. 3. Nodes sleep when they are not actively communicating.

SPIN [10], LEACH [11] and directed diffusion [12] are energy efficient routing algorithms for wireless sensor networks.

Nodes running SPIN protocol name tag their data with descriptors, called meta-data. They use meta-data negotations to eliminate the transmission of redundant data. Moreover, SPIN nodes base their communication decisions upon both application-specific knowledge of the data and upon knowledge of the resources available to them. This allows sensors to efficiently distribute data. LEACH uses hierarchy to reduce the data sent from sensors to the base station. This reduces power consumption. In directed diffusion, data transmission is minimized by caching and processing data in network.

While similar to some previous work, the work presented in this paper is different in several respects. Our techniques minimize energy consumption at all levels of this system - node design, physical layer communications, MAC and network protocols and system design. We have validated our techniques by utilizing them to develop an ultra low-power sensor network composed of tiny and inexpensive nodes. Most importantly, the network and devices have been proven to work reliably and effectively in real life applications.

III. i-Bean Network

The i-Bean network is composed of three types of devices:

1) **Endpoints (or i-Beans)** - The Endpoints are the devices that are directly connected to sensors and embedded in the environment. These Endpoints are tiny (25 x 15 x 5 mm - slightly larger than a dime). They are powered by coin batteries and are extremely power efficient.
   Each i-Bean provides four analog input channels, four digital 8-bit I/O channels, and an UART port for interfacing with sensors and actuators. Multiple sensors and actuators can be connected to an i-Bean.

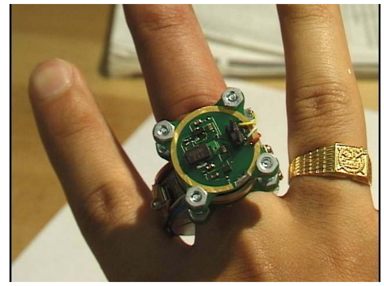

Fig. 1. An Endpoint embedded in a finger ring.

2) **Routers (or Repeaters)** - Routers extend the transmission range of i-Beans. Routers are responsible for forwarding and routing data between i-Beans and base stations. These devices have a small form factor - 56 x 33 x 5 mm. They are also power efficient, but they require more power than i-Beans.
3) **Gateway (or Base station)** - This Gateway is also compact 64 x 51 x 5 mm and designed to be unobtrusive. It serves as the Gateway between the i-Bean network and host computers such as desktops and SBCs[1]. A base station can be connected directly to a RS-232 serial port of a host computer and gets power from the serial port.

We designed our nodes with limited resources using low-cost off-the-shelf components. The nodes have limited computing and capacity. This means the nodes can perform neither sophisticated data processing nor store large volumes of data nor run complex network protocols. Simplicity of sensor nodes does not cause any difficulties, since most sensing applications don't require sophisticated terminal nodes. Further hardware and software details can be obtained from our website [13].

The following sections present the techniques employed to minimize power consumption in these devices.

IV. Power Efficiency in i-Bean Networks

Power efficiency is achieved through ultra-low power nodes and power-efficient communications between those nodes. The following sections describe the node design and networking schemes in detail.

A. Power-Efficient Nodes

All nodes must consume as little power as possible, however power efficiency of Endpoints is critical. The reasons are:

- Endpoints are powered by coin batteries, whereas Routers and Gateway are powered using larger power sources such as AC mains or AA/A batteries.
- Endpoints must be tiny, since they must be unobtrusive to be embedded in unconventional environment. Figure 1 illustrates the importance of Endpoints being tiny - an Endpoint is embedded in a finger ring.
- Typically the number of Endpoints in a network exceeds the number of Routers. The proportion of Endpoints and Routers depends on the deployment site, traffic patern,

[1]Single Board Computers

etc. As a result, collective power consumption could be higher and could also require several batteries to be replaced.

The following sections describe how power consumption by Endpoints is minimized.

1) Dual Processors: The tasks of a processor in a sensor node can be classified into two main categories: 1. conventional computing tasks (including I/O with sensors) 2. communication tasks that employ RF circuitry.

To execute these two types of tasks, the processor must operate at a frequency greater than the highest frequency task. Since RF circuitry operates at a very high frequency, a very high speed processor would be necessary. Unfortunately, a high speed processor wastes a lot of power, since its power consumption is substantial even in idle mode, thus reducing battery life. We overcome this problem by employing two microcontrollers to execute these two different types of tasks and putting the high-speed processor in sleep mode as much as possible.

Each Endpoint has two interconnected processors p_1 and p_2. The processor p_1 operates at clock frequency f_1 and the processor p_2 operates at clock frequency f_2 and the frequency f_1 is much smaller than f_2 ($f_1 << f_2$).

A process called coordinator running on one of these processors allocates tasks in such a way that most of the tasks are run on the slower processor and the faster processor is in sleep mode for most of the time. This usually means that computing tasks execute on p_1 and communication tasks execute on p_2.

Although the coordinator usually runs on p_1, it can execute on either of the two processors. Both p_1 and p_2 have a copy of the coordinator. Only one of the coordinator instances is executed at any time, except when the coordinator wants to "transfer" from one processor to the other. To transfer before going to sleep the coordinator awakens the copy that is currently sleeping.

The coordinator's mobility is critical, since it can execute on p_2, when the system load is high and minimize power consumption by executing on p_1, when the load is less. If further power saving is required, both processors can be in sleep mode, but one processor should wake up and run the coordinator from time to time.

A possible timing diagram of two processors is presented in Figure 2.

2) Narrowband Radio: Power consumption of RF circuitry is highly dependent on the modulation scheme. Wideband RF chips, such as that of Bluetooth [14], consume much more power than typical narrowband radios because of the complexities of base band processing. Although wideband radios offer better immunity to interference, for many sensor network applications, narrowband radios remain a practical choice. We use RFM's TR-1000 chipset that operates in 916 MHz band. This chipset draws no more than 10 mA current at 3 VDC.

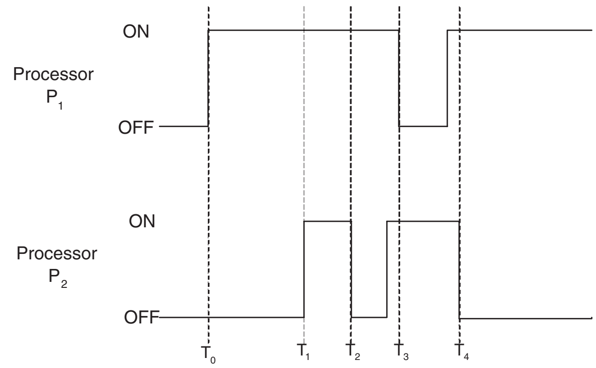

Fig. 2. A sample timing diagram of two processors. At time T_0, the node and p_0 are turned on; at T_1, p_2 is activated by p_1; between T_1 and T_2, both the processors are active; at T_3, coordinator is transferred to p_2; at T_4, coordinator is transferred back to p_1.

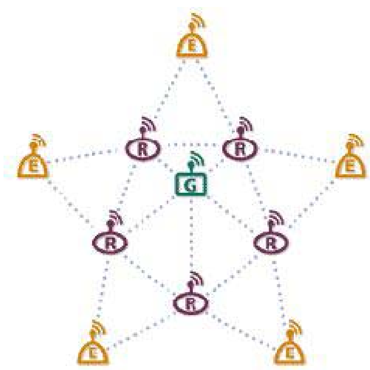

Fig. 3. i-Bean Network. (E - Endpoint, R - Repeater, G - Gateway)

B. Power-Efficient Network

As previously mentioned, most sensing applications require sensor nodes to transmit data to a powerful base station. To support such applications natively, i-Bean Network is designed such that data communications are strictly between the Gateway and the Endpoints. That is, the data packets originate and terminate either in the Endpoints or in the Gateway. Although a Router can communicate with any other Router to relay packets, they never exchange data packets. The i-Bean network design exploits this communication pattern to minimize power consumption. The following sections describe the power-efficient network design.

1) Star-Mesh Hybrid Topology: Among wireless sensor networking topologies, the star system is the lowest in overall power consumption, but is limited by the transmission distance of the radio (typically 10 to 30 meters in the ISM band) in each node back to the base station.

On the other hand, mesh topology consumes more power than star topology due to its higher duty ratio - nodes must always listen for messages for relaying packets for other nodes in the network. However, mesh networks are highly fault tolerant since there are multiple paths between any two nodes.

As shown in Figure 3, the topology of the i-Bean network is a star-mesh hybrid. That is, the Endpoints are connected to

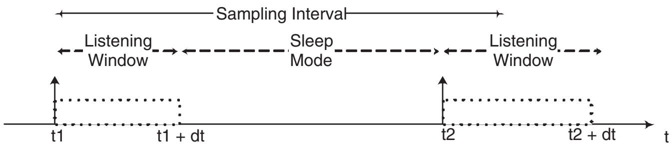

Fig. 4. i-Beans duty cycle.

the nearby Routers using a star topology (Router is the central hub and the Endpoints are the edge nodes), whereas Routers are inter-connected using a mesh topology.

Endpoints never relay packets for other nodes. Routers can communicate with any other node in its vicinity and they do relay and route packets for other Routers and Endpoints.

Using this hybrid topology, power consumed by Endpoints is minimized, while the network is fault-tolerant, since multiple paths can exist between the Endpoints and the Gateway.

2) Multihop Routing: The free space loss models of RF signal show that the radiated power is proportional to the square of required transmission distance. Hence, it is more power efficient to emit low strength RF signals to travel a short distance and be relayed a number of times than transmitting high strength signals for a longer range.

i-Beans transmit packets using low-power signals and the packets are forwarded by Routers. As pointed out by Min and Chandrakasan [15], power consumption in wireless networks can increase with number of hops due to various overheads. In this multihop structure, Routers end up consuming more power. As explained above, higher power consumption by Routers is not a critical issue and our primary objective is to minimize battery power consumed by i-Beans.

3) Heterogeneous Nodes: As described in Section III, an i-Bean network is heterogeneous. The Endpoints are connected to sensors and actuators and they can be either source or destination of network data, but cannot forward data for any other nodes. The Routers are solely responsible for routing data in the network.

Since Endpoints are not relaying packets, they can conserve power by turning off their communication circuitry except when they send or receive packets. Using dedicated Routers, power consumption of Endpoints is minimized.

4) Low Duty Ratio: It is well known that typical radio devices consume a fair amount of power even when they are just in the listening mode. We avoid such active listening and consequent power wastage by employing a small duty ratio - an Endpoint does not waste precious power listening to periodic beacon signals; instead it stays in power-saving idle mode most of the time and wakes up occasionally according to its own schedule. As shown in Figure 4, Endpoints wakeup periodically (period is determined by the sampling rate) to read the attached sensors and transmit their data. After transmitting the sensor data, they remain in receive mode for a short duration and go to sleep until the next sampling time.

5) Progressive Search: Power consumption is further reduced by using the Progressive Search technique. When an Endpoint attempts to join a network, or when it wakes up after staying in the sleep mode for a long period of time, the Endpoint will first broadcast a short 'hello' to search its neighborhood for Routers. These 'hello' packets contain only the identifier of the network that the device would like to join or already belongs to. If the device receives a reply, which is also relatively short, then it will broadcast another hello packet that holds a different inquiry such as the ID of the destination node. After receiving a response that confirms a known route to the Gateway, the Endpoint will transmit a complete packet that contains all the information associated with the device; this information includes status of input/output channels, sampling rate, battery voltage, etc. The main advantage of progressive search is that an Endpoint will not waste power on sending multiple copies of lengthy hello packets when there is no device in the neighborhood to respond. An Endpoint will consume power to transmit the full packet load only when it confirms that there is a route to the destination and one of its neighbors knows the route. An additional advantage of progressive search is the efficient bandwidth usage.

V. Preliminary Results and Discussions

In this paper, we have presented several techiques to minimize power consumption at different levels of the system hierarchy of low data-rate wireless sensor networks. In some instances, we have shown how the individual nodes can be designed to be efficient. In other instances, we presented techniques for developing energy efficient network algorithms and protocols.

Based on these techniques, we have developed the i-Bean Network, an ultra low-power wireless sensor network. From our preliminary studies, we find that power consumption in this network is extremely low. For instance, when powered by a small coin battery (CR2032) with a capacity of 220mAh, the average current consumption is approximately 100 μA, when the sampling interval is 1 second and therefore battery will last for about 80 days. If the sampling interval is increased to 120 seconds, average current consumption drops to 1.92 μA and increasing the battery life to about 13.1 years [2]

Despite these encouraging results, we need to perform more experiments to understand the impact of our design decisions and tradeoffs when the network is large ($>$ 1000 nodes), since even simple protocols and algorithms can exhibit surprising complexity at scale [16].

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[2]Any number more than 10 years may be meaningless, since the battery shelf life itself may be less than the computed time.

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