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i-Beans: An Ultra-low Power Wireless Sensor Network

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ABSTRACT
This paper presents a newly developed short-range, ultra-low power wireless device called the "i-Beans", an ad hoc, self-organizing network protocol, and their application to low data-rate ubiquitous computing applications.

0.1 Keywords
Wireless sensors networks, low-power sensor networks, low data-rate networks, i-Beans.

1. INTRODUCTION
Self-organizing, wireless sensor networks have immediate utility in a variety of industrial, medical, consumer and military applications. But, several challenges need to be addressed before these applications can be realized.

We think designing a sensor network that is suitable for applications with very different requirements - data rates, reliability, power requirements, cost, etc can be too complex a design problem to solve. We have focussed our research on developing a sensor network tailored for applications that require low-data rate (< 115 kbps) and limited computing resources. By studying these applications, we find that the following represents the most common modes of acquiring and propagating sensor data: 1. Periodic Sampling (for e.g., temperature sensing in a conditioned space) 2. Event Driven (for e.g., fire alarms, door and window sensors) 3. Store-and-Forward (sensor data can be captured and stored or even processed by a remote node before it is transmitted to the central base station).

To support these applications, we have developed a reliable and ultra low-power sensor network platform called the i-Bean network. The system details are presented next.

2. SYSTEM DETAILS
As shown in Figure 1, the i-Bean network is composed of three types of devices that are interconnected using RF links. The devices are:

1. i-Bean (or Endpoint) - These are the devices that are directly connected to sensors and embedded in the operating environments. They are tiny (25 x 15 x 5 mm) and power efficient. Each endpoint provides four 8-bit analog input channels, four digital I/O channels, and an UART port for interfacing with sensors and actuators. Multiple sensors/actuators can be connected to an endpoint.

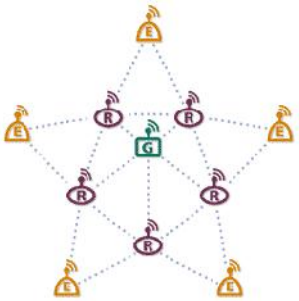

Figure 1: i-Bean Network. (E - Endpoint, R - Repeater, G - Gateway)

2. Repeater (or Router) - Repeaters extend the transmission range of endpoints. Routers are small - 56 x 33 x 5 mm. They consume more power than endpoints as they remain active all the time.

3. Gateway (or Base station) - Gateway is also compact (64 x 51 x 5 mm). It serves as the gateway between i-Bean network and host computers. A base station can be connected directly to a RS-232 port of a host computer and gets power from it. While there can be multiple repeaters and endpoints, there is only one gateway in an i-Bean network.

2.1 User Interface
We have developed a simple monitoring program that runs on host computers. This program can be used to monitor the state of i-Bean networks and modify various operating parameters of i-Beans such as sampling rate, digital input-output channels, ADC and DAC channels etc.

2.2 Significant Features
The significant features of this system are power efficiency and a robust networking protocol. They are described in the following sections.

2.2.1 Power Efficiency
Power efficiency is a critical factor in wireless sensor networks. Although power consumption must be minimized at all points in the system, power consumed by endpoints must be optimized to a higher degree since there are more endpoints in the network than any other

device and also replacing their batteries would be more difficult, as they could be deployed in inaccessible operating environments.

We employ the following techniques to optimize power consumed by i-Beans:

- Dual Processors - Each endpoint has two processors: 1. a high speed processor that usually executes tasks related to RF circuitry. 2. a low speed processor that usually executes conventional computing and I/O tasks. A process called coordinator running on one of these processors allocates tasks in such a way that tasks are run on slower of the two processors and the unused processor is placed in sleep mode. A substantial amount of power is saved by putting the high speed processor in sleep mode for most of the time.

- Heterogeneous Nodes - Endpoints, repeaters and gateways perform totally different functions. Endpoints can either be source or destination of network data, but cannot forward data for any other nodes. This frees endpoints from active listening and they can conserve power by being in sleep mode while not communicating or computing. The repeaters are solely responsible for routing data in the network. Further, i-Beans conserve power by transmitting low-power signals; the repeaters in the vicinity forward their packets to the destination using high power signals.

- Bottom-Up Networking - Endpoints do not waste precious power listening to periodical beacon signals; instead they stay in power saving mode most of the time and wake up occasionally according to their own communication schedule.

Please see our paper [4] that focuses on power conservation strategies for complete details.

2.2.2 Robust Network

The devices in the i-Bean network self-organize themselves into a network and reconfigure themselves if there is any change in the network. The network is self-organizing, self-healing and yet power efficient. As shown in Figure 1, the topology of i-Bean network is a star-mesh hybrid. This hybrid topology takes advantage of the power efficiency and simplicity of the star topology for connecting i-Beans to routers and reliability and reach of mesh networks for interconnecting routers to achieve fault tolerance and range.

We also utilize several other innovative techniques such as generating true random numbers from RF noise, progressive search (devices search using short messages and employ complete messages only after establishing connections) etc to increase reliability of these networks. Please see the publications on our website for further details.

3. RELATED WORK

Researchers have developed several wireless sensor networking platforms. A few prominent ones are Smart Dust [2], BTnodes [1], and Pushpin Computing [3]. i-Bean network is different from these platforms in the following respects:

1. These systems are composed of homogeneous nodes (identical hardware) that perform specialized functions in runtime by using different software; whereas i-Bean network is composed of three different types of devices. The heterogeneous system makes it possible to assign complex functionality to routers and to simplify endpoints, thereby reducing their power consumption.

2. They intend to be general purpose sensor networking platforms, whereas i-Bean network is tuned for low data-rate applications.

3. Their end nodes are capable of performing relatively complex computations. We use endpoints only to interface with sensors and actuators.

4. DISCUSSIONS AND FUTURE WORK

From our preliminary studies, we find that power consumption in i-Bean networks is extremely low. For instance, when powered by a small coin battery (CR2032) with a capacity of 220mAh, the average current consumed by an i-Bean is approximately 100 μA, when the sampling rate is one sample per second and therefore battery will last for about 80 days. If the sampling rate is decreased to one sample per 120 seconds, average current consumption drops to 1.92 μA and increasing the battery life to about 13.1 years. [1]

We need to perform more experiments to understand the impact of our design decisions and tradeoffs when the network is extremely large ($>$ 1000 nodes), since even simple protocols and algorithms can exhibit surprising complexity at scale.

We are also working on further optimizing our algorithms, protocols and hardware.

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