MOBILE NETWORKING FOR "SMART DUST" WITH RFID SENSOR NETWORKS

SHYAM D. BAWANKAR[1], SONAL B. BHOPLE[2] & VISHAL D. JAISWAL[3]

[1,2&3]Department of Electronics Engineering, Datta Meghe Institute of Engineering Technology and Research, Wardha, India.
E-mail : shyam_bawankar@rediffmail.com, sonalbhople@gmail.com & dr.vishal_jaiswal@rediffmail.com

Abstract- Large-scale networks of wireless sensors are becoming an active topic of research.. We review the key elements of the emergent technology of "Smart Dust" and outline the research challenges they present to the mobile networking and systems community, which must provide coherent connectivity to large numbers of mobile network nodes co-located within a small volume. Smart Dust sensor networks – consisting of cubic millimetre scale sensor nodes capable of limited computation, sensing, and passive optical communication with a base station – are envisioned to fulfil complex large scale monitoring tasks in a wide variety of application areas. RFID technology can realize "smart-dust" applications for the sensor network community. RFID sensor networks (RSNs), which consist of RFID readers and RFID sensor nodes (WISPs), extend RFID to include sensing and bring the advantages of small, inexpensive and long-lived RFID tags to wireless sensor networks. In many potential Smart Dust applications such as object detection and tracking, fine-grained node localization plays a key role.

Keywords: *WSN (Wireless Sensor Network), RFID (Radio Frequency Identification), RSNs (RFID Sensor Network).*

I. INTRODUCTION

Wireless sensor networks (WSN) [1] are currently an active field of research. A WSN consists of large numbers of cooperating small-scale nodes capable of limited computation, wireless communication, and sensing. In a wide variety of application areas including geophysical monitoring, precision agriculture, habitat monitoring, transportation, military systems and business processes, WSNs are envisioned to fulfil complex monitoring tasks. In many typical sensor network applications, fine-grained physical locations of individual sensor nodes play an important role. Examples include target detection target tracking and target classification. Techniques for physical location sensing have been studied for a long time, among others, in the context of mobile computing systems [16]. More recently, some of the approaches developed there have been adopted for WSN [3, 4, 6, 10, 13], mainly focusing on systems based on certain characteristics such as time-of-flight, received signal strength, signal range of ultrasound and radio waves. Nevertheless it is often possible (both energy-wise and size-wise) to equip such sensor nodes with low power radios or small ultrasound transducers as enablers for location sensing systems. However, research is already on the way to create the next generation of sensor nodes. Due to their envisioned cubic-millimetre size, they are called "Smart Dust". By making nodes inexpensive and easy-to-deploy, Smart Dust opens up new applications areas.

The radical size reduction mandates a revolutionary change in the used communication technology when compared to current WSN technology. Traditional radio technology presents a problem because Smart Dust nodes offer very limited space for antennas.In this paper that Radio Frequency Identification (RFID) technology has a number of key attributes that make it attractive for smart-dust applications. Passive UHF RFID already allows inexpensive tags to be remotely powered and interrogated for identifiers and other information at a range of more than 30 feet. The tags can be small as they are powered by the RF signal transmitted from a reader rather than an onboard battery; aside from their paper thin antennas, RFID tags are approximately one cubic millimetre in size. Moreover, their lifetime can be measured in decades as they are reliable and have no power source which can be exhausted.

These advantages have resulted in the widespread deployment of RFID for industrial supply-chain applications such as tracking pallets and individual items. However, RFID technology is limited to only identifying and inventorying items in a given space. The focus of this paper is the applications that RSNs enable and the systems challenges that must be overcome for these to be realized. As the traditional RFID usage model is very different from that of WSNs, RSNs face substantial challenges when trying to integrate the two technologies. For example, unlike WSNs, RSNs must cope with intermittent power and unlike RFID must support sensor queries rather than simply identification.

The study of "Smart Dust systems" is very new. The main purpose of this paper is to present some of the technological opportunities and challenges, with the goal of getting more systems-level researchers interested in this critical area. The structure of this paper is organized as follows. Section 2 presents an overview of Smart Dust technology. Section 3 outlines RFID & RSNS. Section 4 describe the challenges for Smart Dust**.** Section 5 presents conclusions**.**

II. SMART DUST TECHNOLOGY

A Smart Dust mote is illustrated in Figure 1. Integrated into a single package are MEMS sensors, a semiconductor laser diode and MEMS beam-steering mirror for active optical transmission, a MEMS corner-cube retro reflector for passive optical transmission, an optical receiver, signal-processing and control circuitry, and a power source based on thick-film batteries and solar cells.

This remarkable package has the ability to sense and communicate, and is self-powered! A major challenge is to incorporate all these functions while maintaining very low power consumption, thereby maximizing operating life given the limited volume available for energy storage.

Within the design goal of a cubic millimetre volume, using the best available battery technology, the total stored energy is on the order of 1 Joule. If this energy is consumed continuously over a day, the dust mote power consumption cannot exceed roughly 10 microwatts.

The functionality envisioned for Smart Dust can be achieved only if the total power consumption of a dust mote is limited to microwatt levels, and if careful power management strategies are utilized .To enable dust motes to function over the span of days, solar cells could be employed to scavenge as much energy as possible when the sun shines or when room lights are turned on. Techniques for performing sensing and processing at low power are reasonably well understood. developing communications architecture for ultra-low-power represents a more critical challenge.

The primary candidate communication technologies are based on radio frequency (RF) or optical transmission techniques. Each technique has its advantages and disadvantages. RF presents a problem because dust motes offer very limited space for antennas, thereby demanding extremely short-wavelength transmission. Furthermore, radio transceivers are relatively complex circuits, making it difficult to reduce their power consumption to the required microwatt levels.

They require modulation, band pass filtering and demodulation circuitry, and additional circuitry is required if the transmissions of a large number of dust motes are to be multiplexed using time-, frequency- or code-division multiple access [6].

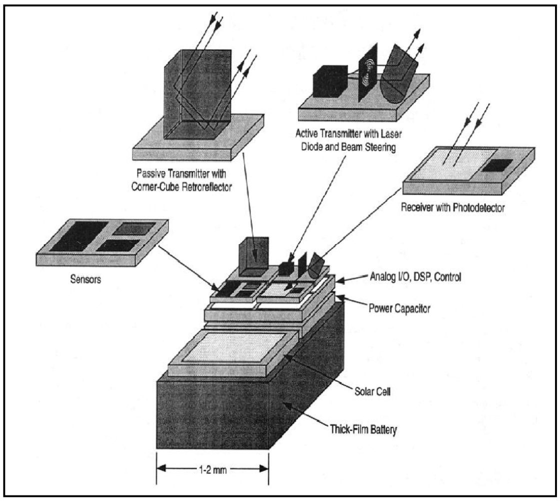

Fig.1 Smart dust mote, containing sensors, optical receiver, passive and active optical transmitters, signal processing and control circuitry, and power sources.

An attractive alternative is to employ free-space optical transmission. Kahn and Pister’s studies [6] have shown that when a line-of-sight path is available, well-designed free space optical links require significantly lower energy per bit than their RF counterparts. There are several reasons for the power advantage of optical links. Optical transceivers require only simple baseband analog and digital circuitry; no modulators, active band pass filters or demodulators are needed. The short wavelength of visible or near-infrared light makes it possible for a millimetre- scale device to emit a narrow beam.

As another consequence of this short wavelength, a base-station transceiver (BTS) equipped with a compact imaging receiver can decode the simultaneous transmissions from a large number of dust motes at different locations within the receiver field of view, which is a form of space-division multiplexing. Successful decoding of these simultaneous transmissions requires that dust motes not block one another’s line of sight to the BTS. Such blockage is unlikely, in view of the dust motes’ small size. A second requirement for decoding of simultaneous transmission is that the images of different dust motes be formed on different pixels in the BTS imaging receiver. To get a feeling for the required receiver resolution, consider the following example. Suppose that the BTS views a 17 meter by 17 meter area containing Smart Dust, and that it uses a high-speed video camera with a very modest 256 by 256 pixel imaging array.

Each pixel views an area about 6.6 centimetres square. Hence, simultaneous transmissions can be decoded as long as the dust motes are separated by a distance roughly the size of a pack of cigarettes.

III. FROM MOTES AND RFID TO RSNS

Two technologies have been widely used to realize real world monitoring applications: wireless sensor networks via motes, and RFID via standard tags and readers.Representative devices for the three technologies are show in Figure 2.

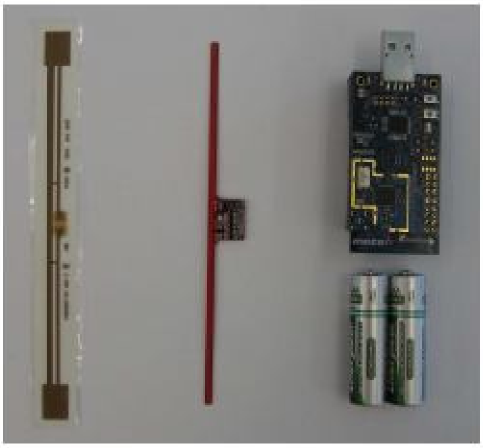

Fig 2: Commercial UHF RFID tag, Accelerometer WISP, Telos mote with batteries.

A] Wireless Sensor Networks (Motes)

Currently, most WSN research is based on the Telos mote [10], which is a battery powered computing platform that uses an integrated 802.15.4 radio for communication. These motes are typically programmed to organize into ad-hoc networks [15] and transmit sensor data across multiple hops to a collection point. To extend network lifetime, motes duty cycle their CPU and radio (e.g., with low-power listening [9]), waking up intermittently to sense and communicate. With a duty cycle of 1%, motes can have a lifetime of up to three years before the batteries are exhausted.

Using multihop communication, WSNs can sense over great distances, which has made them idea for a wide range of applications. However, the large size of the mote and its finite lifetime makes it unsuitable for applications where sensing must be embedded in small objects, or in inaccessible locations where batteries cannot be replaced.

B] RFID

While there are a number of different RFID specifications, that of greatest interest for sensing applications is the EPCglobal Class-1 Generation-2 (C1G2) protocol [4], as it is designed for long-range operation. The C1G2 standard defines communication between RFID readers and passive tags in the 900 MHz Ultra-High Frequency (UHF) band, and has a maximum range of approximately 30 feet. A reader transmits information to a tag by modulating an RF signal, and the tag receives both down-link information and the entirety of its operating energy from this RF signal. For up-link communication, the reader transmits a continuous RF wave (CW) and the tag modulates the reflection coefficient of its antenna. By detecting the variation in the reflected CW, the reader is able to decode the tag response. This is referred to as “backscattering,” and requires that a tag be within range of a powered reader. The MAC protocol for C1G2 systems is based on Framed Slotted Aloha [11], where each frame has a number of slots and each tag will reply in one randomly selected slot per frame. Before beginning a frame, a reader can transmit a *Select* command to reduce the number of active tags; only tags with ID’s (or memory locations) that match an included bit mask will respond in the subsequent round. After a tag replies, the reader can choose to *singulate* the tag, or communicate with it directly, and read and write values to tag memory. RFID tags are fixed function devices that typically use a minimal, non-programmable state machine to report a hard-coded ID when energized by a reader. As they are powered by the reader, the device itself can be very small, though the antenna requires additional area.

C] RFID sensor networks (WISPs + readers)

We define RFID sensor networks (RSNs) to consist of small, RFID-based sensing and computing devices (WISPs), and RFID readers that are part of the infrastructure and provide operating power. RSNs bring the advantages of RFID technology to wireless sensor networks. While we do not expect them to replace WSNs for all applications, they do open up new application spaces where small form-factor, long-lived, or inaccessible devices are paramount. The most recent Intel WISP is a wireless, battery-free platform for sensing and computation that is powered and read by a standards-compliant UHF RFID reader at a range of up to 10 feet. It features a wireless power supply, bidirectional UHF communication with backscatter uplink, and a fully programmable ultra-low-power 16-bit flash microcontroller with analog to digital converter. This WISP includes 32K of flash program space, an accelerometer, temperature sensor, and 8K serial flash. Small header pins expose microcontroller ports for expansion daughter boards, external sensors and peripherals. These include the first accelerometer to be powered and read wirelessly in the UHF band, and also the first UHF powered-and-read strain gage [17]. Even without its sensing capabilities, the Intel WISP can be used as an open and programmable RFID tag: the RC5 encryption algorithm was implemented on the Intel WISP [2]. We believe this is the first implementation of a strong cryptographic algorithm on a UHF tag.

IV. CHALLENGES

RSNs combine the technology of RFID and sensing with the usage models of sensor networks. However, at the systems level, challenges arise due to the mismatch between the RFID usage model and that of wireless sensor networks. We detail several challenges in this section.

4.1 Intermittent Power

RFID readers provide an unpredictable and intermittent source of power. This makes it difficult for WISPs to assure that RSN tasks will be run to completion. WISPs are powered only when in range of a transmitting RFID reader and, for regulatory and other reasons; readers do not transmit a signal continuously. Instead, they transmit power for a brief period before changing channels or entirely powering down. For standard RFID tags where the task is simply to transmit the identifier, this style of communication is sufficient. However, it is a poor fit for RSN tasks that span many RFID commands. The WISP harvests energy from a reader and stores this energy in a capacitor. When enough energy is harvested, the WISP powers up and can begin sensing and communicating. As a result in the WISP losing power in the middle of an operation depending on the task and the reader behaviour. A further complication is that receiving, transmitting, performing computation, and reading/writing to memory all consume different amounts of energy. To run tasks to completion, WISPs will require support for intermittently powered operation. To work well in this regime, RSN devices may also need to cooperate with RFID readers for power management. This would involve signalling by either the reader, of its intended transmission time, or by the WISP, of its needs. Even with signalling, it will be difficult to predict power expectations because the rate at which energy is harvested depends on the frequency of the reader and the proximity of the device to the reader, both of which will change over time. To extend functionality when away from a reader, one approach would be to provide a small amount of energy storage on the device, e.g., a capacitor, and store excess energy when close to an active reader. This storage capacitor would be small relative to a battery, because it would be intended only for short term usage and is wirelessly recharged over time.

4.2 Asymmetric Sensing Protocols

The communication paradigm of RFID results in systems that are limited by up-link bandwidth. When the data of interest is simply each tag's identity, this constraint is not a problem. However, it makes it difficult to develop efficient protocols for gathering sensor data that changes over time. In WSNs, nodes are peers in terms of the physical and link layers of their communication, e.g., each mote has an 802.15.4 radio capable of sending and receiving transmissions with other nodes that are in range. In contrast, because they draw on RFID, RSN nodes are highly asymmetric in terms of their communication abilities. With RFID, readers are able to transmit messages to all tags and tags can transmit messages to the reader. These differences complicate the design of protocols for gathering sensor data. Currently, WISPs with new sensor data must wait until they are interrogated by a reader. This increases the likelihood of many devices wanting to use the bandwidth limited channel at the same time. Techniques to perform data pre-processing within the network (on each RSN device) could help to some extent. However, the standard RFID strategy of identifying and then communicating with each device is wasteful as only some devices would have relevant data – a more dynamic strategy based on the value of the sensor data would be more effective. Consider the eldercare application. However, the set of objects that are moving would change dynamically, as objects are put down and picked up. One might want a protocol which gives priority to the most active objects, politely "yielding" to new objects when they start to move. Existing RFID solutions do not support anything like this functionality. As a first step, one could have WISPs with sensor activity below a threshold not respond to the reader. But an appropriate threshold level might depend on what is occurring in the room, and such a simple scheme would not support the "polite yielding" described above.

4.3 Repurposing C1G2

There would be substantial practical benefit to realizing RSN protocols using the primitives of the C1G2 standard: Commercial off-the-shelf readers could be used for RSN research and deployment, and WISPs would interoperate with ordinary (non-sensing) tags. However, the extent to which RSN protocols could be implemented within the C1G2 standard is an open research question. Additionally, there is the practical consideration of commercial readers not exposing low-level functionality and not implementing the complete C1G2 specification. Because of this, even RSN protocols built on top of the C1G2 specification might not be implementable using standard readers.

Consequently, simple use of the existing C1G2 protocol could provide some level of sensing functionality, but at a significant cost in terms of efficiency. Along with reading sensor data, the C1G2 protocol could support basic sensor queries using the *Select* command. More generally, the *Select* command could be used as a general purpose broadcast channel. The bit mask in the command could be repurposed and interpreted, in the most general case, as opcodes and data. As multiple *Selects* could be sent before each frame, complex tasking and querying could be achieved in this manner. The above mechanisms show that there is potential for using the C1G2 standard to implement RSN protocols. This would have the advantage of being implementable using current reader technology, given a reader that is sufficiently programmable. However, these mechanisms may prove too inefficient or may simply be poorly matched to many applications. Further experimentation is needed.

V. CONCLUSION

We have described Smart Dust, an integrated approach to networks of millimetre-scale sensing/communicating nodes. Smart Dust can transmit passively using novel optical reflector technology which provides an inexpensive way to probe a sensor or acknowledge that information was received. Active optical transmission is also possible, but consumes more power and used when passive techniques cannot be used, such as when the line-of-sight path between the dust mote and BTS is blocked.

By exploiting RFID technology, we can expand the application space of wireless sensor networks to ubiquitous, embedded sensing tasks. We have sketched sample sensor network applications in the space between traditional mote networks and RFID for supply chain monitoring. We have described networking challenges related to intermittent power and RSN protocols for sensor queries. We expect RSNs to be a fruitful new space for networking and systems research, as there is significant work that must be done to translate the capabilities of the WISP into full-fledged RSNs.

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