Challenge: Ultra-Low-Power Energy-Harvesting Active Networked Tags (EnHANTs)

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ABSTRACT

This paper presents the design challenges posed by a new class of ultra-low-power devices referred to as Energy-Harvesting Active Networked Tags (EnHANTs). EnHANTs are small, flexible, and self-reliant (in terms of energy) devices that can be attached to objects that are traditionally not networked (e.g., books, clothing, and produce), thereby providing the infrastructure for various novel tracking applications. Examples of these applications include locating misplaced items, continuous monitoring of objects (items in a store, boxes in transit), and determining locations of disaster survivors. Recent advances in ultra-low-power wireless communications, ultra-wideband (UWB) circuit design, and organic electronic harvesting techniques will enable the realization of EnHANTs in the near future. In order for EnHANTs to rely on harvested energy, they have to spend significantly less energy than Bluetooth, Zigbee, and IEEE 802.15.4a devices. Moreover, the harvesting components and the ultra-low-power physical layer have special characteristics whose implications on the higher layers have yet to be studied (e.g., when using ultra-low-power circuits, the energy required to receive a bit is an order of magnitude higher than the energy required to transmit a bit). These special characteristics pose several new cross-layer research problems. In this paper, we describe the design challenges at the layers above the physical layer, point out relevant research directions, and outline possible starting points for solutions.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design - Wireless communication

General Terms

Algorithms, Design, Performance

Keywords

Ultra-low power communications, energy efficient networking, energy harvesting, energy scavenging, ultra-wideband (UWB)

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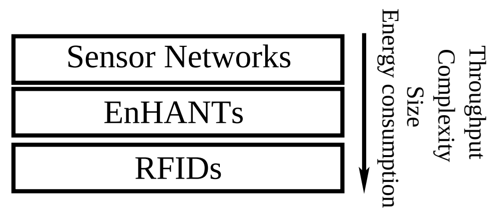

Figure 1: EnHANTs in comparison to Sensor Networks and RFIDs.

1. INTRODUCTION

This paper focuses on the networking challenges posed by a new class of ultra-low-power devices that we refer to as Energy-Harvesting Active Networked Tags (EnHANTs). EnHANTs are small, flexible, and self-reliant (in terms of energy) devices that can be attached to arbitrary objects that are traditionally not networked: books, clothing, produce, etc. EnHANTs will enable novel object tracking applications such as recovery of lost items and continuous monitoring of objects' proximity to each other. The realization of EnHANTs is based on recent advances in the areas of solar and piezoelectric energy harvesting [24] as well as ultra-low-power wireless communications [26, 42]. In particular, recent novel circuit designs that employ ultra-wideband (UWB) communications provide new levels of *ultra-low-power* operation (at the orders of nJ/bit) at short ranges. Moreover, solar energy harvesting based on organic semiconductors allows having *flexible* solar panels [19,25], thereby allowing a pervasive use of tags.

The wireless industry is already taking the first steps towards the design of energy harvesting ultra-low-power tags [2,3]. Hence, following the transition from barcodes to RFIDs, we envision a future transition from RFIDs to EnHANTs that:

- **Network** – Actively communicate with one another and with EnHANT-friendly devices in order to forward information over a multihop network.
- **Operate at ultra-low-power** – Spend a few nano-Joules or less on every transmitted bit.
- **Harvest energy** – Collect and store energy from sources such as light, motion, and temperature gradients.
- **Are energy adaptive** – Alter communications and networking to satisfy energy and harvesting constraints.
- **Exchange small messages** – Exchange limited information (basically IDs) using low data rates, possibly in several transmission bursts.

- **Transmit to short ranges** – Communicate only when in close proximity (1 to 10 meters) to one another.
- **Are thin, flexible, and small (a few square cm at most)**.

As shown in Figure 1, in terms of complexity, throughput, size, and energy requirements, EnHANTs fit between RFIDs and sensor networks. Similarly to RFIDs, the tags can be affixed to commonplace objects. However, EnHANTs will have a power source, will be able to communicate in distributed multihop fashion, and will not have to rely on high-power readers. Compared to sensor nodes, EnHANTs will operate at significantly lower data rates, and will consume less energy. Moreover, unlike sensor nodes, EnHANTs will transmit mostly ID information (either in order to announce themselves or to query for specific EnHANTs). Despite these differences, some of the results obtained for sensor networks (see [14, 16]) *should* apply to EnHANTs.

EnHANTs will be enablers for the *Internet of Things* and as such will support a variety of tracking and monitoring applications beyond what RFID permits. While RFIDs make it possible to *identify* an object, EnHANTs will make it possible to *search* for an object, and to continuously track objects' whereabouts and their proximity to each other. RFIDs are typically activated only when placed near a reader, and only report on themselves. EnHANTs, on the other hand, can operate continuously, achieve pervasive coverage due to their networking capabilities, and can report on themselves and other EnHANTs around them. These EnHANTs capabilities enable many exciting applications, such as, for example, continuous peer monitoring of merchandize in transit, where EnHANTs would be able to identify if a particular box has been taken out at any point during the journey.

One application that we plan to demonstrate in the near future is a *misplaced library book locator*. The initial prototype will enable library books to identify those among themselves that are significantly misplaced (e.g., in an incorrect section), and report the misplacement. To accomplish this task, each book is assigned a unique ID using an assignment scheme closely related to the Dewey Decimal Classification. Each book has a solar powered tag whose power output is sufficient to transmit and receive information within a radius of one meter or less, and to perform some basic processing. Nearby books wirelessly exchange IDs, and IDs of books that appear out of place are further forwarded through the network of books, eventually propagating to sink nodes. A long term objective could be to place books in an arbitrary order, and both determine the book order, and propagate that information to a central server using the multihop wireless network. This type of system can significantly simplify the organization of physical objects.

The same building blocks used in the library application can enable several other applications. In particular, a large variety of items can be tracked and a range of possible desirable or undesirable configurations of objects can be queried for, and can trigger reports. Examples include finding items with particular characteristics in a store, locating misplaced items (e.g., keys or eyeglasses), and locating survivors of disasters such as structural collapse [45].

To enable these applications, various protocols have to be designed. Although networking protocols for energy harvesting nodes recently started gaining attention [6,8,9,11–13,18,22,23,27,35,37, 38] (see Section 2), to the best of our knowledge, the cross layer interactions between circuit design, energy harvesting, communications, and networking have not been studied in depth. Current RF transceiver designs, communication and networking protocols, and energy harvesting and management techniques have been developed in isolation and are inadequate for the envisioned EnHANTs applications. Hence, based on our experience with hardware design, communications, and networking, we outline the cross-layer design challenges that are posed by this new technology. We note that although there are many hardware-specific design challenges, they are out of scope for this paper.

EnHANTs are likely to be implemented by combining flexible electronics technologies (a.k.a. organic electronics) with CMOS chips supporting Impulse-Radio UWB. Flexible technologies can realize energy harvesters (solar cells, piezoelectric, thermal, etc.), passive RF components, and batteries. By embedding CMOS chips in EnHANTs, very low power computation, memory, and communication functions can be added. This technology platform allows for thin, flexible, and very low cost EnHANT fabrication. By using Impulse-Radio UWB, data is encoded by very short pulses (at the order of nano-seconds) and the energy consumption is very low.

To better understand the higher layer design challenges, we first discuss *energy harvesting and energy storage techniques*. Energy storage is required in order to use the harvested energy in periods in which harvesting is not possible. We later describe models that take these techniques and their characteristics into account when determining the UWB pulse patterns, duty cycles, and overall energy consumption. Some of the interesting characteristics include the differences in performance between a capacitor and a battery, and between indoor and outdoor solar energy harvesting.

Next, we discuss *ultra low power UWB communications* and present a number of design challenges. These include a paradigm shift resulting from the fact that when using ultra-low-power communications it is *energetically cheaper to transmit data than to receive data*. Moreover, ultra-low-power tags will operate with inaccurate clocks, thereby requiring the redesign of low-power methods based on coordination of wakeup periods. Finally, EnHANTs may have additional circuitry (e.g., accurate clocks) that can be powered up in some harvesting states and can be used to assist other EnHANTs. Determining how and when to use this circuitry is another challenge.

We then focus on the *design of EnHANTs' communications and networking protocols*. These protocols have to determine the state of the tags (sleeping, communicating, etc.), the operation within a state (transmit, receive, rate control, etc.), and the coordination with peer tags. All these have to be based on the harvesting states of the tags and their capabilities. Clearly, energy harvesting shifts the nature of energy-aware protocols from prolonging the finite lifespan of a device to enabling perpetual life, and from minimizing energy expenditure to optimizing it. The challenges that we describe include not only determining the state and the operation model within the state but also the use of a "harvesting channel" as a mean for nodes synchronization.

Finally, we draw parallels between energy-harvesting EnHANTs and large-scale manufacturing systems. We show that the harvested energy can be treated similarly to inventory in production and storage systems. We show how inventory control models extensively studied in the inventory management field [32, 33] apply to EnHANTs. We then discuss the various challenges resulting from the fact that EnHANTs compose a distributed network with many stochastic components, and outline a number of open problems.

We are currently building a testbed of EnHANTs in which we will evaluate various approaches using energy harvesting and ultra-low-power hardware. We conclude by briefly describing the implementation phases and the hardware components.

This paper is organized as follows. In Section 2 we describe related work. In Sections 3 and 4 we discuss energy harvesting, energy storage, ultra-low-power communications, and the challenges they pose for designing higher layer protocols. Section 5 describes the challenges posed by EnHANTs communications and networking, and Section 6 discusses the application of inventory control models to EnHANTs. Finally, in Section 7 we present our plan for designing an EnHANTs testbed.

2. RELATED WORK

While the idea of pervasive networks of objects has been proposed before (e.g., in the Smart Dust project [41]), the harvesting and communications technologies have recently reached a point where networked energetically self-reliant tags are becoming practical. As mentioned above, EnHANTs fall between RFIDs [40] and sensor networks. To our knowledge, most of the networking research in the area of RFID focuses on the scheduling of query responses by passive tags (e.g., [15]). Extensively studied sensor networks are designed to deal with energy, bandwidth, and other resource constraints (see [14, 16] and references therein). Yet, the underlying communication mechanisms draw power at rates that are too high in environments with weak energy sources (indoor lighting, strain, vibration).

EnHANTs will employ Impulse Radio UWB communications [43], whose corresponding MAC protocols (e.g., [20,31]) have been proposed for communications and accurate ranging in sensor networks. The recent IEEE 802.15.4a standard [4] is based on Impulse Radio UWB and inherits many of the IEEE 802.15.4 (ZigBee) functionalities. Limited hardware data is currently available, but we can assume that the overhead to provide ranging, high data rates (up to 26Mb/s), and backward compatibility will lead to energy consumption largely exceeding the energy we envision available in EnHANTs.

Energy efficiency in wireless networks has long been a subject of research (see reviews [5, 10, 21]). In comparison, only a few works have considered energy-harvesting. One of the major directions in exploiting energy harvesting is adaptive duty cycling in sensor networks. In particular, [8, 11, 12] describe adaptation of the duty cycle to the characteristics of a periodic energy source and [37] develops a "battery-centric" (not requiring an energy source model) duty-cycle adaptation algorithm. Taking energy harvesting into account when making routing decisions is studied in [18, 38, 39]. Recently, [6] jointly calculates link flows and data collection rates for energy-harvesting sensor networks.

Dynamic activation of energy-harvesting sensors has been studied in [9, 13, 22, 23]. A system where mobile nodes deliver harvested energy to different areas of the network is presented in [27]. A system where an energy-restricted node can "outsource" packet retransmissions is described in [34]. A power subsystem for HydroWatch is described in [35], which also provides an overview of deployments that rely on energy harvesting. To the best of our knowledge, current deployments use much more energy than EnHANTs will have available.

Finally, there is an increasing industry interest in bringing together low-power communications and energy harvesting (e.g., [2, 28]). Particularly, Texas Instruments has recently put on the market a solar energy harvesting development kit [3] geared towards sensor developments. Although it is a first step towards EnHANTs, this kit is made of rigid materials and is more than 10x the size of the EnHANTs envisioned in this work.

3. ENERGY HARVESTING

In order to outline the higher layer design challenges, we briefly describe two major harvesting methods and possible energy storage methods. Then, we discuss the effects of the different methods on the design and operation of higher layer protocols. In Sections 5 and 6 we discuss different approaches to the design of such higher layer protocols.

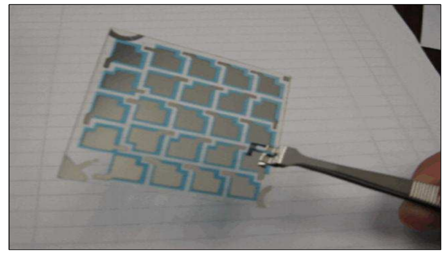

Figure 2: An organic semiconductor-based small molecule solar cell series array developed in the Columbia Laboratory for Unconventional Electronics (CLUE).

3.1 Energy Sources

Many environmental sources of energy are potentially available for harvesting by small devices. These include temperature differences, electromagnetic energy, airflow, and vibrations [24, 30]. Below, we focus on the most promising harvesting technologies for EnHANTs: *solar energy* and *piezoelectric (motion)* harvesting. Other harvesting technologies pose similar design challenges.

Solar energy (light) is one of the most useful energy sources, with typical irradiance (total energy projected and available for collection) ranging from 100mW/cm^2 in direct sunlight to 0.1mW/cm^2 in brightly lit residential indoor environments (notice the significant difference) [24, 29]. Office, retail, and laboratory environments are typically brighter than residential settings, but get much less light energy than outdoor environments. The efficiency of a solar energy harvesting device is defined as the percentage of the available energy that is actually harvested. Conventional single crystal and polycrystalline solar cells, such as those that are commonly used in calculators, have efficiency of around 10%-20% in direct sunlight [7]. However, their efficiency declines with a decline in energy availability (they are less efficient with dimmer sources), which is important to note due to considerable irradiance difference between direct sunlight and indoor illumination. Conventional solar panels are also inflexible (rigid), which makes it difficult to attach them to non-rigid items such as clothing and paperback books.

An emerging and less explored option is solar energy harvesting based on *organic semiconductors* [19, 25] (an array of organic solar cells that we recently designed is shown in Figure 2). With this technology, solar cells can be made flexible. Moreover, organic semiconductor-based panels operate with constant efficiencies over different brightness levels. However, their efficiency is typically 1%-1.5% [7], which is much lower than the efficiency of conventional inorganic solar panels.

To put the numbers in perspective, consider a system with a 10cm^2 organic semiconductor cell. Outdoors, the system will harvest 10cm$^2\cdot$100mW/cm$^2\cdot$0.01=10mW. Under the assumption that reception of a single bit requires 1nJ[1], the achievable data rate will be $(10 \cdot 10^{-3})/(1 \cdot 10^{-9}) = 10$Mb/s. The achievable data rate with indoor lighting will be $(10^{-5})/(1 \cdot 10^{-9}) = 10$Kb/s.

Another potential source of energy is *piezoelectric (motion) energy*. It can be generated by straining a material (e.g., squeezing or bending flexible items). An example is energy harvesting through footfall, where a harvesting device is placed in a shoe and piezoelectric energy is generated and captured with each step [17].

[1]Recall that reception is more expensive than transmission (for more details see Section 4).

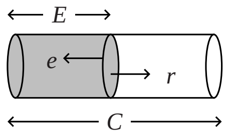

Figure 3: An abstraction of an energy harvesting system for the upper layers: the energy storage capacity C, the current energy level E, the energy charge rate r, and the energy consumption rate e.

Unlike solar harvesting, piezoelectric harvesting may be somewhat controlled by the user.

Piezoelectric harvesting is characterized by the energy captured per actuation at a particular strain (usually 1%-3%). In [17] it was shown how to harvest 4μJ/cm^2 per deflection with a strain of approximately 1.5% from straining polyvinylidene fluoride (PVDF), a highly compliant piezoelectric polymer. Assume that a 10cm^2 of material is employed in an environment where it is strained 60 times per second. This would provide $10 \cdot 4 \cdot 10^{-6} \cdot 60 = 2.4$mW. If, similar to above, we assume that transmission of a bit costs 1nJ, the bit rate that can be supported is $(2.4 \cdot 10^{-3})/(1 \cdot 10^{-9}) = 2.4$Mb/s.

3.2 Energy Storage

Without the ability to store energy, a device can operate only when directly powered by environmental energy. For a tag, *energy storage* components need to be compact and efficient, and need to have very low self-discharge rates. From a higher-layer point of view, it is also important to have storage elements that *are straightforward to measure and control*.

Rechargeable batteries are an excellent option for energy storage, and numerous battery options are available. *Thin film batteries* are particularly attractive for EnHANTs since they are environmentally friendly and can be made flexible. However, a battery needs to be supplied with a voltage exceeding the internal chemical potential (typically 1.5-3.7V) in order to start storing provided energy. This implies that charge generated at a low voltage, such as that possibly produced during low harvester excitation (for example, when a solar cell is located in a very dimly lit place), cannot be stored without voltage upconversion.

Capacitors can also be used for energy storage. Capacitors can receive any charge which exceeds their stored voltage and be cycled many more times than batteries. The disadvantage of using capacitors, however, is that as a capacitor gets more charged, it becomes more difficult to add charge, and large electrolytic capacitors self-discharge over hours or days. The energy density (how much energy can be stored per unit of volume) of capacitors is also much lower. A typical battery can store about 1000J/cm^3, whereas high performance ceramic capacitors can store 1-10J/cm^3 [44].

Different EnHANTs applications will require different types of energy storage. For example, a tag which frequently experiences shallow charging and discharging events will need a capacitor for an acceptable lifetime, whereas an EnHANT that needs to operate for a long period of time without recharging and to store large amounts of energy (say, to charge all day and discharge all night) will need the energy density that a battery offers.

3.3 Higher Layer View of Harvesting

The complexity of the harvesting system needs to be captured in a relatively simple way for the higher layers. A possible abstraction is shown in Figure 3. The system is characterized by the maximum energy storage capacity C (Joules), the currently available energy level E (Joules), the energy charge rate r (Watts), and the energy consumption rate e (Watts). Note that the energy charge rate r depends both on *the harvesting rate and the properties of the energy storage*. For example, when a battery is used, r is positive only when the voltage at the energy harvesting component exceeds the internal chemical potential of the battery. When a capacitor is used, the relationship of r and energy harvesting rate varies with E. The energy consumption rate e is controlled by higher-layer algorithms and with low duty cycle is mostly affected by communication and networking protocols. The effect of these protocols on e will be discussed in Sections 5 and 6.

The available energy E and energy charge rate r can be measured directly from the energy harvesting and power conditioning components. The maximum storage capacity C should be known nominally from the tag design but more precise characterization is possible. For example, if a battery is used, C can be projected from the battery's age, the storage temperature history, and the charge level over time. As the battery continues to age and cycle through charge/discharge events, the capacity will predictably decrease.

The r values of different EnHANTs operating in the same environment will be significantly different. Our experiments with commercial hardware show a lot of variability in the harvesting rates of identical harvesting devices under identical light conditions (i.e., identical solar cells in the same location harvest energy at rates that can differ by about 30%). In addition, the r values will differ for closely located solar cells due to differences in how the cells are located with respect to light sources and obstacles [29].

4. LOW POWER COMMUNICATIONS

Ultra-wide band (UWB) impulse radio (IR) is a compelling technology for short range *ultra-low-power wireless communications* [4, 43]. It uses very short pulses (on the order of nano-seconds) that are transmitted at regular time intervals with the data encoded in the pulse amplitude, phase, frequency, or position. At low data rates, the short duration of the pulses allows most circuitry in the transmitter or receiver to be shut down between pulses, resulting in significant power savings compared to narrow-band systems.

Practical CMOS IR circuits with energy consumption on the order of a nJ per bit have been recently demonstrated. For example, in [42] a UWB receiver and transmitter require 2.5nJ/bit and 43pJ/bit, respectively at a pulse rate of 17Mpulses/s.[2] Recent publications [26, 36] as well as our ongoing research demonstrate that UWB IR transceivers in the 3-5GHz band with data rates in the 100Kbit/s to 1Mbit/s range and a transmitter energy of less than 50pJ/bit and receiver energy of less than 500pJ/bit are within reach.

In this section, we outline our envisioned design of UWB transceivers for EnHANTs and the resulting higher layer challenges. These customized circuits will support ultra low energy consumption and will be integrated with energy harvesting devices while supporting networking capabilities.

4.1 Energy Costs - a Paradigm Shift

The first networking challenge emerging from the design of the ultra-low-power transceivers is that *the energy to receive a bit is much higher than the energy to transmit a bit*. This is significantly different from traditional WLANs, where the energy to transmit is higher than the energy to receive, and 802.15.4, where they are on the same order. This requires novel networking algorithms for EnHANTs, since many legacy algorithms are developed under the assumption of transmission being more expensive than reception.

[2]Energy consumption is measured at a particular pulse rate, since per-bit parameters differ at different bit rates. Note that at lower bit rates, the energy per bit can increase due to the impact of fixed, pulse independent, circuitry.

In conventional systems in which narrow-band modulated sinusoids are transmitted, the transmitter has to be active for the entire duration of the signal transmission. As mentioned above, in UWB very short pulses convey information, so the transmitter and receiver can wake up for very short time intervals to generate and receive pulses, and can sleep between subsequent pulses. The receiver's energy is mostly spent on running low-noise amplification and data-detection circuits that are consuming energy *whenever the device listens to the medium*. Hence, there is no difference (in terms of energy) between receiving information and listening to the medium.

The new energy tradeoffs call for the design of new algorithmic approaches. For example, in order to take the burden off a receiver, a transmitter would have to enable a receiver to listen to the medium for short time intervals (e.g., repeat its pulses many times in such a way that a receiver listening to a short window of pulses would get all the information transmitted). In Section 5 we discuss in more detail the effect of this phenomenon on the design of higher layer protocols.

4.2 Inaccurate Clocks

Accurate on-chip references or clocks cannot be powered down and consume a lot of energy; they have to be avoided to achieve ultra-low-power operation. One viable solution is to use energetically cheap clocks (e.g., clocks available from ultra-low-power ring oscillators). However, the frequency of such clocks will vary significantly from tag to tag and its stability over time is also poor.

A UWB receiver has to wake up at certain times in order to receive pulses. Determining these times with inaccurate clocks imposes major challenges and hence while inaccurate clocks save energy, they increase the energy spent on reception. Moreover, traditional low-power sleep-wake protocols (see [14, 16]) heavily rely on the use of accurate time slots. Hence, eliminating the availability of accurate clocks in a tag requires redesigning protocols that were originally designed specifically for energy efficient networking.

4.3 A High Power Mode

In some cases it may be beneficial to spend more energy than what is typically spent by a tag (e.g., when the battery is fully charged $E = C$ and the tag is harvesting energy). In such cases a tag can operate in a *high-power mode*. EnHANT circuitry can be designed to contain optional power-hungry hardware modules that would allow, for example, for a more accurate/faster clock to be turned on. Other components that could be considered are more sensitive receiver stages, more selective filters, and more elaborate pulse detection methods. The inclusion of such components will increase the probability of successful communications but all performance enhancements will require additional power.

The challenge is to realize the benefits of these high power modes at the higher layers. An example of a clear benefit is a tag with an accurate clock that helps other tags to synchronize. Another example is running the receiver or transmitter more often to help other nodes to detect each other and to establish communication. Given a set of high power physical layer capabilities, numerous questions arise: what is the right harvesting status to use/stop using each of these capabilities? How will using these capabilities in one tag affect other tags? Is it enough to have these capabilities in a subset of the tags and what is the right size of the subset?

5. COMMUNICATIONS & NETWORKING

We now outline EnHANTs-related communications and networking challenges. Recall that given the power constraints, EnHANTs will be communicating within ranges of 1 to 10 meters. We identify three states of pairwise EnHANT communications, and note that the rate of energy consumption *e* can be adjusted within each state, and also by moving between states. We also outline the challenges related to routing, information dissemination, and network security. Some of the concepts discussed in this section are well known in sensor networking. Hence, we highlight the new challenges, such as *presence of transmit-only devices* and *making use of the always-open harvesting channel*.

5.1 Pairwise EnHANT Communications

In pairwise EnHANT communications, three states can be identified: *independent*, *paired*, and *communicating*. To control its energy spending, a tag can move between states with respect to each of its neighbors. In each particular state, a tag can consume different amounts of energy *e* depending on its own energy parameters (C,E,r), and, when relevant, on the energy parameters of other EnHANTs involved in communications.

In the *independent* state a tag does not maintain contact with the other tag. In this state the tag needs to decide how much energy it wants to spend on listening to the medium and transmitting pulses (to enable others to find it). The amount of energy consumed can be controlled by changing the spacing between transmitted pulses and listening periods, as well as by changing the overall duty cycle.

If a tag is very low on energy, it could transmit pulses but not listen to the medium. This "transmit-only" mode is feasible and logical for EnHANTs, since, as described in Section 4, it is energetically cheaper for a tag to transmit than to listen. Accommodating the presence of such *transmit-only devices* is an interesting networking challenge.

To start communicating, EnHANTs need to synchronize with each other. Two EnHANTs will be able to start pairing when a pulse burst sent by one tag overlaps with a listening interval of the other tag, or when one tag overhears another tag's communications with third parties. Since EnHANTs' activity intervals are functions of their energy levels, the time-to-pair is also a function of the tags' energy levels.

Once *paired*, EnHANTs need to remain synchronized, by periodically exchanging short bitstreams. The *paired* state is similar to low power modes of IEEE 802.11 and Bluetooth. However, it should be noted that the "keep-alive" messages EnHANTs exchange are short pulse bursts, rather than beacons that include tens of bytes. The minimum frequency of burst exchanges is limited by the devices' clock drifts. If *high-power nodes*, discussed in Section 4, are present, it would help with both improving the time-to-pair and keeping devices synchronized.

Communicating EnHANTs need to coordinate their transmissions in order to ensure that they do not run out of energy. To make joint decisions on communication rates, the EnHANTs need to exchange information about their energy states. EnHANTs are so energy-constrained that exchanges of their energy parameters (C,E,r,e) may be too costly. It is a challenge to determine how much information EnHANTs should exchange (e.g., exchange their current C,E,r,e values or current C,E,r,e values along with a set of predictions of future values) and how frequently the information exchange should be conducted.

In the communicating state, a tag's energy consumption *e* is closely related to its data rate: lower data rates allow less transmission and listening. EnHANTs need to communicate at ultra-low data rates, which necessitates making provisions for EnHANTs taking pauses between transmissions of bits. This *delay tolerance on the bit level* is a challenge for networking protocols that often consider a packet as an atomic unit.

5.2 Communications of Multiple EnHANTs

A benefit of the harvesting system is that EnHANTs in close proximity will be subject to common stimuli *through their energy harvesting channels*. Examples include lights turning on/off or running with modulated intensity (e.g., the 60Hz variation in fluorescent lighting), or vibrations felt by more than one tag. For instance, when a light is turned on, a tag can assume that the energy parameters of all its neighbors change, and behave accordingly. Information about the relative similarities or differences between EnHANTs stimuli can provide information about proximity and can be used for *synchronization via a channel which is effectively always open*.

In communication with each of its neighbors, a tag decides on both a state of communication and, in the chosen state, rate of energy consumption e. When many devices are involved in communication, the decisions are far from trivial. *EnHANTs' joint energy decisions on states and rates are a large-scale optimization problem*, and a suitable solution for the problem needs to be calculated by low-power EnHANTs without extensive exchange of control information. Developing the algorithms that will make this possible and will take into account the realistic considerations discussed in Sections 3 and 4 is one of the major challenges for EnHANTs.

5.3 Higher-layer Challenges

EnHANTs' capabilities also influence the design of higher-layer protocols, such as protocols for routing and information dissemination. A variety of energy-efficient routing schemes proposed for ad-hoc and sensor networks can serve as starting points for EnHANTs routing. Both information *pulling* (extracting data through a query) and information *pushing* (EnHANTs proactively exchanging information to assist in a pull) should be used. Deciding on the right levels of push and pull is an interesting problem that has strong relation to work in caching and peer-to-peer networks.

Security and privacy are very important issues for the proposed EnHANTs applications. Lightweight techniques that have been designed for sensor networks and for RFIDs can serve as starting points in EnHANTs security research. Moreover, congestion control and interference resolution techniques for EnHANTs could be a future research direction. Currently, short communication ranges and low transmission rates ensure that congestion and interference are not primary concerns.

6. ENHANTS AS AN INVENTORY SYSTEM

In section 5 we outlined Enhants communications and networking challenges, and noted that EnHANTs' joint decisions on energy management are a large-scale optimization problem. In this section we introduce inventory control theory as a tool that can potentially be used to approach this problem.

Much like the harvest of a farmer, the "harvest" of a tag needs to be carefully managed. In spending their harvest, the farmer and the tag both make sure they neither waste harvest due to storage space limitations, nor run out of harvest when it is needed. This type of problem is not well studied in wireless networking, However, it has been examined in depth in the mature field of *inventory management* [32, 33]. In this section we show how concepts developed in the inventory management field apply to EnHANTs.

An energy-harvesting tag can be viewed as a *manufacturing system* composed of *a factory and a warehouse*. Consider the abstraction of the energy harvesting system shown in Figure 3, which identifies system parameters C, r, e, and E. A real-world factory-warehouse has a finite capacity, a rate at which products are manufactured (supply rate), a rate at which products are purchased (demand rate), and a level of inventory – all of which directly correspond to the listed harvesting system parameters. A warehouse inventory management system strives to ensure that the demand is met and that there are no shortages. Similarly, the tag's energy management system should ensure that it utilizes its resources to communicate efficiently and does not run out of energy. Below, we explore the similarities between the EnHANTs domain and the inventory management domain. We give two examples of direct applications of inventory management models to the EnHANTs domain, and demonstrate that due to the distributed operation and the dependencies between EnHANTs parameters (see Section 5), a network composed of EnHANTs is more complicated than a manufacturing system. This calls for the extension of the well-established inventory theory models to the EnHANTs domain.

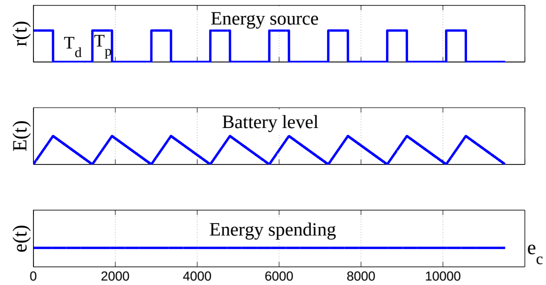

Figure 4: Application of the *Economic Production Quantity (EPQ)* model to the EnHANTs domain with a periodic on/off energy source: (i) the energy charge rate $r(t)$, (ii) the energy level $E(t)$, and (iii) the energy consumption rate $e(t)$.

6.1 Deterministic Model

Our first example considers a tag which harvests energy from an on/off periodic energy source shown on the the upper graph of Figure 4. Such an on/off source can be found, for example, in an office environment where an indoor lighting system is turned on in the morning and off at night. The source is on during the period T_p, in which the tag charges at a constant rate r and it is off during T_d. Throughout both periods the tag consumes energy at a constant rate e_c. In the inventory management domain this scenario directly matches the classic *Economic Production Quantity (EPQ)* model [32,33]. It can be easily shown that in this model the highest consumption rate that can be maintained is $e_c = T_p \cdot r/(T_d + T_p)$. For the EnHANTs domain, the consumption rate can be directly translated to bit rate, duty cycle, or level of communications.

Consider a scenario where a tag with a 10cm^2 solar cell of 1% efficiency is located on a dimly lit shelf in an enclosed office, where the irradiance is 50μW/cm^2 when the office light is on and 0 when it is off. If the light in this office is turned on for 10 hours per day, the tag can spend energy at a constant rate of $50 \cdot 10^{-6} \cdot 10 \cdot 0.01 \cdot 10/24 = 2.08\mu$W. Assuming that reception of one bit requires 1nJ (similar to section 3.1), this tag will be able to maintain the data rate of 2.08Kb/s throughout the entire diurnal office cycle.

Figure 4 shows an example of all the parameters of this system which directly correspond to the EPQ model's dynamics of the supply, the demand, and the inventory in a warehouse as well as in a tag. The EPQ model is very simple, yet it demonstrates an encouraging resemblance of a tag's energy harvesting system and a large-scale factory-warehouse system.

6.2 Stochastic Model

For environments where energy sources are not deterministic, other models are needed. An example of an inventory model that

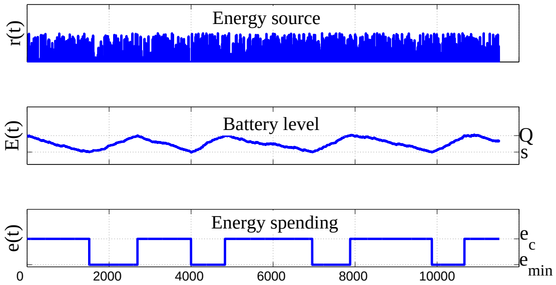

Figure 5: Application of the *order-point, order quantity* (s,Q) inventory model to the EnHANTs domain: (i) energy charge rate $r(t)$, (ii) the energy level $E(t)$, and (iii) the energy consumption rate $e(t)$.

applies directly to the EnHANTs domain is the *order-point, order-quantity* (s,Q) model [32, 33], which takes the stochastic nature of demand for inventory into account. To avoid shortages, in this model the level of inventory is tracked, and when it falls below a predetermined level *s*, additional *Q* items are ordered. This results in the inventory level curve similar to the middle graph in Figure 5.

The following EnHANT energy spending policy, similar to the "battery-state-based" strategy described in [22], results in the same inventory level (battery level) dynamics. A tag spends energy at a constant rate e_c, but if the tag's battery level drops below a predetermined value *s*, the tag switches to a "safety" mode in which it spends energy at a rate not exceeding a minimal rate e_{min}. The values for *s* and e_{min} should be selected such that a tag in the "safety" mode is able to function at some level, for example *pair* with a few of its neighbors. The tag stays in the minimum-spending mode until its battery level reaches *Q*. Then, it returns to spending energy at its normal e_c rate. An example of applying the (s,Q) policy to a tag with a stochastic source is shown in Figure 5.

6.3 Novel Energy-Inventory Models

While, as shown above, certain inventory management models directly map to the EnHANTs domain, EnHANTs and, particularly, *networks of EnHANTs* call for extensions of existing inventory management models. Compared to the inventory management domain, in the EnHANTs domain the environment is more random with fewer parameters known with certainty and fewer parameters under control. For example, while warehouse capacity is usually known and constant, a tag's storage capacity *C* may not be accurately known and may change over time. Also, an EnHANT cannot manufacture more inventory (energy) when needed, and does not control the cycles of production. Moreover, in inventory management, the demand is usually stochastic but the supply is mostly deterministic. In the EnHANTs domain, both the supply (energy harvested) and the demand (communications) are likely to be stochastic.[3] Existing inventory models need to be extended to take into account this uncertainty and randomness.

A particular challenge in EnHANTs is the *dependency* of energy spending of different communicating tags. A tag should spend energy on transmissions only if the tag it communicates with is ready to spend energy on reception. Hence, one tag's energy spending necessitates another tag's energy spending. Moreover, the transition of different tags between states are somewhat correlated. Hence, the resulting system can be viewed as *a network of factories* in which the behavior of one significantly affects the behavior of the others. While some inventory theory models consider multiple warehouses (multi-echelon models), they will need to be extended to capture the complexity of EnHANTs. Further, while in a manufacturing system the central controller has complete knowledge, in a network of tags, distributed low complexity algorithms using partial knowledge will have to be employed. *Extending inventory management models to handle the unpredictability of EnHANTs and EnHANTs dependencies, and creating realistic and implementable EnHANTs energy spending algorithms is an exciting challenge.*

[3]However, as can be seen in Figure 5, the tag can somewhat control its inventory level by adjusting its energy spending rate.

7. TESTBED DESIGN

Experimentation with the various device designs and algorithms in real-world settings is crucial in order to better understand the design considerations. However, wireless mote designs are optimized for wireless sensor applications and typically use IEEE 802.15.4 RF transceivers [14, 16]. These transceivers do not leave room for experimentation with physical layer communications protocols. Hence, we are in the process of building EnHANTs prototypes.

In the first phase, these prototypes will be based on commercial off-the-shelf (COTS) components. Currently, they are physically much larger and consume more power than the targeted EnHANT. They do not include a UWB transceiver, flexible solar cell, and a custom battery but will serve as a platform for preliminary experiments. One prototype is based on a MICA2 mote attached to a TAOS TSL230rd light-to-frequency converter for light measurements and to an Si solar cell for energy harvesting. Another prototype is based on a LabJack and a TAOS TSL230rd light-to-frequency converter. Using these prototypes, we have been performing energy harvesting measurements in various environments. These measurements will enable us to develop real-world energy supply models that will support the development of the algorithms described in Sections 5 and 6. In addition, we have been using the MICA2-based prototype to emulate harvesting-aware communications protocols.

In the next phase, we will replace the COTS components with custom designed hardware (flexible harvester similar to the one in Figure 2 and a UWB transceiver). This platform will allow us to demonstrate initial feasibility for the transceiver and harvester and to test networking protocols with the actual energy budgets. Further testbed information and results will be available at [1].

8. CONCLUSIONS

We believe that ultra-low-power Energy Harvesting Active Networked Tags (EnHANTs) are enablers for a new type of a wireless network which lies in the domain between sensor networks and RFIDs. While RFIDs make it possible to *identify* an object which is in proximity to a reader, EnHANTs make it possible to *search* for an object on a network of devices and continuously monitor objects' locations and proximity to each other. EnHANTs enable novel tracking applications such as recovery of lost items, locating items with particular characteristics, continuous monitoring of merchandize, and assistance in locating survivors of a disaster.

EnHANTs necessitate rethinking of communication and networking principles, and require careful examination of the particularities of ultra-low-power and energy harvesting technologies. We have shown that the nature of EnHANTs requires a cross-layer approach to enable effective communications and networking between devices with severe power and harvesting constraints. In order to discuss the design challenges, we outlined several important characteristics of EnHANTs, pointed out a number of open problems and possible research directions, and introduced inventory control theory as a tool that might be used to address open problems related to the tags' energy management.

9. ACKNOWLEDGMENTS

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