The Internet of Tags: Energy-Harvesting Adaptive Algorithms

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1. INTRODUCTION

In this thesis, we will focus on the design and performance evaluation of networking algorithms for energy-harvesting tags. We will build upon our recent work on developing Energy-Harvesting Active Networked Tags (EnHANTS) [3–5]. In this capacity, we have taken a bottom-up approach and integrated ultra-low power Ultra-Wideband Impulse-Radio (UWB-IR) transceivers with energy harvesting circuitry. In this thesis, we will take a top-down approach and develop energy harvesting adaptive algorithms to support the Internet of Tags (IoTags). We believe that IoTags will be a key component of the Internet of Things (IoT).

In the near future, objects equipped with heterogeneous devices such as sensors, actuators, and tags, will be able to interact with each other and cooperate to achieve common goals. The IoT has been gaining increased attention from academia and industry [1], with applications in healthcare, smart buildings, assisted living, manufacturing, supply chain management, and intelligent transportation. Small, flexible, and energetically self-reliant, IoTags will be attached to objects that are traditionally not networked, such as books, furniture, walls, doors, toys, produce, and clothing. In their capacity as active tags, IoTags will provide infrastructure for novel tracking applications.

We have already taken steps toward developing IoTags in our ongoing EnHANTs project. *Our goal is to build upon our ongoing research to design and evaluate energy-harvesting adaptive algorithms to enable IoTag networks.*

2. PROPOSED RESEARCH

The EnHANTs research took a bottom-up approach towards developing IoTags. In this capacity, we have developed UWB-IR transceivers and energy harvesting circuitry. With the acquired knowledge of the hardware constraints and enabling technologies, we will now take a top-down approach to develop algorithms for applications of IoTags (i.e., searching for objects.As such we will develop algorithms for network topology adaptation, flow control, and Medium Access Control (MAC). Following our experience on the EnHANTs project, we will develop a testbed and prototype upon which to evaluate the proposed algorithms.

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2.1 Network Topology Determination and Adaptation

To enable applications (i.e., searching for an object), the network should provide the functionality for end-to-end connectivity between the tags. This clearly requires a simple light-weight routing protocol. However, the dynamic energy availability, in combination with high energy costs of maintaining active links between different tags, will necessitate frequent network topology adaptations. This also calls for the development of *distributed topology adaptation algorithms* that will take into account short-term and long-term tag energy availability. Topology adaptation protocols should not only adapt the topology but should be able to report partial topology information to some of the network services (e.g., when searching for a tag).

Our preliminary experimental results, conducted using a small-scale network in the existing EnHANTs testbed indicate that, due to the time-varying and highly dynamic energy harvesting rates and the limited energy budgets, even relatively insignificant network protocol parameters substantially affect the performance of the protocols. For example, tag energy use is directly affected by how frequently the network topology is changed (for details, see [5] and references therein). Thus, it is important to design flow control algorithms for practical energy harvesters and RF transceivers.

Hence, *we will develop and evaluate algorithms for joint adaptation of tag energy spending rates and network topologies* that consider the various trade-offs in topology adaptation frequency, throughput, energy sustainability, and complexity. Such approaches may, for example, spend energy more conservatively in tags that have many decedents than in leaf tags (leading to less frequent topology adaptations).

2.2 Energy Harvesting Adaptive MAC

In some cases it may be beneficial to create a high power mode and spend more energy than what is typically spent by a tag (e.g., when the battery is fully charged and the tag is harvesting energy). We plan to design, develop, and evaluate cross-layer flow MAC layer solutions and policies which dynamically adapt to energy availability.

In our preliminary MAC research in the EnHANTs testbed, we analyzed tradeoffs between the energy cost of Carrier Sense Multiple Access (CSMA) due to channel listening and the throughput benefit [4, 5]. Using our small-scale testbed

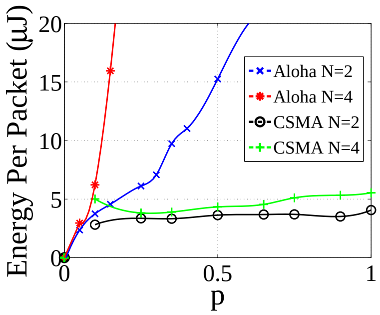

Figure 1: Average energy spent per successful packet transmission, as a function of p.

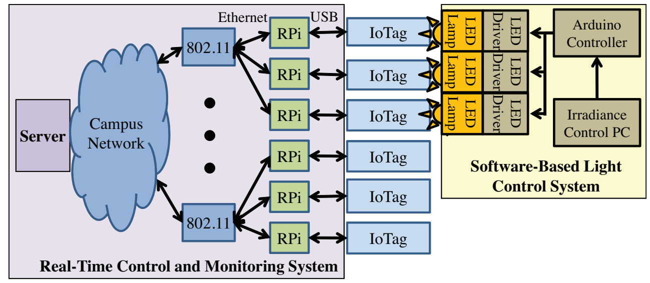

Figure 2: A schematic diagram of the envisioned IoTag testbed.

of two and four 'infinitely backlogged' (i.e., sending as often as possible) nodes, we implemented and deployed two basic MAC protocols: p-persistent CSMA (enabled by our implementation of Clear Channel Assessment [CCA]) and slotted Aloha. The energy spending per successful packet is shown in Fig. 1. We found that the collision avoidance provided by CSMA reduced the average energetic cost per successful packet significantly as compared to Aloha, despite the added cost of CCA. This example motivates further research on low power MAC design.

Major energy saving can be achieved by placing the tags into a low-power sleep mode. Sleeping tags cannot send or receive messages resulting in delays which is acceptable in some applications, such as searching for an object. In contrast to sensor network sleep scheduling algorithms, which aim to maximize node lifetime for a fixed battery, energy-harvesting IoTags aim to optimally use their available energy. Moreover, transceivers have time and energy requirements to shut down or wakeup. Sleep scheduling polices need to be designed and evaluated taking into account application specific latency demands, tag energy profiles, and transceiver wakeup costs. Receiver initiated wake up strategies (e.g., [2]), can shift the energy demand of sending a packet from the receiver to the sender, and will be investigated for IoT applications.

The remaining research problems are concentrated on realizing efficient synchronization in multi-tag networks. When nodes are unsynchronized, the high cost of non duty-cycled reception while searching for the packet start results in significant energy waste. Synchronization can then be maintained through the use of a light weight overhead connection. This consumes some energy, however, and when to keep or drop synchronization is an open area of research to be investigated. One possible approach is to use immediate hardware initiated acknowledgments and leverage the energy savings of the existing synchronization. We aim to substantially reduce or eliminate synchronization energy costs through the development of a cross-layer protocol, optimized to application requirements.

We also plan to further investigate MAC layer solutions which use adaption of data rate, modulation, and coding according to a received signal strength indicator.

2.3 Prototype and Testbed Development and Algorithm Evaluation

We will evaluate the proposed algorithms when supporting several applications including searching for an object, data collection, and network-based alert generation (i.e., removing a tag from the network). To enable the experiments, we will design and deploy a large testbed of next-generation EnHANTs prototypes. The testbed, illustrated in Fig. 2, will consist of (i) an externally powered "backbone" network supporting real-time prototype monitoring and control, (ii) next-generation EnHANT prototypes forming an adaptive multi-hop short-range wireless network, and (iii) an environmental energy emulation system to support controlled experiments.

The backbone network will monitor the prototype's communication, networking, and energy states in real time. Key to that is the separation between the *control channel* and the *experimental communication channel*. This two-tier architecture will allow extensive and detailed prototype state logging (including details of power consumption, harvesting rate, and battery charge, as well as communication rates and routing information) without burdening the wireless communication channel. This architecture enables real-time analysis of the IoTag prototypes on a central server.

Evaluating the algorithms in the presence of energy harvesting is a difficult challenge. To enable controlled experiments using energy harvesting, we will utilize the software-based light control system from [5].

Acknowledgements

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3. REFERENCES

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