DESIGN AND IMPLEMENTATION OF APPLICATION-SPECIFIC MEDIUM ACCESS CONTROL PROTOCOL FOR SCALABLE SMART HOME EMBEDDED SYSTEMS

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A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the degree of

MASTER OF SCIENCE

By

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Fairbanks, AK

May 2016

Abstract

By incorporating electrical devices, appliances and house features in a system that is controlled and monitored either remotely or on-site, smart home technologies have recently gained an increasing popularity. There are several smart home systems already available, ranging from simple on-site home monitoring to self-learning and Wi-Fi enabled systems. However, current systems do not fully make use of recent technological advancement and synergy among a variable number of sensors for improved data collection. For a synergistic system to be provident it needs to be modular and scalable to match exact user needs (type of applications and adequate number of sensors for each application). With an increased number of sensors intelligently placed to optimize the data collection, a wireless network is indispensable for a flexible and inexpensive installation. Such a network requires an efficient medium access control protocol to sustain a reliable system, provide flexibility in design and to achieve lower power consumption. This thesis brings to light practical ways to improve current smart home systems.

As the main contribution of this work, we introduce a novel application-specific medium access control protocol able to support suggested improvements. In addition, a smart home prototype system is implemented to evaluate the protocol performance and prove concepts of recommended advances. This thesis covers the design of the proposed novel medium access protocol and the software/hardware implementation of the prototype system focusing on the monitoring and data analysis side, while providing inputs for the control side of the system. The smart home system prototype is Wi-Fi and Web connected, designed and implemented to emphasize system usability and energy efficiency.

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Chapter 1 Introduction

In the last few decades, smart home systems, also referred to as home automation technology, have increasingly gained the interest of home owners as well as technology manufacturing industries. Some smart home benefits include improved convenience and comfort, reinforcement of security features, facilitating an energy-efficient environment, etc. Smart home systems range from centralized control of lighting to complex, entire-home smart control systems. Popular applications include environmental (humidity [1], temperature [2], air quality monitoring [3] and conditioning, etc.), HVAC[1] systems [4], security details [5] [6] (door lock, safe/vault monitoring, motion/presence detection, etc.), and more complex systems combining different home features and appliances [7] (entertainment centers, refrigerators, laundry machines, etc.). On top of applications aiming for common home features and appliances, the recent rise of applications aimed to help the soaring number of the elderly [8] and the current increase of wearable devices [9] [10] either for medical purposes, health monitoring or fitness, suggests an all-encompassing approach for improved performance for the next generation of smart homes.

Besides the general-purpose systems intended for the wide-ranging market, there is a rising interest in special-purpose smart home systems aimed to improve and support independent living of elderly people or people with disabilities. These specific systems, also referred to as *health smart home* systems, strive to use a non-invasive approach to monitor the occupants' health and wellness, and provide them with facilities to enable a more comfortable lifestyle, a higher degree of independence, and more affordable care, which also reduces the financial pressure on the healthcare system [11]. Health smart home systems are used to detect abnormal activities and changes in behavioral patterns, which may be indicative of underlying health or wellness problems or emergency situations, and forward information to appropriate overseers for proper and timely response [12] .

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[1] HVAC: Heating, Ventilation and Air Conditioning

The term *smart*, sometimes used interchangeably with *intelligent* and/or *automated*, is both widely and ambiguously used. In the context of this thesis the term *smart* refers to an autonomous system that is equipped with reasoning capabilities from a centralized processing node based on sensory inputs and it deduces a set of corresponding decisions [13]. In addition, some nice-to-have but not indispensable features of a *smart* system include self-adaptation to the environment, aptitude of anticipating subsequent course of actions, and possibly learning capabilities from previously acquired data to improve performance.

The term *smart home system* in this context refers to electrical devices integrated into a residential building to provide the inhabitants with improved convenience in monitoring and controlling the building's features and/or appliances. The system can be extended to include and interact with wearable devices for a synergistic effect. This integrated system consists of an embedded hardware which runs a software system capable of collecting and processing sensory inputs from the home environment, connected home features, wearable devices, and physical devices found in residential buildings. On top of sensing, processing, and reporting or visualizing sensed data, the system can also control monitored home features and physical devices. The term *control* in this context refers to the system's ability to initiate desired actions or changing states of controlled devices such as appliances.

This work explores available smart home systems, their current shortcomings and suggests feasible enhancements for the next generation of smart home systems. We introduce a novel application-specific medium access control (MAC) protocol tailored to smart home applications and capable of supporting suggested improvements. A smart home system prototype is built to evaluate the protocol's performance and to experimentally confirm suggested improvements.

1.1 Contribution of this Thesis

This thesis takes a scientific approach to improve on existing smart home solutions. By exploring current smart home systems, we identify their limitations and propose practical improvements. The following are major contributions of our work.

1. We developed a novel Application-Specific MAC Protocol, with features tailored to smart home systems and capable of supporting recommended improvements.

2. We introduced the concept of system scalability and synergistic effects into smart home systems and proved the concepts.

3. We designed and implemented a smart home system prototype to evaluate the performance of the designed protocol. The prototype is also used as the proof of concept for improvements recommended for the next generation of smart home systems.

4. Based on the implemented prototype, we performed extensive power consumption evaluation for sensor nodes (SN) and deduced the expected battery lifetimes for the system.

1.2 Organization of this Thesis

The remaining of this thesis is organized as follows.

In Chapter 2, we review smart home technology from both researchers' and consumers' perspectives, and explore currently available products and their limitations.

In Chapter 3, we start by exploring the feasibility of Internet of Things (IoT) compared to wireless sensor network (WSN). Subsequently, improvements we recommend to the next generation of smart home systems are discussed, and we conclude this chapter by detailing our contribution to bringing recommended improvements to life.

In Chapter 4, we start by presenting the importance of MAC protocols in WSN, and then we explore the distinctive behavior of smart home systems that led to the design of an application-specific MAC protocol. Before describing our novel MAC protocol we survey some popular MAC protocols generally designed for WSN and highlight why they are not suitable for improved smart home systems.

In Chapter 5 we discuss the development of our implemented smart home embedded system prototype. Details of implementation are provided from hardware selection to software configuration.

In Chapter 6 we discuss the functionality and evaluate the performance of the implemented prototype and the MAC protocol specifically. We present detailed power measurements and perform calculations to estimate the system battery lifetime. In this chapter we also explain integrated time synchronization technique.

Chapter 7 concludes our work and discusses future work.

Chapter 2 Existing Smart Home Systems and Associated Shortcomings

2.1 Overview of Smart Home Technology

It is uncertain when home automation started exactly. However, some home automation systems to control buildings' environment such as heating and lighting have been available for a long time. "The term smart house was first used in an official way as early as in 1984 by the American Association of House Builders, though the first "wired houses" were actually built by hobbyists in the early 1960s" [14]. By smart, they were not referring to environmentally friendliness or power efficiency, but rather the interactive technologies that were contained in the house. But it was not until the last couple of decades ago that smart home technology decisively captured the interest of both researchers and technology manufacturing industries. In this chapter we review smart home technology from both researchers' and consumers' perspective, and explore currently available products and their limitations.

2.2 Smart Home Technology from Research Perspective

Most research projects approach smart home technology by developing the idea of equipping a home with intelligence and the ability to make decisions regarding its state and interactions with its residents. Although all the projects obviously include hardware, most projects emphasize mainly on the computing side. Other explored aspects include the way technology affects inhabitants' privacy, the utilitarian's aspect, and less often, acceptance and financial cost of smart home technology.

In the early 1990s, the University of Colorado was investigating smart home technology through the Adaptive House Boulder project [15]. With 75 sensors installed in an actual residence (home-laboratory), the goal was to develop a home with learning capabilities capable of self-adaptation to the lifestyle and desires of the inhabitants. The goal was to make the Adaptive House "not a programmable house, but a house that programs itself. House adapts to the lifestyle of the inhabitants." One of the lessons learned from the project concluded that the more sensors the better [15].

In 1997 Carnegie Mellon University developed the concepts for the Intelligent Workplace [16] with intent of improving building performance while decreasing energy requirements. It was highlighted that the key to achieving these goals is the comprehensive integration of all systems in order to create the necessary performance improvement in lighting, heating, cooling and ventilation of the buildings [16].

The Aware Home project developed at Georgia Institute of Technology [17] was based on the premise that one possible factor hindering a full integration and acceptance of smart home technology in consumers' everyday life is that the then technologies did not address a coherent need, instead they merely augmented current entertainment and communication practices. Their research was based on the premise that the next revolution of technology in the home will arise from devices that help older adults maintain their independence and quality of life in general. Researchers explored the design, development, and evaluation of different home technological possibilities, including compensating for physical decline, aiding recall of past actions, and supporting awareness for extended family relatives. Some of the technology used in the Aware Home consisted of human position tracking through ultrasonic sensors, RF technology and video, recognition through floor sensors and vision techniques. One of the applications of the tracking and sensing technologies in the Aware Home is a system for finding frequently lost objects such as keys, wallets, glasses, and remote controls. The system uses RF tags attached to each object the user would like to track and a long-range indoor positioning system to track these objects [17].

The University of Florida's Mobile and Pervasive Computing Laboratory developed the Gator Tech Smart House [18] as a programmable pervasive space in which a smart space exists as both a runtime environment and a software library. The project was intended to supersede the Matilda Smart House, a 900 square-foot laboratory prototype designed to prove the feasibility and usefulness of assistive environments, in which researchers "realized that hacking hardware and software together resulted in some impressive demonstrations but not something people could actually live in." The Gator Tech Smart House was built from the ground up as an assistive environment to support independent living for older people and individuals with disabilities. The goal was to create assistive environments such as homes that can sense themselves and their residents and enact mappings between the physical world and remote monitoring and intervention services [18]. In 2009, The Gator Tech Smart House was using a self-sensing service to enable remote monitoring and intervention caregivers of elderly persons living in the house. The application has served as a classical example that illustrates the conflict found between preserving privacy and providing useful smart environment benefits [19].

The University of Texas developed the MavHome (Managing an Intelligent Versatile Home) [20] project to create a home that acts as a rational agent. The agent's goal was to maximize inhabitants comfort and minimize operation cost. MavHome perceives the environment using deployed sensors and acts on the environment using power line controllers. MavHome was intended to observe resident activities, identify repetitive patterns and use predictors to determine likely future activities. The performance was evaluated based on the MavHome ability to predict and automate daily interactions with the environment that the resident would typically perform manually. From one month of data collected on a volunteer resident, MavHome was able to reduce the needed daily interactions by 76%, on average [20] [21].

Both academia and industry have shown great interest in exploring smart home technology. However, for understandable reasons little to almost nothing is released by business industries about their research. Some of the known industry establishments currently conducting smart home technology related research include Siemens AG, the largest engineering company in Europe [22], Koninklijke Philips N.V., commonly known as Philips [23], Microsoft Corporation [24], Nest Lab, a subsidiary of Alphabet Inc., a parent company of Google [25] and many more including several companies with smart technology products already on the market, which will be briefly discussed later.

2.3 Smart Home Technology from Consumer Products' Perspective

There is a perceptible gap between the visionary research advances and adoption of smart home systems consumers' products. Nonetheless, the use of smart home systems by residential households is still marginally small and mostly limited to only few applications. Figure 1 illustrates the low adoption rate of smart home technology by consumers as of 2015. As discussed by a Business Insider (BI) Intelligence report [26], there are many barriers preventing mass-market smart home adoption, including high device prices, limited consumer demand and long device replacement cycles. BI argues that technological fragmentation of the smart home ecosystem, in which consumers need multiple networking devices, apps and more to build and run their smart home is the largest barrier. The current adoption point is characterized as *chasm*, which is the crucial stage between the early-adopter phase and the mass-market phase. To go past this point, manufacturers need to prove a real need for the technology and efficiently address related barriers and consumers' concerns. In the following section, we identify some of the factors hindering the spread of smart home technology.

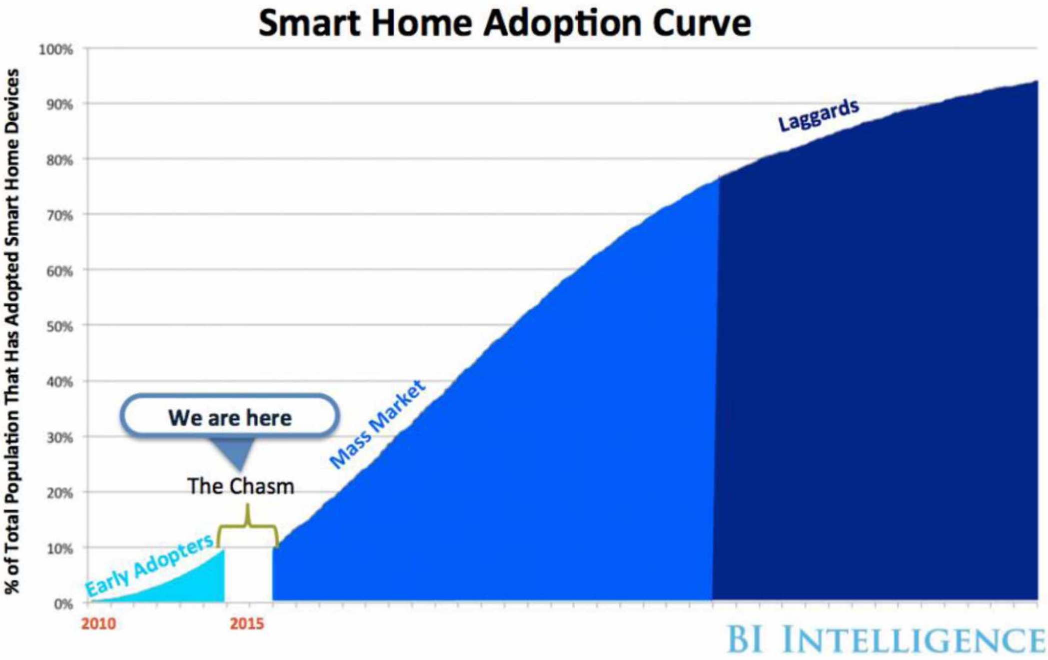

Figure 1: Illustration of current smart home low adoption [26]

2.3.1 Factors Hindering the Spread of Smart Home Technology Include:

1. **Security concerns**: With an increasing number of cyberattacks, ranging from banking hacks to malicious mobile applications, smart home technologies are not immune to the threat [27] which makes consumers less enthusiastic to adopt. Recent home automation security breaches include a hijacked baby monitor in Cincinnati, OH [28]. Manufacturing companies face a serious security challenge to prevent existing and projected security breaches to smart home technology. It is indispensable for the manufacturer to ensure maximum security of the system to gain consumers' confidence. Moreover, for a system requiring professional installation, some homeowners are reluctant to allow unknown individuals access to their homes, fearing that the knowledge gained therein could be used later to the homeowner's disadvantage. Understandably, the idea of having someone else knowing the details of the home's security system might be unsettling.

2. **Menace to home privacy**: Some systems are designed to require constant monitoring and support from providing companies. This approach puts a middleman between the house and its owner. On top of increasing the overall cost, it also adds home owners' worry of having someone else constantly aware of the details of what happens in their home. For instance, a leak of information about users' habits as well as their presence can be abused to plan burglaries [29]. Clearly, this practice potentially demeans the consumers' privacy by inserting a third party into their business. Current popular instances of home privacy invasion by so called smart technology include the Samsung Smart TV case. Samsung authorities warned customers that their spoken words including personal or other sensitive information are among the data captured and transmitted to a third party through the use of TV's Voice Recognition feature [30].

3. **Compatibility and interoperability**: The compatibility of the smart home system with the technology that already exists in the household is essential for consumer satisfaction, and is still a major hindrance for smart home technology acceptance. Currently, there are many networks, standards, and devices being used to connect the smart home, creating interoperability problems and making it confusing for consumers to set up and control multiple devices. The lack of standards in present smart home systems, the interoperability problems of different hardware and software components, and limited service scalability prevent their mass adoption [31].

4. **Financial Cost**: Although advances in technology have considerably reduced the price of electronic devices in general, the cost of smart home systems is still noticeably high. On top of the purchase cost, most systems entail installation charges, set up fees, and maintenance cost. In addition, most systems comprising security features necessitate reoccurring fees for service support often bounded with a contract. Moreover, some consumers get discouraged by the fact that they would need different systems to fulfill different household solicitations. On the other hand, based on a limited number of available applications, most consumers still consider smart home systems’ benefits as a luxury, rather than a necessity.

5. **Increased complexity and inconvenience**: Some smart home systems are sophisticated in terms of configuration and use, consequently requiring a steep learning curve for the user. This learning challenge appears in different forms, such as complex set up of the system, uneasiness in routine interaction with the system or a lack of a friendly or appealing user interface, sometimes requiring a new monitoring device even when computers and smart phones are already present in the household.

2.4 Available Smart Home Systems Products and their Limitations

Currently, home automation systems have advanced to the point where almost any electrical feature or appliance within the house can be integrated into the system. Furthermore, this technology has improved from the basic tasks of simply turning devices on and off, to incorporate more sophisticated features such as self-adaptation, environment-awareness and remote controlling and monitoring. Despite tangible improvements and the time elapsed since home automation systems were introduced, smart home systems currently available do not fully make use of recent technologies' aptitude and consequently leave much room for improvement which we discuss in our proposed solution. We have arranged home automation systems in three different groups based on consumers' familiarity and adoption: thermostats, security systems and standalone automated appliances.

2.4.1 Smart Thermostats

A thermostat is a structure equipped with a temperature sensor and a mechanism to control heating or cooling systems in order to maintain the surrounding near preset temperature point. Smart thermostats are possibly the most adopted of available smart home automation technology. Some of the top manufacturing competitors in the smart thermostat category include the Nest Thermostat [32], the Ecobee3 [2] and the Honeywell Wi-Fi Smart Thermostat [33]. All these units come with Wi-Fi capabilities enabling remote control and monitoring. They are each priced over $200 at this time, while typical non-smart thermostats could cost less than $20 [34]. Other common features include occupancy detection for self-regulation, programmable temperatures or self-learning and adaptation to user's preference. Of all these systems, only the Ecobee3 can control multiple zones by using remote sensors, otherwise multiple units are required for different room or zone temperatures.

In spite of aforementioned engaging features, these systems do not exploit the full potential of current technology. While most users would like to monitor other home phenomena such as carbon monoxide, smoke detection, humidity or air quality; all these systems are single-application systems, which means that the user is required to acquire additional systems for other control/monitoring needs. Moreover, each of these systems uses only one sensor to monitor the average temperature of the monitored space. This is inefficient because the temperature measured by that one sensor might not adequately reflect the comfort level in all parts of the space. Even the Ecobee3 multiple sensors act independently, without any collaboration among them or data fusion of any sort. But most importantly, these systems miss on the synergy because they are incapable of fetching the data from other subsystems (wearable devices, security systems) that can possibly affect monitored phenomenon. Currently, the only known attempt to exploit synergistic effects in smart thermostats is limited to the incorporation of motion sensors to detect presence within the room. This approach has presented very limited increase in efficiency, especially for home owners who leave their pets inside the house.

2.4.2 Smart Home Security Systems

Smart home security systems are smart home systems dedicated and optimized to reinforce home security features. There are several available home security services including SimpliSafe [35], Protect America [6], ADT [36], Frontpoint [37], AT&T Digital Life [38], and more. Most reviews including Consumers Advocate [5], A Secure Life [39], and Reviews.com [40] have picked Frontpoint by General Electric as their overall best home security system. A basic Frontpoint kit comes with very attractive features and includes one motion detector, two window or door sensors, a key chain remote, two light controls and a free application for smartphones. Frontpoint systems start at $199.93 for equipment and activation fee, plus a monthly fee of $49.99 and require a minimum contract of 3 years. Additionally, Frontpoint offers the flexibility of adding extra sensors and features at additional cost.

Common features for most home security systems include 24/7 monitoring performed by a providing company; remote access and control from user's cell phone, tablet or PC; text and email alerts; cellular wireless communication which is commonly more reliable than landline and broadband systems, and also prevents burglars from disabling communication by cutting wires. Moreover, recent improvements include a more trustworthy DIY (do-it-yourself) installation eliminating the intrusive approach that required professional personnel to access premises to be monitored or protected. Furthermore, companies are enhancing security systems' flexibility by adding the ability to support added sensors to match user's needs.

In spite of considerable recent developments, home security systems still leave room for improvement. On top of the obvious high cost of purchase most companies are still requiring monthly fees. Due to increasing competition some of the companies are dropping the contract tradition, however all the reliable home security systems, including all the above-mentioned companies, are still requiring reoccurring fees. This is mainly encouraged by the required constant monitoring and support from providing companies. Although this practice can be considered as an extra layer of protection, we recommend that it should be left up to the consumer to decide whether or not the company should stay continually involved. Ideal smart home system would enhance consumer's authority by placing maximum control of the house at their disposition, and putting them on top of their home status, keeping the intermediary just as an option. This will both reduce the accumulated cost and address privacy concerns for some.

Most importantly, although some of these systems cover numerous applications or support a variable number of sensors; current designs neither exploit synergistic effect among diverse applications, nor use data fusion for improved data collection. As an example, systems equipped with both thermostats and security system features fail to combine gathered information for synergistic effect. For instance, information from an outside door sensor initially intended for security reasons can save the heating system from ineffective efforts to regulate the temperature, by instead soliciting the synergistic system to inform the user about the inefficiency of regulating indoor temperature while the outside door is open.

2.4.3 Diverse Home-Automation Systems

On top of the smart thermostats, energy consumption-management systems, and home security systems, there is an increasing number of home automation apparatus such as automated and/or remotely controlled appliances. This category includes smart lighting systems as well. Unfortunately, most of these automated appliances are usually not networked with the rest of the house and run as stand-alone applications. This is due to the lack of standards in current home automation industry and the interoperability issues of different hardware and software components. Manufacturers and researchers are contemplating the idea of interconnected objects/appliances within a home, paralleling the concept of the prominent IoT [41].

SmartThings Inc. [42] is one of many smart home technology companies claiming to be currently working on IoT and having released early products. SmartThings Inc., lately acquired by Samsung (August 2014), is committed to building an open platform for smart homes and the consumers of IoT. The company focuses on making hubs or gateway-home controllers, clients' applications for iOS and Android smart phones, cloud platform and a variety of SmartThings branded sensors. According to [42], SmartThings' platform is composed of three main parts: 1. a system that is intended to enable everyday "things," e.g., household appliances, lights, switches, etc., to connect to the Internet; 2. an application platform called SmartApps that enables the user to install applications on their everyday "things," like they could on their phones; and 3. tools for makers and developers enabling them to create their own smart things. SmartThings was named as one of Time's Best Gadgets of 2014 [43] and was honored as a 2015 International Consumer Electronics Show Editor's Choice Award winner [44]. As most of other commercial products, details of SmartThings' implementation are protected. For instance, the number of maximum sensors per hub, the system execution latency and other details are still undisclosed. Some of the early adopters experimenting with SmartThings Hub have shared their experience on SmartThings community forum stating that the system acted "flakey" when they connect more than 4 sensors, while others claim to have connected up to hundred without complication [45]. However, all this information is still unreliable.

Chapter 3 Bridging Research and Consumer Products: Improvements and Contributions

3.1 Introduction

Considering the sizable gap between research advances and the low adoption of smart home technology, and factoring in the limitations of available products, we decided to take a scientific approach to address current inadequacies and suggest a scientific, yet low cost and practical smart home platform.

Lately, it has become quite impossible to address the future of smart home technology without being interrupted by the escalating idea of IoT. Consequently, we start by exploring the feasibility of IoT compared to the common and currently used approach, WSN.

3.2 Wireless Sensor Network versus Internet of Things

IoT consists of a wireless network in which all comprised nodes, nominally known as smart things or smart objects, allegedly become active participants and directly serviceable over the Internet [46] [47], as depicted in Figure 2. This definition debunks the misuse of the term IoT for systems, such as SmartThings' platform [42], where various sensors placed around a home connect to the hub which in turn connects to a home's internet router. IoT is still partially a paradigm, although expected to gradually become a reality. However, from home automation consumers' perspective, although IoT has recently dominated the news, at this time IoT is almost still an enigma. There are still serious conceptual and technical challenges. The most challenging of the requirements for IoT complete realization seems to be the security [47].

On the other hand, a WSN consists of a wireless network composed of several spatially distributed, autonomous sensing nodes [48]. A WSN can become Web-connected by implementing Internet Protocol on at least one of the SN (Figure 3). Contrary to IoT, where all nodes are active agents of the Internet, a Web-connected WSN can use only one gateway node to access the Internet (Figure 2).

Figure 2: The IoT generic scenario [49]

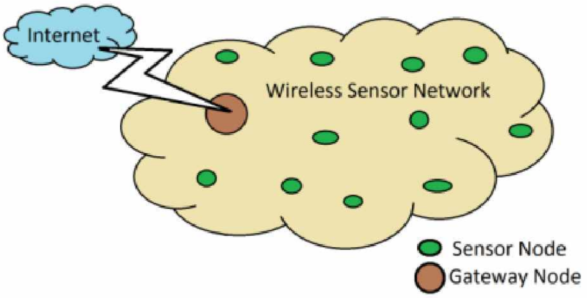

Figure 3: Generic Scenario of an Internet Connected WSN

For a practical solution, the WSN-based approach has two important advantages over IoT: reduced design cost and alleviated security concerns.

3.2.1 Security Concern

As mentioned in Section 2.3.1, security concern is still one of the major factors impeding the mass-adoption of smart home technology. The National Intelligence Council (NIC) has placed IoT on the list of six disruptive civil technologies with potential impact on US interests out to 2025 [50]. Pushing IoT based designs on home automation costumers before ensuring thoroughgoing cyber-security measures is not commendable. Although WSNs are not invulnerable to cyber-attacks [27], they minimize the risk by potentially limiting security measures on only one node.

3.2.2 Design Cost

Although various approaches are contemplated, Transmission Control Protocol/Internet Protocol (TCP/IP) stacks are considered as the best solution to integrate smart things, or the gateway node in case of WSN, to the Internet. The implementation of TCP/IP on each node significantly increases the design cost considering both hardware and software implementation requirements. WSN significantly reduces the cost by connecting the entire network to the Internet with TCP/IP and web services implementation on only one node, the gateway node. WSN is considered the main building block of IoT [51].

It is recognizable that until some new cyber-security measures are introduced and the cost of connecting nodes to the Internet is drastically reduced, smart home automation will stay based on either wired or wireless sensor networks.

3.3 Proposed Improvements

On top of noticeable features that current smart home technologies present, we propose an improved smart home system with additional features that will be described next.

3.3.1 Improved Data Collection

As described in [15], data collection can be improved by increasing the number of sensors. Instead of one-size-fits-all approaches [32] [2] [33], in which systems come with predetermined number of sensors regardless of the size of monitored space, we propose a system that enables the user to choose a variable number of sensors depending on their needs. Most importantly, this increased number of sensors will work collaboratively and provide opportunity for advanced processing for fine-grained data scrutiny. With an increased number of sensors, care must be taken to not compromise the system usability features, such as response time. To dynamically handle a changing number of sensors hassle-free, the system must be scalable and easy to reconfigure or self-reconfigurable.

3.3.2 Scalable and Reconfigurable System

An improved system should be robust and dynamic in terms of scalability and re-configurability. This feature will enable the user to easily remove or add a number of sensors to match their specific needs. In addition to a user friendly experience, a self-reconfigurable system enhances the system efficiency by preventing the failure of the entire system in case one or more SNs are compromised.

3.3.3 A Modular and Synergistic System

Modularity in the current context refers to the system's ability to encompass multiple but independent applications (temperature/thermostat, security, lighting, etc.). Synergy is defined as increased or mutually advantageous conjunction of distinct participants that results when two or more structures work together. We propose a modular system such that information from one application can be used in a different application to improve efficiency of the overall smart home system.

3.3.4 Consumer-empowered Design

Current designs, particularly those comprising security features, still require constant monitoring and support from providing companies. At the wake of embedded web servers, we propose a smart home system that places maximum control of the house at the consumer's disposition. We propose that the intermediary constant monitoring by providing company becomes an optional feature. This approach will reduce the accumulated cost of the system, it will address the privacy concern for some, and it will reinforce consumers' authority over their property.

3.3.5 Improving Low Power Consumption

Low power consumption constitutes one of the most important characteristics of all embedded systems, especially WSNs. Low power consumption design not only reduces the cost of the system, but also increases the operational lifetime of the system. Nonetheless, a smart house system with a low power consumption design assures that every node can be battery-powered for an extended time, which enables the user to efficiently and neatly place the SN without being constrained to the availability or placement of power outlets in the house.

3.4 Our Contribution

In WSN, controlling access to a communication channel, generally known as MAC, plays a vital role in determining channel utilization, and most importantly, in minimizing power consumption. In specific applications such as smart home systems, MAC protocols directly regulate usability features such as network delays in terms of system response and execution time.

As our contribution to the next generation of smart home systems, we designed a novel MAC protocol tailored to smart home applications. We built a smart home system prototype to evaluate the protocol’s performance, and to prove concepts of proposed improvements aforementioned. We also performed extensive evaluation to determine estimated power consumption and approximated system’s operational lifetime.

3.4.1 Development of a Novel Smart Home System Oriented MAC Protocol

The designed MAC protocol is tailored to smart home systems’ features. It is explicitly derived from envisioned structure and distinctive characteristics of smart home systems’ applications and is capable of supporting improvements we recommend for the current smart home systems.

The designed protocol is optimized for:

i. A well balanced two-way communication, enabling controlled system execution latency.

ii. Network-level broadcast communication capability, while simultaneously taking advantage of unrestricted source of energy at a central/gateway node and minimizing SNs’ energy consumption.

iii. Low data-rate network, but capable of handling momentarily increased traffic intentionally triggered in specific occasions.

iv. The use of variable number of sensors for improved data collection, with the flexibility of adjustable various response times based on application time sensitivity.

3.4.2 Introduction of System Scalability and Synergistic Effects

Synergistic effect has been long ignored by smart home systems developers. Most of the systems are standalone applications, and for systems combining various applications there is no synergy between supported applications. In this work we introduce the synergistic effect in smart home system and we prove the concept using our prototype. We developed a system that is scalable in terms of dynamically handling a varying number of SNs and capable of adjusting the data collection and processing accordingly.

3.4.3 Development of a Smart Home System Prototype

We developed a smart home system prototype intended mainly to evaluate the performance of the designed protocol in terms of determining SNs’ battery lifetime based on power consumption, and design-flexibility in adjusting system response and execution latency. In addition, this prototype is used as a platform to prove the feasibility of the improvements we recommend for the next generation of smart home systems. The prototype is Wi-Fi and Internet connected, equipped with a standalone embedded web server enabling the user to interact with the system using any device that can run a standard web browser, wherever access to the Internet is available. This feature allows the user to interact with the system, both on-site and remotely, with minimum resources, and without requiring an intermediary between the system and the user.

3.4.4 Power Consumption Evaluation and System Operational Lifetime Approximation

Based on the implemented prototype, we scrutinized the power consumption in different system configurations and settings. After determining optimized settings for balanced steadfast hardware-software performance and minimized power consumption, we measured the power consumption on a typical SN and deduced an estimated system operational lifetime.

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Chapter 4 Broadcast Application-Specific MAC Protocol

4.1 Generalities

Like in most wireless networks, where all SNs share a communication medium to transmit data, controlling the access to the radio channel is of paramount importance for a reliable communication and energy efficient design [52]. The increasing practicability of WSNs, the need of an increased number of sensors for improved data collection, and the need of minimizing their energy consumption have amplified an interest in MAC protocol development [53] [54] [55] [56]. MAC is a vast research area and there are multiple MAC designs including both standardized and atypical protocols. Based on the way nodes access the radio channel, most primitive MAC protocols intended for WSNs can be broadly categorized in two major classifications: contention-based and contention-free protocols.

In contention-based (asynchronous) protocols, a node senses the common channel by listening for ongoing transmissions. If the channel is free of traffic, the node proceeds to transmission. Otherwise, it waits for a moment, commonly known as a contention interval, before attempting to transmit again. Techniques used to sense the traffic, such as the use of Request-to-Send (RTS) and Clear-to-Send (CTS) packets, and the management of the contention interval (random or fixed), constitute the major difference between different contention-based protocols. Since communication can only occur when two nodes communicating are in active mode, when contention-based protocols are deprived of all scheduling, nodes have to potentially be full duty cycle (sleepless) in order to communicate. Although contention-based protocols are simpler to implement and robust in the sense that they virtually offer unlimited scalability and they do not require time synchronization, they are power profligate and become extremely ineffective in time of increased traffic.

On the other hand, contention-free protocols use various practices to grant multiple nodes an access to radio channel. Techniques include frequency division, code division, and space division. However, time scheduling is the most prevalent tactic in WSN MAC protocols. Time scheduling-based (synchronized) protocols [57] divide the medium into fixed periodical time-frames that are subdivided into time-slots. Each node within the cluster is assigned a time-slot and therefore commonly referred to as the slot-owner. In regular time scheduling-based protocols, only the slot-owner may transmit during that particular time-slot. To ensure the finesse in scheduling, time scheduling-based protocols require time synchronization among the nodes. The major difference between time scheduling-based protocols resides mainly in their scheduling and synchronization techniques. Time scheduling-based protocols are efficient in increased data traffic and time-sensitive applications because of their periodic nature and data collision avoidance. Moreover, time division becomes more appealing when the network includes a central node that can manage slot allocation. However, they are negatively affected by considerably reduced channel utilization and increased latency for a low data rate network. Additionally, time scheduling-based protocols suffer from a limited scalability and intricate implementation due to the time-synchronization requirement.

The aforementioned limitations for both contention and time-scheduling based protocols suggest that none of them is adequate for WSNs while standing alone. Consequently developers have explored ways of combining their strengths while counterweighing their weaknesses; therefore some protocols combine both approaches and are consequently referred to as hybrid protocols.

4.2 Designing an Application-Specific MAC Protocol Tailored to Smart Home Systems

Most MAC protocols are designed for WSNs in a general way, and consequently not optimized for specific applications. As our contribution, we propose an application-specific MAC protocol tailored to smart home systems. In this section, we start by exploring envisioned structure and behavior of an improved smart home system. Considered features and distinctiveness suitable to a smart home system will be discussed next.

4.2.1 Unchanging Network Topology

The network architecture or topology refers to the schematic description or arrangement of the network. It describes the geometric layout and hierarchical organization of the network elements. Depending on the application, a WSN can be implemented using different topologies, including single-hop star, multi-hop star, multi-hop mesh and grid, two-tier hierarchical cluster, etc. [48]. The choice of the appropriate topology depends on different factors, such as deployment method, battery life requirements, whether the nodes will be stationary or mobile etc., but most importantly, the network architecture is determined by the transmission distance, the amount and frequency of the data to be transmitted. Based on the normal size of a regular house (generally less than 100 meters of length) and the data-rate expected from a smart home application system, the single-hop star topology architecture is perhaps the most appropriate network topology for smart home system. This topology is preferable when all wireless end-point nodes can be within direct communication range from the central node. It allows all the nodes to communicate directly with the central node, consequently providing the simplest and lowest power network architecture, and reducing networking concerns to a minimum. It provides a reliable configuration by preventing routing and hidden-node problems. The most relevant limitations to this topology are the physical coverage limited by the transmission range and network scalability which can be improved through finesse in controlling medium-access [48].

Unlike MAC protocols addressing WSNs in multi-hop mesh deployment, our system is based on WSN with a fixed single-hop star topology composed with two kinds of nodes – one central node and several end-point nodes. The central node, also referred to as a base station (BS), is the gateway node of the network. End-point nodes, which can consist of a sensor and/or an actuator, are generally referred to as SN for simplicity. Some SNs can be mobile or change their spatial location; however, the network structure is not expected to change over time. A node might move around within the network, or even leave the network and re-join later, but it will only interact with the network while it is situated within direct communication range with the BS. This structure solves the routing-related problems and challenges of interference irregularities [58] [48].

Moreover, a BS in direct communication with all SNs facilitates the implementation of a time scheduling-based protocol since it can manage slot allocation in a straightforward manner [48]. If needed, this design can be considered as the base level of a larger network, where other WSNs with similar architecture can be added for further applications and larger network, for example in a case of a multi-story house or an apartment.

4.2.2 Heterogeneity of Sensor Nodes

Contrary to most WSNs where all (or most of the) SNs monitor the same physical condition, thus becoming suddenly and simultaneously active when something is detected, smart home systems are composed with nodes carrying out varied functions: sensors and actuators. In addition, a smart home network can be composed of temperature sensors, light sensors, motions sensors, carbon monoxide sensors, etc. This heterogeneity of sensors greatly decreases the likeliness of spontaneous increased activity throughout the network, consequently reducing the concern of unpredicted increased data traffic. It is highly unlikely that a single event will simultaneously trigger all the nodes. This feature makes smart home systems WSN unique in terms of being generally low data traffic networks, but the data traffic can be momentarily and deliberately increased for specific occasions such as network maintenance or special functions.

The diverseness of SNs is also reflected in different aspects including time-sensitivity in both executing commands and/or reporting sensed events. For instance, while a motion detector for security features is supposed to act as soon as a motion is detected, a SN monitoring a slow phenomenon such as a room temperature can afford to have a longer delay in reporting. Similar time-sensitivity can also be observed in urgency for actuators to execute commands. This feature makes appeal to a dynamic protocol that will accommodate different time alertness levels without compromising the system power consumption.

4.2.3 Inequality of Nodes in Power Resources

Most MAC protocols designed for WSNs have no prior knowledge of resources (processing power, remaining battery life, etc.) distribution among nodes, or they simply assume equal resources for all participating nodes. For smart home systems, normally SNs are the only ones suffering from energy and computational constraints, while the BS is designed for superior computational capabilities with virtually unlimited power/energy resources. Therefore, it is crucial to implement a MAC protocol that relies on power resourcefulness of the BS while minimizing power consumption on SNs.

Moreover, contrary to multi-hop mesh WSNs where, over time, nodes can assume different responsibilities depending on their remaining battery life, our design relies on a permanent BS equipped with enhanced computational capability and devoid of power consumption constraint. The BS is the only node capable of fulfilling the task and consequently, cannot be replaced over time. On the other side, all SNs face a tight power consumption constraint and share all the same layers (Physical, Data link, Network, and Transport) [54], except the Application layer.

4.2.4 Necessity of Balanced Two-Way Communication

Most WSNs are focused on sensing and gathering data, thus employing MAC protocols that optimize unidirectional movement of data from the SNs (ends of the network) to one specific point of the network, such as a sink node. End-points in a smart home system network not only serve the sensing purpose but often perform as actuators as well (e.g. thermostats). On top of monitoring, a smart home system enables the user to also control monitored house features using the system interface. Therefore, in addition to the data coming from SNs to BS, there is an important stream of data from the BS in form of commands (adjusting temperature in a certain rooms, turning on/off some appliances, etc.) expected to go towards the end-points.

This aspect of the system requires a well-adjusted approach to balance the latency in both directions: 'Execution latency' referring to the maximum allowable delay a user's command can be queued at the BS before being transmitted to the end point of the network; and ‘Report latency’ referring to the maximum allowable delay collected data can be queued at a specific SN before being transmitted to the BS. Consequently, it is imperative to design a specialized MAC protocol suited for a balanced back and forth communication, from SNs to BS and vice versa.

4.2.5 Instantaneous Broadcasting Capabilities

Most WSN applications do not support broadcasting communication mainly depending on either the intended goal (such as WSN intended for monitoring and conveying data to one specific sink node), or limited possibilities (WSN covering a much larger physical area than the direct communication range). Some WSNs use broadcast transmission for specific purposes such as time synchronization [59], but they usually adopt a flooding technique, which requires multiple transmissions per node, and it generally requires MAC layer time-stamping [60]. On the other hand, instantaneous broadcast (the opposite of flooding technique) can keep an entire network synchronized, with neither time-stamping nor transmission required to end-nodes [59]. Instantaneous broadcast requires a minimal of two conditions: all nodes to be physically located within one hop from the transmitter (which is already met by the proposed single-hop star topology), and concurrent listening. To take advantage of a synchronization protocol that minimizes power on SNs, it is inevitable to implement a MAC protocol that supports concurrent listening.

In addition to network synchronization at low energy cost, instantaneous broadcast ability is an engaging feature for smart home applications, for several reasons. Broadcast information may include control packets, program update or sensor-queries on the network level such as node(s) inventory query. Broadcasting will be more efficient in events involving multiple SNs simultaneously and requiring fast action. For example, in the case of a break in, the status of several SNs needs to be acquired and reported in a timely manner. Less urgent, but similar event could occur when the user leaves the house and several rooms in the house need to adjust to a prefixed temperature, switching off several lights, switching multiple appliances to idle state, and locking a number of doors, etc. It is apparent that a broadcast message is clearly more efficient than addressing each node individually. Consequently for an efficient smart home system, we recommend a MAC protocol capable of supporting instantaneous broadcast transmission.

4.2.6 Predictability of Gathered Data

Unlike some WSNs in which the size and frequency of gathered data is uncertain, data sets expected from a smart home network are generally small, quantifiable and predictable. For instance, a monitored appliance will have finite number of states that can be reported by the connected sensing node; also, monitored physical conditions (temperature, air quality, humidity, motion detection, etc.) in the house will only swing within a predictable range, and therefore can be communicated using a pre-fixed number of bits. A MAC protocol with pre-fixed format and message size entails reduced overhead message, consequently reducing both energy consumption and transmission time.

4.3 Overview of Closely Related Available MAC Protocols

As mentioned in Section 4.1, hybrid protocols tend to be more practical for WSN since they combine the strengths while offsetting the weaknesses of time-scheduling and carrier sensing based protocols. They generally combine contention techniques when transmitting and time division techniques when scheduling duty cycles. However, they vary from the way they manage duty cycle, synchronize, accord priorities to nodes, or sense the channel before transmitting. In this section we review the most popular hybrid MAC protocols and discuss why they are not optimized for smart home systems. Sensor-MAC (S-MAC), Time-Out MAC (T-MAC), and Zebra-MAC (Z-MAC) are some of the most popular protocols considered hybrid and are presented next.

4.3.1 Sensor-MAC [61]

S-MAC, which is designed for multi-hop networks and does not necessary require time synchronization on network level, is one of the well-known slotted contention-based MAC protocols and most hybrid protocols are based upon it. S-MAC assumes most communications occur between nodes as peers, rather than to a single base station, and emphasizes time synchronization between neighboring nodes. Scheduled exchange is achieved by periodical synchronization packet broadcast to immediate neighbors. Basically, S-MAC divides time into fixed frames, generally large. Every frame is composed of two main portions: an active period and a sleeping period. During the sleeping part, a node turns off its radio to preserve energy. During the active part, the node begins by synchronizing with its neighbors, and then communicates by sending any messages queued during the sleeping part. To avoid data collision during the active period, nodes use RTS/CTS techniques before transmitting. Figure 4 depicts S-MAC scheme.

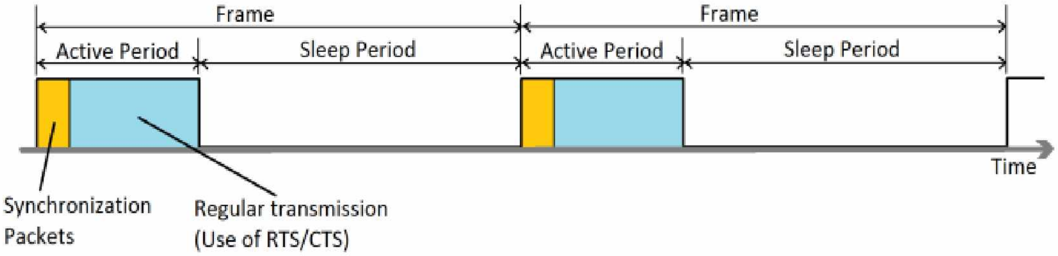

Figure 4: S-MAC Scheme depicting periodic listening and sleeping

S-MAC requires time synchronization, but less critical than in regular time division-based protocols since the time scale is much larger (in order of tens milliseconds). The S-MAC protocol prioritizes energy consumption at the expense of throughput and latency. Throughput is directly proportional to the duty cycle, which in turn is inversely proportional to saved power. Correspondingly, latency linearly increases with the sleep period, since events that occur during sleep time are queued until the start of the next transmission part. In the worst case scenario, the latency can be as long as the sleep period plus synchronization time. Consequently, the size of the sleep period is dictated by both the latency requirement and the hardware/software buffering capacity. On the other hand, although it is desirable to make the active period as small as possible, this period must be large enough to enable nodes to transfer all data gathered during both active and sleep time within the active time. The experimental results in [62] show that, on a source node, an 802.11-like MAC consumes 2–6 times more energy than S-MAC for traffic load with messages sent every 1–10 s.

Although S-MAC prioritizes energy consumption over throughput and latency, which is equally desirable for our design, S-MAC was designed with the assumption that SNs are scattered and use multi-hop communication, which is not the optimal network topology for smart house systems. By assuming that most communications occur between neighboring nodes as peers, S-MAC approach can hardly support instantaneous network level broadcast communication. Nonetheless, S-MAC does not address a way of taking advantage of the smart house central node or base station generally devoid of power constraint. S-MAC assumes nodes will remain largely inactive for long periods of time, but then all will become suddenly active when something is detected. Although the sudden activity within the network might be partially applicable to our WSN, S-MAC assumption implies a network in which all (or most of the) nodes monitor the same physical condition, which is not the case for a smart home applications since a smart home WSN is likely to be made up of SN monitoring varied physical condition (temperature, humidity, appliances, security features, etc.). The aforementioned discrepancies make S-MAC unfitting for our intended smart home system design.

4.3.2 Time-Out MAC [63]

T-MAC takes after S-MAC's assumptions but points out that reducing the idle listening time with a fixed duty cycle, like the S-MAC protocol, is efficient but not optimal. By assuming that the message rate will constantly change with the network, there is a considerable amount of energy still being wasted on idle listening during the active time of S-MAC. T-MAC builds upon S-MAC, and introduces a new idea of timing out when nothing is heard during the active time. This approach enables an active time that is dynamically adjusted depending on current activities. A node maintains an optimal active time by timing out whenever nothing is heard during the active time.

The frame size is fixed; but the active and sleep time vary depending on ongoing activities. TA (Time After) is the fixed time before nodes time out after the last activation event. An activation event can be: a. the firing of a periodic frame timer (like the end of synchronization), b. the reception of any data on the radio, c. the sensing of a communication on the radio, d. the end-of-transmission of a node's own data packet or acknowledgement, e. or the knowledge, acquired through overhearing prior RTS and CTS packets that a data exchange of a neighbor has ended. Figure 5 illustrates T-Mac scheme.

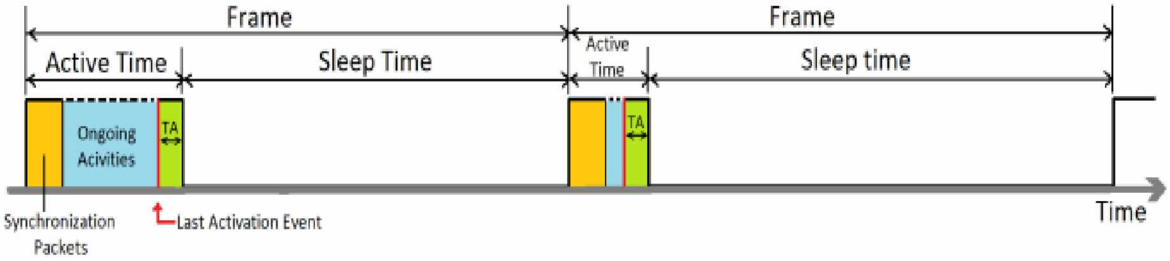

Figure 5: T-MAC Scheme illustrating dynamic active time

Contrary to S-MAC that suggest an overhearing avoidance technique that require nodes to sleep after hearing an RTS or CTS destined for another node, T-MAC points out that a node may miss other RTS and CTS packets while sleeping and disturb some communication when it wakes up. This technique was left as an option for T-MAC but it was suggested that it must not be used when an increased throughput is of interest. Consequently, nodes keep listening and potentially transmitting, as long as they are in an active period. After the last detected activity over the medium, TA constitutes the upper bound on the idle listening time per frame. Contrary to S-MAC that uses a fixed active period, in T-MAC the active period ends when no activation event has occurred for a time TA.

Although T-MAC improves on power consumption over S-MAC; it upholds similar assumptions such as SNs communicating in a multi-hop fashion, with peer-to-peer based communication, and a sudden increased activity all over the network after long periods of inactivity. Evidently, T-MAC does neither support broadcast communication throughout the WSN, nor takes advantage of a central node that has virtually unlimited power source, consequently making it unsuitable for our intended design.

Other MAC protocols, such as the Medium Access Control with a Dynamic Duty Cycle for Sensor Networks (DSMAC) [64], take after S-MAC with a different approach on how to manage active/sleep time-slots. DSMAC improves on S-MAC by adjusting the latency tradeoff over power consumption by introducing the idea of adjustable duty cycle with varying traffic conditions without any prior knowledge of application requirements. However, none of these protocols are explicitly intended for single hop-star architecture, nor do they support broadcast communication throughout the network. An ideal protocol for smart house systems should take advantage of a central node with a practically unlimited power source and support instantaneous network-level broadcast communication, which is indispensable for smart home applications.

4.3.3 Zebra-MAC [65]

Contrary to previously discussed MAC protocols, which focused on contention-based protocols with active/sleep (fixed or adjustable) duty cycles, Z-MAC takes a different approach by fusing contention and scheduling together. Z-MAC focuses on increasing the network adaptability to a different level of contention by behaving like CSMA[2] under a low level contention and like TDMA[3] under a high level contention. Z-MAC uses CSMA as the baseline MAC scheme, but uses a TDMA schedule as a "hint" to enhance contention resolution. In Z-MAC, a time-slot assignment is performed at the time of deployment—higher overhead is incurred at the beginning. Unlike conventional time-division based protocols in which only the slot-owner is allowed to transmit during the time-slot, Z-MAC lets any node to attempt to transmit during any time-slot. Before a node transmits during a non-owned slot, it always performs carrier-sensing and transmits a packet when the channel is clear. However, an owner of that slot always has a higher priority in accessing the channel over its non-owners. Figure 6 illustrate the Z-MAC scheme.

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[2] CSMA: Carrier Sense Multiple Access

[3] TDMA: Time Division Multiple Access

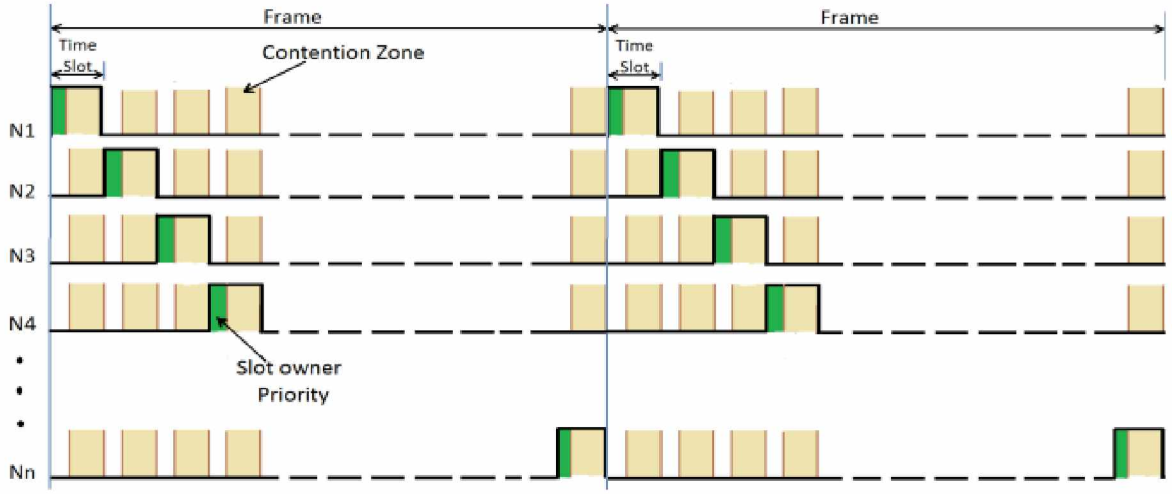

Figure 6: Z-MAC Scheme illustrating CSMA fused into TDMA

The priority is implemented by adjusting the initial contention window size in such a way that the owners are always given earlier chances to transmit than non-owners. During the slots where owners have data to transmit, Z-MAC reduces the chance of collision by giving owners earlier chances to transmit and scheduling their slots a priori to avoid collision, but when a slot is not in use by its owners, non-owners can steal the slot. This priority scheme has an effect of implicitly switching between CSMA and TDMA depending on the level of contention.

Similarly to other hybrid MAC protocols discussed previously, Z-MAC is designed with multi-hop mesh topology in mind. Additionally, it puts considerable efforts in addressing time varying channel conditions and possible topology changes, which does not apply to our design. Although a smart home system may involve mobile nodes within the network, or even nodes that might leave and re-join the network later, the network architecture is unvarying. Moreover, only one node designed for the purpose can assume the role of the central node, and the rest can only act as SNs. Similarly to previously described protocols, Z-MAC scheme benefits neither from the use of a BS without power constraint, nor the advantage of network-level broadcasting which is important for our current design.

Although the aforementioned protocols present specific benefits, such as improved power consumption, they are not optimized for smart home systems application because they do not address envisioned structure and desired behavior in a specific way.

4.4 Broadcast Application-Specific MAC Protocol Design and Description

Similarly to other MAC protocols designed for WSN, we combined time-scheduling with contention-based protocols. However, we took a novel approach, different from a commonly used method that usually blends contention and scheduling together to obtain a contention-based protocol with duty cycles. The MAC protocol we designed is optimized for:

1. Low data-rate network, but is capable of handling momentarily increased traffic intentionally triggered for specific occasions.
2. Network-level broadcast communication while simultaneously taking advantage of unrestricted source of energy at the central/gateway node.
3. A well-balanced two-way communication enabling controlled 'Execution latency.'
4. Low power consumption achieved through extended sleep mode for SNs.

Our novel protocol, which we named Broadcast Application-Specific MAC protocol (BAS-MAC), consists of a dynamic combination of time-scheduling contention-free and carrier sensing contention-based protocols. The contention-free zone consists of a single frame of customary time-division multiple access (TDMA) executed sporadically, while the contention-based part is a carrier sensing multiple access (CSMA) protocol modified to support network – level broadcast. The protocol takes advantage of virtually unlimited source of power at the BS, and focuses on minimizing energy consumptions on SNs by providing a balanced/controlled latency for both event reporting and command execution for the system. Network throughput and per-node fairness are assigned a lower priority based on the expected low data rates in the network. Figure 7 illustrates the BAS-MAC structure depicting a dynamic juxtaposition of TDMA and modified CSMA.

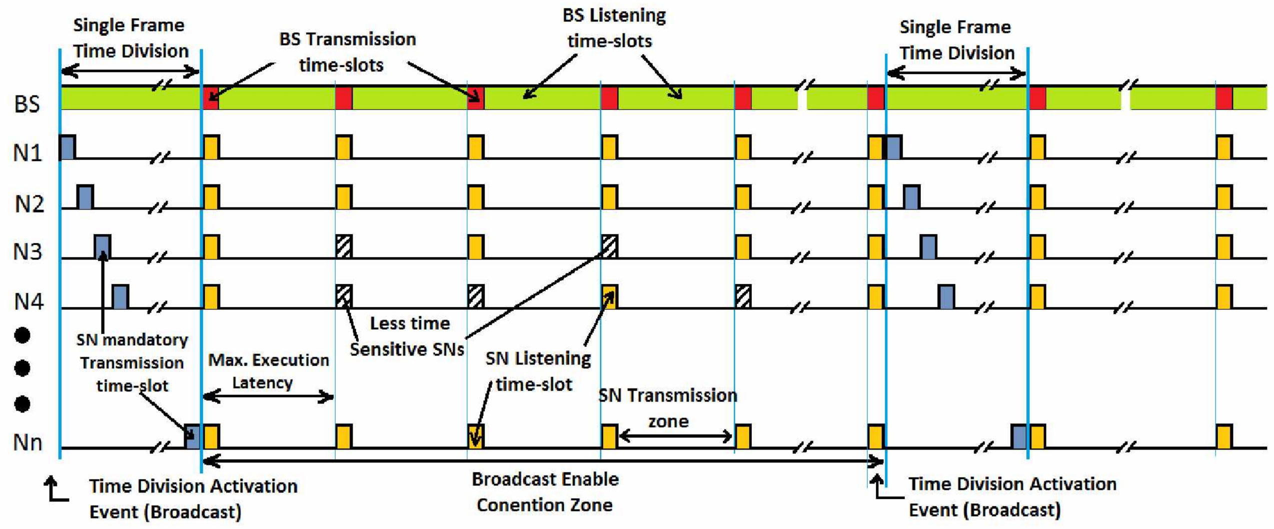

Figure 7: BAS-MAC scheme

In the following sub-sections we explain in details the main constituents of the BAS-MAC.

4.4.1 Single Frame Time Division

Single Frame Time Division (SFTD) is the contention-free segment of the protocol executed after a broadcast-type command requiring more than one SN to respond. The SFTD length is determined by a balanced tradeoff between the maximum (desired) number of nodes per network and the Maximum Execution Latency (MEL). MEL is the maximum time a command can be queued on the BS station from the time it is received until it is transmitted to the addressee SN. SFTD must be large enough to accommodate time-slots for maximum desired number of SNs, but less than or equal to MEL.

(Time-slot's width) x (number of SNs/cluster) ≤ SFTD's width ≤ MEL

The time-slot width is defined by the necessary time for a SN to execute a complete communication transaction. A complete transaction embodies the transmission of a data-package followed by ACK reception, or conversely data-package reception and ACK transmission, whichever takes longer.

During SFTD, the network executes a regular time division protocol. The medium usage is optimized by the fact that each SN addressed is required to use its assigned time-slot to respond to the event that triggered the SFTD procedure. During this period, it is mandatory for addressed SNs to respond, hence the ‘SN Mandatory Transmission time-slot’ term.

The SN Mandatory Transmission time-slots are alternated time-slots with fixed size, individually assigned to each SN. It is desirable to make these time-slots as small as possible but large enough for a complete transaction. During the SFTD Single Frame, each SN keeps its radio off until its assigned time-slot is up, and goes back to sleep right after ACK reception. In case a SN does not receive an ACK, it goes back to sleep at the end of its assigned time-slot and waits until the end of the SFTD to retry a transmission.

4.4.2 Time Division Activation Event

A Time Division Activation Event (TDAE) is any broadcast transmission from the BS requiring more than one SN to respond. Broadcast transmissions include execution commands sent from the BS to multiple SN/actuators instructing them to perform activities at their end. SFTD’s width sets the lower boundary of the minimum time between two consecutive TDAEs and has virtually no upper boundary.

SFTD’s width ≤ min. time between two consecutive TDAEs

This means that two consecutive TDAEs must be separated at least by a minimum time greater or equal to SFTD width to allow the maximum of concerned SNs to respond to the earliest event.

Depending on the application, the TDAE upper boundary can be dictated by the allowable maximum time for network to self-reorganize. For network reorganization, the central node sends a network-level broadcast message to make inventory of available SNs. For a user friendly system, this reorganization function can be initiated by the user in case changes (added or removed SN) have been intentionally made to the network.

4.4.3 Broadcast Enabled Contention Zone

The Broadcast Enabled Contention Zone consists of a CSMA customized for broadcast capabilities. The contention zone is situated at the end of each SFTD. The protocol consists of a regular contention-based protocol periodically interrupted by synchronized wake-up time-slots called SN Listening time-slots. During SN Listening time-slots, SNs simultaneously wake up and solely listen for a possible transmission from the BS; the transmission can be a network-level broadcast or destined for an individual SN. SNs are strictly prohibited to transmit during this period since it is reserved for BS's transmission; hence they could be alternatively referred to as BS Transmission time-slots.

Consecutive SN Listening time-slots are separated by SN transmission intervals. MEL constitutes the fundamental interval period between two SN Listening time-slots. The variation of time intervals between different SNs offers a flexibility to save more power on less time-sensitive nodes extending the interval between SN Listening time-slots.

During SN transmission intervals, the BS switches its radio to receiving mode for a possible oncoming communication. On the other hand, SNs execute regular CSMA. For transmission, an SN initially sleeping, wakes up and senses the common channel by listening for ongoing transmissions. If the channel is free of traffic, the node proceeds to transmission. Otherwise, it switches its radio off and waits for a random contention interval before attempting to transmit again. The random contention interval helps prevent two different SNs from waking up again at the same time. Due to the fact the BS is always awake and that the data rate within the network is low, the use of RTS/CTS was left as an option for current protocol. It is important to note that the length of the broadcast-enabled contention zone is dynamically determined by the occurrence of TDAEs.

Chapter 5 Smart Home Embedded System Prototype Hardware/Software Implementation

5.1 Description

In order to evaluate the BAS-MAC protocol’s performance, we designed and implemented a smart home embedded system prototype. The same prototype is used to prove concepts of improvements suggested in this work. This chapter covers software/hardware co-design and implementation of the prototype system. The prototype is a small scale of smart home system comprising three SNs and one BS. The prototype is Wi-Fi connected and emphasizes system usability and energy efficiency. Figure 8 shows a simplified diagram of the prototype layout.

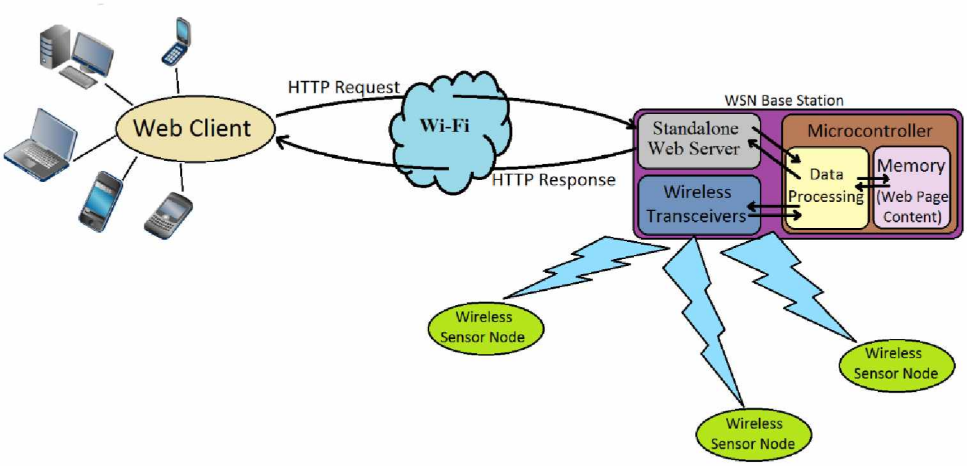

Figure 8: Simplified diagram illustrating prototype layout

5.2 Hardware Selection

To achieve a power conscious design, it is important to start the process from the selection of the right hardware; it is crucial to make the right balance between cost, performance and power consumption. The goal was to develop a realistic prototype, capable of supporting virtually any sensors depending on developers’ application. Consequently, the focus is directed to selecting the right processor and transceivers units as the core components of the design.

5.2.1 Processor Unit: Microprocessor versus Microcontroller

For a reliable WSN, the processor must be able to competently and concurrently handle radio communication and data processing. This requires the processor to be robust and fast. Moreover, for a smart home network platform to be worthwhile, the processor at each node must be able to efficiently interface with the majority of the currently used sensors in order to host diverse applications, and have the ability to drive any potential actuator that could be physically connected to it. Most common embedded interface types include Analog to Digital Converter (ADC) with decent resolution, Universal Asynchronous Receiver-Transmitter (UART), Inter-Integrated Circuits interface (IIC or I^2C), Serial Peripheral Interface (SPI), and more. In addition, the right processor must possess sufficient number of interrupt channels, robust timers, and an adequate number of General Purpose Input / Output pins (GPIO). More importantly, the processor must be power-conscious and possess a flexible power management system including variable voltage levels and sleep-time modes. Other influential factors include storage memory, start-up and wake-up times and power supply requirements.

There are two main distinct subclasses of processors: microcontrollers and microprocessors. However, from the embedded systems viewpoint, microcontrollers are more commonly used in embedded-systems field for various reasons [66]. Although microprocessor-based designs tend to have the edge over microcontrollers when it comes to instruction-processing throughput, microcontrollers are more suitable for real-time embedded systems. Microcontrollers require just one single voltage power rail, while microprocessors require several difference voltage rails, for instance, the voltage level for the core is usually different from voltage levels of different classes of memory, etc. This fact makes microprocessor-based design more exorbitant by requiring additional power ICs and on-board converters. On the other hand, microcontrollers use on-chip embedded flash memory to store and execute the program, which allows microcontrollers to have a very short start-up period. The only practical limitation for microcontrollers is the limited memory space, while microprocessors do not have memory constraints in the same way. Microprocessors use external memory to provide program and data storage. The program is typically stored in non-volatile memory, and at start-up is loaded into an external DRAM and then initiates execution, thus significantly increasing the start-up time [67].

From aforementioned significant factors, the proper processing device for the current system was selected to be a microcontroller unit. The compact 16-bit RISC Architecture, Von Neumann CPU core MSP430F5438A [68] Microcontroller from Texas Instrument proved to be a perfect pick for the job. The MSP430 is a mixed-signal microcontroller family designed specifically for low cost and low power consumption embedded applications. MSP430F5438A consumes as little as 1.2 µA in low power mode, and it includes a state of the art power management module allowing the microcontroller to wake up from low power modes to active mode as fast as in 3.5 µs. The MSP430F5438A features an adequate memory of 16 KB SRAM and 256 KB of flash memory, and an internal clock system up to 25 MHz or 32 MHz with external high frequency crystals. Figure 9 shows the functional block diagram of an MSP430F5438A microcontroller.

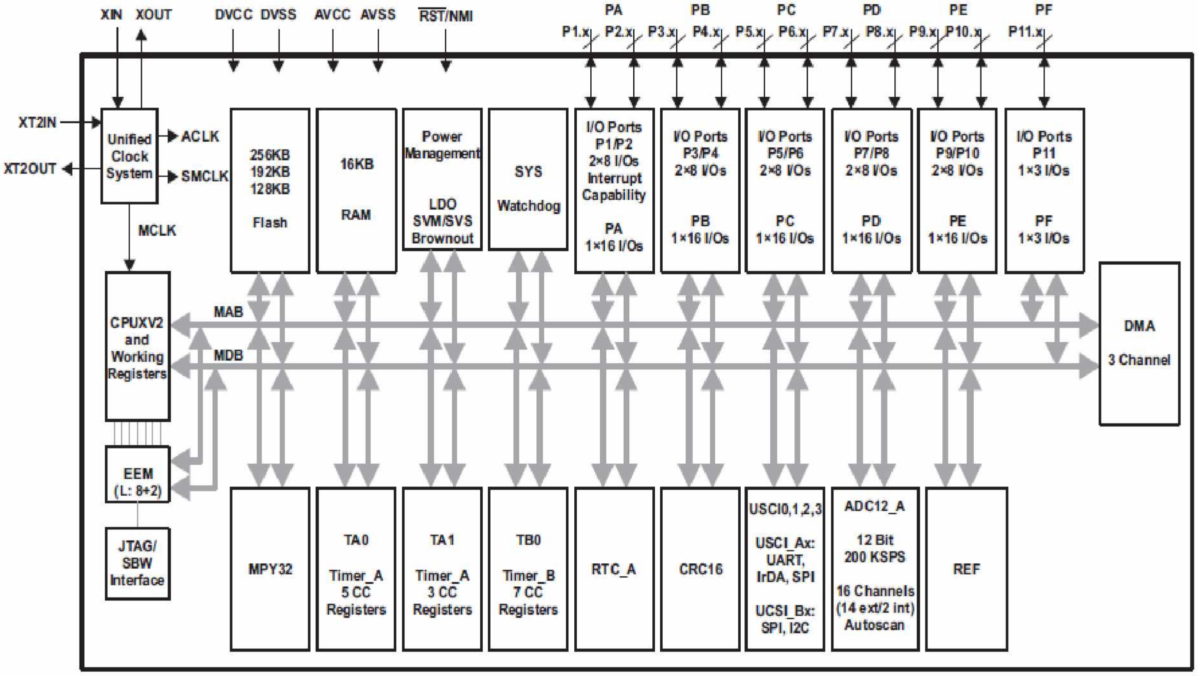

Figure 9: Functional Block Diagram of MSP430F5438A Microcontroller [68]

Other features that make this microcontroller a perfect pick for a design intended to virtually support any sensors or actuators depending on developers' application include:

- *Watchdog Timer*: The watchdog timer is failsafe feature critical for embedded systems; the watchdog initiates a fresh restart in case of a software malfunction. Despite effort put in designing an impeccable firmware, the watchdog timer serve as last line of defense against unforeseen behavior or failure.

- *Digital Inputs/Outputs*: With more than 80 pins that can be configured as general purposes inputs/outputs, including 14 individually configurable interrupts, MSP430F5438A offers an outstanding flexibility in interfacing either actuators or a diversity of sensors.

- *32-bit Hardware Multiplier (MPY32)*: The magnificence of this feature resides in the fact MPY32 is completely separated from the CPU; this means MPY32 activities do not interfere with CPU activities. MPY32 support fractional numbers, both signed and unsigned multiplication, up to 32-bit operands with saturation handled, and more.

- *Analog-to-Digital Converter (ADC)*: MSP430F5438A support both 10 and 12-bit analog-to-digital conversions; with a speed greater than 200 kilo-sample-per-second; it supports both on chip selectable reference voltages or external positive and/or negative references, with up to 16 conversion-results storage registers; selectable conversion clock source, etc.

- *Timers*: MSP430F5438A has 3 asynchronous, interrupt-driven, 16-bit timers/counters with four different operating modes each, selectable and configurable clock sources, with up to seven configurable capture/compare registers per timer.

MSP430F5438A also features eight Universal Serial Communication Interface (USCI) modules. One USCI supports multiple serial communication modes with one hardware module. Different USCI modules support different modes. Supported communication modes include:

- *Universal Synchronous/Asynchronous Receiver-Transmitter (USART):* With either 7 or 8-bits data odd, even or no-parity, this mode also handles either LSB or MSB-first data transmit and receive, with independent interrupt capabilities, separate transmit and receive buffer registers, programmable or automatic baud-rate detection, and other features for increased flexibility and low power consumption.

- *Inter-Integrated Circuits interface (IIC or I^2C):* This mode complies with Philips Semiconductor I^2C, with either 7-bit or 10-bit device addressing modes and up to 400 Kilo-bits-per-second. It is configurable in either slave or master mode, with multi-master transmitter/receiver mode capability, programmable clock frequency and more.

- *Serial Peripheral Interface (SPI)*: It supports either 7- or 8-bit data lengths, can handle both LSB and MSB-first data transmit and receive, either in 3- or 4-pin SPI applications. It has independent interrupt capabilities, separate transmit and receive buffer registers, selectable clock polarity and phase control, can be configured in either slave or master mode with programmable clock, and has other features for increased flexibility and low power consumption.

The abundance of interface modules makes this microcontroller ideal for a platform intended to host further development. Other notable MSP430F5438A features include a Real-Time Clock module, Direct Memory Access Controller module, RAM controller and Backup RAM, and more.

5.2.2 Transceiver Unit

Transceivers are devices combining a transmitter and a receiver on the same integrated circuit. The term *radio transceiver* is commonly used for a wireless transceiver. Radio transceivers are a critical constituent of any WSN. With the requirement of moving data between nodes, radio transceivers must be reliable, powerful enough to transmit over a required range, with sufficient data-rate and fast processing to efficiently handle implemented protocols. Some of the factors to consider when selecting a radio transceiver for a specific application include cost, supply voltage and power consumption, frequency range, data rate, packaging type and output power. Suitable radio transceivers must possess a moderate power consumption to not compromise the entire system's efficiency and be capable of competently transmitting over the required range. Power conscious transceivers are vital for an extended lifespan of a node particularly, and the entire network in general. Although considerable effort is put in implementing protocols that reduce power consumption of the transceivers by optimizing their sleep time, it is equally important to select the right hardware for the task.

After an extensive research, the Nordic nRF24L01+ [69] transceivers were selected to be used for this project for various reasons. The Nordic nRF24L01+ is a highly integrated, ultra-low power 2 Mbps RF transceiver IC for the 2.4 GHz ISM (Industrial, Scientific and Medical) band, allowing worldwide development license-free. With peak RX/TX currents around 15 mA, a low power mode in order of micro ampere, advanced power management, and a flexible 1.9 to 3.6 V supply range; the Nordic nRF24L01+ is fit for the task. These transceivers are specifically designed for low power wireless applications, enabling months to years of battery life. Figure 10 shows the functional block diagram of nRF24L01+ transceiver.

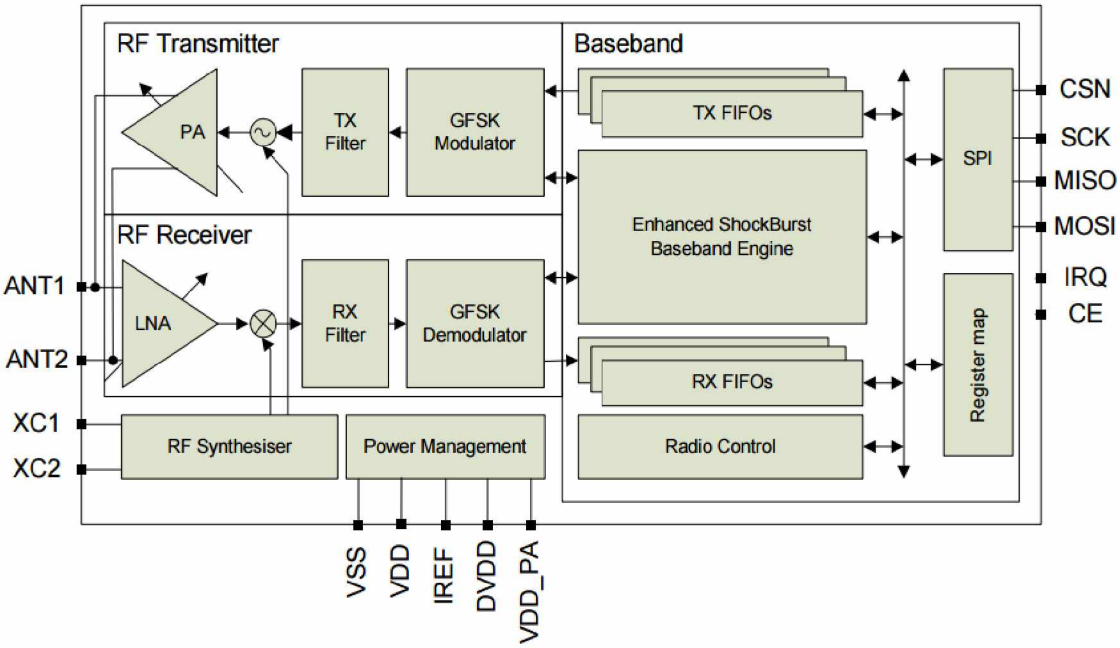

Figure 10: Functional block diagram of nRF24L01+ Transceiver [70]

The Nordic nRF24L01+ integrates a complete 2.4 GHz RF transceiver, RF synthesizer, and baseband logic including enhanced hardware protocol accelerator supporting a high-speed SPI interface for the application controller. The nRF24L01+ is available in a compact 20-pin 4 x 4 mm QFN package, and does not require excessive peripherals such as external loop filter, resonators, only a 16 MHz crystal, matching circuitry, and antenna. Nordic nRF24L01+ features a high air data rate up to 2 Mbps with options of 250 kbps or 1 Mbps, programmable output power from 0 to -18 dBm in decrements of 6 dBm, a dynamic payload length up to 32 bytes, automatic packet transaction handling, idle modes, and fast start-up time of 1.5 ms from cold start or 130 µs from standby mode. It also features a 4-pin hardware SPI for host interface, with a maximum rate of 10 Mbps.

5.2.3 Selecting Embedded Web Server

An integrated embedded web server enables the user to interact with the system using Hypertext Transfer Protocol (HTTP). It provides a very effective and familiar user interface in the form of web pages. The integration reduces the overall cost of the system by eliminating the need for a customized client hardware/software for interface. With proper credentials, embedded web server can be connected to the Internet through a router, providing the user with the possibility to remotely interact with the system from virtually anywhere around the globe at low cost. The WiFly RN171 [71], which is a complete standalone embedded wireless LAN access device, is appropriate for the task. The WiFly RN171, initially manufactured by Roving Networks and recently (2014) bought by Microchip, was able to stay relevant in wireless embedded system development due to its upgradable firmware. It also has the simplest hardware configuration requiring only four pins (power, TX, RX, and ground) through UART communication. It is equipped with 8 Mbit flash memory, 128 KB RAM, 2 KB ROM, and 2 KB of battery backed memory. The RN171 is a fully qualified and Wi-Fi Certified 2.4GHz IEEE 802.11b/g transceiver. It features configurable transmit power, ranging from 0 to +12 dBm, it supports ad-hoc and infrastructure networking modes, and secure Wi-Fi authentication schemes (WEP/WPA/WPA2) with full onboard TCP/IP networking stack.

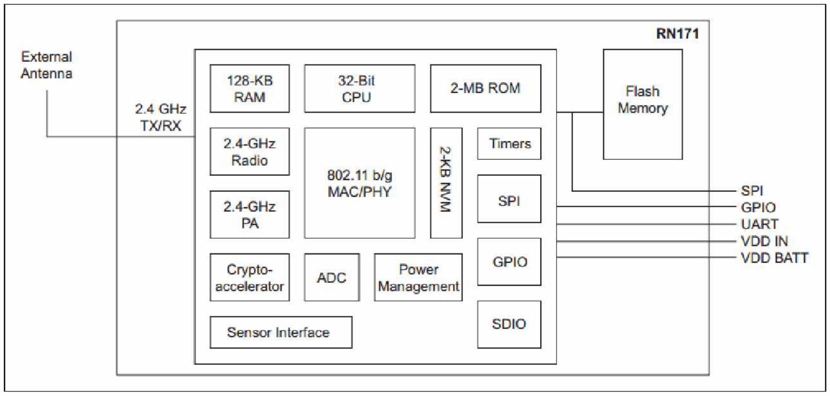

Figure 11: The functional block diagram of the WiFly RN171 [72]

Figure 11 shows the functional block diagram of the WiFly RN171. The RN171 can independently maintain a low-power wireless network connection. Its compact footprint, low power sleep state, and the flexible power management make it suitable for embedded system applications. Built-in networking applications include a DHCP client, DNS client, ARP, ICMP ping, FTP client, TELNET, HTTP, UDP, and TCP.

Although it is a low power consumption device drawing only 4 µA in sleep mode, 38mA receiving, and 120 mA while transmitting at 0 dBm, RN171 delivers high throughput data rate of 921 kbps transmitting, 500 kbps receiving with TCP/IP and WPA2 over UART and up to 2 Mbps over SPI as a slave. The RN-171 also includes a built in HTML client to automatically post serial UART data to a web server.

5.3 Hardware Design

5.3.1 Base Station

The BS has two main functions. Firstly, it implements all the aspects of the WSN operation, including constant transmission of time synchronization heartbeat messages, processing data from different SNs for synergistic effect, and issuing various commands to specific SNs. Secondly, the BS connects remotely to the user interface through Wi-Fi. The BS consists of three main hardware components: the MSP430F5438A microcontroller, nRF24L01+ Wireless Transceiver, and the embedded wireless LAN access WiFly RN171.

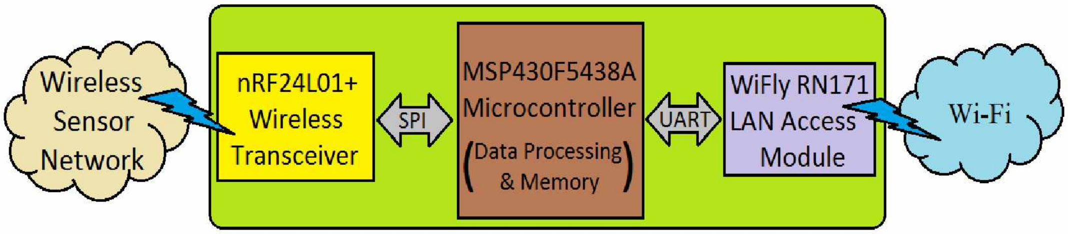

Figure 12: Hardware block diagram of the Base Station bridging the WSN to Internet

The BS is designed for superior computational capabilities with virtually unlimited power/energy resources since it is expected to be connected to the building power supply, with a backup battery in case of a power outage. Figure 12 shows the hardware block diagram of the BS.

5.3.2 Sensor Nodes

All SNs are also based on a MSP430F5438A microcontroller and are designed to represent both typical sensors and actuators in a smart home application. In smart home systems applications, generally each SN consists of four main components: a processing unit (host microcontroller), a radio transceiver, a sensing and an actuator unit, and a power source (battery). Figure 13 illustrates a simplified SN hardware block diagram.

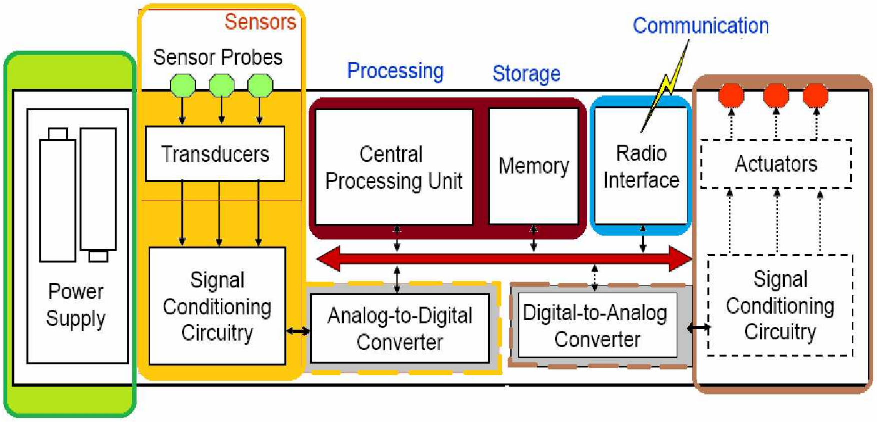

Figure 13: Comprehensive SN Hardware block diagram

For our prototype, each SN is equipped with a diffused tri-color LED (RGB LED) and an on-chip temperature sensor. The RGB LED emulates controlled actuators, allowing the user to send up to five different commands with different observable outcomes. The RGB LED can be set in one of the five following states: 1. Off, 2. Red, 3. Green, 4. Blue, 5. White (Red + Green + Blue).

For a fast and cost effective prototyping process, MSP430F5438 Experimenter Boards (Figure 14) with MSP430F5438A microcontroller chip were used. For the same reason, an RN171-EK Evaluation Board (Figure 15) with an RN171 Module was used as an embedded web server, and nRF24L01+ Transceiver Breakouts Boards (Figure 16) from different vendors were used to implement wireless functionality.

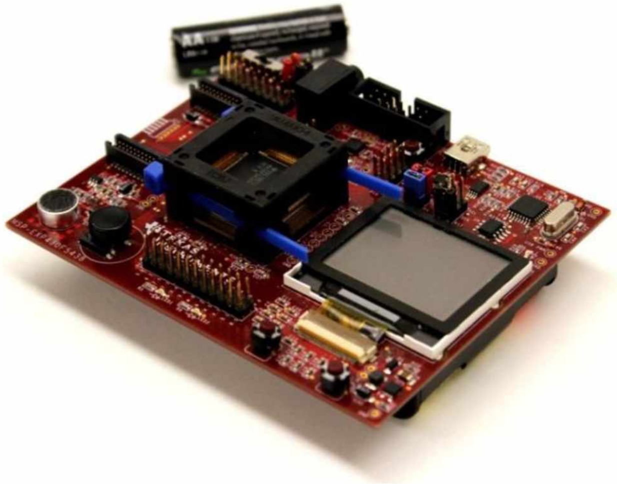

Figure 14: MSP430F5438 Experimenter Board

Figure 15: RN171 Evaluation Board

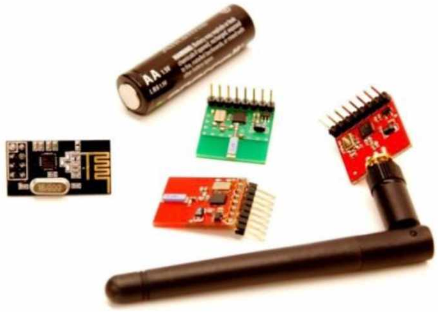

Figure 16: Different nRF24L01+ Breakout Boards

5.4 Software Design

With the right combination of hardware, the next step of implementation consists of identifying the right configuration to achieve a balance between steadfast hardware-software performance and minimized power consumption.

5.4.1 Host Microcontroller

In WSN, the host microcontroller is the core constituent of each node. At a SN, the host microcontroller interfaces a radio transceiver and a sensor or an actuator. At the BS, it interfaces a radio transceiver and the web server. It is essentially the regulator and coordinator of all activities at the node level. The host microcontroller's main clock determines how fast instructions are executed, while the peripheral clock determines how fast the microcontroller can interact with hosted components. Microcontroller power consumption is normally directly proportional to the system clock; consequently, a balance between speed and power consumption must be established. While the BS runs at 25 MHz (the fastest recommended system clock for MSP430F5438A) for optimized computational capabilities, all SN host microcontrollers run on a main clock of 8 MHz, the fastest recommended system frequency that does not require increasing the microcontroller core voltage with the power supply of approximately 3 V (a typical regulated voltage that can be achieved from 2 AA batteries).

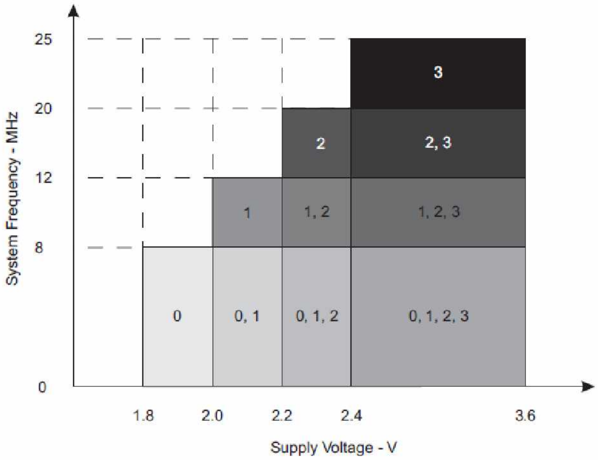

Figure 17: MSP430F5438A: Frequency versus voltage core increment [73]

Figure 17 shows the required voltage core increment for different system frequencies at different supply voltages.

5.4.2 nRF24L01+ Wireless Transceivers

nRF24L01+ transceivers are connected through a 4-pin SPI interface with a baud rate of 8 Mbps, 8-bit data format, MSB first. nRF24L01+ transceivers hardware requires the clock polarity and phase to be set so that transmitted data are shifted at the falling edge of the clock as depicted in Figure 18.

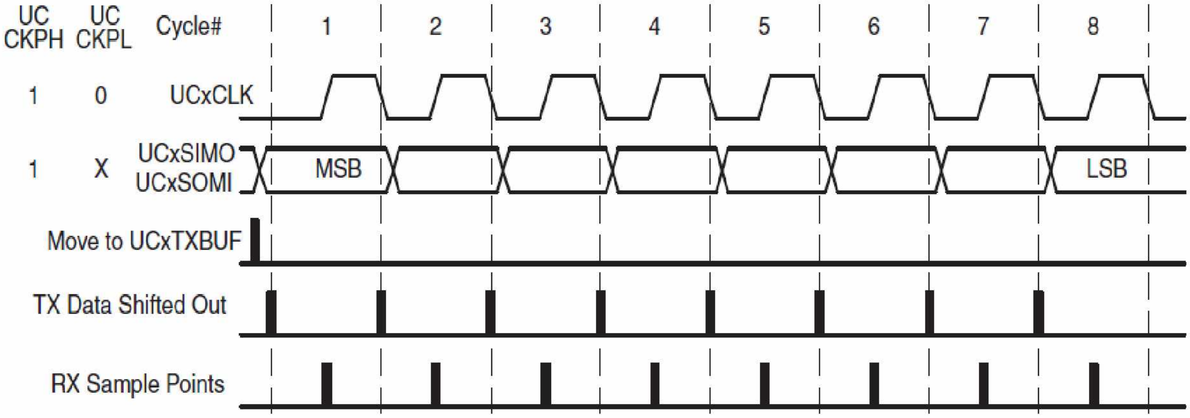

Figure 18: SPI Serial Clock Polarity and Phase configurations to interface nRF24L01+ [73]

nRF24L01+ transceivers are also equipped with interrupt capabilities, allowing automatic transfer of software execution to service transceiver's events in a timely manner without constant polling. Consequently, on top of normal 4 pins required for SPI communication (CSN, SCK, MISO, and MOSI), nRF24L01+ requires a total of 8 physical connections including VCC, GND, IRQ (Interrupt pin) and CE (Chip Enable) used to control data transmission and reception when in TX and RX modes, respectively. nRF24L01+ are configured and controlled by accessing the register map through interface communication.

They are also equipped with an enhanced power management allowing radios to sleep between RX and TX operations with a reduced wake up time and switching between operating modes. This feature is crucial for transceivers to efficiently handle a dynamic communication protocol requiring radios to instantaneously switch between RX and TX modes, or prompt wake up form sleep mode. Figure 19 shows nRF24L01+'s operation modes state diagram and the respective transition times.

Since radio transceivers dissipate more than 90% of the total power consumption at a SN, considerable efforts were invested in scrutinizing transceivers' behavior to ensure they are configured to optimal settings for a well-adjusted performance with minimized power consumption. In this section we investigate how different transceivers settings affect their performance and power consumption

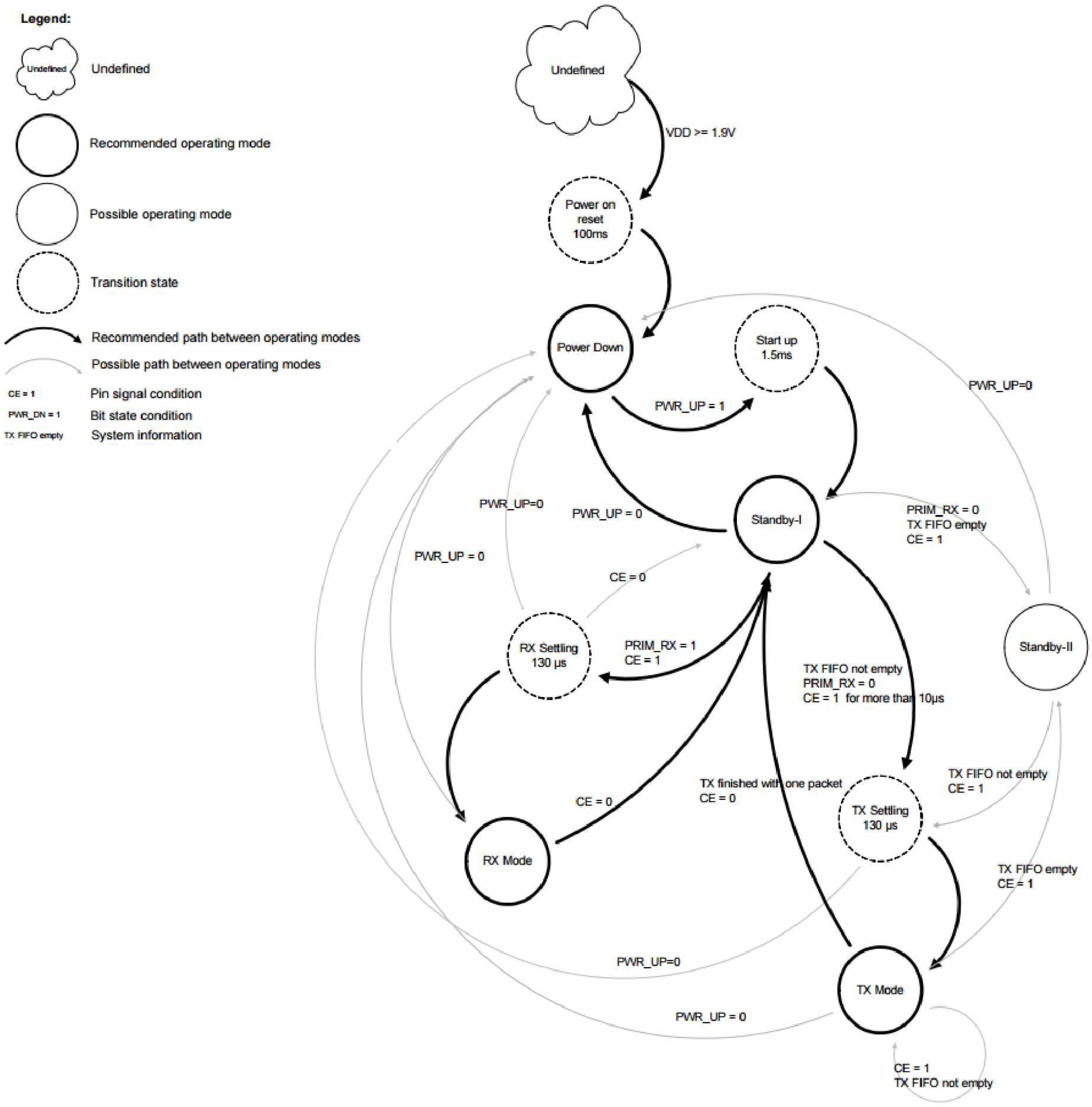

Figure 19: nRF24L01+ Operational modes state diagram [70]

5.4.2.1 Serial Interface Communication

Both host microcontrollers (BS and SN) interface with nRF24L01+ radio transmitters through SPI at a baud-rate of 8 Mbps, the fastest baud rate possible at 8 MHz system clock. The baud rate determines how fast the host microcontroller can interact with the hosted radio transceiver either while loading and unloading data from TX/RX FIFOs or configuring registers for operation settings. Testing results have proven that baud rate does not affect the transceiver's power consumption; on the contrary, a slower baud rate increases the interaction time between the host microcontroller and the radio transceivers. Therefore, the fastest baud rate possible is used to allow the host microcontroller to spend the least amount of time in the active mode.

5.4.2.2 Radio Frequency Output Power

The power consumption during transmission mode depends on the RF output power settings. Increased RF output power yields extended range of an RF system. In transmission mode, nRF24L01+ transceivers power amplifier have four programmable steps: 0 dBm, -6 dBm, -12 dBm, and -18 dBm. The following images show different current profiles of communication transactions at highest power (0 dBm in Figure 20) and at the lowest power (-18 dBm in Figure 21) both at 1 Mbps air data rate.

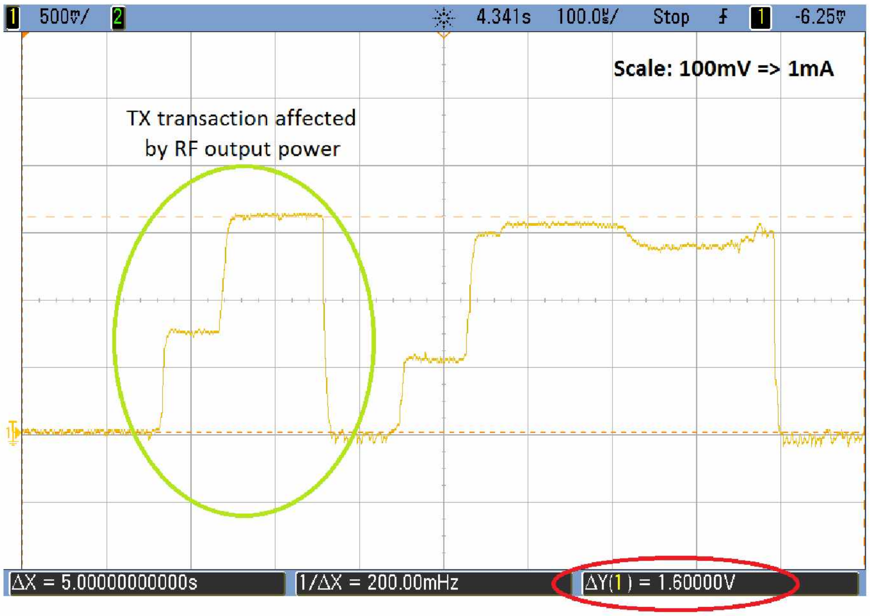

Figure 20: Transmit power consumption at 0 dBm (16 mA while transmitting)

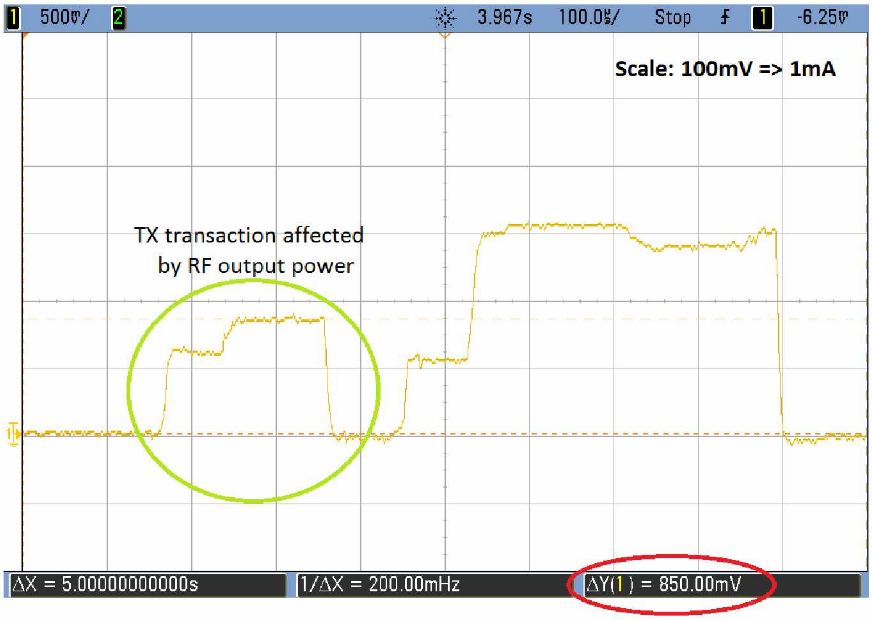

Figure 21: Transmit power consumption at -18 dBm (8.5 mA while transmitting)

RF output power settings can be changed on the fly. At reset, the node starts with the lowest RF output power settings (-18 dBm). If the communication transaction succeeds, the same settings are maintained; otherwise, the output power is incremented one step at time for subsequent tries. For power calculation and operational lifetime estimation, we use the 0 dBm output level as the worst-case scenario.

5.4.2.3 Air Data Rate

Contrary to the TX mode, the power consumption in the RX mode is independent of the output power, and slightly affected by air data rate. nRF24L01+ offers three programmable air data rates: 250 kbps, 1 Mbps or 2 Mbps. While lower air data rate gives better receiver sensitivity, higher data rate gives marginally lower average current consumption due to reduced transaction duration, which in turn reduces probability of on-air collisions. However, with a well-orchestrated medium access control, data collision presents very little concern. The following images show current consumption and time duration of TX-RX transactions of a 10-Byte packet with RF power output of 0 dBm, at air data rate of 250 kbps (Figure 22) and 2 Mbps (Figure 23).

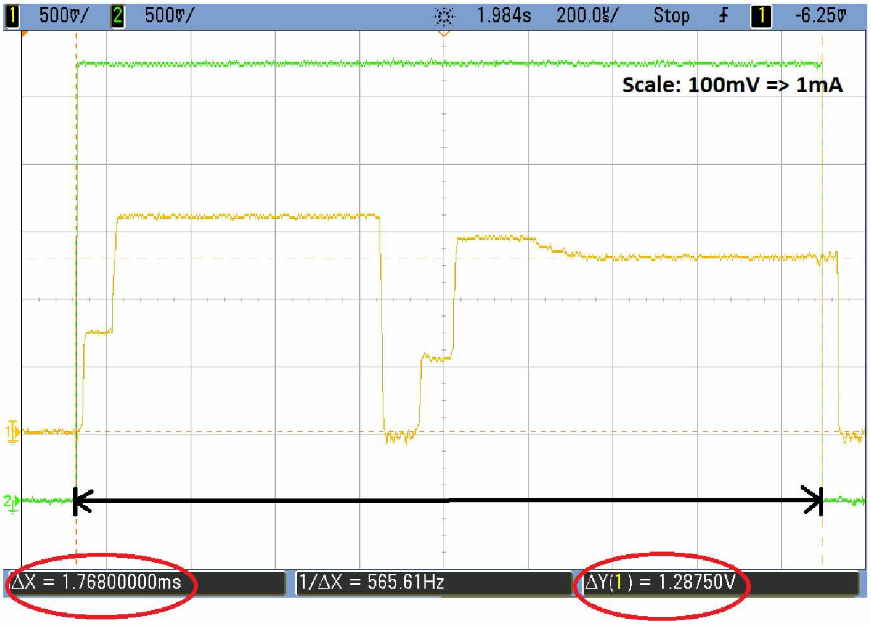

Figure 22: Duration of communication transaction at 250 kbps (1.768 ms)

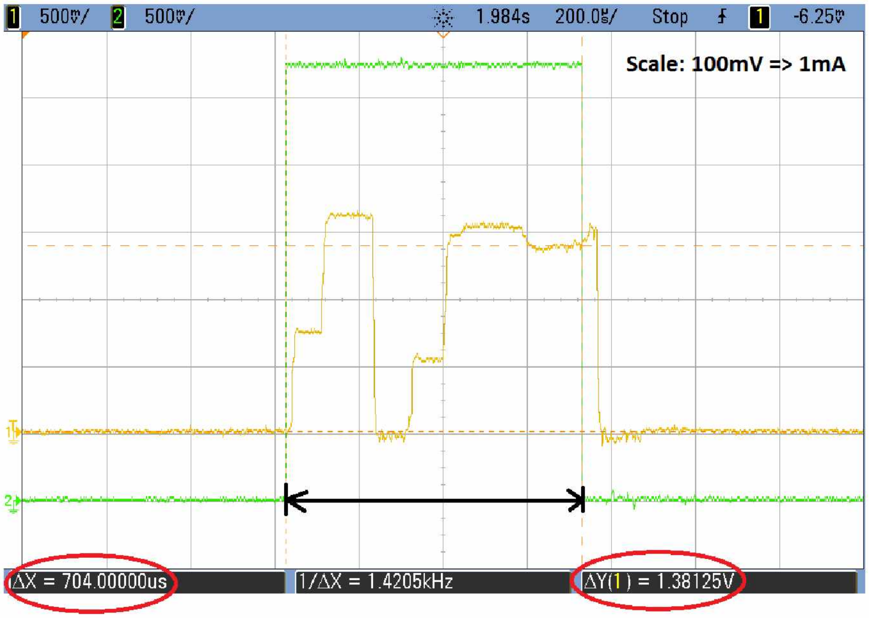

Figure 23: Duration of communication transaction at 2 Mbps (704 µs)

The duration is measured using a GPIO pin (channel 2 in green) set right before the transmission is initiated and toggled right after an RX interrupt is triggered by a radio transceiver. By changing the data rate from 250 kbps (1.768 ms) to 2 Mbps (704 µs), the complete communication transaction’s duration is reduced to less than 40% of the original duration. Although the measured current consumption during a receiving operation increases by almost 1 mA (13.813 mA – 12.875 mA = 938 µA), which is roughly a 7% increase when going from 250 kbps to 2 Mbps, the duration for the receiving operation is drastically reduced from approximately 915 µs to 340 µs, which is roughly a 63% reduction in duration. As a result, it is evident that a higher air data rate is the correct setting for a power conscious system. Therefore, in our implementation the air data rate is set to 2 Mbps.

5.4.2.4 Payload Size

The payload is the user defined content of the packet. nRF24L01+ supports payloads of up to 32 Bytes and provides two alternatives for handling payload lengths: static and dynamic. With a static payload length all packets between a transmitter and a receiver have the same length. Dynamic payload length enables the transmitter to send packets with a variable payload length. This means that for a system with different payload lengths it is not necessary to pad the packet to the longest supported payload size.

As discussed in Section 4.2.6, one main advantage of a MAC protocol with a pre-fixed format and message size is the reduced overhead message and reduced processing (message parsing) after reception, consequently reducing both energy consumption and transmission time. Therefore, it is comprehensively sound to implement a pre-fixed format and payload size communication protocol.

The communication transaction’s duration depends on the payload size. The bigger the payload, the longer it takes to transmit and/or receive the packet. The following images show TX-RX transaction duration of a 3-byte static payload packet (Figure 24) and a 32-byte static payload packet (Figure 25), both at RF power output of 0 dBm, 2 Mbps air data rate.

Figure 24: TX-RX transaction's duration of a 3-bytes payload packet (578 µs)

Figure 25: TX-RX transaction's duration of a 32-bytes payload packet (1.110 ms)

After scrutinizing radio transceiver's behavior in terms of power consumption, the test-bench program for power consumption approximation is set as follow:

- RF output power set to 0 dBm
- Air data rate set to 2 Mbps
- Static payload length fixed to 10 bytes
- Serial communication interface set to 8 Mbps baud rate.

5.4.3 Interfacing WiFly RN171

The WiFly RN171 is operated at 3.3 V, and configured using ASCII commands transmitted through UART communication, which allows a simple physical connection consisting of two wires (TX and RX) on top of the VCC and GND connections. The baud rate is set to 230400 bps, the fastest supported by the latest firmware (Version 4.1). WiFly RN171 module can be configured through UART or remotely via telnet. It is practical to configure the module standing alone, before being incorporated within a more complex design. The configurations settings can be saved to a file with an optional file name and be booted later for activating the settings. The device has the ability to perform a probe scan of available access points; as results, the module returns the MAC address, signal strength, SSID name, and security mode of the access points it finds.

Chapter 6 Results: Functionality and Performance Evaluation

Throughout our evaluation and testing, we used available physical SNs to emulate multiple virtual SNs.

6.1 Power Consumption Measurement

There are three main components to consider when evaluating power consumption: radio transceivers, a sensor or an actuator, and the microcontroller unit. In the following section, we approximate SN's activities within one response period to deduce an estimated lifetime.

6.1.1 Radio Transceiver

Figure 26 shows the main stages of a transceiver's activity during a complete transaction, with measurements of both duration and average current at each stage:

(1) Represents the TX-RX transaction duration (704 µs) measured from right before the transmission is initiated until a RX interrupt is triggered by radio transceiver to confirm the reception of an ACK message. This duration characterizes the minimum time-slot allowable for a complete communication transaction.

(2) Represents TX-Settling time; the average current consumption is 7.375 mA and the duration is measured to be 72 µs.

(3) Represents TX time; the average current consumption is 16.063 mA and the duration is measured to be 120 µs.

(4) Represents RX-Settling time; the average current consumption is 5.375 mA and the duration is measured to be 80 µs.

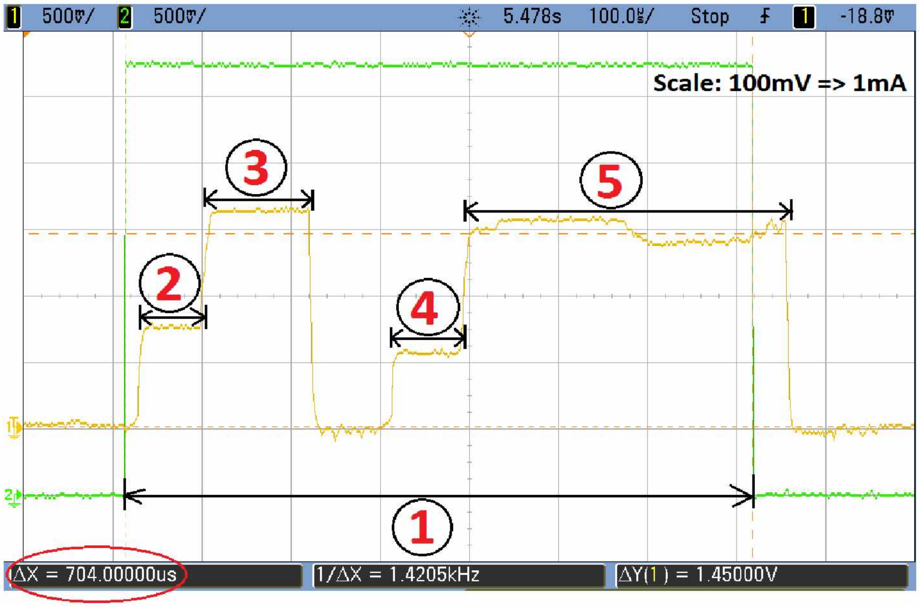

Figure 26: Main stages of a transceiver's activity during TX-RX transaction

(5) Represents RX time; the current consumption for the first fragment of this segment is slightly above 15 mA which represents the time transceiver is in RX mode waiting from packets. The current consumption for the last segment is measured around 14 mA. The average current consumption for the entire segment is approximated to 14.5 mA.

Outside the transaction window, radio transceivers are set in power down mode. In power down mode nRF24L01+ is disabled, drawing current measured at 1 µA. All register values available are maintained and the SPI is kept active, enabling change of configuration and the uploading/downloading of data registers. nRF24L01+ requires 1.5 ms start up time. At wake-up time, the current consumption jumps to 1.0 mA for 500 µs before dropping back to 30 µA. Figure 27 shows the current profile when nRF24l01+ transitions from power down mode to active states.

It is important to note that start-up time and other preparations such as loading/unloading data payload are performed outside the allocated time slot.

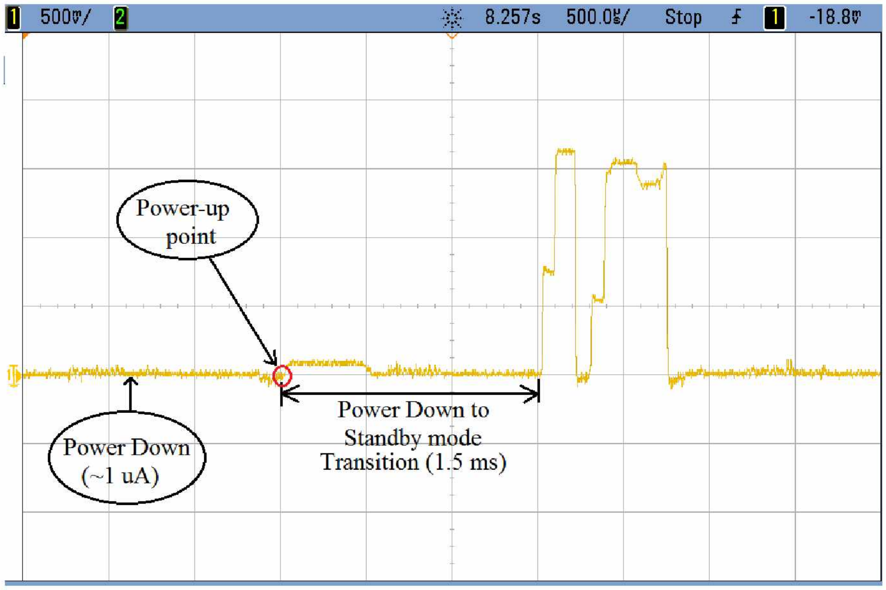

Figure 27: nRF24L01+ transitioning from sleep mode to active state

In addition of a typical TX-RX transaction, in the contention zone a SN spends nearly 1 ms sensing the channel before it transmits. Table 1 summarizes the power consumption associated with transceiver’s activity for a complete transaction.

Table 1: Summary of transceiver’s power consumption within one execution period

Stage/Activity	Duration	Average Current
At start-up	500 µs	1.000 mA
Oscillator start-up	1000 µs	0.030 mA
TX- Settling	72 µs	7.375 mA
TX Mode	120 µs	16.063 mA
RX-Settling	80 µs	5.375 mA
RX Mode	362 µs	14.500 mA
RX Mode (Sensing channel)	1000 µs	14.500 mA
Power Down Mode	T^* – 3134 µs	0.001 mA

T: represents the selected MEL in milliseconds for a specific SN

6.1.2 Sensor or Actuator

Commonly, each SN in a smart home system is equipped with either a sensor or an actuator, or both. For a more realistic power consumption approximation, we consider a temperature sensor connected to a SN. For calculation, we picked Melexis's MLX90614-BAA non-contact infrared thermometer [74] (Figure 28), which can be also used for motion detection. MLX90614-BAA uses both PWM and System Management Bus (SMBus) communication interface. MLX90614 is not the most power efficient temperature sensor, however with a cost of less than $20 per unit, 2.6 to 3.6 V voltage supply, a supply current on the order of milliamps and wake up time in tens of milliseconds, this sensor represents a typical sensor predisposed for smart home applications. Table 2 summarizes MLX90614-BAA characteristics.

Table 2: MLX90614-BAA noticeable characteristics

Voltage supply	2.6 – 3.6 V
Power-down supply current	1 – 6 µA
Supply current (typical)	1.5 mA
Maximum baud rate	100 KHz
Measurement resolution	0.02° C
Accuracy	0.5° C
Wake up request (min. time)	33 ms
Wide temperature range	-40° C to +125° C

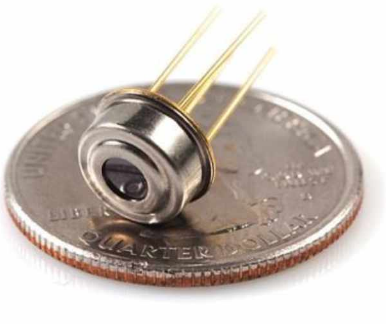

Figure 28: MLX90614 Infra-Red Thermometer

With a host microcontroller running at 8 MHz, the MLX90164-BAA is interfaced at its maximum baud rate, 100,000 bps. Since this sensor consumes a maximum current of 2.5 mA and MSPMSP430F5438A general output pins can supply up to 15 mA, the sensor is powered through a digital pin; consequently the sensor's current draw is monitored through the overall MSP430's current activity.

6.1.3 Host Microcontroller

The host microcontroller interfaces radio transceivers with sensors or actuators. It is desirable to keep the microcontroller in the deepest sleep mode possible while maintaining an active clock signal for time synchronization. MSP430F5438A has 5 different sleep modes. Our design keeps the host microcontroller in Low Power Mode 3 (LPM3) while maintaining a clock signal with a resolution close to 500 µs. The following figures (Figure 29 – 32) show MSP430's current draw combining clock servicing, sensor interface, transceiver interface and general data processing.

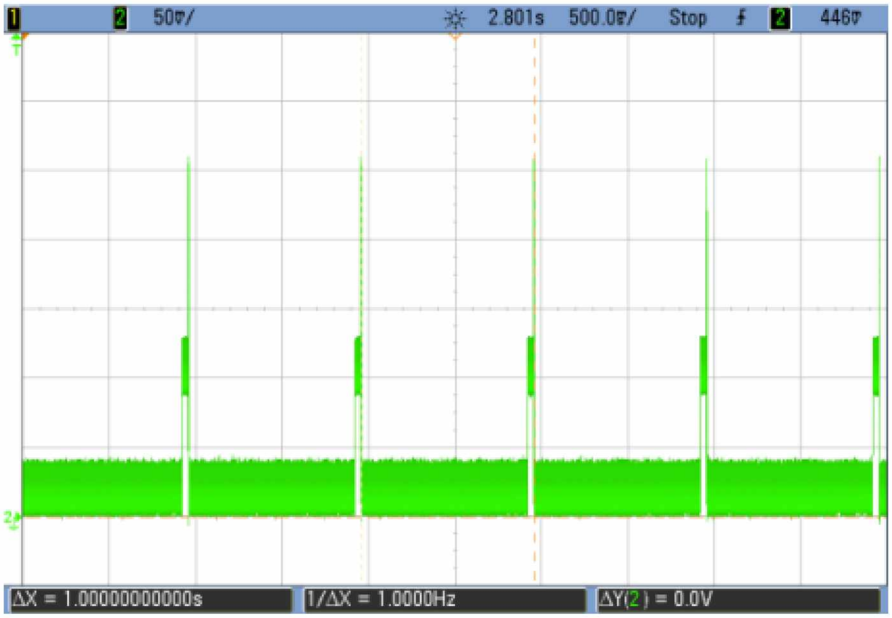

Figure 29: Current profile of the host microcontroller servicing peripherals every second

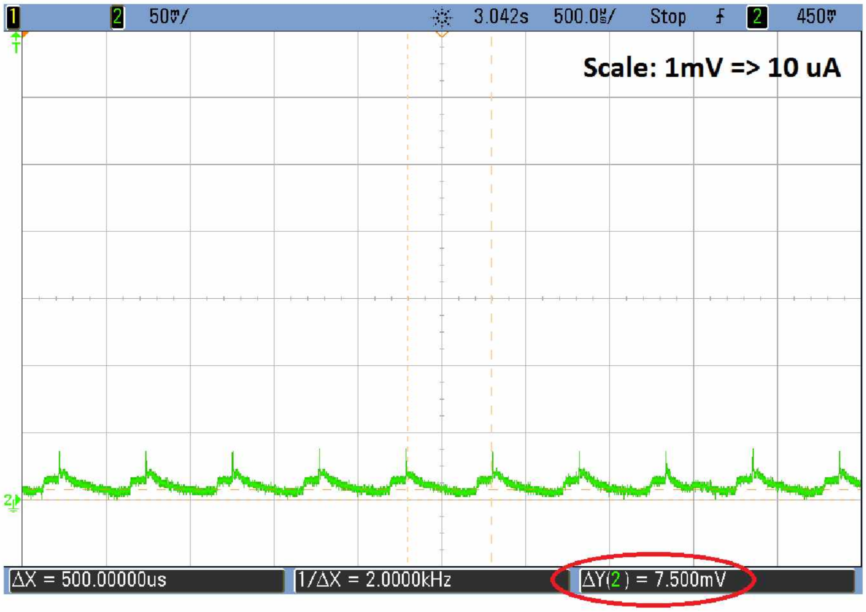

Figure 30: Sleep mode interrupted by clock servicing approximately every 500 µs

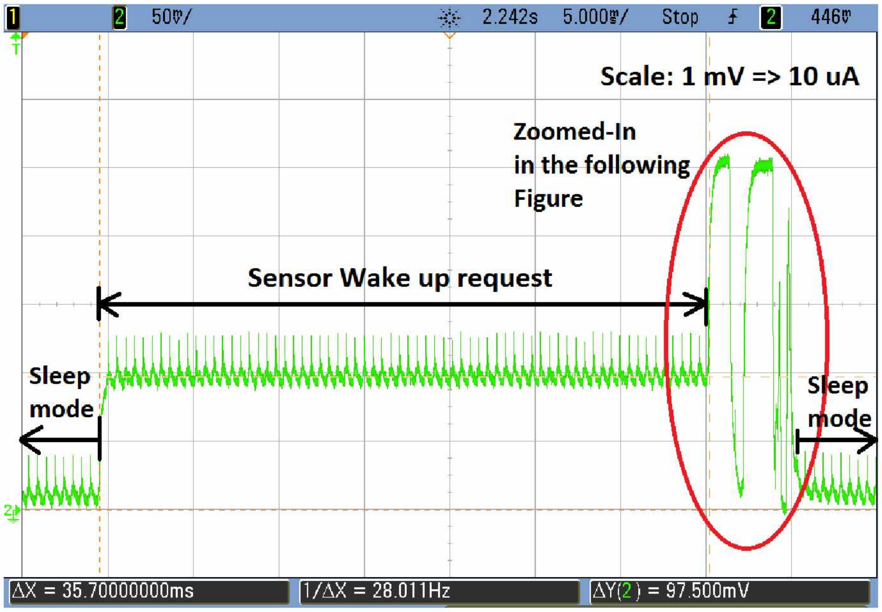

Figure 31: Sensor warm-up before data sampling

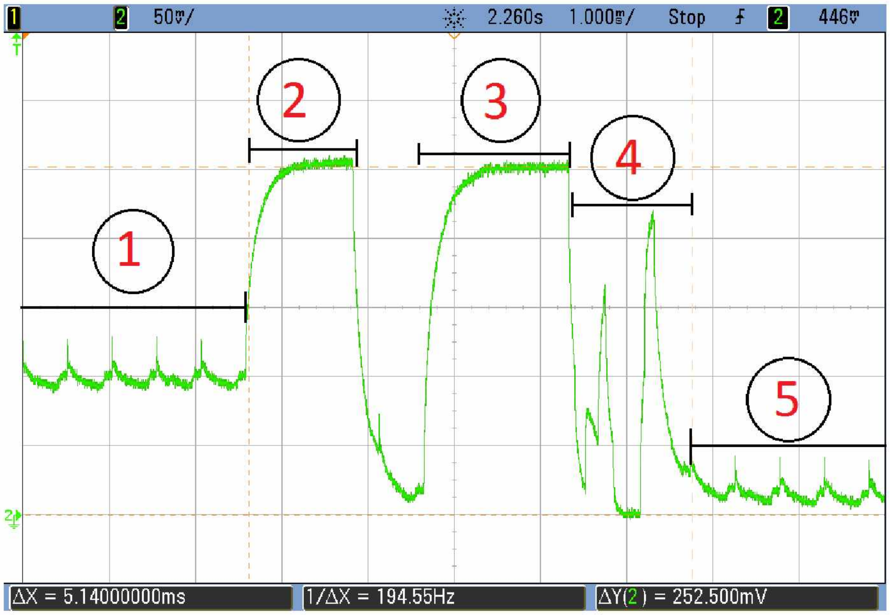

Figure 32: A closer look at microcontroller activities at crunch time

Table 3 summarizes the combined power consumption of the sensor and the host microcontroller.

Table 3: Summary of the sensor and host microcontroller power consumption

Stage / Activity		Duration	Average Current
1	Sensor wake up	35.70 ms	975.00 µA
2	Sensor interfacing	1.15 ms	2525.00 µA
3	Transceivers interfacing	1.60 ms	2525.00 µA
4	Other processing	1.20 ms	1150.00 µA
5	Sleep mode & clock servicing	T*–39.65 ms	75.00 µA

T is the selected MEL in milliseconds for a specific SN

6.2 Calculations and Lifetime Approximation

To estimate SN’s lifetime, we assumed that a SN will perform two communication transactions within one maximum response period. One transaction is the SN receiving packet from the BS and conceivably sending an ACK. The second transaction is assumed to be the SN transmitting sensed data and receiving an ACK from the BS. One report per response period is very generous since depending on the SN application, a SN might be required to report much less frequently than every response time. Nonetheless, it is important to note that not all received packets require an ACK. Only query packets initiating actions are followed by an ACK; routine heartbeat messages for synchronization purposes are not acknowledged. Table 4 summarizes assumed SN activities within one response time, for battery lifetime calculations.

Table 4: Summary of assumed activities occurrence within one response time

Activities	Occurrence
TX-RX complete Transaction	2
Microcontroller - Transceiver interfacing	2
Other processing	2
Microcontroller –Sensor/actuator interfacing	1

In embedded systems, battery capacity and performance remains a complex area because it involves many intricate, highly non-linear electrochemical phenomena. For calculation purposes, we considered Energizer E91 1.5 V AA batteries [75]. Figure 33 shows a graph estimating battery capacity based on constant current draw. Although the SN current draw is sporadic, even for a one second response time, the node will spend more than 95% of the time in sleep mode. Consequently, it is reasonable to estimate that the average draw current will be close to the sleep mode current.

At an average of 76 µA (Microcontroller sleep mode current + Transceiver's sleep mode current) current draw, the estimated battery capacity is slightly over 3000 mAh. Based on presented measurements and estimation, we used MatLab to calculate estimated operational system lifetime. Figure 34 shows SN's estimated lifetime as a function of response time in one second increments.

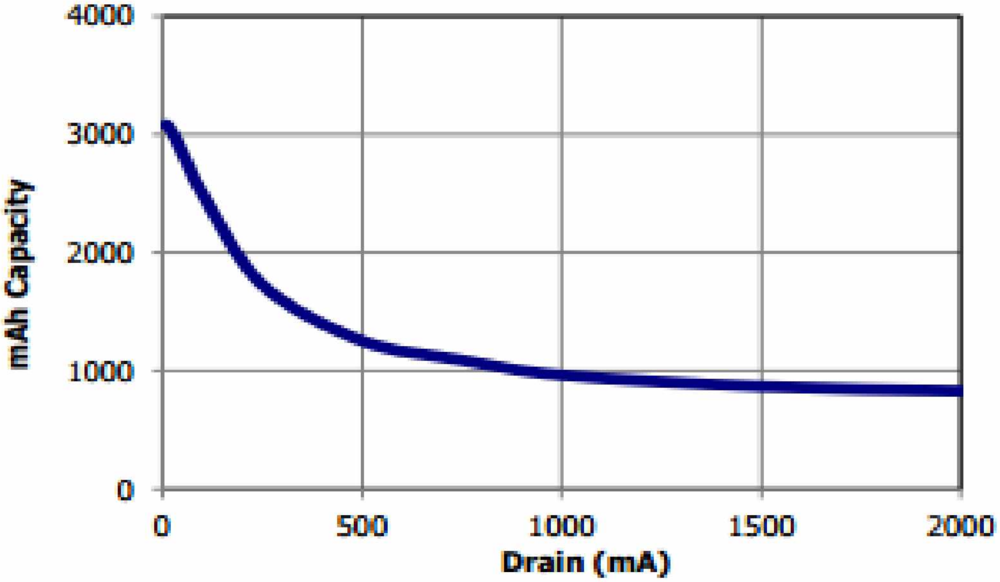

Figure 33: Constant Current Performance of the Energizer E91

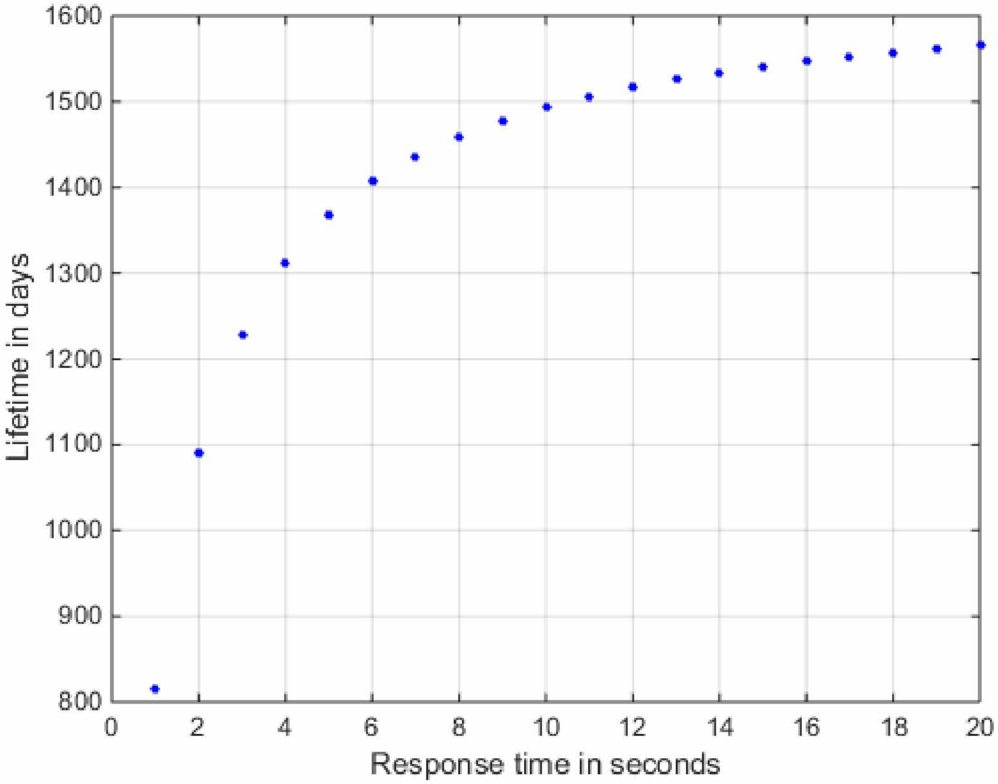

Figure 34: SN Estimated lifetime in function of time response

6.3 MAC Protocol Performance Evaluation in Different Stages

6.3.1 Network Synchronization and BS Transmission Time-Slots

The BAS-MAC is designed with time synchronization in mind. Since the protocol supports a network-level instantaneous broadcast, we integrated the Reference Broadcast Synchronization technique [59]. All SNs simultaneously wake up every MEL to listen for a possible transmission from the BS. The transmission can be a package destined to an individual SN, a group of SNs, or a network-level broadcast message. In case there is no command or query message to be transmitted, the BS broadcasts dummy messages referred to as heartbeat messages, destined to synchronize the entire network. Both query packets and heartbeat messages are used for synchronization purpose since SNs use arrival time as a point of reference to adjust their clock. The message contains no explicit timestamp because it is not important exactly when the message was sent or what was its destination. At the reception of the packet, each SN restarts its timer/counter, consequently being continuously re-synchronized at the beginning of every MEL.

It is important to note the precision limitations due to hardware constraints and data types used in processing. Any calculated value for timing has to be rounded to the nearest integer since hardware timer-counters are incremented or decremented by one.

Using the following formula:

$$\boldsymbol{Time = \frac{number\ of\ cycles}{Oscillator\ frequency}}$$

Plugging in the numbers for a periodic time of 500 µs using a 32.768 kHz yields the following required number of cycles:

$$\mathbf{500}\ \mu\boldsymbol{s}\ \boldsymbol{x}\ \mathbf{32.768}\ \boldsymbol{kHz} = \textbf{16.384 cycles}$$

This means that it is theoretically impossible to precisely count 500 µs using a 32.768 kHz crystal oscillator. However, 32.768 kHz crystal oscillator establishes a balanced tradeoff between power consumption and fine-grained time resolution. In our design, to minimize power consumption, SNs maintain a clock signal sourced from a 32.768 kHz crystal oscillator. The timer-counter is incremented every 16 cycles, to produce a clock resolution close to 488 µs.

Figure 35 shows radio activities of two synchronized SNs. SNs normally in sleep mode synchronously wake up every second to listen. After extensive hardware testing, it was proven that the wake up time of radio transceivers varies slightly radio to radio. To offset both clock and hardware imprecision, a safety cushion for a reliable system was added. Each SN wakes up one count earlier than the exact theoretical calculated value of the listening window. One count of the timer-counter is equal to 16 cycles of a 32.768 kHz crystal oscillator which is approximately a half millisecond. This approach is only applied when SNs are listening to avoid possibly missing a package arriving at the beginning edge of the listening window. For transmission, a SN does not have to transmit exactly at the very beginning of the window as long as the transmission is completed within its assigned time-slot.

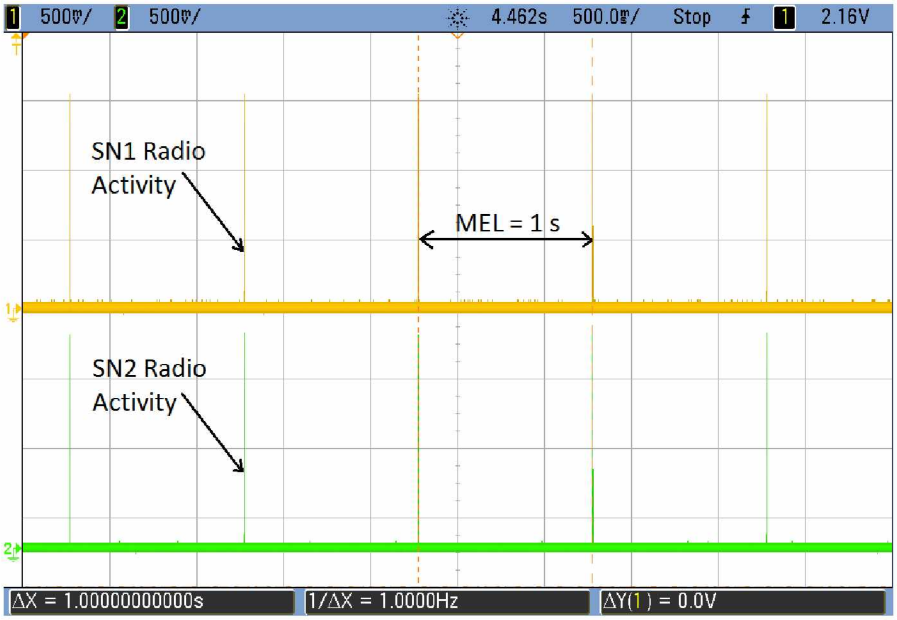

Figure 35: Radio activities of two synchronized SNs

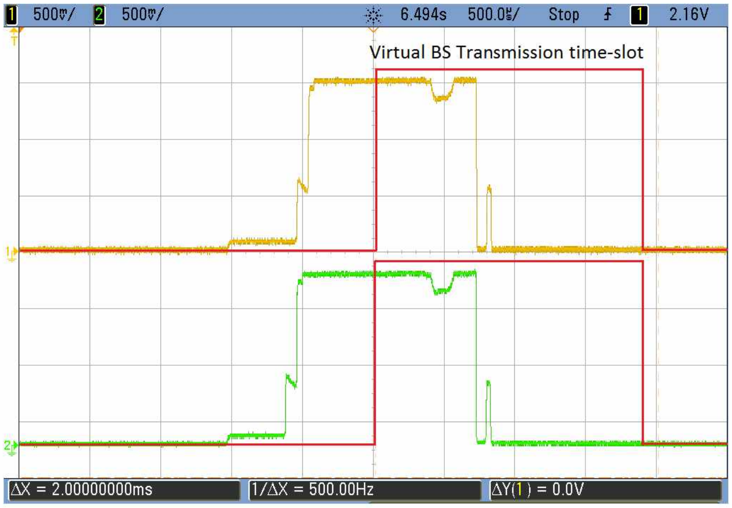

Figure 36: Closer look of synchronized SNs waking up for listening

Figure 36 shows a closer look of synchronized SNs waking up for listening. Notice that the message reception is not followed by ACK transmission since it is a routine heartbeat message. The red line represents the approximated virtual BS transmission time-slot.

6.3.2 Single Frame Time Division

To test the contention-free part of protocol, we used available physical SNs to emulate multiple virtual SNs. Each SN acts as multiple nodes, responding to and receiving messages with various sensor IDs. That way we are able to better test the reliability and scalability of our system, which are both highly dependent on hardware implementation, without having to implement a large number of nodes. The presented experiment uses two physical SNs, each acting as hundreds of virtual nodes. Figure 37 shows a 1-second time frame. At the beginning, both SNs wake up from low power mode to listen, and the broadcast reception is followed by a time division frame that last exactly one second.

Figure 38 gives a closer look. One SN emulates virtual SNs with odd numbers, and the second emulates virtual SNs with even number. They alternate to respond to a Time Division Activation Event broadcast from the BS. Each time-slot is slightly less than 2 ms wide, which is equivalent to 64 clock periods.

The experiment was designed and conducted to determine if a large number of nodes can be accommodated within a given MEL. A software count is incremented each time a physical node successfully acts as one of the virtual nodes it emulates (transmission and ACK reception). For one second, both SNs counted 243 virtual nodes each, to amount to a total of 486 possible SNs. This value differs from a theoretical value of 32768 / 64 = 512.

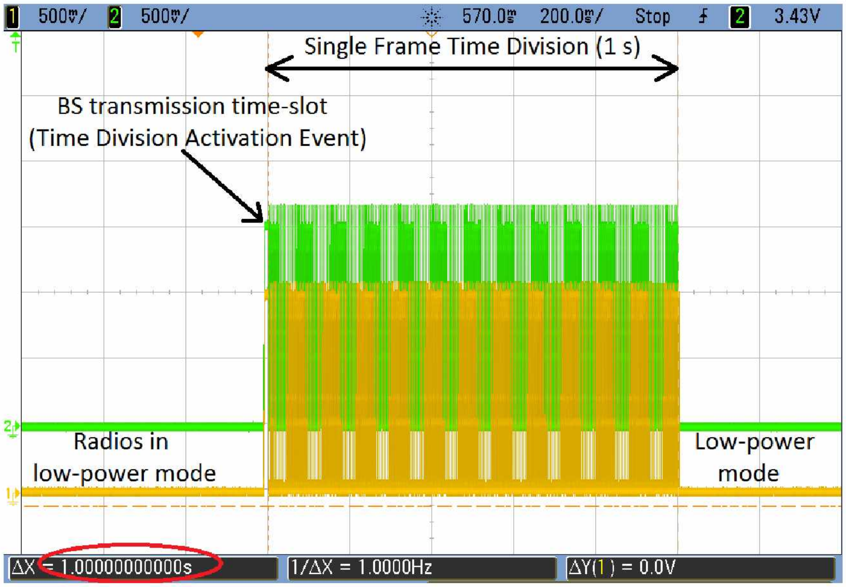

Figure 37: Node activity during a Single Frame Time division of 1 second

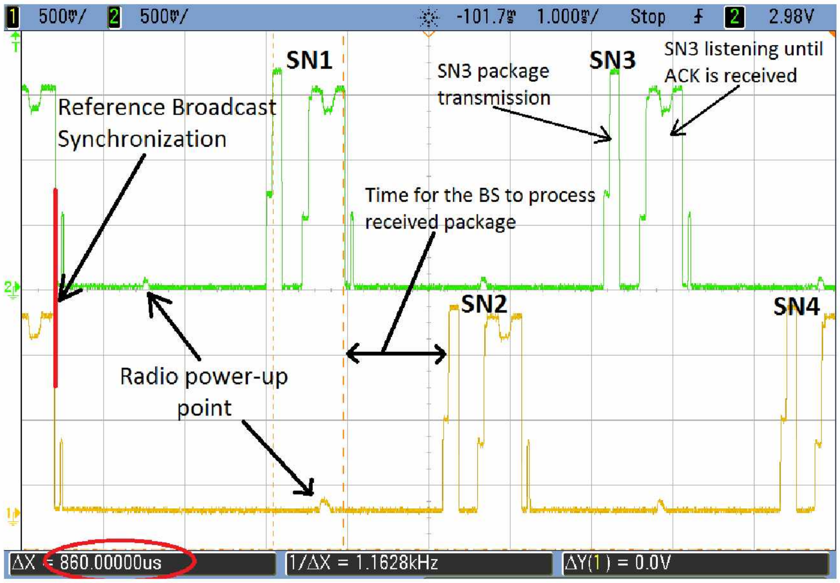

Figure 38: A closer look at time division testing experiment

There is (nearly) a half millisecond right after the broadcast, before the first node responds to the time division event. Since our clock resolution is 16 clock cycles of a 32768 kHz crystal oscillator, this is the minimum time allowed to SN1 to process received packages before it responds. The rest of the time uncounted for can be associated to different factors, including imperfect clock signal; however, the most pertinent explanation can be associated with interrupt handling. MSP430 typically requires 6 clock cycles before the interrupt service routine (ISR) begins executing, and ISR always finishes with the return from interrupt instruction, requiring 5 cycles. Nonetheless, without pre-emptive interrupts, if an interrupt fires while an ISR is executing, it will be serviced only once the current ISR is complete. For an extremely time-sensitive application, MSP430 allows pre-emptive interrupts, where an interrupt with higher priority is allowed to interrupt a lower priority ISR's execution. This approach would complicate the organization of the software, but it would also result in variable interrupt request processing time, albeit somewhat less pronounced.

During the time division part of the protocol, the BS does the heavy lifting. It is required to receive, respond and process data from the previous SN, and get ready for the following node within the allocated time-slot. Figure 39 shows BS radio activity during Single Frame Time Division. It is essential to notice that the radio is active both before and after the single frame time division.

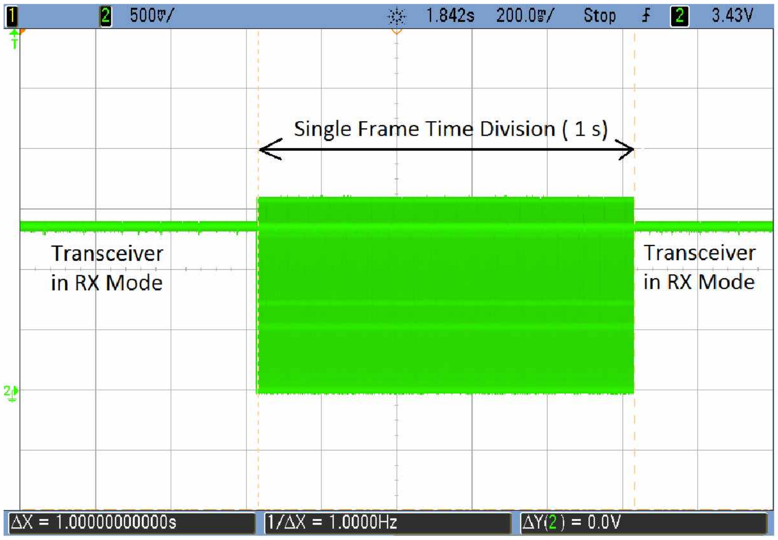

Figure 39: BS Radio transceiver's activity in Single Frame Time Division

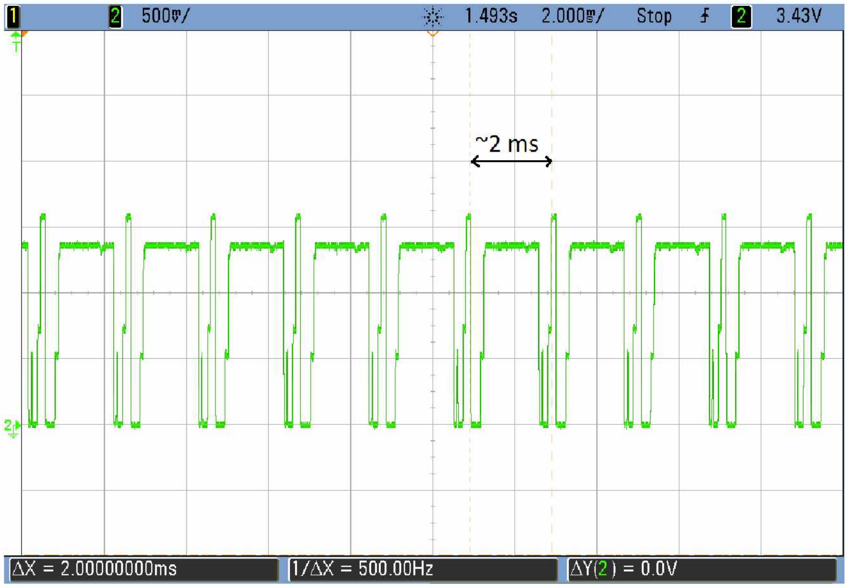

Figure 40: A closer look of BS' transceiver activity during Single Frame Time Division

BS' transceiver is always active, either transmitting or listening. BS is optimized for computational power and low latency, and therefore has virtually no power constraint. Figure 40 shows a closer look of BS' transceiver activity, receiving package and acknowledging reception from a virtual SN approximately every 2 ms.

6.3.3 Contention Zone

The contention zone is located between BS Transmission time-slots. The protocol consists of a regular carrier sensing contention-based protocol. A SN normally in low-power mode wakes up and switches to RX mode and senses the common channel for 1 ms by listening for ongoing transmissions. If the channel is free of traffic, the node proceeds to transmission. Figure 41 shows the activity of a SN while transmitting within a contention zone. Otherwise, it waits for a moment, commonly known as a contention interval, before attempting to transmit again. In our system, the contention interval is random and ranges from 2 to 10 ms, with a half-millisecond increment. Figure 42 shows the results of an experiment with forced contention. Two SNs wake up almost at the same time, the first SN starts transmitting while the second is still sensing the channel. The second overhears the transmission, goes back to sleep and wakes up to sense the channel after a random contention interval.

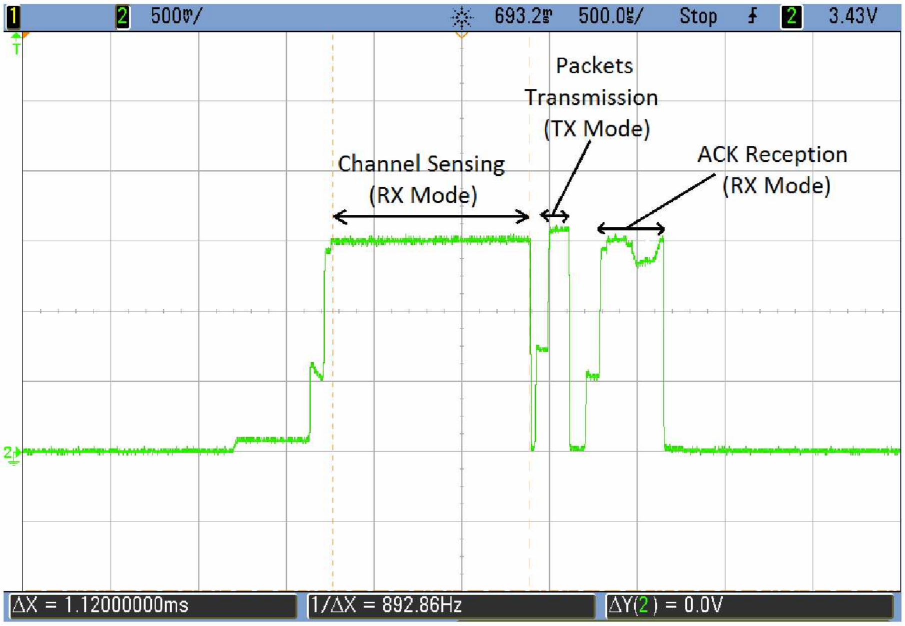

Figure 41: Typical SN transaction in contention zone

Figure 42: Handling overhearing situation in contention mode

6.3.3.1 Handling Overhearing

Overhearing happens when a node receives packets that are destined for other nodes. Since each SN senses the common channel for 1 ms before they start transmitting, we generated an overhearing situation by physically triggering three SNs a half millisecond apart. In other words, the first SN starts transmitting while the other two are possibly sensing the common channel. Using software variables we tracked how many attempts it took each node before successfully transmitting 100 messages. The experiment was facilitated by controlled external triggers spaced half a millisecond apart, generated every second. For SNs that overhear a transmission before transmitting, or that transmitted but received a non-corresponding ACK, a random contention interval is generated and a new transmission is attempted. All the attempts were completed before the following trigger was generated approximately 1 second later.

Table 5: Overhearing Experiment Results: Number of successful transmissions for each attempt

Sensor Nodes	1st Attempt	2nd Attempt	3rd attempt
SN1	100	-	-
SN2	-	99	1
SN3	-	100	-

6.3.3.2 Handling Data Collision

Data collision happens when a transmitted packet was corrupted and could not be successfully received by the receiving node. We attempted to create data collision by simultaneously triggering three SNs by the same external interrupt physically connected to each node. Assuming that transceivers at each node will take approximately the same time to start up, we were hoping to generate data collision and observe how the protocol handles the situation. The set up was similar to the overhearing testing except that all SNs were triggered at the same time.

In every attempt, the BS was able to successfully receive no corrupted packets from one of the three messages and send an ACK to the recipient. For SNs that received an ACK message that did not correspond to their ID, they proceeded by executing overhearing procedure. The following table summarizes how the protocol handled the situation in 100 attempts.

Table 6: Data Collision Test Run 1:

Number of successful transmissions at each attempt

Sensor Nodes	1st Attempt	2nd Attempt	3rd Attempt
SN1	100	-	-
SN2	-	98	2
SN3	-	100	-

The lack of collision in our experiment shifted our attention towards hardware. Waking up radios at the same time does not mean they will transmit exactly at the same time. As Figure 19 shows, there are some internal stages such as the *Crystal oscillator startup (Tpd2stby)*, completely out of control of the host microcontroller. The maximum timing at each stage is given in the device data sheet; however, in some cases transceivers take less than the maximum time. Figure 43 shows the situation where two radios enters an internal stage at the same time but takes more than 80 µs apart to reach the next stage.

Figure 43: Discrepancy in hardware timing

Unable to produce data collision in a controlled way, we designed an experiment to demonstrate how SNs would handle the real situation. Two SNs are coerced to transmit at the same time with tagged messages. The BS station is programmed to not respond to the tagged messages; consequently, transmitting SNs will not receive any ACK, which is likely to be the case when data collision happens. In single frame time division, our protocol instructs that when a SN does not receive an ACK within its assigned time-slot, it turns off its radios and waits until the single frame time division is over to retry. In contention zone, when a SN does not receive an ACK within 1 ms of listening time, it turns off its radio, waits for a random contention interval (between 2 and 10 ms) and retransmits again. The results of one experiment in which scenario was repeated hundred times are summarized in Table 7.

Table 7: Data Collision Test Run 2:

Number of successful transmission at each attempt

Sensor Nodes	1st Attempt	2nd Attempt	3rd Attempt
SN1	-	100	-
SN2	-	99	1

The 99% percent success in the second attempt proves the efficiency of random contention interval for contention based protocols.

6.3.3.3 Handling a Chaotic Situation

As discussed earlier, smart home system are generally low data networks. However, we assumed a scenario in which an unpredictable event happens and incites several sensors to transmit frequently. The experiment is set as follows: From time zero, SN1 starts transmitting packets every 11.5 ms continuously until three seconds are elapsed. Similarly, both SN2 and SN3 start transmitting at time zero but at the interval of 9.5 ms and 7.0 ms respectively until three seconds are expired. A software counter is implemented on each SN to track every retransmission while the BS records the total number of successfully received messages. The goal was to simulate an unpredictable pattern since the first attempt to transmit will certainly require a random contention interval.

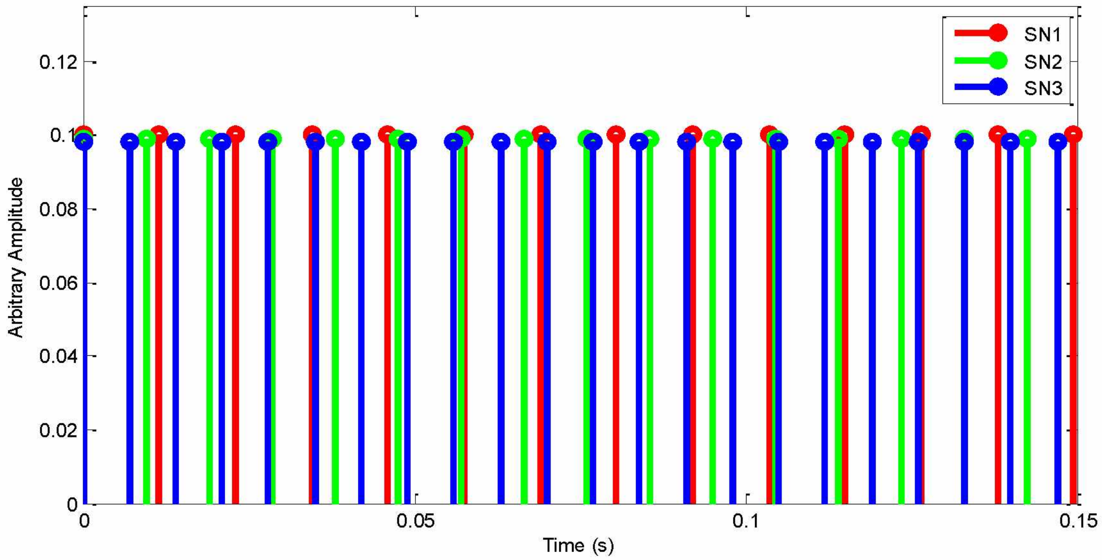

Figure 44: Simulated chaotic pattern (overhearing/retransmission ignored)

At the end of the experiment, the BS had recorded 1147 messages successfully received while 8 retransmission attempts were counted. Figure 44 shows the chaotic pattern in the first 150 ms ignoring the possibility of overhearing/retransmission. The result proved that the protocol is robust enough to handle such situation. Table 8 summarizes the experimental results we obtained.

Table 8: Chaotic Pattern Test Results

Sensor Nodes	Recorded Retransmissions	Percentage of Retransmission
SN1	2	-
SN2	1	-
SN3	5	-
Total	8	0.70%

6.4 Proof of Concept

Although the main focus of testing was to determine the performance of the BAS-MAC protocol, we also used the prototype to experimentally prove the feasibility of improvements suggested in this work.

The current prototype consists of three SNs and one BS. SNs are labeled Room 1, Room 2 and Room 3 to represent SNs deployed around the house. Each SN is equipped with an RGB LED and an on-chip temperature sensor. The SNs are programmed to sense the temperature every second but transmit the data to the BS only if the current sensed temperature is $\pm 1^{o}$ Celsius apart from the last reported temperature.

The prototype is Wi-Fi connected and equipped with a standalone wireless embedded web server. The web server creates an ad-hoc network that a user can join as a web client using any standard web browser (cellphones, personal computers, etc.). Once connected, the user can interact with the system through a web page. Information displayed on the web page includes the light status and temperature at each available room, and the average temperature calculated based on available sensors. The user can control the system by sending desired commands through the web page. The web page is dynamically updated by the web server as soon as there is a change from last update. This network organization was selected only to avoid dealing with the University firewall. In normal operation, where the user is in control of their own modem and router, they can chose to securely open the incoming and outgoing traffic to allow access from the Internet. No changes in our system will be needed to accommodate this remote access.

6.4.1 System Scalability and Re-configurability

The prototype system is designed to be scalable in terms of dynamically handling a varying number of SNs and adjusting the computational processing accordingly. Although we did not test our system using a large number of physical nodes, we did all we could to demonstrate the feasibility of scalable smart home systems, partially by using several physical nodes to emulate a large number of nodes. Some features could be sufficiently tested using only three nodes. For example, we were able to test that our system is capable of adapting to dynamic changes in the number of SNs in the network. When one or two SNs are removed, the web page is promptly updated to only show available SNs. Similarly, the displayed information is updated when a new SN (re)joins the network. The average temperature displayed is always calculated based on available SNs, which is a simplified scenario that proves how a scalable system can improve data collection, and expand opportunities to more complex data fusion.

6.4.2 Modularity and Synergistic Effect

To prove the concept of synergistic effect, we set up an experiment to represent a scenario in which the system would need to fetch information from different subsystems to improve the interpretation or handling of sensed data. The concept consists of a room with monitored temperature. If the room temperature swings by $\pm 3^{o}$ Celsius from the desired room temperature, there is a possibility of one or a combination of the following scenarios: 1. The adjacent door to the outside is left open (security application), 2. The oven's door is open (appliance application), or 3. The refrigerator door is open (appliance application). The system fetches information from all these other subsystems, simulated by mechanical switches on our prototypes, and displays relevant information to the user. The swing of the temperature is simulated by a push of a button that coerces the SN to send pre-fixed temperature for the purposes of this experiment. This is a very simplified scenario, which serves as a proof of concept. In real life, further actions based on sensor synergy could be implemented. Other students in our group are working on incorporating more sensors and different types of sensors into our network, in order to further experiment with sensor synergy.

6.5 Manageable Number of SN per Network

With MEL of 1 second, the single frame time division experiments proved that the system can effectively manage up to 486 SNs. This number is 97.2% of the envisioned 500 SN per network. By physically implementing the prototype, we learned subtle nuances between theoretical and physical implementation of the system. Although the host microcontroller has multiple timer-counters, it is more practical and less complex to base most implementation features on one clock. This means most activities and protocol features such as slot-time, channel sensing time, radio start-up time, random interval generation and more, should be a multiple of the main clock resolution. With a clock resolution close to 500 µs, although it is possible to start other clocks that will generate finer resolution, it is recommendable to base the design on this one clock. Consequently, the next smaller size of SN mandatory transmission slot possible while maintaining the same clock is 1.5 ms, which is theoretically possible but will put a considerable strain on the protocol implementation.

In the event of increased data traffic BAS-MAC adopts a TDMA approach, which maximizes network throughput. In the event of low data traffic, BAS-MAC adopts a modified contention protocol customized to support network-level broadcast. Additionally, BAS-MAC offers the flexibility of changing MEL to match desired usability and system performance. Fixed MEL and regulated transaction duration determine the maximum number of SNs a single network can host.

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Chapter 7 Conclusion and Future Work

There is an apparent gap between research projects related to smart home technology and the products available on the market. Our attitude throughout this project was to avoid doing the same. We persistently drew from the results of scientific research, with the vision of improving consumer's products. We limited ourselves to practical solutions that are currently implementable, and with our implemented prototype we proved the feasibility of each improvement we recommend.

BAS-MAC carries the strength of TDMA-based protocols in the event of increased traffic and behaves as a CSMA in the event of reduced traffic. All these while constantly supporting network-level instantaneous broadcast and controlled execution latency. The BAS-MAC draws strength from other MAC protocols to create an optimized protocol tailored for smart home systems. Although most of the techniques, such as instantaneous broadcast, carrier sensing in the contention zone, and reference broadcast synchronization are not new in the field of MAC protocols, in BAS-MAC protocol we combine them in a way that has never been attempted before. The contention zone, periodically interrupted by synchronized wake-up time-slots, opens a new horizon to new flexibility including the accommodation of heterogeneous sensors with different latency requirements. With BAS-MAC protocol, specific features generally overlooked in general purpose MAC protocols are exploited to provide flexibility of design without compromising the power consumption of the system.

We extensively tested each phase of the BAS-MAC protocol using means at our disposal. However, we recommend more testing to be done with more diverse physical sensors and a larger number of sensor nodes, especially in testing the system scalability and contention handling. Several indications suggests that our proposed WSN with BAS-MAC can be implemented on the base level of a larger, multi-tiered network, where other WSNs with similar architecture can be added for further applications and larger networks, for example in a case of a multi-story house or an apartment. The fact that BS is physically connected to the house power line, giving it an unrestricted power source, and that the higher level of the network will likely consist of a very small number of nodes, gives the network designer a flexibility in choosing what protocol to use. Some of the options include Power-Line Communication [76] or use of different radios that will not interfere with the lower network hierarchy.

We introduced the idea of synergy and data fusion into smart home applications, but the concept was not fully developed in terms of implementation. We envision many scenarios in which we believe BAS-MAC protocol implemented on a scalable and modular system will significantly improve and change the concept of a smart home system as we know it today. The integration of wearable devices carrying information such as user's condition (health, age, etc.), recent activities (workout, gardening, etc.) or user's recent whereabouts (plowing snow in a cold weather, chopping wood on a hot day, etc.) are essential for an interactive environment we expect from a smart home.

Currently, an inexpensive wearable, cellular network connected health monitoring system capable of continuously monitoring the activity of older or disabled people is being developed by others in our research group at UAF. Once fully developed, the system could be integrated into our prototype as a traveling SN. When this project is done, a more inclusive testing can be carried out. The rise of mobile nodes, such as wearable devices or connected cars, highlights the importance of system scalability. A system that seamlessly and dynamically accommodates a varying number of SNs and adjusts data processing accordingly, becomes essential under those conditions. We have great hope that this prototype will serve as a platform for future smart home related projects to be developed at UAF and elsewhere.

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