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MODEL FOR PREDICTING BLUETOOTH LOW ENERGY MICRO-LOCATION BEACON COIN CELL BATTERY LIFETIME

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Abstract

Bluetooth Low Energy beacon devices, typically operating on coin cell batteries, have emerged as key components of micro-location wireless sensor networks. To design efficient and reliable networks, designers require tools for predicting battery and beacon lifetime, based on design parameters that are specific to micro-location applications. This design science research contributes to the implementation of an artifact functioning as a predictive tool for coin cell battery lifetime when powering Bluetooth Low Energy beacon devices. Building upon effective and corroborated components from other researchers, the Beacon Lifetime Model 1.0 was developed as a spreadsheet workbook, providing a user interface for designers to specify parameters, and providing a predictive engine to predict coin cell battery lifetime. Results showed that the measured and calculated predictions were consistent with those derived through other methodologies, while providing a uniquely extensible user interface which may accommodate future work on emerging components. Future work may include research on real world scenarios, as beacon devices are deployed for robust micro-location applications. Future work may also include improved battery models that capture increasingly accurate performance under micro-location workloads. Beacon Lifetime Model 1.x is designed to incorporate those emerging components, with Beacon Lifetime Model1.0 serving as the initial instantiation of this design science artifact.

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Chapter 1 – Introduction

Bluetooth Low Energy (BLE) beacon devices are an enabling technology for the emerging field of micro-location. Micro-location involves methods of identifying the location of a mobile device by determining its proximity to beacon devices that have established locations. A community of BLE beacon devices, distributed throughout a region for the purpose of providing micro-location services, is considered a BLE beacon network or a micro-location network. The BLE beacons are nodes in that micro-location network. Furthermore, when a micro-location connection is established between a beacon and a mobile device, that connection forms a dynamic Bluetooth piconet. The BLE beacons are crucial nodes in the piconets.

BLE beacons are small electronic devices of varying shapes and sizes. They communicate using the Bluetooth Low Energy protocol, also known as Bluetooth Smart. Most commercial models are smaller than a two-inch by two-inch square. The BLE protocol was first documented as an industry standard in 2010, and it was updated in 2013 (Bluetooth Special Interest Group, 2013). Commercial BLE devices, such as iBeacon devices, are now being deployed in fledgling usage scenarios. When a mobile device establishes its micro-location by recognizing a nearby BLE beacon, an application on the mobile device communicates with servers to execute functionality based on that micro-location information. For example, the mobile device application may display coupons for nearby products or kiosks, or the server may monitor device movement throughout the region to analyze customers’ shopping habits.

BLE device designers frequently design and configure beacon devices to operate solely from coin cell battery power. A coin cell battery powers a beacon when it is broadcasting its unique ID, when it is establishing a connection with a mobile device, and also when it is exchanging data with mobile devices in a piconet. When a beacon’s battery power is insufficient for operation, the beacon becomes an inactive node in the micro-location network, compromising the network’s topology and its data integrity. Without battery power, the beacon also becomes an inactive node in an established or potential piconet, compromising that piconet’s topology and data integrity. Although beacon lifetime has a direct impact on network reliability, there are few tools available for designers to accurately predict battery lifetime, associated beacon node lifetime, and ultimately micro-location network and piconet reliability. This research study focused on developing an artifact, the *Beacon Lifetime Model* (BLMod1.0), an algorithmic model with which designers may accurately predict BLE beacon battery lifetime. BLMod1.0 contributes a step toward establishing best practices in this emerging field of micro-location.

Purpose Statement

The purpose of this research study was to design and build an algorithmic model that designers may use to predict coin cell battery lifetime for BLE beacons, contributing to power management best practices in the field of micro-location. The *Beacon Lifetime Model,* referred to as BLMod1.0, is the algorithmic model resulting from this research study. BLMod1.0 provides a spreadsheet interface for designers to quantitatively define the parameters that impact power consumption for BLE beacons in real-world usage scenarios, such as beacon transmission power, operating range, connection interval, and advertising interval. BLMod1.0 incorporates an initial predictive algorithm for battery lifetime, with acknowledged experimental uncertainty, as an evolving tool toward best practices for the field.

Research Questions

This research sought to answer three key research questions:

1. When functioning in a micro-location scenario, how much power does each BLE beacon device consume as it cycles through its states?
2. Based on initial battery models and designed to incorporate emerging, improved battery models, what is the anticipated coin cell battery lifetime for each BLE beacon device that is tested in a micro-location scenario?
3. Does BLMod1.0 accurately predict BLE beacon device lifetime?

Rationale

The broad field of Wireless Sensor Networks (WSNs), established in 1954, has evolved as a result of extensive research and engineering work ("SOSUS: First-generation," 2005). Power management is one of many aspects of WSNs that has been deeply studied, resulting in well-documented best practices and models (Asorey-Cacheda, García-Sánchez, García-Sánchez, García-Haro, & González-Castano, 2013; Bicakci & Tavli, 2009; Chen, Andreopoulos, Wassell, & Rodrigues, 2013; Ekstrom, Bergblomma, Linden, Bjorkman, & Ekstrom, 2012). It is widely accepted among researchers that sensor energy consumption is primarily due to node sensing, communication, and data processing (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002a). Maximizing the lifetime of WSN nodes has been recognized as key to maximizing the lifetime of the networks themselves; the most common reason that nodes fail is lack of power (Dietrich & Dressler, 2009; Kailaimani, 2013; Nguyen, Förster, Puccinelli, & Giordano, 2011; Rukpakavong, Phillips, & Guan, 2012).

Nomenclature around beacons and micro-location is still evolving, so it may be useful to clarify certain terminology used in this research. Beacons are one type of node in a WSN. While many nodes in WSNs are considered sensors, beacons are a specialized type of sensor with a more limited role. WSN sensor nodes are electronic devices that typically sense the physical environment, translate analog sensed data into digital data, and wirelessly transmit the digital data from the field to a data receiver (Buratti, Conti, Dardari, & Verdone, 2009). For example, a thermometer sensor detects temperature and communicates that data to a sink, controller, or monitor in its WSN, where the data may be processed or forwarded to a server via a gateway. A beacon, functioning as a specialized sensor, repeatedly broadcasts an identifying packet. A beacon may sense the environment by pairing with another device that responds to its broadcast. The paired devices contribute data to the piconet and to a WSN sink. Beacons are referred to as sensors for this reason, and also because they are sometimes packaged with traditional sensors to contribute a wider range of functionality to the WSN.

Micro-location with beacons. Micro-location is an emerging field. It shares attributes with related areas of work, such as “indoor locating,” “indoor positioning,” “location awareness,” and “local position(ing) systems”. Micro-location, in this study, collectively refers to methods of identifying the location of a mobile device by determining its proximity to beacon devices that have established locations. The specific beacon devices of interest in this study are Bluetooth Low Energy (BLE) beacon devices, using the BLE protocol as specified by the Bluetooth Core Specification Version 4.1 (Bluetooth Special Interest Group, 2013). BLE was designed for short-range low-data-rate communication between devices requiring low power consumption, typically powered by coin cell batteries (Decuir, 2010).

In a micro-location usage scenario, as described earlier, a BLE beacon repeatedly broadcasts its ID and availability for pairing until a mobile device recognizes it and pairs to form a piconet. The known location of the BLE beacon provides a proximity location for the mobile device (Townsend, Cufí, Akiba, & Davidson, 2014).

Several research teams have verified that, in a single lab scenario, BLE sensors use power efficiently, consistent with the BLE specification. The teams of Mackensen, Lai, and Wendt (2012a) (2012b); Gomez, Oller, and Paradells (2012); Dementyev, Hodges, Taylor, and Smith (2013); and Siekkinen, Hiienkari, Nurminen, and Nieminen (2012) each have completed a theoretical analysis and a lab measurement analysis of BLE sensor power consumption in a single configuration. Along with guidelines from Texas Instruments Incorporated, this peer-reviewed research was especially helpful in establishing baselines and acceptable methodologies for precisely measuring BLE device power consumption (Kamath & Lindh, 2012). However, none of these teams tested with a micro-location usage scenario. It was not within their scope to test extensively with various configuration parameters (such as transmission power, operating range, connection interval, and advertising interval), which may impact power consumption in a real-world deployment. It was not within their scope to analyze available energy by considering a variety of coin cell battery capacities. Kamath and Lindh (2012) formulated a spreadsheet for predictive calculations, but none of the researchers formulated a parametric model that designers may use to calculate micro-location beacon network lifetime, as other researchers have done to establish best practices for other types of WSNs (Casilari, Cano-García, & Campos-Garrido, 2010; Dâmaso, Freitas, Rosa, Silva, & Maciel, 2013; Dâmaso, Rosa, & Maciel, 2014).

The importance of predicting beacon and network lifetime. Wireless sensor network researchers have established that network lifetime is critical to a network's availability, security, and integrity (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002b). Understanding and predicting network lifetime has become a key aspect of best practices in the broad field of wireless sensor networks, of which beacon micro-location is a member (Landsiedel, Wehrle & Gotz, 2005; Lahiri, Raghunathan & Dey, 2004). A network's lifetime ends when its critical nodes fail (Dietrich & Dressler, 2009). A node's lifetime is a function of the rate at which the node consumes energy and how much energy it has available.

Similarly, micro-location beacon networks and BLE piconets are only as reliable as the beacon device nodes that comprise the networks. Without power, a BLE beacon node becomes a liability for its network(s), degrading the topology and integrity of the network(s). If beacon node batteries fail unexpectedly, the micro-location network will not meet performance expectations or it may have unplanned maintenance expenses (Dietrich & Dressler, 2009).

The contribution of BLMod1.0. The *Beacon Lifetime Model*, BLMod1.0, contributes a first step toward filling a gap in the field of micro-location. By increasing the understanding of BLE beacon power consumption, in the context of operating parameters and available coin cell battery power, designers will be better equipped to predict beacon node lifetime when designing micro-location networks. The BLMod1.0 captures that knowledge in a new, useful tool, designed to evolve as technology improvements emerge.

Chapter 2 – Review of Literature and Research

This literature review was organized in support of the research questions and rationale presented in Chapter 1. In order to examine the first two research questions, with a focus on beacon device power consumption and coin cell battery lifetime prediction, it was important to review literature covering WSN power management. The research published in the literature identified the highest priority characteristics that impact WSN power provisioning, and best practices for managing power. The research published in the literature also demonstrated that predicting WSN node lifetime is crucial to reliable network operation. Using beacons for micro-location draws upon specialized scenario configurations, therefore it was important to study published work about BLE beacon configurations and micro-location operating parameters.

The complexity of accurately predicting BLE beacon coin cell battery lifetimes emerged from the literature review, as did the need for tools that address this complexity for designers. The BLMod1.0 artifact meets the requirements for such a tool, contributing a valuable solution to the field of work. In order to quantitatively specify the BLMod1.0 artifact, it was necessary to thoroughly study battery performance measurement, tools, and models found in the literature. Furthermore, in order to examine the third research question, assessing the BLMod1.0 artifact for accuracy, the literature provided valuable benchmarks for test methodology and for appraising the tool’s predictions.

Power Management for Wireless Sensor Networks

Wireless sensor networks (WSNs) may operate from a variety of power sources, including batteries. As Akyildiz et al. (2002a) stated in their seminal survey of WSN research, power management is a key performance metric because unavailable nodes limit the WSN lifetime. After defining the domains of WSN power consumption as sensing, communication, and data processing, they emphasized that data communication is the node’s main power consumption task, and noted that startup power is a significant covert energy consumer.

Transmission power is one parameter of WSNs that was assumed to significantly influence power consumption until researchers began to quantitatively measure its impact. Ekstrom, Bergblomma, Linden, Bjorkman, and Ekstrom (2012) closely examined Bluetooth 2.0 power management for four transmission power settings ranging from -5dBm to 10dBm. They collected data that validated the work of other researchers, demonstrating that the transmission power parameter has an insignificant impact on total power consumption for short distances. They also developed formulas for an equation-based empirical energy model and verified that the model’s predictions were accurate within a 3% error margin.

As best practices for WSN power management have been defined, energy imbalance has been a topic of study. Bicakci, Gultekin, and Tavli (2009) addressed energy imbalance. They pointed out that if network energy balance is not monitored and managed, a node may become a hotspot of activity, depleting its power source (e.g., its coin cell battery) and becoming inactive earlier than expected, thereby impacting network topology for all remaining active nodes. Also contributing to best practices in WSN power management, Asorey-Cacheda, García-Sánchez, García-Sánchez, García-Haro, and González-Castano (2013) proposed a hierarchical network architecture that is aware of each node’s power sources. In their proposed power management framework, a WSN may be composed of primary nodes with renewable power sources (e.g., AC power or solar power) and secondary nodes with finite power sources (e.g., batteries). Tasks may be assigned to the nodes in a way that leverages or conserves their respective power supplies.

Nataf and Festor looked closely at WSN power management in the context of battery models (Research Centre Nancy – Grand Est, 2012). They studied sensor power usage characteristics and duty cycles of transceiver events and inactivity. They incorporated the impact of duty cycle events and inactivity into their battery models to define best practices in the field.

Chen, Andreopoulous, Wassell, and Rodrigues (2013) advanced an innovative paradigm called Distributed Compressed Sensing (DCS). DCS is based on opportunistic correlation of collected data and harvested energy. By matching energy demand to a profile of harvested energy supply, retransmission rates may be optimized and energy may be conserved.

The Importance of Predicting WSN Node Lifetime

Akyildiz et al. (2002b) observed that fault tolerance and reliability are key design considerations for WSNs. However they also recognized that, when sensor nodes fail, the network topology is significantly impacted. Because many sensors rely on battery power, predicting sensor node battery lifetime forms a basis for predicting reliability of the entire WSN.

Dietrich and Dressler (2009) published a comprehensive work on their study of WSN lifetimes. They reviewed the field for definitions of WSN lifetime and introduced new measures such as service disruption tolerance, connected coverage, and application-aware graceful degradation. Building upon the work by Akyildiz et al. (2002b), they noted that, if the energy demands of sensing, communication, and data processing are not accurately modeled for single nodes, the WSN lifetime performance deviates uncontrollably.

Micro-location With Beacons

Micro-location beacon networks depend on their beacon nodes for reliable operation. Micro-location is an innovative, emerging use for BLE beacons. While there are few peer-reviewed papers about research using beacons for micro-location, because it is such a new sub-field of WSNs, there are resources from publishers and manufacturers of nascent commercial products. Furthermore, the Bluetooth 4.1 Specification is a definitive source of details about the BLE protocol (Bluetooth Special Interest Group, 2013).

Townsend, Cufí, Akiba, and Davidson (2014) published one of the first books for BLE developers and designers. In it, they explained how to configure BLE beacons for a wide variety of scenarios. Their work thoroughly introduced the BLE configuration parameters, protocol layers, and design considerations that impact power management. Their descriptions of the complex configurations, options, parameters, and power tradeoffs corroborated the need for effective management tools for designers. They also documented use of BLE by beacons that were specifically nodes in an indoor locating network or micro-location network, exploring the specialized usage scenarios that are central to the research questions in this study.

Gast (2014) published a book on use of BLE beacons for proximity and location services. His work explained BLE beacon configuration parameters, optimization, methodology for programming and operation, and known limitations. He noted that manufacturer battery life claims are optimistic. He cited one example of a commercial BLE beacon product, with claims of years of battery lifetime, which consumed one-fifth of its battery capacity in the first month of field operation. He stated that management, configuration, and monitoring tools are needed for mature BLE beacon networks.

Documentation from Apple Incorporated (Apple Inc., 2014), Texas Instruments Incorporated (Kamath & Lindh, 2012), Estimote (Estimote Team Blog, 2014), Roximity (Roximity, 2014), and StickNFind (StickNFind, 2014) specified design and implementation details for micro-location beacon networks. Texas Instruments Incorporated published bench testing performance details and testing methodology for their core BLE technology. The other manufacturers provided general performance claims without publishing verification data, and some of those claims have anecdotally failed when products have been deployed in real-life operations.

Toward Battery Performance Measurement, Tools and Models for Lifetime Calculations

Researchers have studied battery performance measurement for WSNs in general, and some are beginning to study battery performance specifically for BLE nodes. After measuring WSN node power consumption and gathering quantitative data about battery performance, some researchers have formulated tools and models toward predicting lifetimes. Researchers are identifying and isolating covert energy consumers in WSN nodes, which must be understood in order to formulate accurate predictive models.

For this study, the work by Kamath and Lindh (2012) is a cornerstone. Acknowledging that BLE was designed so that devices could achieve lifetimes of months or years from a single coin cell battery, Kamath and Lindh provided a detailed Texas Instruments Application Note for measuring BLE power consumption. They specified a test bed setup and measurement procedure to capture event-based power waveforms on an oscilloscope. They identified and accounted for the software-based operating system periodic events as a covert energy consumer. They documented certain setup choices, such as using a regulated DC power supply when taking measurements, rather than batteries, to avoid having battery characteristics incorrectly bias the data. Their test node was a TI CC2541 BLE system-on-a-chip. After measuring test cases, they generalized their data to formulate predictive calculations in a spreadsheet. The scope of their work did not include measuring power consumption for beacons, based on specific beacon operating parameters such as operating range and advertising interval, nor extending their spreadsheet calculations to forecast battery lifetime in micro-location usage scenarios.

Other researchers who took an experimental approach to battery performance measurement based their work on the TI series of BLE systems-on-a-chip. Siekkinen, Hiienkari, Nurminen, and Nieminen (2012) setup a TI-based testbed, gathered basic operating data, and then formulated a set of equations to model energy consumption optimization in various states of BLE connection events. Also using TI technology, researchers at the University of Applied Science of Southern Switzerland measured WSN node lifetime. Nguyen, Förster, Puccinelli, and Giordano (2011) observed that theoretical lifetime estimates differed significantly from actual lifetime results that negatively impacted real-world deployments. They focused their work on the duty cycle of the node’s RF communication, logging performance data to on-board flash memory, and measuring non-linear battery discharge behavior that varies across battery brands. Unlike Kamath and Lindh (2012), Nguyen et al. measured performance of five brands of alkaline AA batteries, and cautioned against use of a DC power supply testbed. They identified covert energy consumption in the energy footprint of the flash memory. Based on their observation, they summarized best practices for tuning WSN nodes to optimize node lifetime. In other published work, the University of Applied Science of Southern Switzerland researchers examined the lack of realistic behavior in simulated WSN node lifetime models. Garg, Förster, Puccinelli, and Giordano (2012) defined a baseline of credibility for predictive models, identifying aspects that have been oversimplified and must be modeled more accurately. They concluded that each WSN simulation must include a fine-grained energy expenditure model, a non-linear battery model, and an application model, and they recommended that such improvements be tested in future research. Research by Park, Savvides, and Srivastava (2001) stated that linear models, discharge rate-dependent models, and relaxation models fail to accurately account for DC/DC switching regulators that are now commonly used in coin cell powered VLSI circuits, such as those for BLE beacon devices. In his research, Jensen closely measured CR2032 coin cell battery performance during BLE load profile states (Jensen, 2010).

Dementyev, Hodges, Taylor, and Smith (2013) examined the configuration parameters that impact measured power consumption for WSN nodes, comparing BLE to other protocols. Like Nguyen et al. (2011), they considered the duty cycle, but Dementyev et al. focused on leveraging the sleep intervals. For their work, they specified a testbed setup and a measurement procedure to capture operating power consumption on an oscilloscope and to capture sleep interval power consumption using a multimeter. Similar to Kamath and Lindh (2012), but differing from Nguyen et al. (2011), they used a 3.3V DC power supply instead of batteries in their testbed. They collected power consumption data during sleep, awake, and transmitting states, observing that the dominant power consumption parameters were related to reconnecting after a sleep cycle. The scope of their work specifically did not include testing the impact of configuration parameters such as packet size variations and transmission distances between nodes. Their conclusions highlighted the impact that reconnecting after a sleep cycle has on BLE device power consumption, but they discouraged generalizing their findings because they did not examine other influential factors such as BLE parameters.

Gomez, Oller, and Paradells (2012) noted that, based on settings for common BLE parameters, the theoretical lifetime of a BLE node could range from 2.0 days to 14.1 years. Seeking to investigate that wide range further, they specified a test bed setup and measurement procedure to capture power consumption data with a power analyzer. They examined the length of time between two connection events, known as the connection interval or *connInterval,* and the number of connection events that a slave device can ignore for power savings, known as the connection slave latency or *connSlaveLatency*. Using a TI system-on-a-chip, they stepped through settings of the *connInterval*, from 7.5ms to 4000ms, and settings of the *connSlaveLatency* from 0 to 7, collecting power consumption data. They also stepped through settings of the piconet size and throughput, collecting power consumption data. Their analysis of the data resulted in optimization recommendations for tuning the parameters to achieve efficient power consumption, and suggestions for future research on BLE performance in real-life deployment scenarios.

Ikram and Thornhill (2013) recognized that designers and maintenance personnel need tools to forecast necessary WSN node maintenance. Their work-in-progress paper presented their research on tools for network node lifetime estimation. They noted that lifetime models must reflect the complexity of components - batteries, transceivers, memory, sensors - as well as the impact of protocols and characteristics that vary with time, environment, and usage scenarios. The result of their work was a graphical user interface that allowed designers and maintenance personnel to specify many complex parameters as a front end to complex lifetime models. Their published work was an initial design of this GUI, with references to future research that may include implementation and testing of the design.

Peukert’s Law and Ragone Plots are tools used to forecast performance of certain chemistries of batteries, though not necessarily adapted for the lithium/manganese dioxide chemistry (Buchmann, 2015c; Buchmann, 2015d; Hausmann & Depcik, 2013).

Characteristics of beacon devices in indoor-locating scenarios, which have an impact on battery models, may include temperature of the BD placement location (e.g., high on a wall or ceiling, to avoid vandalism or theft), storage life (issues of self-discharge), connection event traffic and neighbor discovery activity, range and transmit power parameters, duty cycle, battery recovery effect, wake-up spike and capacitor-mitigated peak current draw (Buchmann, 2015b; Buchmann, 2015c; Ikram & Thornhill, 2013; Jensen, 2010; Nguyen, Förster, Puccinelli, Giordano, 2011). Furset and Hoffman (2011), and other researchers, noted that wireless sensor nodes may intermittently impose pulsed peak current loads on coin cell batteries that may significantly shorten battery life (Zhang & Harb, 2013). Ganssle examined covert power consumers, self-discharge, use of capacitors to mitigate peak current loads, and the role of internal resistance (Ganssle, 2012; Ganssle, 2014b; Ganssle, 2014c).

Kindt, Yunge, Diemer, and Chakraborty identified a need for precise Bluetooth Low Energy modeling that accounts for all key BLE parameters and operating modes (Kindt, Yunge, Diemer, & Chakraborty, 2014). They implemented a computational model, written in C, called BLEeMod, based on the TI CC2540 chipset. To encourage its use toward best practices for the field of BLE wireless sensor networks, they published the C code under a license that permits others to incorporate the algorithms in emerging tools.

The BLMod1.0 Artifact Contributes Toward Filling a Void in the Field

The breadth and depth of research presented by the literature of the field assisted in shaping this study's response to its research questions. Researchers have examined the impact of WSN node settings on power consumption and network reliability. They have demonstrated repeatable experimentation methods for measurement and analysis, but they have not specifically examined the full range of BLE beacon node settings on beacon node power consumption. Researchers have examined WSN battery performance. They have demonstrated repeatable experimentation methods for measurement and analysis, but the scope of their work has not included coin cell battery lifetime in micro-location scenarios. The duty cycle characteristics of micro-location scenarios are not yet fully understood. Finally, researchers have established models and tools to automate proven analysis techniques for WSN node and battery lifetimes, and have observed the absence of reliable beacon node battery lifetime predictions, but none have specifically formulated models or tools to accurately predict BLE beacon battery lifetime. The BLEMod1.0 artifact has taken a step forward toward filling this void, contributing a needed tool to the field of study.

Chapter 3 – Methodology

Design science research for information science requires that a proposed artifact must provide a solution to an important and relevant business problem (Hevner, March, Park, & Ram, 2004). As the WSN literature suggests, best practices for reliable deployment of BLE beacon micro-location networks will eventually include accurate predictions of coin cell battery lifetimes. Today, designers have few tools to assist in making accurate predictions, although the predictions are recognized as crucial to reliability of the micro-location networks (Kamath & Lindh, 2012; Kindt, Yunge, Diemer & Chakraborty, 2014). BLMod1.0, as a functional artifact, provides a template, bringing together BLE power consumption analysis and battery models for the purpose of predicting BLE beacon coin cell battery lifetime.

The purpose of this research was to address the research questions specified in Chapter 1. BLMod1.0 is the algorithmic model resulting from this research. The methodology to build the BLMod1.0 predictive tool required three distinct steps. The first step involved designing and implementing a data analysis spreadsheet, providing a basic user interface for designers to access integrated Beacon Device (BD) power consumption data and battery models. This data analysis spreadsheet is the format for the BLMod1.0 predictive tool. The second step involved modeling BD power consumption, based on measurements, published data, statistical and mathematical calculations, and the few available tools. The BLMod1.0 tool was designed to accommodate future power consumption analysis tools and emerging data, as the field evolves. The third step in the methodology involved modeling coin cell batteries that are typically used by BDs. The initial battery models are relatively simple, but the BLMod1.0 tool was designed to accommodate mature battery models in the future, as the field evolves.

BLMod1.0 Methodology Step 1: Designing and Implementing BLMod1.0 Spreadsheet

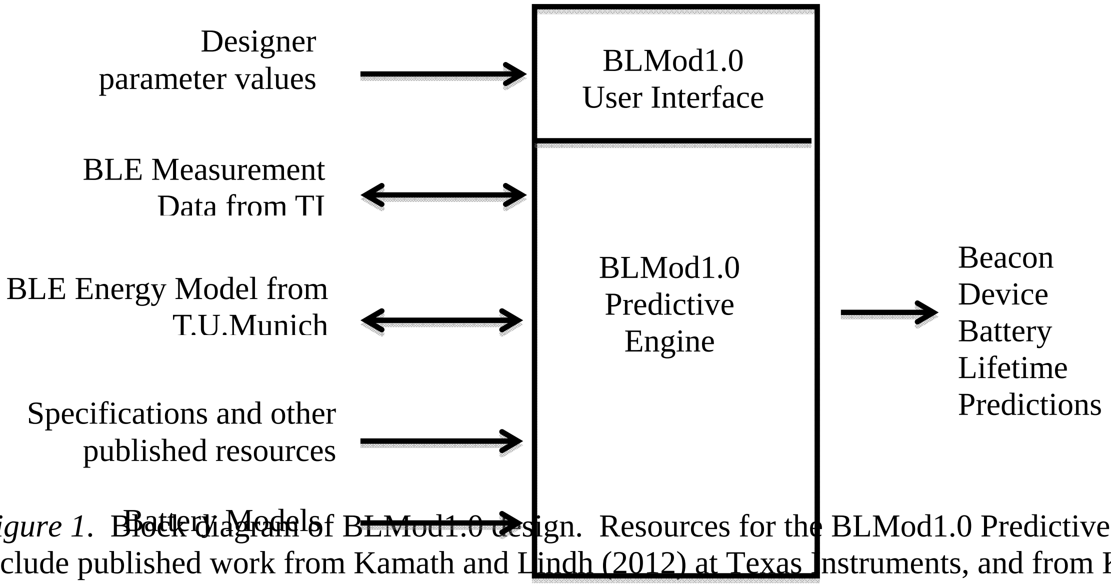


Figure 1. Block diagram of BLMod1.0 design. Resources for the BLMod1.0 Predictive Engine include published work from Kamath and Lindh (2012) at Texas Instruments, and from Kindt et al. (2014) at the Technical University of Munich.

As shown in Figure 1, the BLMod1.0 spreadsheet was designed with two components: the BLMod1.0 User Interface and the BLMod1.0 Predictive Engine. Both components were implemented in a Microsoft Excel® spreadsheet workbook, using labeled cells, formulas, and macros in Visual Basic for Applications (VBA).

The BLMod1.0 User Interface was implemented as the first sheet in the spreadsheet workbook. The User Interface provides labeled cells into which a BD designer may enter configuration parameters that are especially important when modeling BDs used for micro-location applications.

The BLMod1.0 Predictive Engine was implemented as a set of sheets in the spreadsheet workbook. The Predictive Engine leverages input and data exchange with a number of resources, including spreadsheets that implement analysis techniques published by the teams of

Kamath and Lindh (2012), Kindt et al. (2014), and the formal specification from the Bluetooth Special Interest Group (2013). The Predictive Engine also uses data from a sheet, included in the spreadsheet workbook, which provides a template for battery models. Appendix A shows printed examples of the sheets in the BLMod1.0 spreadsheet: the BLMod1.0 User Interface, BLMod1.0 Predictive Engine, Interface to TI resource, Interface to the Technical University of Munich resource, and Battery Models.

The BLMod1.0 Predictive Engine generates beacon device battery lifetime predictions as its output. It was designed with the future possibility of daisy-chaining BLMod1.x output as input into downstream calculators and modeling tools.

An important facet of the BLMod1.0 spreadsheet is that it provides a template to incorporate future research, emerging models, and improved statistical calculations. As best practices mature for micro-location beacon network design and operation, this template format for the BLMod1.0 predictive tool may provide a straightforward interface for adding new operating parameters, values, and battery models.

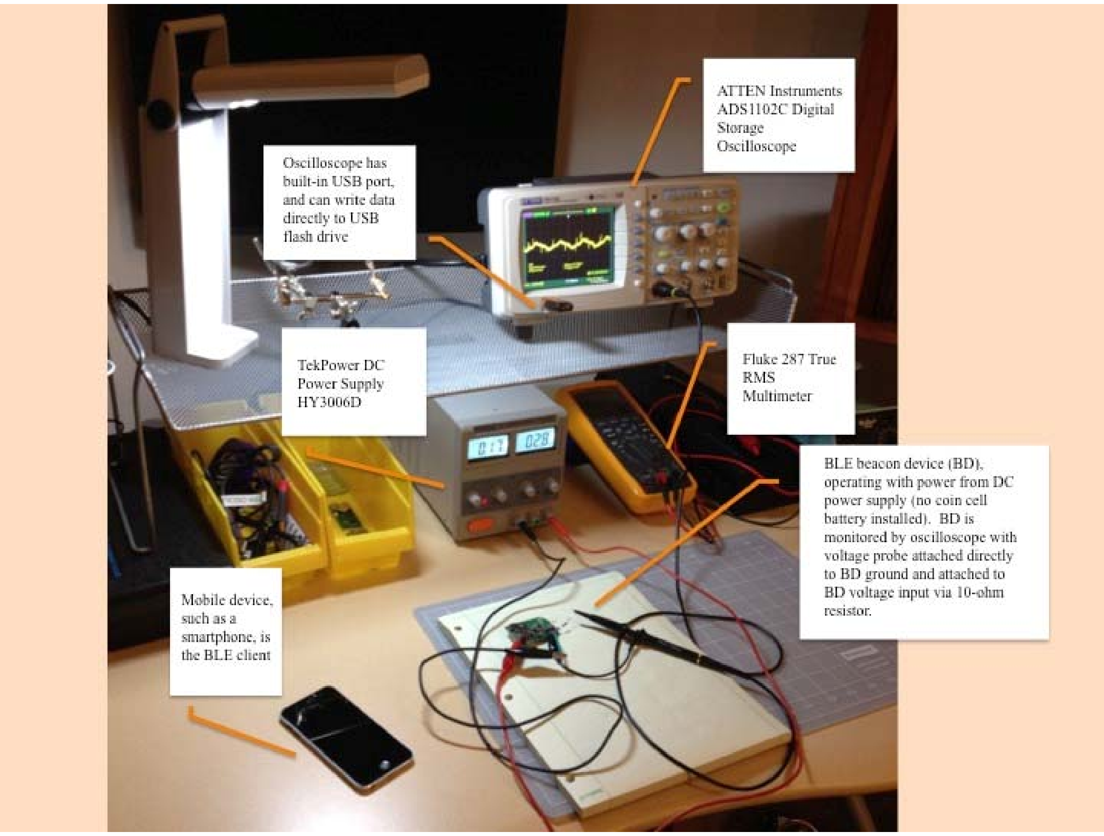
BLMod1.0 Methodology Step 2: Power Consumption Calculation

BLE devices consumed power during specified operational states and a sleep state. Power consumption was measured and calculated, using methods demonstrated and documented by Kamath and Lindh (2012); by Dementyev et al. (2013); and by Kindt et al. (2014). Power consumption calculation was also designed to incorporate current and future data such as specifications of the microcontroller core, peripherals, associated sensors, and power management firmware.

Setup to Measure BD Power Consumption.

The measurement setup was designed to measure and verify beacon device power consumption during expected operating conditions. The design and procedures were similar to those used by Kamath and Lindh (2012) at Texas Instruments, corroborating their findings. The design and procedures were also influenced by the work of Dementyev et al. (2013). Both of these sources have contributed toward best practices in the field. Measurement equipment details are shown in Figure 2. Measurement device connections are shown in Figure 3. Figure 4 shows an annotated example of the oscilloscope data graph of voltage vs time, during beacon device operation.

The measurement setup was built in a professional engineering lab at Alpha and Omega, Inc., a small Denver research and development company (of which the author is co-founder and Chief Technical Officer). The server, where the experimental data was stored, was in this engineering lab. The server was on a local area network (LAN) that was connected to the Internet, and was protected by a firewall and password security. Company staff shared this LAN, but the server and its data were accessible only by the researcher working on this study.



ATTEN Instruments ADS1102C Digital Storage Oscilloscope

Oscilloscope has built-in USB port, and can write data directly to USB flash drive

TekPower DC Power Supply HY3006D

Fluke 287 True RMS Multimeter

BLE beacon device (BD), operating with power from DC power supply (no coin cell battery installed). BD is monitored by oscilloscope with voltage probe attached directly to BD ground and attached to BD voltage input via 10-ohm resistor.

Mobile device, such as a smartphone, is the BLE client

Figure 2. Measurement setup for BLMod1.0 research study. This figure shows the specific measurement equipment used for the study.

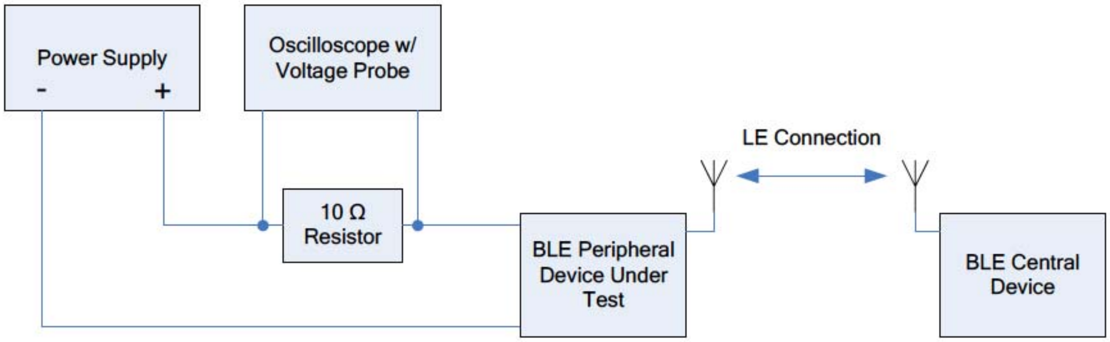


Figure 3. Block diagram for BLMod1.0 study measurements, from Kamath and Lindh (2012). This diagram shows measurement device connections.

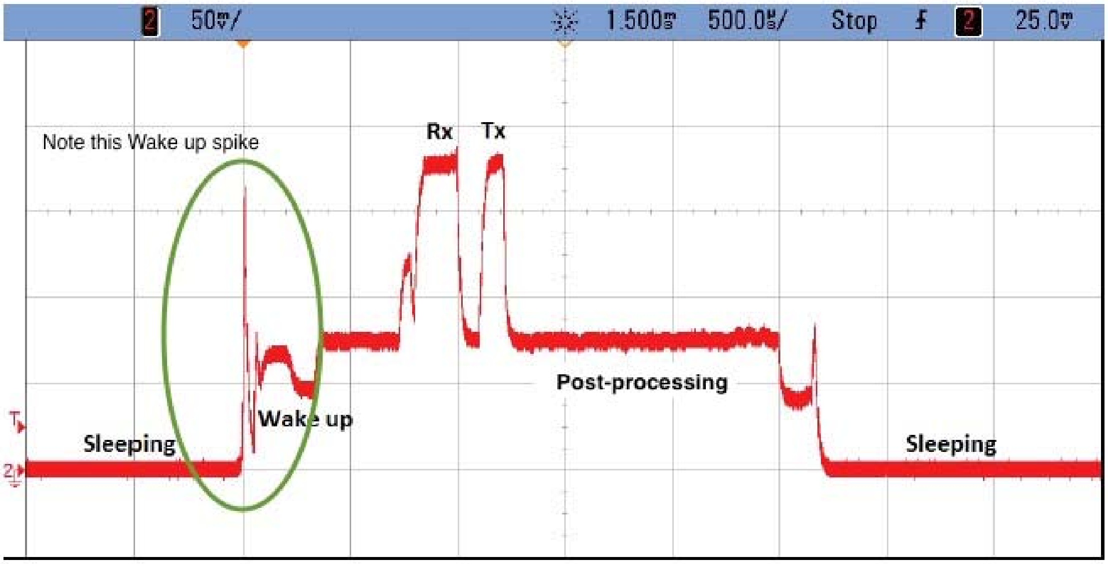


Figure 4. Annotated oscilloscope screen capture, adapted from Kamath and Lindh (2012). This diagram shows the operational states for BLE and the sleep state, for an empty packet transfer, highlighting a significant spike in power consumption when initiating the wake-up state.

Procedures for measuring power consumption in the eight operational states and the sleep state included these measurement methods for three commercial Beacon Devices (BDs). For anonymity, the BDs were referred to as BD#1, BD#2, and BD#3 throughout this study. BD#1 was based on the TI CC2541 MCU (microcontroller), using a CR2032 coin cell battery. BD#2 and BD#3 were based on the Nordic Semiconductor nRF51822 MCU, respectively using CR2032 and CR2477 coin cell batteries. The following measurement methods were used:

- Measured BD nodes' active current with an oscilloscope, capturing voltage and current as a function of time. Used a 10-ohm resistor inline with a voltage probe, as a reliable alternative to using a current probe. For this analysis technique, voltage is measured as a function of time, then divided by the resistance (Ohm's law, I=V/R) to calculate the current consumed as a function of time.
- Measured BD nodes' sleep current with a Digital Multimeter (DMM), collecting precise current measurements ranging between the mA-range and the µA-range in cycles that are a few seconds in length.
- Used a DC power supply, instead of a battery, to collect data that is not compromised by variability in battery performance (reliably addressing battery performance variance in the model, instead of in the measurement setup itself).
- Used a smartphone running a BLE app as a BLE client, connecting to the BD as a mobile device does in a micro-location scenario.
- Logged experimental data from the digital oscilloscope onto a USB flash drive, using a port built into the oscilloscope. Logged experimental data from the DMM into the DMM's internal data logger. Experimental data was transferred to and stored on a local server.

Integration of the BLE Energy Model.

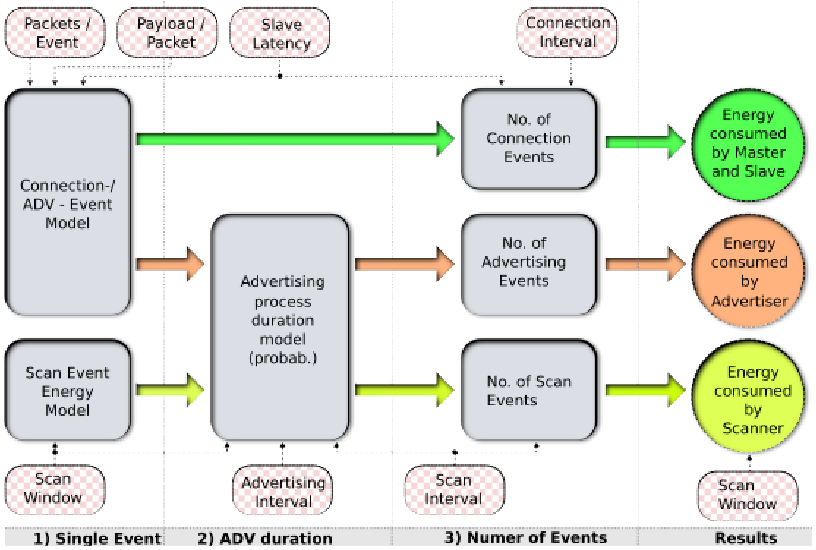


Figure 5. Block diagram of BLE Energy Model designed by Kindt et al. (2014).

The BLE Energy Model, shown in Figure 5, was designed and implemented by a team of researchers at the Technische Universität München/Technical University of Munich (Kindt, Yunge, Diemer & Chakraborty, 2014). This team incorporated thorough statistical analysis into the BLE Energy Model, implementing their tool in a C application called BLEeMod. To utilize their work, the methodology for this research study required porting the BLEeMod C application to Microsoft Excel functions and macros. This port was implemented and tested as part of the development of BLMod1.0, with use of resources provided by Alpha and Omega, Inc.

Appendix B lists the BLE Energy Model files, along with their counterparts in the Excel implementation for BLMod1.0. Appendix B also includes details about access to the source code and spreadsheets for BLE Energy Model (Technical University of Munich) and BLMod1.x (Alpha and Omega, Inc.).

Specification resources.

In addition to using measured power consumption data for BDs and using statistically calculated power consumption data, specifications and further calculations were used to augment, analyze, verify, and correlate power consumption data (Donovan, 2011). The Bluetooth Special Interest Group published the Bluetooth specification version 4.1 (2013), with details about expected and theoretical performance of Bluetooth Low Energy devices, which was used as a resource for this research study.

One of the BDs was based on the TI CC2541 Microcontroller (MCU). Texas Instruments, Inc. published a complete specification for the MCU, which was used in this research study, including details about sensors, regulating capacitors, and other covert energy consumers that are packaged with the CC2541 in TI’s SensorTag™ line of commercial Bluetooth Low Energy devices (Texas Instruments, 2013). TI also published an Application Note and spreadsheet calculator (Kamath & Lindh, 2012), which this research has relied upon extensively, and a White Paper detailing an analysis of peak current draw for coin cell batteries (Jensen, 2010).

Two of the BDs were based on the Nordic nRF51822 microprocessor. Nordic Semiconductor published a complete specification for the MCU (Nordic Semiconductor, 2014), which was used in this research study. Nordic Semiconductor also published a paper detailing an analysis of coin cell batteries under pulsed loads such as Bluetooth Low Energy devices (Furset & Hoffman, 2011).

Battery manufacturers have published specifications about the technical performance details of their batteries. For aspects of this research study that depended upon performance of CR2032 and CR2477 batteries, this work drew information from specifications by Energizer, Duracell, Maxell, and Renata (Energizer Holdings, n.d.; Duracell, n.d.; Maxell, 2012; Panasonic, 2005a; Panasonic, 2005b; Renata, 2006).

BLMod1.0 Methodology Step 3: Coin Cell Battery Model

Coin cell batteries are a typical power source for beacon devices, having emerged as a popular battery for low power electronics over the past ten years (Powers, 1995). Research to develop the BLMod1.0 included the study of lithium/manganese dioxide (Li/MnO2) CR2032 and CR2477 coin cell batteries, representing two ends of the capacity spectrum and the size spectrum of coin cell batteries currently used in commercial beacon devices. CR2032 batteries studied in this research were 3V coin cell batteries with a rated capacity of 240 mAh (Energizer Holdings, n.d.). Once a CR2032 battery has been discharged to 2.0v, it is considered no longer viable as a power source (Energizer Holdings, n.d.; Ganssle, 2014a). CR2477 batteries studied in this research were 3V coin cell batteries with a rated capacity of 950 mAh (Renata, 2006). Once a CR2477 battery has been discharged to 2.0v, it is considered no longer viable as a power source (Ganssle, 2014a ; Renata, 2006). As shown in Figure 6, the physical sizes of these two batteries are significantly different; measured dimensions of the CR2032 batteries are 20mm diameter and 3.2mm height, while the CR2477 batteries are 24.5mm diameter and 7.7mm height. Use of the larger-capacity CR2477 battery impacts BD design, requiring a much larger printed circuit board footprint than does the lower-capacity CR2032 battery. There is also a cost difference between the two types of batteries; one Energizer CR2032 battery costs approximately US$.33 while one Renata CR2477 battery costs approximately US$1.74 (Digikey Electronics, 2015; Mouser Electronics, 2015).

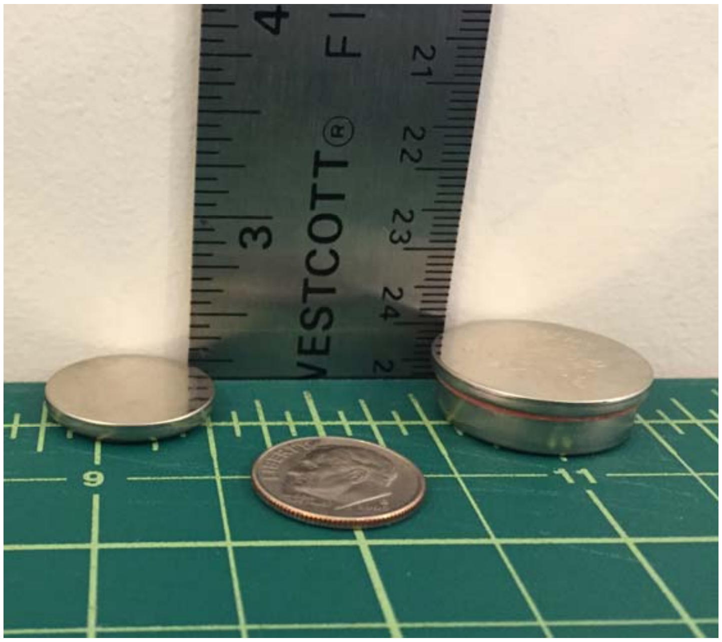


Figure 6. Photo of CR2032 and CR2477 coin cell batteries, with a US dime and a ruler. Note the relative size of the coin cells, especially the height of the CR2477 battery.

Battery Model #1 uses a simple approach. Building upon the manufacturing specification that the coin cell battery is considered dead at 2.0V, and the general operating range of 4-12 mA per BLE connection event and 0.01-0.05mA per BLE connection interval, the battery model started with the simple formula of 80% manufacturer capacity available to a beacon device (Dementyev, Hodges, Taylor & Smith, 2013; Diewald, 2013; Kamath & Lindh, 2012).

Battery Model #2 reflects capacity under a pulsed load that is typical for beacon devices used in micro-location scenarios. Pulsed load usage reduces battery lifetime more rapidly than, for example, low-amperage continuous usage. Other researchers' work suggested an average 40% reduction in battery capacity; some researchers are converging on statistical models that incorporate the impact of neighbor discovery (Ganssle, 2012; Ganssle, 2014b; Jensen, 2010;

Kamath & Lindh, 2012; Kindt, Yunge, Diemer & Chakraborty, 2014; Liu & Chanfeng, 2012a; Liu & Chanfeng, 2012b).

Battery Model #3 is emerging as a model to consider, based on recent work of Ganssle (2014c). Ganssle questioned the longtime assumption that internal resistance provides an accurate way to model coin cell battery performance, especially when the coin cell is powering an MCU with a low background load and intermittent pulse loads. Ganssle identified behavior in the battery chemistry that reduces capacity by an additional 10% compared with Battery Model #2.

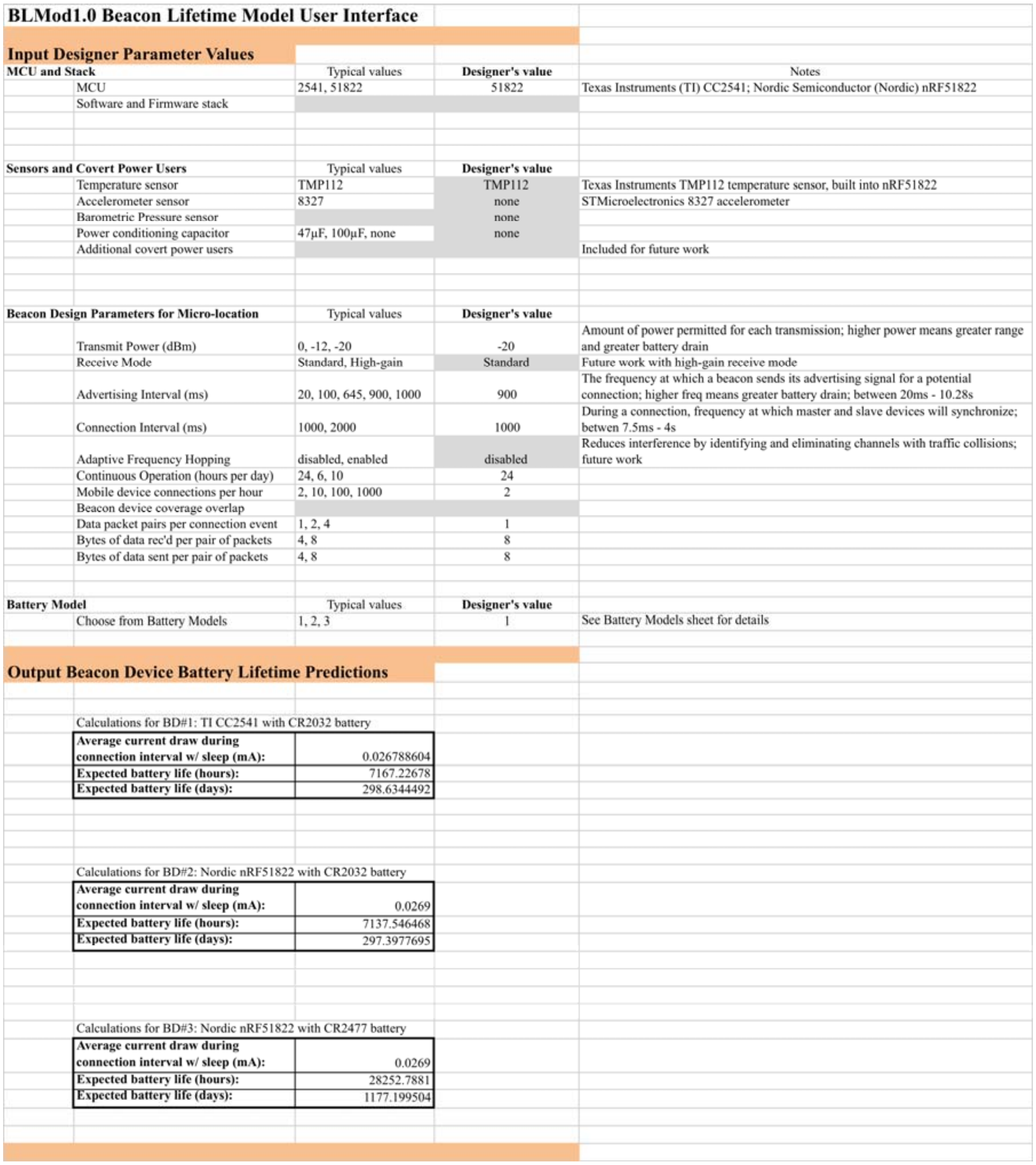
As stated earlier, experimental uncertainty was anticipated by the overall methodology, and is one reason the BLMod1.0 predictive tool was implemented as a template (Feeney, Andersson & Starborg, 2012). Anticipating that battery researchers will continue to develop increasingly accurate battery models for BLE beacon coin cell usage, the BLMod1.0 template is configured to incorporate those emerging models into version 1.x, replacing the initial Battery Models used in version 1.0.

Chapter 4 – Project Analysis and Results

The BLMod1.0 predictive tool, implemented as a spreadsheet worksheet during this study, provides an interface for designers to set operating parameters that accurately reflect micro-location beacon usage scenarios. Furthermore, as beacon devices are improved for efficiency in the future, such as using capacitors to maximize battery capacity under BLE pulsed loads, leveraging MCU low power modes, and optimizing Bluetooth adaptive frequency hopping, designers may easily adjust values to accurately represent the device operating state (Golmie, Rebala & Chevrollier, 2003; Jensen, 2010; Samek, 2007).

Data Excerpts and Battery Life Predictions

For this research study, the BLMod1.0 predictive tool calculated battery lifetime in micro-location usage scenarios. Its calculations were based on measured and specified performance values for BD#1, BD#2 and BD#3, and its calculations used three battery models.



BLMod1.0 Beacon Lifetime Model User Interface

Input Designer Parameter Values

MCU and Stack	Typical values	Designer's value	Notes
MCU	2541, 51822	51822	Texas Instruments (TI) CC2541; Nordic Semiconductor (Nordic) nRF51822
Software and Firmware stack			

Sensors and Covert Power Users	Typical values	Designer's value	
Temperature sensor	TMP112	TMP112	Texas Instruments TMP112 temperature sensor, built into nRF51822
Accelerometer sensor	8327	none	STMicroelectronics 8327 accelerometer
Barometric Pressure sensor		none	
Power conditioning capacitor	47µF, 100µF, none	none	
Additional covert power users			Included for future work

Beacon Design Parameters for Micro-location	Typical values	Designer's value	
Transmit Power (dBm)	0, -12, -20	-20	Amount of power permitted for each transmission; higher power means greater range and greater battery drain
Receive Mode	Standard, High-gain	Standard	Future work with high-gain receive mode
Advertising Interval (ms)	20, 100, 645, 900, 1000	900	The frequency at which a beacon sends its advertising signal for a potential connection; higher freq means greater battery drain; between 20ms - 10.28s
Connection Interval (ms)	1000, 2000	1000	During a connection, frequency at which master and slave devices will synchronize; betwen 7.5ms - 4s
Adaptive Frequency Hopping	disabled, enabled	disabled	Reduces interference by identifying and eliminating channels with traffic collisions; future work
Continuous Operation (hours per day)	24, 6, 10	24	
Mobile device connections per hour	2, 10, 100, 1000	2	
Beacon device coverage overlap			
Data packet pairs per connection event	1, 2, 4	1	
Bytes of data rec'd per pair of packets	4, 8	8	
Bytes of data sent per pair of packets	4, 8	8	

Battery Model	Typical values	Designer's value	
Choose from Battery Models	1, 2, 3	1	See Battery Models sheet for details

Output Beacon Device Battery Lifetime Predictions

Calculations for BD#1: TI CC2541 with CR2032 battery

Average current draw during connection interval w/ sleep (mA):	0.026788604
Expected battery life (hours):	7167.22678
Expected battery life (days):	298.6344492

Calculations for BD#2: Nordic nRF51822 with CR2032 battery

Average current draw during connection interval w/ sleep (mA):	0.0269
Expected battery life (hours):	7137.546468
Expected battery life (days):	297.3977695

Calculations for BD#3: Nordic nRF51822 with CR2477 battery

Average current draw during connection interval w/ sleep (mA):	0.0269
Expected battery life (hours):	28252.7881
Expected battery life (days):	1177.199504

Figure 7. Screenshot of BLMod1.0 User Interface sheet, with configuration parameters and battery lifetime predictions. This shows a sample configuration calculated for three beacon devices and one battery model.

Figure 7 shows the BLMod1.0 User Interface after it was used to calculate the battery lifetime prediction for a beacon device. The top area of the sheet is the area where configuration parameters were entered as input. Parameter values were entered in the “Designer’s value” cells.

The bottom area of the sheet is where the output from the Predictive Engine calculations are displayed. Because this is the first version of BLMod1.x, certain cells are grayed out to show that they are in the framework for future inclusion in calculations, but they are not included in calculations at this time.

For this research study, many configurations of parameters were tested. Data is presented in Appendix C. Figure 8 illustrates calculated average current draw for three parameter configurations for each beacon device in three micro-location scenarios. Figure 9 shows the predicted coin cell battery life for each of those scenarios.

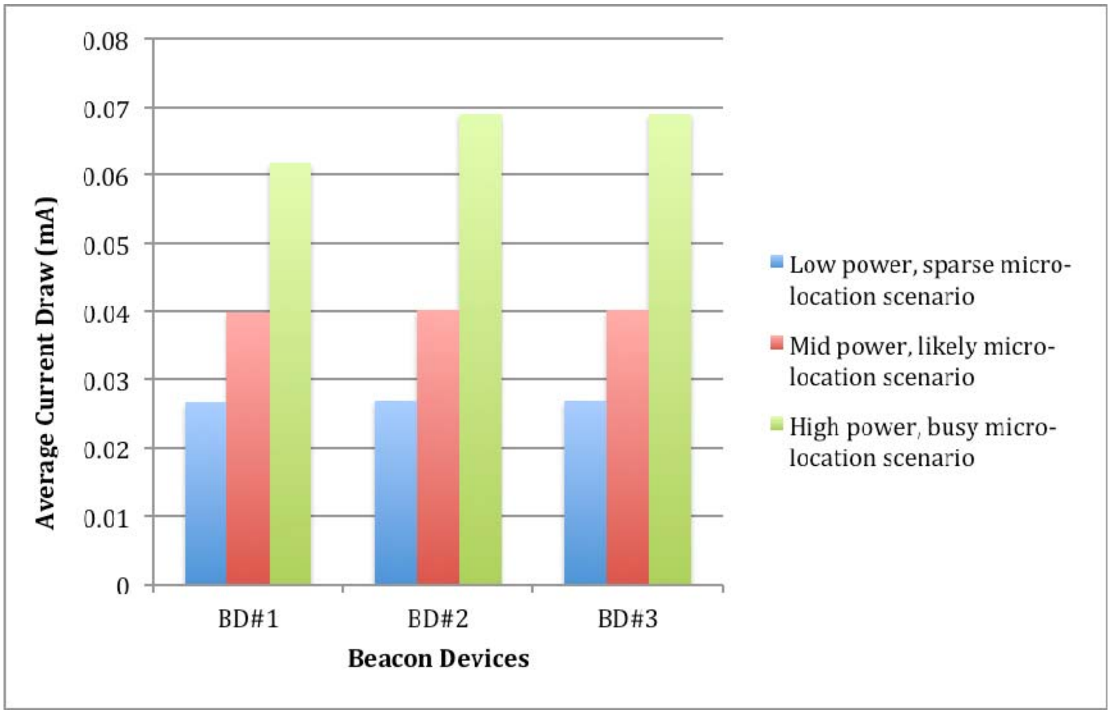


Figure 8. Average current draw, calculated by BLMod1.0, for three micro-location scenarios.

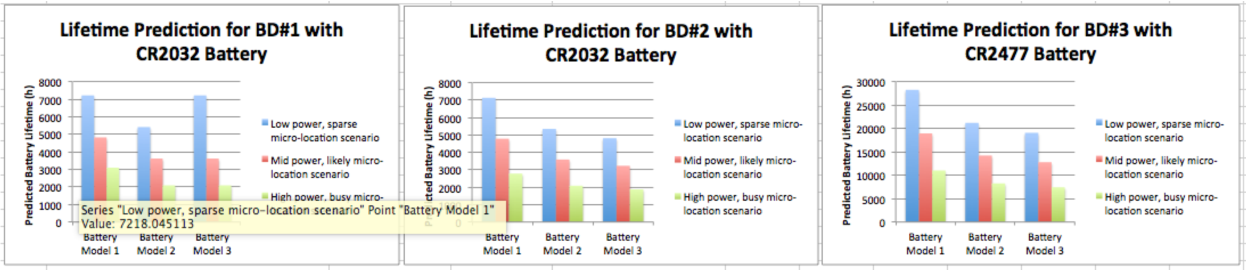


Figure 9. Battery lifetime predictions from BLMod1.0, for three beacon devices, three micro-location scenarios, and two batteries.

Notably, using a micro-location usage scenario that may reasonably be expected in a real world deployment, BD#1 and BD#2 were predicted to have CR2032 battery life ranging from 300 days under the most optimistic battery model to 78 days in the most pessimistic battery model. Using that same usage scenario, BD#3 was predicted to have CR2477 battery life ranging from 1177 days to 309 days.

Comparing BLMod1.0 Results to Others in the Field

Collecting analysis data from BLMod1.0, by using various parameter values and scenarios, allowed this research study's results to be compared with other researchers' published results. BLMod1.0 results corroborated published results from Kamath and Lindh (2012), with small adjustments for a 5µs measurement difference for the pre-sleep state, and measurement variations with and without the 47µF capacitor that comes standard on the CC2541 board. BLMod1.0 results first corroborated published results from Kindt et al. (2014), then followed with new calculations replacing their MSU parameter extraction with parameters estimated from MSU specifications (Nordic Semiconductor, 2014). The Kindt et al. results were especially notable because that team of researchers presented a model that incorporated extensive support for precise parameter values. BLMod1.0 built upon that published work.

BLMod1.0 results corroborated and also predictably differed from results published by Aislelabs (2014). The Aislelabs team's methodology was to set transmit power (0dBm, -12 dBm, -20dBm) and advertising interval (100ms, 645ms, 900ms) parameters; then they operated the beacons 24x7 for 3 months while measuring battery levels. With this data, the team estimated current draw and extrapolated to determine battery and beacon lifetime predictions. Adjusting for the difference in methodologies, the results were comparable. However, the Aislelabs methodology assumptions about battery performance and lack of support for analysis of additional parameters that are significant for micro-location scenarios resulted in anticipated differences.

Key Findings

Analysis of the data generated by the BLMod1.0 predictive tool suggested three key findings:

(1) The wake-up spike (highlighted in Figure 4) had a relatively low impact in usage scenarios with lengthy sleep cycles and relatively few wake-up states, but its power consumption cost accumulated to have a significant impact for typical micro-location usage scenarios with a high occurrence of wake-up states.

(2) Parameter optimization, addition of conditioning capacitors, and use of other techniques that reduce a beacon device's average current consumption had the most significant impact on extending coin cell battery lifetime. This finding corroborated the work on conditioning capacitors by Jensen (2010), which suggested potential gains of

approximately 40% by using conditioning capacitors to reduce impact of peak loads. However, hardware and software techniques for reducing average current consumption may also add covert power users, so a provision has been made for future covert power user analysis within the BLMod1.0 predictive tool.

(3) Published battery life predictions that are not based on thorough, realistic parameter configurations for beacon devices may not be accurate when those beacon devices are deployed in real world micro-location scenarios.

Chapter 5 – Jesuit Values

Two key values in Jesuit higher education are *cura personalis* and *contemplatives in action* (Regis University, 2015). *Cura personalis* means "care for the person" -- caring for the mind, body, and spirit of people. *Contemplatives in action* refers to pairing action with the study of social issues. These Jesuit values acknowledge the stewardship responsibilities that technologists have when developing emerging technologies. These Jesuit values have influenced this research study because wasted or dangerously disposed coin cell batteries potentially harm people and the earth, and because coin cell battery ingestion is a growing health concern.

Toxic waste from batteries.

This research study provides tools to help beacon device (BD) designers accurately predict battery lifetime in BDs used for micro-location. The BLMod1.0 predictive tool helps designers reduce the number of discarded coin cell batteries by helping them to optimize battery use and to accurately predict the need for replacement batteries.

Single-use batteries, also known as primary batteries, disposable batteries, or non-rechargeable batteries, are discarded at a high rate, generally co-mingled with garbage in landfills and in garbage dumps. Buchmann (2015a) estimated that, in fleet applications or critical missions, primary batteries are frequently disposed of with 50% of their capacity remaining. The abundance of caution that leads WSN maintainers to replace batteries before they are depleted results in excessive waste. In some developed countries, there are recycling facilities that specifically handle end-of-life for lithium-metal primary batteries, such as the coin cell batteries analyzed in this work (Marlair & Lisbona, 2012). However, batteries sent to those facilities are not necessarily collected from residential or business consumers; consumer trash typically becomes a part of societal e-waste. E-waste may be processed domestically in developed countries; sometimes it is exported to developing countries where its hazards may not be adequately addressed. E-waste export to developing countries is a huge and growing societal problem (Bradley, 2014; Interagency Task Force on Electronics Stewardship, 2011; Lisbona & Snee, 2011; Lundgren, 2012; Terada, 2012). Advances in wireless sensor networks are likely to increase use of batteries for deployed sensors, which may also increase the unfortunate global e-waste problem in developing and developed countries.

Lithium-metal batteries are manufactured with materials and chemicals that may be flammable and hazardous to people and the environment. Lithium-metal batteries include manganese dioxide, carbonmonofluoride, iron disulphide, vanadium pentoxide, copper oxide, copper oxyphosphate, thionyl chloride, and organic solvents (Lisbona & Snee, 2011). Hazards of these materials include highly flammable hydrogen gas formed by contact between lithium-metal and water. These water-reactive toxic materials greatly complicate fire-fighting options when a fire does erupt from lithium-metal batteries, or when such batteries are included with incinerated trash (Bradley, 2014; Lisbona & Snee, 2011). Hazards also include a high incidence of flammability due to internal short circuits and multi-battery contact short circuits, as well as projectiles ejected from fires that involve lithium batteries. Pallets of new lithium-metal batteries must meet certain cargo packaging criteria for safety, following several incidents of such pallets of batteries catching fire as airplane cargo (International Civil Aviation Organization, 2014a; International Civil Aviation Organization, 2014b; Lisbona & Sneet, 2011). Tragically, children and adults in developing countries, who routinely burn trash that includes domestic and international e-waste, may be injured by the toxic smoke, toxic gases, and battery projectiles from burning lithium-metal batteries (Bradley, 2014; Interagency Task Force on Electronics Stewardship, 2011; Ives, 2014; Lundgren, 2012; Terada, 2012).

Health risks from coin cell battery ingestion.

Coin cell batteries have other health risks as well. Because coin cell batteries are relatively small and smooth components, children sometimes mistake them for a treat and swallow the batteries. Adults with mental impairment (e.g., someone with dementia who is also handling hearing aid coin cell batteries) and adults who attempt to "test" a battery by placing it in their mouth are at risk of swallowing coin cell batteries. Coin cell battery ingestion can cause life-threatening burns and other injuries to a child or adult's esophagus if the battery is not removed within two hours (National Capital Poison Center, n.d.a). During each year between 2004 and 2013, over 3000 coin cell battery ingestions were reported in the United States annually, including more than 130 fatalities during that time (Litovitz, Whitaker, Clark, White & Marsolek, 2010; National Capital Poison Center, n.d.b). Coin cell batteries may also cause serious injuries if inserted into a person's nose or ear (National Capital Poison Center, n.d.a).

Responsibilities.

With Jesuit values as a guide, technologists must embrace a *cura personalis* responsibility to care for the people, stemming the tide of wasted, underutilized batteries, and protecting people from battery hazards. Technologists must embrace a responsibility to *contemplate* the challenges that grow with technology advancements, and *take action* to mitigate damage, hazards, and harm from those advances (Lundgren, 2012). Such responsibility calls for best practices in each field of technology advancement. The BLMod1.0 predictive tool contributes toward Wireless Sensor Network (WSN) best practices by empowering designers to reduce toxic waste, and to more precisely manage batteries that may be harmful in certain environments.

Chapter 6 – Conclusions and Further Work

This research study has addressed all three key research questions that were articulated in Chapter 1. The research study has resulted in the design and implementation of BLMod1.0, a predictive tool that designers may use to predict coin cell battery lifetime for beacon devices in micro-location scenarios.

When functioning in a micro-location scenario, how much power does each BLE device beacon consume as it cycles through its states? The data that answers this question precisely is displayed in the **Interface to TI Resource** and **Interface to TUMunich Resource** sheets in the BLMod1.0 spreadsheet workbook. The data is derived from measurements, specifications, and calculations, based upon the parameter values provided by the designer as input to BLMod1.0. Typically, a BD operating in a micro-location scenario has parameters that are mid-power and mid-busy with opportunistic connections. Such a BD may consume 8-10mA of current during the states between wake-up and pre-sleep, then on the order of 0.001mA of current during the sleep state. The average current consumed in a 1000ms connection interval, with both awake and sleep states, could typically be 0.05-0.08mA. If the micro-location network is very busy with mobile device traffic, exchanges more than 8 bytes of data between the BD and each mobile device, or advertises at a high frequency, current consumption will be measurably higher.

Based on initial battery models and designed to incorporate emerging, improved battery models, what is the anticipated coin cell battery lifetime for each BLE beacon device that is tested in a micro-location scenario? The **BLMod1.0 User Interface** sheet in the spreadsheet workbook displays beacon device battery lifetime predictions in its output area. These results are based, in part, on the models that are represented in the **Battery Models** sheet, which is configured to incorporate improved battery models as those become available. Typically, a BD with an average of 0.06mA current consumed during each connection interval will deplete a CR2032 coin cell battery in approximately 4000 hours or a CR2477 coin cell battery in less than 16,000 hours. If the micro-location network remains on 24 hours per day, advertising even when there are no mobile devices available for hours, or if the number of mobile devices is in the hundreds of connections per hour, batteries will be depleted measurably sooner.

Does BLMod1.0 accurately predict BLE beacon device lifetime? Based on research results corroborated with the results of other published findings, initial indications suggest that BLMod1.0 does accurately predict BLE beacon device lifetime. However, this is an emerging field, and this research reflects that there is some experimental uncertainty accompanying this first instantiation of the Beacon Lifetime Model. One achievement of this model’s design is its extensibility; it is designed to incorporate improved, emerging battery models, statistical calculation functions, and predictive engines.

While completing this research, many interesting questions arose that suggested directions for future research and refinement of measurement methodologies. This initial model works with BLE parameters such as transmit power, advertising interval, and connection interval. Valid questions arose about working with additional parameters, such as adaptive frequency hopping and receive mode. Further questions arose about integrating power consumption attributes of the firmware stack, on-board sensors such as those for temperature and accelerometer, and other covert power users that may impact long-term battery performance. Those questions were identified, documented, and in some cases incorporated into the BLMod1.0 spreadsheet workbook.

As a functional artifact, BLMod1.0 provides an initial predictive tool for BLE designers working with micro-location applications. BLMod1.0 is making a contribution toward solving this important and relevant information science problem. Therefore this design science research study has made an initial and valuable contribution to the body of knowledge in this field.

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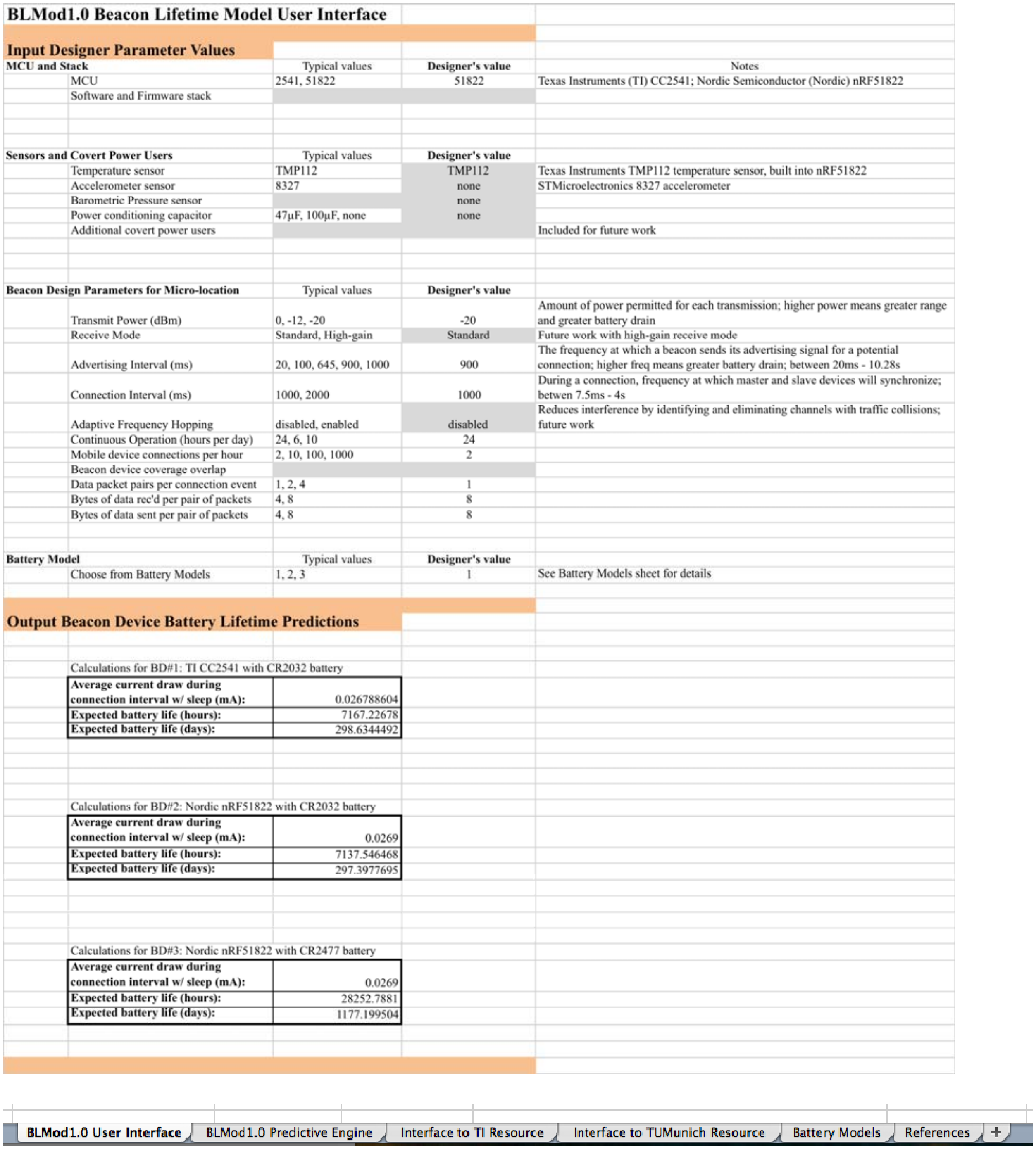
Appendix A

BLMod1.0 Spreadsheet Workbook

Tab: BLMod1.0 User Interface



BLMod1.0 Beacon Lifetime Model User Interface

Input Designer Parameter Values

MCU and Stack	Typical values	**Designer's value**	Notes
MCU	2541, 51822	51822	Texas Instruments (TI) CC2541; Nordic Semiconductor (Nordic) nRF51822
Software and Firmware stack			
Sensors and Covert Power Users	Typical values	**Designer's value**	
Temperature sensor	TMP112	TMP112	Texas Instruments TMP112 temperature sensor, built into nRF51822
Accelerometer sensor	8327	none	STMicroelectronics 8327 accelerometer
Barometric Pressure sensor		none	
Power conditioning capacitor	47µF, 100µF, none	none	
Additional covert power users			Included for future work
Beacon Design Parameters for Micro-location	Typical values	**Designer's value**	
Transmit Power (dBm)	0, -12, -20	-20	Amount of power permitted for each transmission; higher power means greater range and greater battery drain
Receive Mode	Standard, High-gain	Standard	Future work with high-gain receive mode
Advertising Interval (ms)	20, 100, 645, 900, 1000	900	The frequency at which a beacon sends its advertising signal for a potential connection; higher freq means greater battery drain; between 20ms - 10.28s
Connection Interval (ms)	1000, 2000	1000	During a connection, frequency at which master and slave devices will synchronize; betwen 7.5ms - 4s
Adaptive Frequency Hopping	disabled, enabled	disabled	Reduces interference by identifying and eliminating channels with traffic collisions; future work
Continuous Operation (hours per day)	24, 6, 10	24	
Mobile device connections per hour	2, 10, 100, 1000	2	
Beacon device coverage overlap			
Data packet pairs per connection event	1, 2, 4	1	
Bytes of data rec'd per pair of packets	4, 8	8	
Bytes of data sent per pair of packets	4, 8	8	
Battery Model	Typical values	**Designer's value**	
Choose from Battery Models	1, 2, 3	1	See Battery Models sheet for details

Output Beacon Device Battery Lifetime Predictions

Calculations for BD#1: TI CC2541 with CR2032 battery

Average current draw during connection interval w/ sleep (mA):	0.026788604
Expected battery life (hours):	7167.22678
Expected battery life (days):	298.6344492

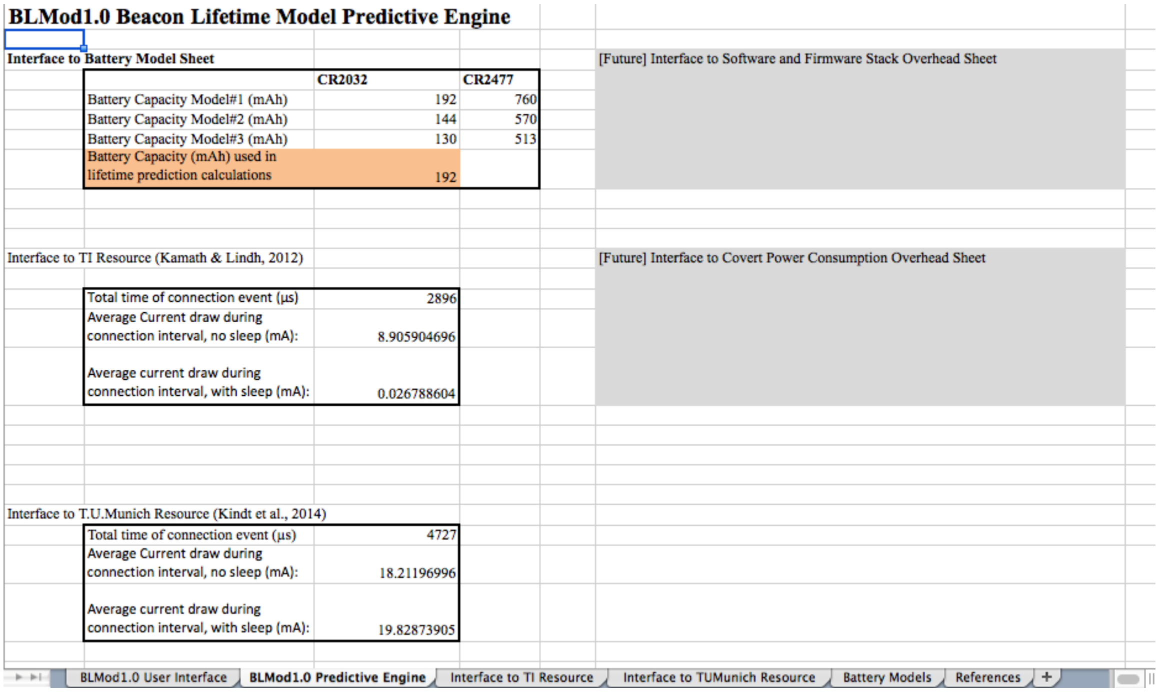
Calculations for BD#2: Nordic nRF51822 with CR2032 battery

Average current draw during connection interval w/ sleep (mA):	0.0269
Expected battery life (hours):	7137.546468
Expected battery life (days):	297.3977695

Calculations for BD#3: Nordic nRF51822 with CR2477 battery

Average current draw during connection interval w/ sleep (mA):	0.0269
Expected battery life (hours):	28252.7881
Expected battery life (days):	1177.199504

Tab: BLMod1.0 Predictive Engine



BLMod1.0 Beacon Lifetime Model Predictive Engine

Interface to Battery Model Sheet

	CR2032	CR2477
Battery Capacity Model#1 (mAh)	192	760
Battery Capacity Model#2 (mAh)	144	570
Battery Capacity Model#3 (mAh)	130	513
Battery Capacity (mAh) used in lifetime prediction calculations	192	

[Future] Interface to Software and Firmware Stack Overhead Sheet

Interface to TI Resource (Kamath & Lindh, 2012)

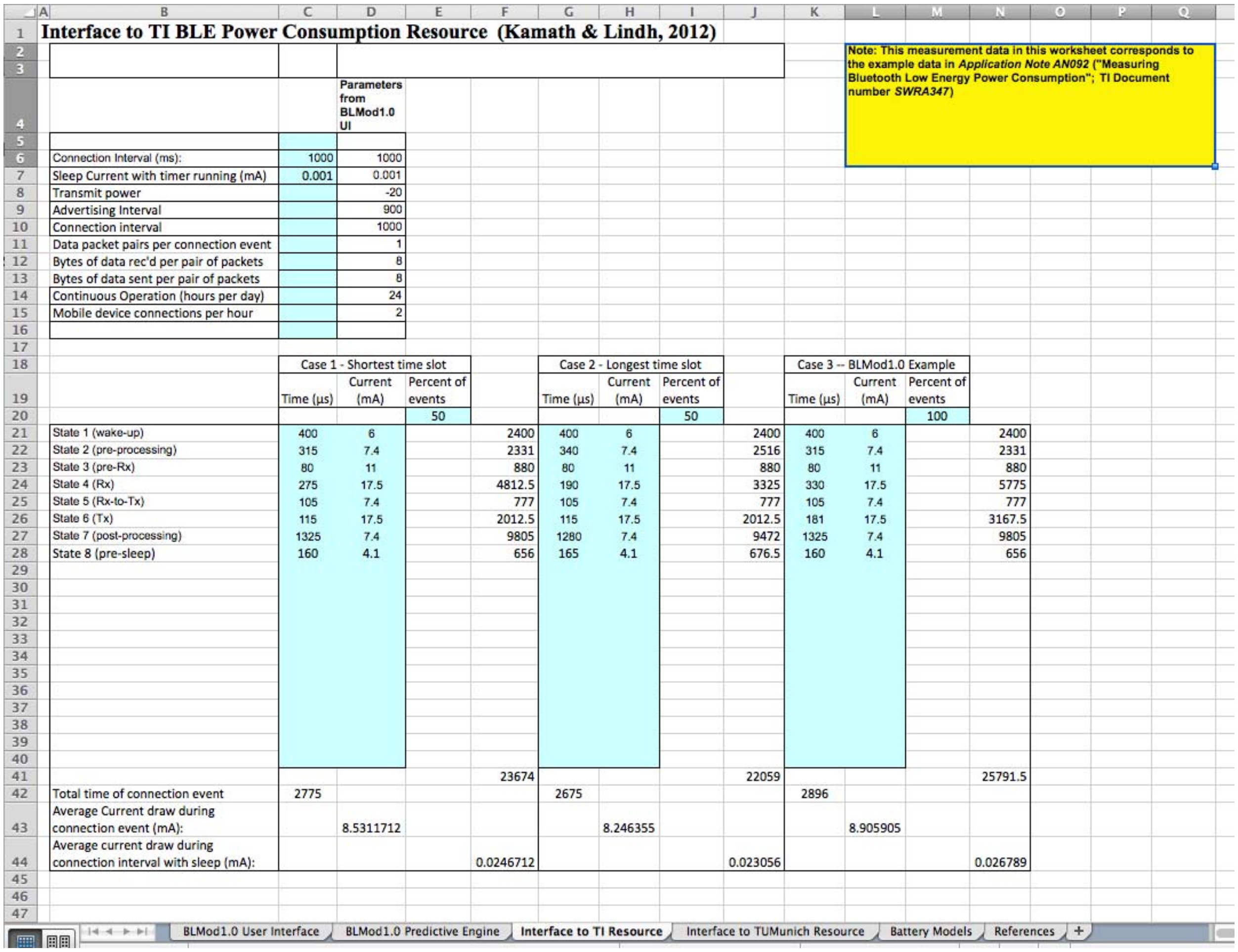
Total time of connection event (µs)	2896
Average Current draw during connection interval, no sleep (mA):	8.905904696
Average current draw during connection interval, with sleep (mA):	0.026788604

[Future] Interface to Covert Power Consumption Overhead Sheet

Interface to T.U.Munich Resource (Kindt et al., 2014)

Total time of connection event (µs)	4727
Average Current draw during connection interval, no sleep (mA):	18.21196996
Average current draw during connection interval, with sleep (mA):	19.82873905

Tab: Interface to TI Resource



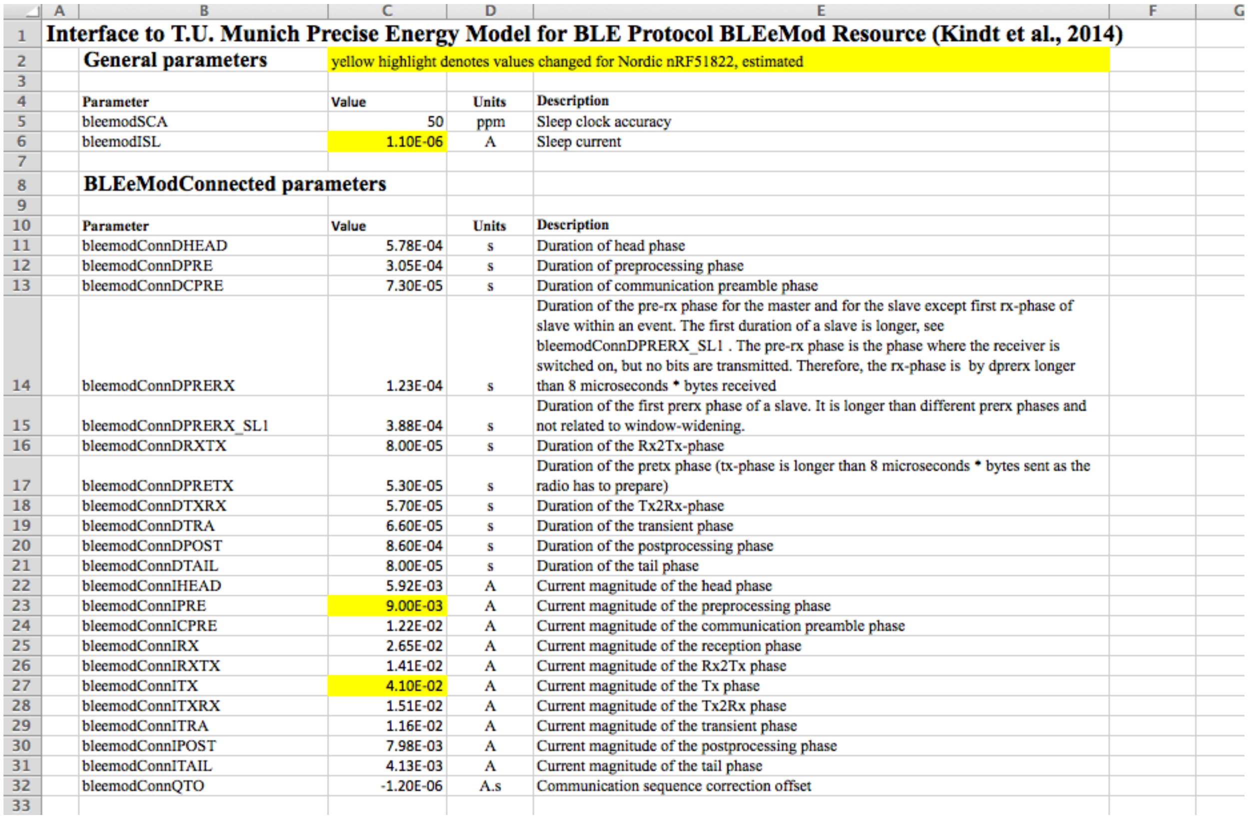
Interface to TI BLE Power Consumption Resource (Kamath & Lindh, 2012)

Note: This measurement data in this worksheet corresponds to the example data in *Application Note AN092* ("Measuring Bluetooth Low Energy Power Consumption"; TI Document number *SWRA347*)

		Parameters from BLMod1.0 UI
Connection Interval (ms):	1000	1000
Sleep Current with timer running (mA)	0.001	0.001
Transmit power		-20
Advertising Interval		900
Connection interval		1000
Data packet pairs per connection event		1
Bytes of data rec'd per pair of packets		8
Bytes of data sent per pair of packets		8
Continuous Operation (hours per day)		24
Mobile device connections per hour		2

	Case 1 - Shortest time slot				Case 2 - Longest time slot				Case 3 -- BLMod1.0 Example			
	Time (µs)	Current (mA)	Percent of events		Time (µs)	Current (mA)	Percent of events		Time (µs)	Current (mA)	Percent of events	
			50				50				100	
State 1 (wake-up)	400	6		2400	400	6		2400	400	6		2400
State 2 (pre-processing)	315	7.4		2331	340	7.4		2516	315	7.4		2331
State 3 (pre-Rx)	80	11		880	80	11		880	80	11		880
State 4 (Rx)	275	17.5		4812.5	190	17.5		3325	330	17.5		5775
State 5 (Rx-to-Tx)	105	7.4		777	105	7.4		777	105	7.4		777
State 6 (Tx)	115	17.5		2012.5	115	17.5		2012.5	181	17.5		3167.5
State 7 (post-processing)	1325	7.4		9805	1280	7.4		9472	1325	7.4		9805
State 8 (pre-sleep)	160	4.1		656	165	4.1		676.5	160	4.1		656
				23674				22059				25791.5
Total time of connection event	2775				2675				2896			
Average Current draw during connection event (mA):		8.5311712				8.246355				8.905905		
Average current draw during connection interval with sleep (mA):				0.0246712				0.023056				0.026789

Tab: Interface to TUMunich Resource



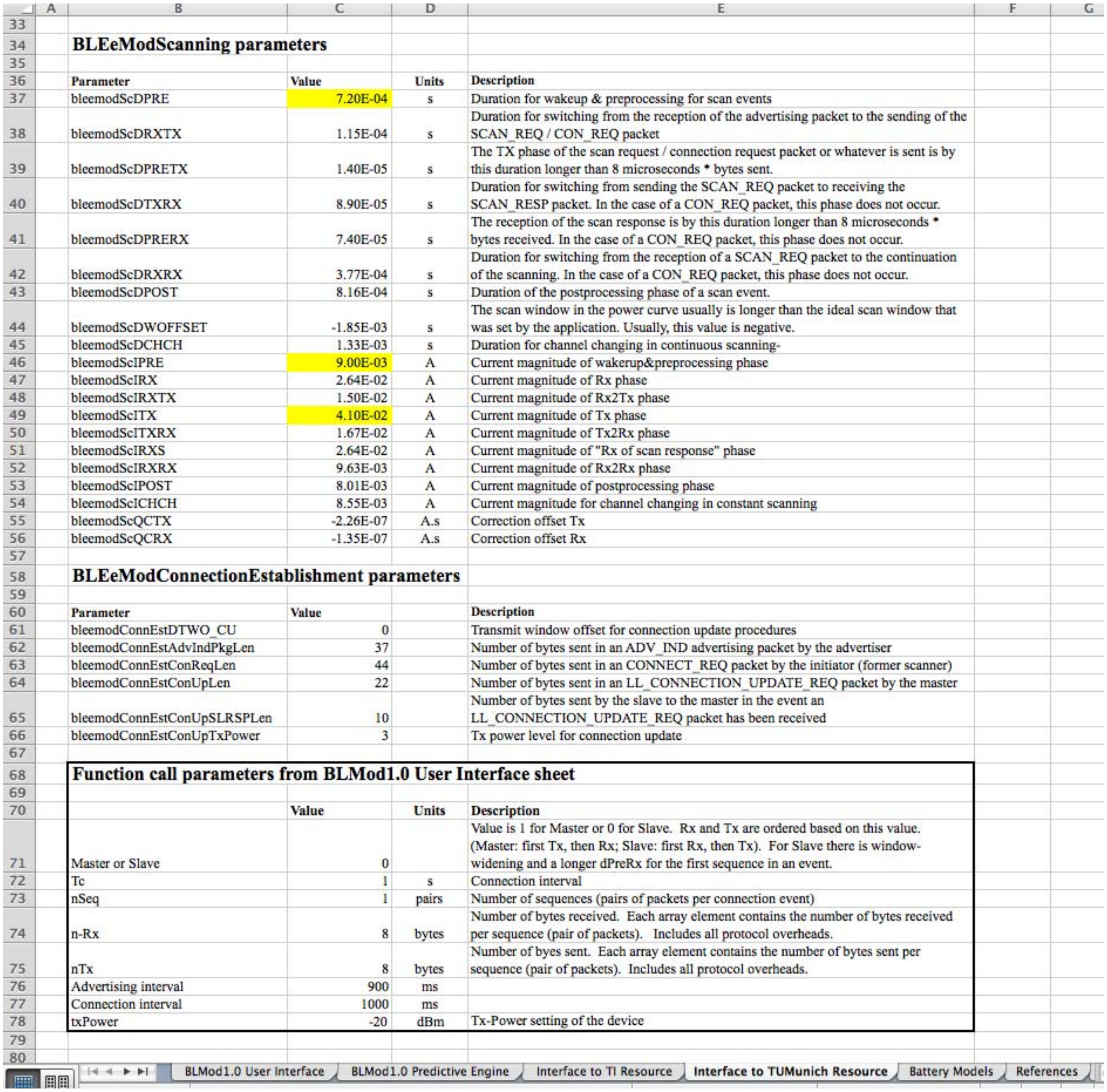
Interface to T.U. Munich Precise Energy Model for BLE Protocol BLEeMod Resource (Kindt et al., 2014)

General parameters yellow highlight denotes values changed for Nordic nRF51822, estimated

Parameter	Value	Units	Description
bleemodSCA	50	ppm	Sleep clock accuracy
bleemodISL	1.10E-06	A	Sleep current

BLEeModConnected parameters

Parameter	Value	Units	Description
bleemodConnDHEAD	5.78E-04	s	Duration of head phase
bleemodConnDPRE	3.05E-04	s	Duration of preprocessing phase
bleemodConnDCPRE	7.30E-05	s	Duration of communication preamble phase
bleemodConnDPRERX	1.23E-04	s	Duration of the pre-rx phase for the master and for the slave except first rx-phase of slave within an event. The first duration of a slave is longer, see bleemodConnDPRERX_SL1 . The pre-rx phase is the phase where the receiver is switched on, but no bits are transmitted. Therefore, the rx-phase is by dprerx longer than 8 microseconds * bytes received
bleemodConnDPRERX_SL1	3.88E-04	s	Duration of the first prerx phase of a slave. It is longer than different prerx phases and not related to window-widening.
bleemodConnDRXTX	8.00E-05	s	Duration of the Rx2Tx-phase
bleemodConnDPRETX	5.30E-05	s	Duration of the pretx phase (tx-phase is longer than 8 microseconds * bytes sent as the radio has to prepare)
bleemodConnDTXRX	5.70E-05	s	Duration of the Tx2Rx-phase
bleemodConnDTRA	6.60E-05	s	Duration of the transient phase
bleemodConnDPOST	8.60E-04	s	Duration of the postprocessing phase
bleemodConnDTAIL	8.00E-05	s	Duration of the tail phase
bleemodConnIHEAD	5.92E-03	A	Current magnitude of the head phase
bleemodConnIPRE	9.00E-03	A	Current magnitude of the preprocessing phase
bleemodConnICPRE	1.22E-02	A	Current magnitude of the communication preamble phase
bleemodConnIRX	2.65E-02	A	Current magnitude of the reception phase
bleemodConnIRXTX	1.41E-02	A	Current magnitude of the Rx2Tx phase
bleemodConnITX	4.10E-02	A	Current magnitude of the Tx phase
bleemodConnITXRX	1.51E-02	A	Current magnitude of the Tx2Rx phase
bleemodConnITRA	1.16E-02	A	Current magnitude of the transient phase
bleemodConnIPOST	7.98E-03	A	Current magnitude of the postprocessing phase
bleemodConnITAIL	4.13E-03	A	Current magnitude of the tail phase
bleemodConnQTO	-1.20E-06	A.s	Communication sequence correction offset



BLEeModScanning parameters

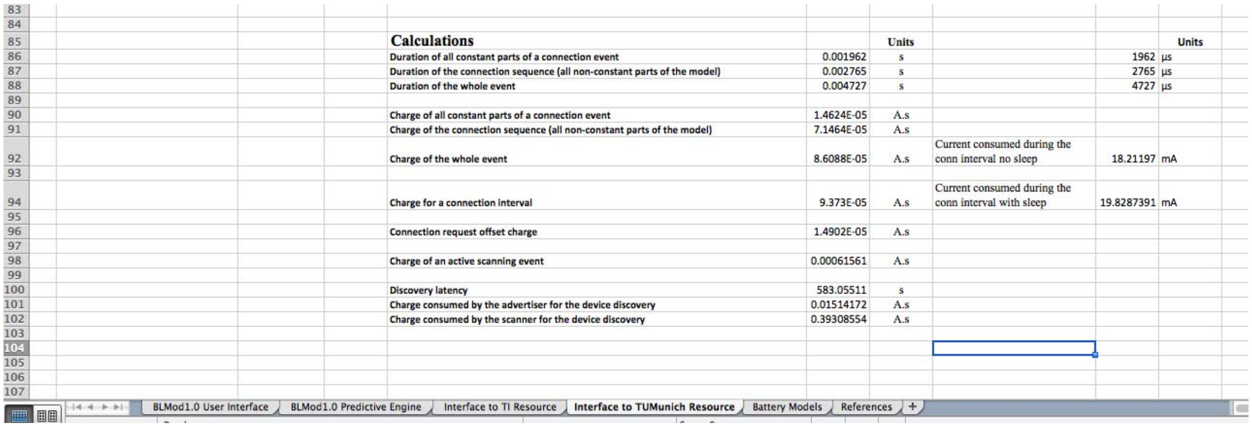
Parameter	Value	Units	Description
bleemodScDPRE	7.20E-04	s	Duration for wakeup & preprocessing for scan events
bleemodScDRXTX	1.15E-04	s	Duration for switching from the reception of the advertising packet to the sending of the SCAN_REQ / CON_REQ packet
bleemodScDPRETX	1.40E-05	s	The TX phase of the scan request / connection request packet or whatever is sent is by this duration longer than 8 microseconds * bytes sent.
bleemodScDTXRX	8.90E-05	s	Duration for switching from sending the SCAN_REQ packet to receiving the SCAN_RESP packet. In the case of a CON_REQ packet, this phase does not occur.
bleemodScDPRERX	7.40E-05	s	The reception of the scan response is by this duration longer than 8 microseconds * bytes received. In the case of a CON_REQ packet, this phase does not occur.
bleemodScDRXRX	3.77E-04	s	Duration for switching from the reception of a SCAN_REQ packet to the continuation of the scanning. In the case of a CON_REQ packet, this phase does not occur.
bleemodScDPOST	8.16E-04	s	Duration of the postprocessing phase of a scan event.
bleemodScDWOFFSET	-1.85E-03	s	The scan window in the power curve usually is longer than the ideal scan window that was set by the application. Usually, this value is negative.
bleemodScDCHCH	1.33E-03	s	Duration for channel changing in continuous scanning-
bleemodScIPRE	9.00E-03	A	Current magnitude of wakerup&preprocessing phase
bleemodScIRX	2.64E-02	A	Current magnitude of Rx phase
bleemodScIRXTX	1.50E-02	A	Current magnitude of Rx2Tx phase
bleemodScITX	4.10E-02	A	Current magnitude of Tx phase
bleemodScITXRX	1.67E-02	A	Current magnitude of Tx2Rx phase
bleemodScIRXS	2.64E-02	A	Current magnitude of "Rx of scan response" phase
bleemodScIRXRX	9.63E-03	A	Current magnitude of Rx2Rx phase
bleemodScIPOST	8.01E-03	A	Current magnitude of postprocessing phase
bleemodScICHCH	8.55E-03	A	Current magnitude for channel changing in constant scanning
bleemodScQCTX	-2.26E-07	A.s	Correction offset Tx
bleemodScQCRX	-1.35E-07	A.s	Correction offset Rx

BLEeModConnectionEstablishment parameters

Parameter	Value	Description
bleemodConnEstDTWO_CU	0	Transmit window offset for connection update procedures
bleemodConnEstAdvIndPkgLen	37	Number of bytes sent in an ADV_IND advertising packet by the advertiser
bleemodConnEstConReqLen	44	Number of bytes sent in an CONNECT_REQ packet by the initiator (former scanner)
bleemodConnEstConUpLen	22	Number of bytes sent in an LL_CONNECTION_UPDATE_REQ packet by the master
bleemodConnEstConUpSLRSPLen	10	Number of bytes sent by the slave to the master in the event an LL_CONNECTION_UPDATE_REQ packet has been received
bleemodConnEstConUpTxPower	3	Tx power level for connection update

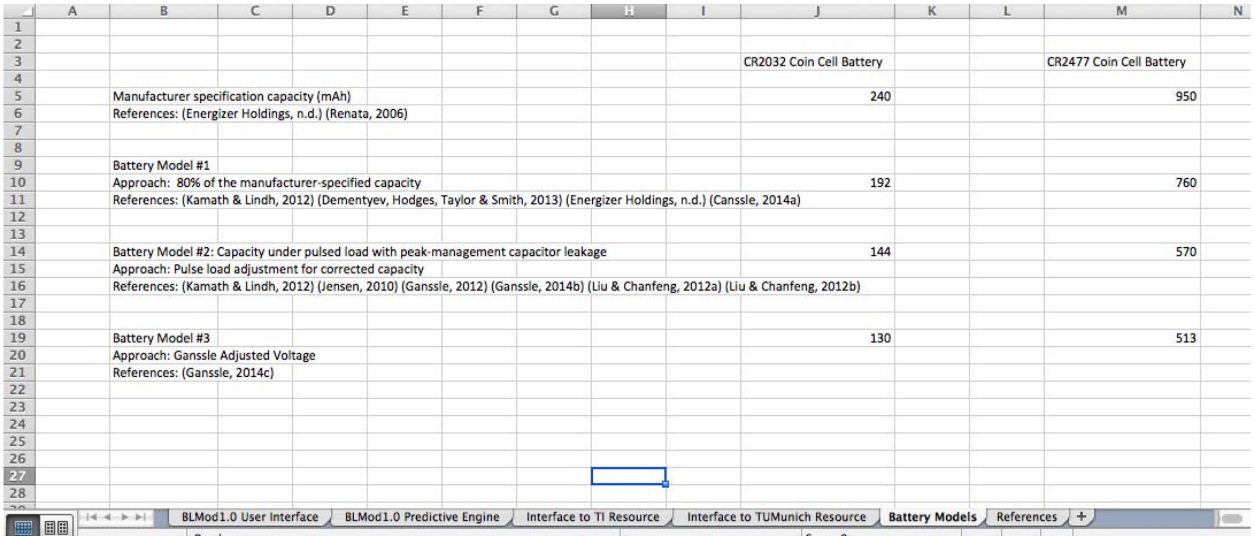
Function call parameters from BLMod1.0 User Interface sheet

	Value	Units	Description
Master or Slave	0		Value is 1 for Master or 0 for Slave. Rx and Tx are ordered based on this value. (Master: first Tx, then Rx; Slave: first Rx, then Tx). For Slave there is window-widening and a longer dPreRx for the first sequence in an event.
Tc	1	s	Connection interval
nSeq	1	pairs	Number of sequences (pairs of packets per connection event)
n-Rx	8	bytes	Number of bytes received. Each array element contains the number of bytes received per sequence (pair of packets). Includes all protocol overheads.
nTx	8	bytes	Number of byes sent. Each array element contains the number of bytes sent per sequence (pair of packets). Includes all protocol overheads.
Advertising interval	900	ms	
Connection interval	1000	ms	
txPower	-20	dBm	Tx-Power setting of the device



85	**Calculations**		**Units**			**Units**
86	Duration of all constant parts of a connection event	0.001962	s		1962	µs
87	Duration of the connection sequence (all non-constant parts of the model)	0.002765	s		2765	µs
88	Duration of the whole event	0.004727	s		4727	µs
90	Charge of all constant parts of a connection event	1.4624E-05	A.s			
91	Charge of the connection sequence (all non-constant parts of the model)	7.1464E-05	A.s			
92	Charge of the whole event	8.6088E-05	A.s	Current consumed during the conn interval no sleep	18.21197	mA
94	Charge for a connection interval	9.373E-05	A.s	Current consumed during the conn interval with sleep	19.8287391	mA
96	Connection request offset charge	1.4902E-05	A.s			
98	Charge of an active scanning event	0.00061561	A.s			
100	Discovery latency	583.05511	s			
101	Charge consumed by the advertiser for the device discovery	0.01514172	A.s			
102	Charge consumed by the scanner for the device discovery	0.39308554	A.s			

Tab: Battery Models



	B	J	M
3		CR2032 Coin Cell Battery	CR2477 Coin Cell Battery
5	Manufacturer specification capacity (mAh)	240	950
6	References: (Energizer Holdings, n.d.) (Renata, 2006)		
9	Battery Model #1		
10	Approach: 80% of the manufacturer-specified capacity	192	760
11	References: (Kamath & Lindh, 2012) (Dementyev, Hodges, Taylor & Smith, 2013) (Energizer Holdings, n.d.) (Canssle, 2014a)		
14	Battery Model #2: Capacity under pulsed load with peak-management capacitor leakage	144	570
15	Approach: Pulse load adjustment for corrected capacity		
16	References: (Kamath & Lindh, 2012) (Jensen, 2010) (Ganssle, 2012) (Ganssle, 2014b) (Liu & Chanfeng, 2012a) (Liu & Chanfeng, 2012b)		
19	Battery Model #3	130	513
20	Approach: Ganssle Adjusted Voltage		
21	References: (Ganssle, 2014c)		

Appendix B

Source Code Files, Credits, and Licenses

(Files will be available online beginning June 2015)

BLE Energy Model Credits and License
The code, documentation, research paper, credits and licenses may be found on this website:
https://www.rcs.ei.tum.de/forschung/wireless-sensor-networks/bleemod/
BLE Energy Model: 2013, Philipp Kindt, Daniel Yunge,Robert Diemer, Samarjit Chakraborty
BLEeMod library: 2013, Philipp Kindt
The function _ble_model_discovery_gausscdf(double x) in ble_model_discovery.c
is taken from www.johndcook.com/cpp_phi.html
It is released in public domain according to the website mentioned above:
"This code is in the public domain. Do whatever you want with it, no strings attached."

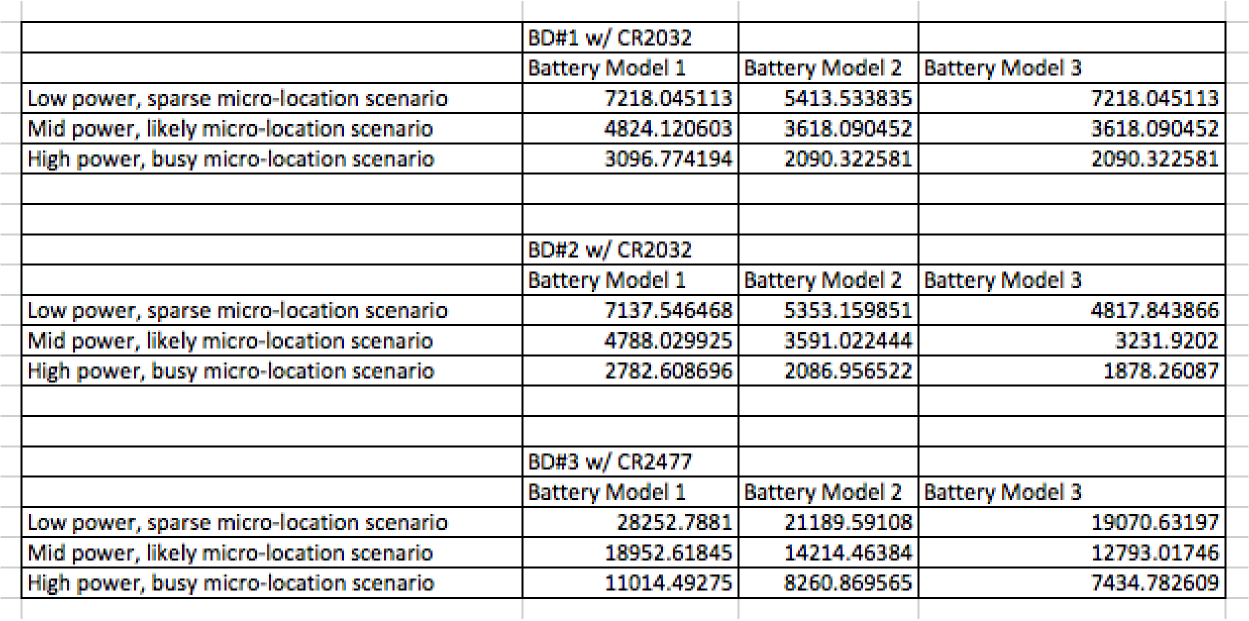
BLEeModXLSAO Credits and Licenses
The code, documentation, associated research papers, credits and licenses may be found on these websites:
www.IfThenSensors.com
https://www.rcs.ei.tum.de/forschung/wireless-sensor-networks/bleemod/
BLEeModXLSAO Excel code and macros: 2015, Alpha and Omega, Inc.

BLE Energy Model File List	**Description**	**BLEeModXLSAO File List**
ble_model.h	Master-include for the BLE Power model	bleemodXLSAO.xlsm
ble_model_connected.c		blemodConnected.bas
ble_model_connected.h	BLE Energy model for the connected mode	
ble_model_connection_establishment.c		blemodConnectionEstablishment.bas
ble_model_connection_establishment.h	Energy model for BLE connection request procedures and for connection update procedures	
ble_model_discovery.c		bleemodDiscovery.bas
ble_model_discovery.h	Energy model for device discovery in BLE	
ble_model_params_connected.h	Device-dependent model params for Bluegiga BLE112 devices in connected mode	
ble_model_params_connection_establishment.h	Energy model params for connection establishment and connection parameter updates	
ble_model_params_general.h	Device-dependent model params for Bluegiga BLE112 devies that are independant from the mode (connected/advertising/scanning/...)	
ble_model_params_scanning.h	Model parameters for scan events for BLE112-devices	
ble_model_params.h	Master include for all numerical values	bleemodParameters.bas
ble_model_scanning.c		bleemodScanning.bas
ble_model_scanning.h	Energy model for BLE scan events	

Appendix C

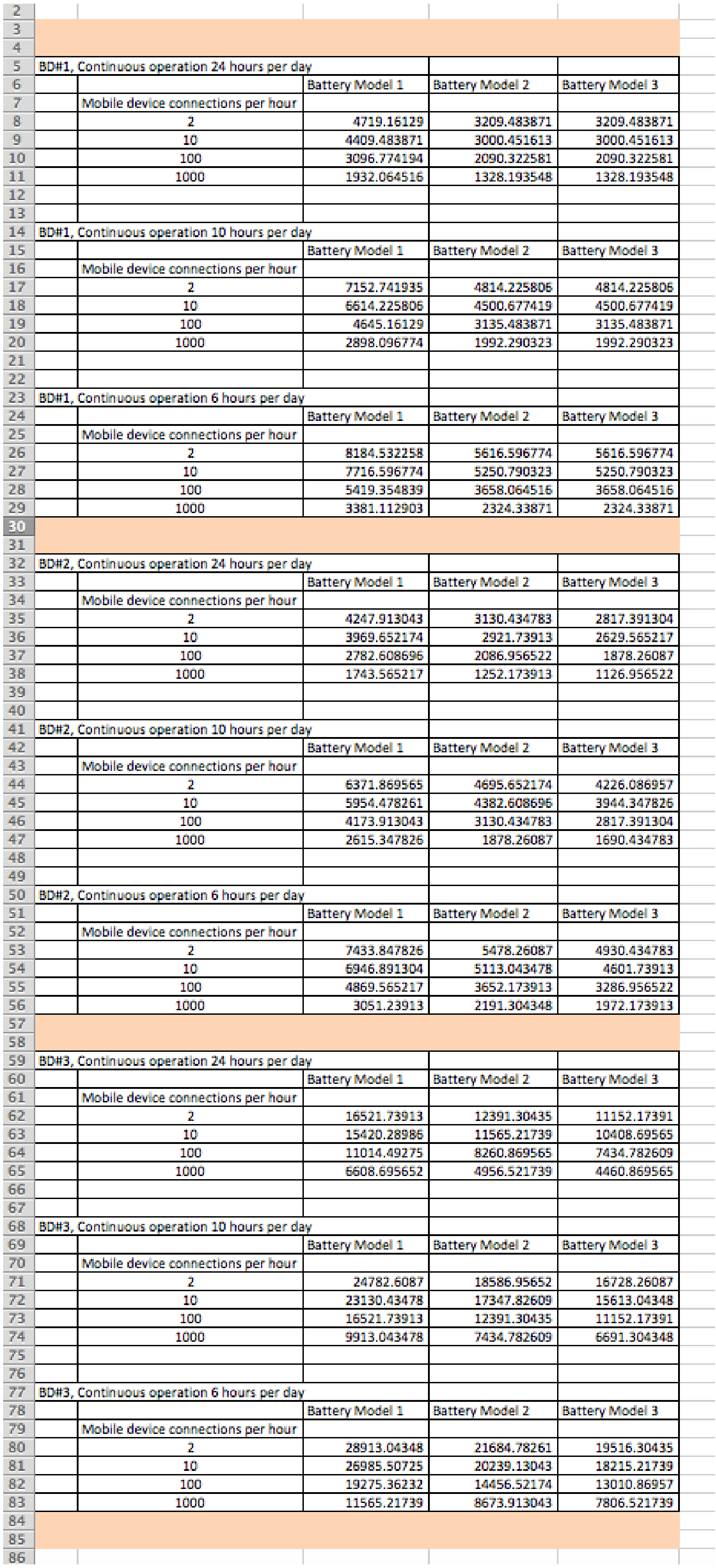
Data from BLMod1.0 Scenario Runs

This data is for micro-location scenarios configured with parameters such as transmit power, advertising interval, connection interval, continuous operation, mobile device connections per hour, and bytes of data transfer. Measured and calculated values are predicted battery lifetime in hours.



	BD#1 w/ CR2032		
	Battery Model 1	Battery Model 2	Battery Model 3
Low power, sparse micro-location scenario	7218.045113	5413.533835	7218.045113
Mid power, likely micro-location scenario	4824.120603	3618.090452	3618.090452
High power, busy micro-location scenario	3096.774194	2090.322581	2090.322581
	BD#2 w/ CR2032		
	Battery Model 1	Battery Model 2	Battery Model 3
Low power, sparse micro-location scenario	7137.546468	5353.159851	4817.843866
Mid power, likely micro-location scenario	4788.029925	3591.022444	3231.9202
High power, busy micro-location scenario	2782.608696	2086.956522	1878.26087
	BD#3 w/ CR2477		
	Battery Model 1	Battery Model 2	Battery Model 3
Low power, sparse micro-location scenario	28252.7881	21189.59108	19070.63197
Mid power, likely micro-location scenario	18952.61845	14214.46384	12793.01746
High power, busy micro-location scenario	11014.49275	8260.869565	7434.782609

This data is for micro-location scenarios configured with static values for transmit power (-20dBm), receive mode (standard), advertising interval (900ms), connection interval (1000ms), disabled adaptive frequency hopping, and 8 bytes of data transferred per connection event; and dynamic values for continuous operation and mobile device connections per hour. Measured and calculated values are predicted battery lifetime in hours.



2					
3					
4					
5	BD#1, Continuous operation 24 hours per day				
6			Battery Model 1	Battery Model 2	Battery Model 3
7		Mobile device connections per hour			
8		2	4719.16129	3209.483871	3209.483871
9		10	4409.483871	3000.451613	3000.451613
10		100	3096.774194	2090.322581	2090.322581
11		1000	1932.064516	1328.193548	1328.193548
12					
13					
14	BD#1, Continuous operation 10 hours per day				
15			Battery Model 1	Battery Model 2	Battery Model 3
16		Mobile device connections per hour			
17		2	7152.741935	4814.225806	4814.225806
18		10	6614.225806	4500.677419	4500.677419
19		100	4645.16129	3135.483871	3135.483871
20		1000	2898.096774	1992.290323	1992.290323
21					
22					
23	BD#1, Continuous operation 6 hours per day				
24			Battery Model 1	Battery Model 2	Battery Model 3
25		Mobile device connections per hour			
26		2	8184.532258	5616.596774	5616.596774
27		10	7716.596774	5250.790323	5250.790323
28		100	5419.354839	3658.064516	3658.064516
29		1000	3381.112903	2324.33871	2324.33871
30					
31					
32	BD#2, Continuous operation 24 hours per day				
33			Battery Model 1	Battery Model 2	Battery Model 3
34		Mobile device connections per hour			
35		2	4247.913043	3130.434783	2817.391304
36		10	3969.652174	2921.73913	2629.565217
37		100	2782.608696	2086.956522	1878.26087
38		1000	1743.565217	1252.173913	1126.956522
39					
40					
41	BD#2, Continuous operation 10 hours per day				
42			Battery Model 1	Battery Model 2	Battery Model 3
43		Mobile device connections per hour			
44		2	6371.869565	4695.652174	4226.086957
45		10	5954.478261	4382.608696	3944.347826
46		100	4173.913043	3130.434783	2817.391304
47		1000	2615.347826	1878.26087	1690.434783
48					
49					
50	BD#2, Continuous operation 6 hours per day				
51			Battery Model 1	Battery Model 2	Battery Model 3
52		Mobile device connections per hour			
53		2	7433.847826	5478.26087	4930.434783
54		10	6946.891304	5113.043478	4601.73913
55		100	4869.565217	3652.173913	3286.956522
56		1000	3051.23913	2191.304348	1972.173913
57					
58					
59	BD#3, Continuous operation 24 hours per day				
60			Battery Model 1	Battery Model 2	Battery Model 3
61		Mobile device connections per hour			
62		2	16521.73913	12391.30435	11152.17391
63		10	15420.28986	11565.21739	10408.69565
64		100	11014.49275	8260.869565	7434.782609
65		1000	6608.695652	4956.521739	4460.869565
66					
67					
68	BD#3, Continuous operation 10 hours per day				
69			Battery Model 1	Battery Model 2	Battery Model 3
70		Mobile device connections per hour			
71		2	24782.6087	18586.95652	16728.26087
72		10	23130.43478	17347.82609	15613.04348
73		100	16521.73913	12391.30435	11152.17391
74		1000	9913.043478	7434.782609	6691.304348
75					
76					
77	BD#3, Continuous operation 6 hours per day				
78			Battery Model 1	Battery Model 2	Battery Model 3
79		Mobile device connections per hour			
80		2	28913.04348	21684.78261	19516.30435
81		10	26985.50725	20239.13043	18215.21739
82		100	19275.36232	14456.52174	13010.86957
83		1000	11565.21739	8673.913043	7806.521739
84					
85					
86					