Power Consumption and Maximum Number of Supported Nodes for BLE Biosensor Applications

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***Abstract*— There has been significant growth in wearable wireless patient physiological monitoring over the last decade. Many applications require a real-time, low-latency, small profile, and low-power-battery system. In this work, various Bluetooth low energy (BLE) configurations were tested in a multi-channel, wireless system to determine the lowest peripheral power configuration and the number of supported peripherals for each BLE configuration. Using nodes that continuously sampled at 1 kHz, connection intervals from 10-100 ms and event lengths of 2500, 5000 and 7500 µs were tested. The lowest current consumption, 2.39 mA, was measured for a connection interval of 100 ms, event length of 2500 µs, and maximum transmission unit (MTU) of 247 bytes. The maximum number of supported peripheral connections was observed to be 11 for a connection interval of 100 ms, event lengths of 5000 and 7500 µs, and MTU size of 247 bytes. We found that using longer connection intervals led to decreases in power consumption and shorter event lengths allowed for support of more peripheral sensors nodes for a given connection interval, assuming the event length is long enough to transmit the desired amount of data. Future work should investigate techniques to optimize power consumption further and to extend the number of supported peripheral nodes.**

Keywords*— Bluetooth Low Energy, Wireless Biosensors, Electromyogram, Power Consumption, Internet of Things (IoT)

I. Introduction

Over the last decade or so, there has been considerable growth in the adoption of wireless and wearable biopotential sensors for a variety of applications. These applications span from digital health applications such as remote patient monitoring and diagnostics [1], to human-machine interfaces for robotic or prosthesis control [2, 3], to more niche applications such as virtual and augmented reality controllers [4]. To support this wide spectrum of applications, robust, reliable and low-power wireless communications are required.

One of the most used communication protocols for these applications is Bluetooth Low Energy (BLE). BLE is ideal for wearable systems because it is low power, inexpensive, and widely used across a variety of platforms, making it easy to integrate with existing systems (computers, smart phones, smart watches, etc.). Other protocols such as ZigBee and low-power Wi-Fi have been used in some wearable biopotential sensing applications but have found more use in home automation and industrial spaces. In comparison to BLE, Zigbee offers lower transmission rates while low power Wi-Fi has a greater power consumption than BLE [5].

The goal of this work is to explore the use of BLE in a wireless biopotential system; specifically, how the BLE parameters of connection interval, maximum transmission unit (MTU) size, and event length influence power consumption as well as number of sensing nodes supported. The relationship between these parameters can help guide system designers in their development of wireless biopotential systems for applications such as multi-site monitoring of electromyograms for gait analysis, rehabilitation, or prosthesis control.

There are a few methods available to improve system performance, such as running in an interference-free setting (which is not practical in some applications) or selecting the ideal connection parameters for a given application. In this work, this second approach is explored. Understanding how the critical connection parameters (connection interval, event length, and MTU size) influence system operation can be instructive in designing a robust and reliable wireless system.

II. Background

BLE has been used in various wireless communications applications across disciplines. Its versatility makes it ideal for close-range transmission environments such as from the human body to a mobile phone or laptop. Additionally, BLE offers flexibility in selecting the transmission event length, length of the connection interval, and size of the transmission. Understanding how these factors influence power consumption and number of supported sensor nodes is critical when developing reliable, wearable, battery-operated systems. In the case of medical devices, where there may be multiple sensor nodes, these data are critical to proper diagnostics and patient monitoring.

A. Prior Works

Prior works have explored some of these parameters, but not all of them and not under the same test conditions as studied herein. Additionally, many of these prior works have used BLE version 5.0 or earlier. In this work, BLE version 5.3 was used.

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BLE 5.3 specifically has upgrades that enable lower power consumption, improved reliability, and reduced latency through new features such as enhanced periodic advertising, improved channel classification and connection subrating. Enhanced periodic advertising implements a more efficient handling of redundant data which results in power consumption reductions and increases in the reception duty cycle. The improved channel classification allows the peripherals to share their RF conditions with the central node to determine whether it is operating under favorable RF conditions, helping the central node manage how it classifies connections as viable or not. This management results in improved reliability. Connection subrating enables dynamic, rapid switching of the BLE connection parameters which can reduce the connection's duty cycle during times of inactivity, which can reduce power consumption [6].

Tipparaju et al. [7] used two peripherals and a single central node (different central nodes were used to study the influence of OS: iOS-based device, Android device, and Raspberry Pi) to study data loss and its relationship to MTU size and the influence of the external environment and interference on data loss (distance between central and peripheral nodes, physical obstacles in the path, other wireless signals, etc.). They proposed a mitigation protocol that reduces frequency of transmission and bundles the data with a timestamp to detect lost packets. If a packet loss is detected, their re-request routine is run to recover the lost data.

Touati et al. [8] used a single peripheral device to study the quality of service (QoS) as defined by the application throughput, packet error rate, and end-to-end delay (average time between packet generation at the source and its arrival at the destination). Work conducted by Brunelli et al. [9] explored the use of BLE 4.1 operating on Texas Instruments' CC2650 BLE microcontroller in a wireless acquisition system for surface EMG signals. In their BLE experiments, they looked specifically at the relationship between connection interval and nominal throughput, interference and environmental influences, and the current consumption profile during a connection event.

Tosi et al. [10] present an overview of the BLE protocol and how various parameters are related such as the number of peripherals a single central node can handle and the influence of the connection interval on throughput and power consumption. They also review other BLE-based studies, both theoretical and experimental, whose results are derived from a mix of simulation and measurement on different platforms (TI's CC2541, Nordic Semiconductors's nRF51822, STMicroelectronics's BlueNRG). Karvonen et al. [11] specifically look at interference of various wireless protocols (BLE, Wi-Fi and Zigbee) in a hospital setting. They used the nRF52840 to measure the transmit power and received signal strength indicator (RSSI) of a peripheral node as it is moved from its initial position at the central node. Using the measurements, the packet error rate was computed. While these prior works considered the influence of parameters such as connection interval and MTU size on system performance, they used earlier BLE versions and in most cases limited analysis to two or fewer peripheral nodes. In this work, we utilize BLE version 5.3 and extend our analysis to more than two peripherals.

B. BLE Parameter Definitions

To aid in understanding the parameters studied in this work, the following BLE definitions have been included.

a) Connection Interval: the amount of time between consecutive connection events between the central and peripheral devices [12].

b) Maximum Transmission Unit (MTU): the maximum packet size to be sent between connected devices [12].

c) Event Length: the allocated time within a connection interval for the data transfer to occur between a central and peripheral device [13].

III. Methods

A. Experimental Set-up

The goal was to measure power consumption and maximum number of supported peripheral devices as a function of connection interval, MTU, and event length. A single central node used a Nordic Semiconductor nRF52840-DK (discovery kit featuring the nRF52840 System-on-Chip) connected to and was powered by the USB port of a PC. Up to 16 peripheral nodes each used the Adafruit Feather nRF52840 Express. The peripheral node used for measuring supply current was powered by Analog Device's ADALM2000 and the other peripheral nodes were powered by USB connections.

The number of peripherals varied depending on the configuration used. The peripheral nodes were placed approximately two feet away from the central node in a semi-circle fashion equidistant from the central node. The ADC inputs of the peripheral devices were left unconnected, but a single channel of the 12-bit ADC was left enabled and continuously converting at 1 kHz to account for its power consumption. Data transmitted from each peripheral device consisted of the raw ADC data (two bytes per sample) as well as 20 bytes of timing and header information. Hence the MTU size scaled with the connection length to account for the number of available data samples. Note that when the connection interval was 100 ms, we rounded this size from 220 bytes to 247 bytes to test the maximum permitted MTU size. The peripheral devices were configured to transmit using a BLE transmit power of 0 dBm. On the central node, the raw ADC data and header information are sent via UART to the host PC for off-line processing. On the host PC, a custom MATLAB application was used to decode the incoming UART stream and log the data.

B. Measuring Power Supply Current

Current consumption was measured from a single (connected) peripheral device using the Power Profiler Kit II (PPK2) from Nordic Semiconductor as an ammeter. The PPK2 device is placed in series with the 5 V power supply output of the ADALM2000 multi-function instrument [11] and power input (USB pin) of the Adafruit Feather nRF52840 Express board. The Power Profiler application (v3.5.4) found in the nRF Connect for Desktop application (v4.0.0) was used to control the PPK2 device and log measured current consumption each trial. Average current was measured over 7 seconds (default measurement time window of the PPK2 device).

C. *Determining Number of Supported Peripheral Devices*

All combinations of BLE parameters, shown in Table I (connection interval, MTU, and event length), were investigated. To determine the maximum number of peripheral connections that can be supported in a trial, the number of peripherals was increased from a single device in increments of one until the central device was no longer able to accept additional incoming data. If further connections cannot be supported, the central device reports a failure to receive incoming data at which point, the additional peripheral would be powered off. Once the maximum number of connections has been established, data received by the central node are streamed for 10 minutes on the PC to observe sustained connections. This entire process was repeated for a few parameter combinations at two additional distances between the central and peripheral nodes: 15 and 30 ft.

IV. RESULTS

TABLE I. POWER CONSUMPTION AND NUMBER OF SUPPORTED PERIPHERALS FOR COMBINATIONS TESTED. EACH CELL SHOWS AVERAGE CURRENT (MA), NUMBER OF SUPPORTED PERIPHERALS

Event Length (µs)	Connection Interval (ms), Scaled MTU Value (bytes)				
	10, 40	20, 60	30, 80	50, 120	100, 247
2500	2.93, 4	2.68, 8	2.59, 10	2.53, 9	2.39, 5
5000	2.95, 2	2.68, 4	2.58, 6	2.52, 10	2.46, 11
7500	2.92, 1	2.68, 2	2.59, 4	2.53, 6	2.55, 11

A. *Power Consumption*

As shown in Fig. 1 (see also Table I for all results), current consumption decreased as connection interval increased, with the largest decrements occurring at the shortest connection intervals. This trend was observed across all event lengths and absolute power consumption only differed substantially at a connection interval of 100 ms. Power reduced ~8% when increasing the connection interval from 10 to 20 ms and power savings of ~18% were achieved when increasing the connection interval from 10 to 100 ms, both for an event length of 2500 µs.

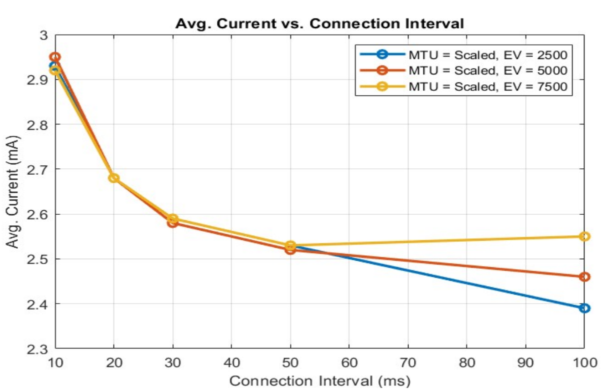

Fig. 1. Current consumption vs. connection intervals.

B. *Number of Connected Devices*

Fig. 2 shows the number of connected peripherals vs. connection interval and event length. As the event length increases from 2500 µs to 7500 µs, the number of connected peripherals decreased by more than 50% for connection intervals of 10, 20, and 30 ms. For a connection interval of 50 ms, a less drastic decrease (40%) in the number of connected peripherals was observed as event length increased. For a connection interval of 100 ms, an event length of 2500 µs provides a very narrow time window for the data transmission to occur which results in fewer successful transmissions under these conditions. In this case, increasing the event length to 5000 and 7000 µs allows for more successful transmissions to occur and in turn a greater number of sustained peripheral connections.

Using the smallest possible event length of 2500 µs enables a greater number of peripheral devices to be connected in each connection interval, except for a connection interval of 100 ms. Note when selecting the event length, developers must take caution to ensure that the event length chosen provides sufficient time to transmit the data desired.

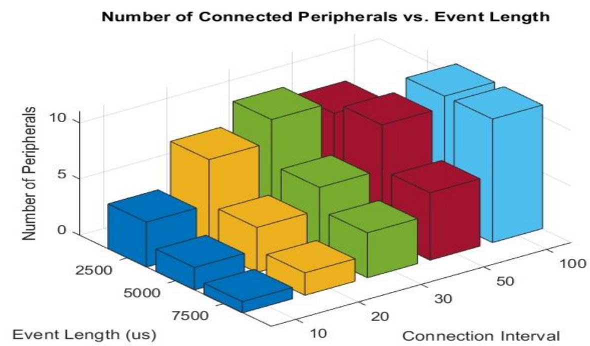

Fig. 2. Comparison of the number of connected devices vs. event length.

C. *Number of Connected Devices vs. Distance*

In practice, the distance between the central and peripheral devices may vary as a user moves or the distance may depend upon the application environment. Typically, as the distance between the central and peripheral nodes increases, the strength of a BLE connection reduces, and connections are lost. As shown in Fig. 3, as the distance between the peripherals and central nodes increases, the number of connected peripherals decreases substantially for the conditions tested; This behavior was observed across the three event lengths considered, with Fig. 3 only showing results for the middle event length of 5000 µs. Moving from 2 ft to approximately 30 ft cut the number of supported connections by 50% or more for connection intervals above 30 ms and an event length of 5000 µs. For most combinations tested, this trend was observed. Exceptions to this trend include the connection interval-event length combinations of: (10 ms, 5000 µs), (10 ms, 7500 µs) and (20 ms, 7500 µs). In these cases, all connections were sustained over distance.

V. DISCUSSION

In this work, Nordic Semiconductor's nRF52840 system-on-chip was used to study the relationships between power consumption and the number of supported peripheral connections for different BLE configurations. When designing wearable BLE-based biosensor networks, developers should consider how to configure their BLE communication to ensure they meet their design requirements for power consumption and

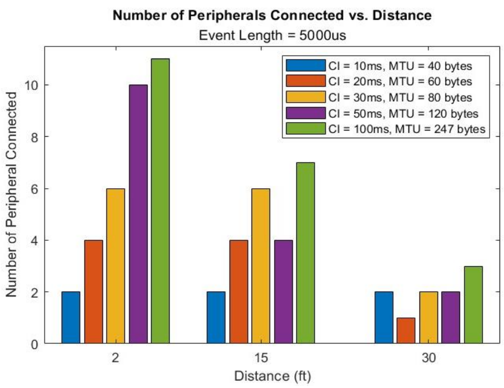

Fig. 3. Number of connected devices as the distance between the peripherals and central device increases.

number of sensors. In applications where power is constrained, it is recommended to use a longer connection interval – when latency concerns permit. If the developer is aiming to maximize the number of peripheral sensors in their network, using a smaller event length allows for more data transfers to occur in a given connection interval, assuming the selected event length provides sufficient time for the data to be transferred.

It is important to note that devices from different manufacturers may vary in terms of their power consumption, connection parameters, and configurability. The results shared in this work may vary depending on the device(s), firmware, and software development kits selected as well as with future advancements of the BLE standard.

Future work should look at potential performance improvements that may come from use of different hardware and software development kits, software optimization and upgrading to BLE version 5.4 [7]. Future work could focus on developing software optimized for power savings or improving the number of peripherals vs. distance. The application software used was custom developed and did not take advantage of low power modes or power cycling schemes to reduce power consumption during run time. Additional power savings could be achieved using BLE version 5.3's connection subrating feature to dynamically adjust the BLE connections' duty cycle. The connection subrating feature could be beneficial in wearable devices as it can dynamically reduce power during inactive times which in turn improves battery life. To improve the number of peripherals supported vs. distance, a dynamic transmit strength adjustment scheme could be used to change the transmission strength based on the RSSI at a given distance.

VI. Conclusion

With the introduction of BLE 5.x, more extensive and lower power wireless biological signal sensor networks can be developed. Selection of BLE parameters such as connection interval and event length all influence power consumption and number of peripheral devices that the sensor network can reliably support. In this work, different configurations were tested to observe how the BLE configuration influences performance of the sensor network to guide application development. It was observed that increasing connection interval from 10 to 100 ms reduced power consumption by ~18%. To increase the number of supported peripheral sensor nodes, designers should select the minimum event length for their data transmission size. Future work should consider the addition of power optimization methods and latency in the microcontroller's firmware as well as the use of the latest BLE versions.

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