POWER CONSUMPTION, LATENCY, AND MAXIMUM NUMBER OF SUPPORTED NODES FOR BLE BIOSENSOR APPLICATIONS

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ABSTRACT

Wearable wireless physiological monitoring devices have emerged as powerful tools in healthcare, facilitating continuous monitoring of vital signs and physiological parameters in real-time. Many of these applications require small profile, and low-power battery operated devices. Bluetooth Low Energy (BLE) is a commonly selected wireless communication protocol as it provides fast data transfer, low cost, and low power. Physiological monitoring applications do not have as strict real-time latency requirements as control applications. For control use-cases, such as prosthesis control, real-time latency has a direct impact on user experience. In this work we explored various BLE parameter configurations in a multi-channel sensor node system to determine their relationship to power consumption, the number of supported peripheral nodes, and latency. Data collected during these experiments indicates that using longer connection intervals leads to a decrease in power consumption and that shorter event lengths allows for support of more peripheral sensor nodes for a given connection interval. It was observed that the typical latency between the application of an input signal at a peripheral node and its detection on the central node is approximately one connection interval. Future work should continue to investigate techniques to optimize power consumption, extend the number of supported peripheral nodes, and minimize latency through the system specifically for control applications.

INTRODUCTION

There has been considerable growth over the last decade in the adoption of wireless and wearable biopotential sensors for a variety of applications, including: remote patient monitoring and diagnostics [1] and human-machine interfaces for robotic or prosthesis control [2, 3]. 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 of its small form factor, low power, affordability, and interoperability across a variety of platforms, making it easy to integrate with existing systems (smart phones, computers, etc.).

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, the number of sensing nodes supported, as well as the impact on latency. Real-time biomedical applications such as multi-site monitoring of electromyograms for gait analysis, rehabilitation, or prosthesis control typically require low-latency (100 ms or less) communication protocols [4] and multiple peripheral nodes communicating with a single central node. Understanding how the important BLE transmission parameters of connection interval, event length, and MTU size influence system operation can be instructive in designing a robust and reliable wireless system.

BACKGROUND

BLE has been used in various wireless communications applications across disciplines. BLE offers a compelling combination of low power consumption, small form factor, affordability, interoperability, fast data transfer up to 2 Mbps [5], and security features, making it well-suited for a wide array of wireless wearable applications. 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, the data these sensors generate are critical to proper diagnostics and patient monitoring.

BLE Parameter Definitions

The following BLE definitions have been included to aid in understanding the parameters studied in this work.

- **Connection Interval (CI):** time between consecutive connection events between central and peripheral devices [6].
- **Maximum Transmission Unit (MTU):** the maximum packet size to be sent between connected devices [6].
- **Event Length:** allocated time within a CI for the data transfer to occur between a central and peripheral device [7]

Prior Works

Connection interval, MTU size and event length have been studied in prior works, but under different test conditions and in different combinations than those considered here. Additionally, BLE version 5.0 or earlier was used in many of these prior works. In this work, BLE version 5.3 was used as it specifically has upgrades that enable lower power consumption, improved reliability, and reduced latency through new features such as enhanced periodic advertising, connection subrating and improved channel classification [8].

Tipparaju et al. [9] 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 lost packet is detected, their re-request routine is run to recover the lost data. Work conducted by Brunelli et al. [10] 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. [11] present an overview of the BLE protocol and how various parameters are related such as the maximum number of peripherals per central node and the influence of 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. In this work, we utilize BLE version 5.3 and extend our analysis to more than two peripherals.

METHODS

Experimental Apparatus

The goal of this work was to measure power consumption, maximum number of supported peripheral devices, and latency as a function of connection interval, MTU, and event length. Combinations of connection interval values between 10–100 ms, and event length values between 2500–7500 µs were considered. These values were selected as appropriate for real-time control applications such as prosthesis/orthosis and robotic control. The MTU value was scaled to maximize the number of analog-to-digital converter (ADC) samples sent for a given connection interval. An additional twenty bytes of each BLE data packet were reserved for timing and header information.

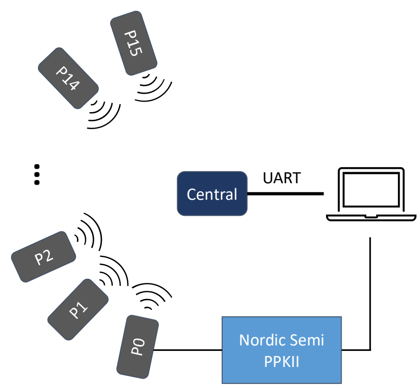

Figure 1 - Diagram of experimental setup.

Both the central and peripheral devices (up to 16) used a nRF52840 System-on-Chip (SoC) from Nordic Semiconductor running BLE version 5.3. All measurements were taken with a transmit power of 0 dBm. The peripheral nodes were placed in a semicircle 0.5 m away from the central node in an equidistant fashion (Figure 1). A single channel of the internal 12-bit ADC was enabled and continuously converting at 1 kHz to account for its power consumption. On the central node, the received packets are sent via UART to the host PC for off-line processing (although, unused in this study). The number of peripherals varied depending on the configuration used.

Determining Number of Supported Peripheral Devices and Measuring Power Supply Current

A separate set of trials measured both number of supported peripheral nodes and current consumption. All combinations of BLE parameters (connection interval, MTU, and event length) were investigated. 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. All non-connected peripherals were then powered off. Once the maximum number of connections has been established, data received by the central node were streamed for 10 minutes on the PC to observe sustained connections.

Once per minute during this 10 minutes of streaming, current consumption was measured from a single (connected) peripheral device using the Nordic Power Profiler Kit II (PPK2). The PPK2 device is placed in series with the power supply output and power input of the nRF52840. The Nordic Semiconductor Power Profiler application (v3.5.4) 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).

Measuring Latency

A logic analyzer was used to measure the time latency between the application of an analog signal to the ADC of one peripheral node and the arrival of its digital samples at the central node via BLE. To do so, a step input is applied to the ADC input of a peripheral node. The rising edge of the step input triggers the beginning of the measurement. Software edge detection is implemented on the central node to determine when the step input edge was detected in a received BLE packet. This software detection was used to emit a hardware logic signal on the central node. For each combination of event length and connection interval tested, 10 trials were completed.

RESULTS

Power Consumption

As shown in Table I, 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 ~18% when increasing the connection interval from 10 to 100 ms, both for an event length of 2500 µs.

Table 1 - Average power consumption and number of supported peripherals for each parameter combination tested. Each cell shows the mean of the average current consumed across 10 trials in mA and the maximum number of supported peripherals at a distance of 0.5 m.

Event Length (µs)	Connection Interval (ms), Scaled MTU Value (bytes)					
	10, 40	20, 60	30, 80	40, 100	50, 120	100, 247
2500	2.84, 4	2.56, 8	2.50, 11	2.46, 12	2.35,12	2.33, 10
5000	2.85, 2	2.59, 4	2.47, 6	2.41, 8	2.45, 10	2.38, 10
7500	2.78, 1	2.58, 2	2.49, 4	2.47, 5	2.43, 6	2.38, 11

Number of Connected Devices

Figure 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, 30, and 40 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. When selecting the event length, ensure that the event length chosen provides sufficient transmission time to send the data desired within a single event.

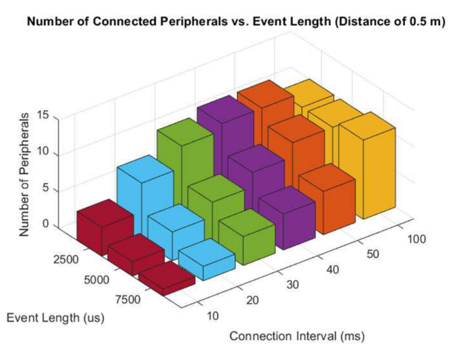

Figure 2 - Comparison of number of connected devices vs. event length and connection interval.

Latency

As connection intervals increased, the latencies also increased for a given configuration. To directly compare latency across the different configurations tested, each measurement was normalized by dividing the latency value by its connection interval. Figure 3 shows histograms of the normalized latency measurements, pooling all six connection intervals and three event lengths. Latency from application of the analog input on the peripheral to digital sample arrival on the central shows a triangle-like distribution with a mean of 1.14 connection intervals and variance of about 0.21 connection intervals. This triangle-like distribution is consistent with summing two, independent, uniformly distributed latencies, each of one connection interval duration [12]: (1) the delay from analog signal arrival at the peripheral node to completion

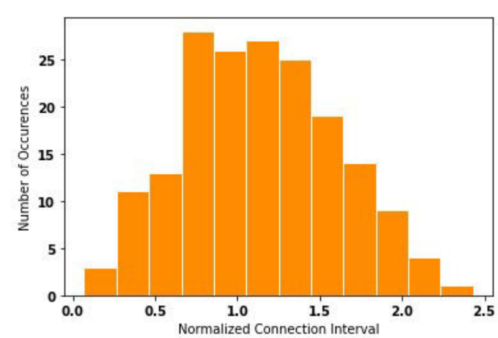

Figure 3 – Normalized latency: Edge detected in BLE data on Central.

of acquiring a full block of ADC samples, and (2) BLE transmission delay between the peripheral and central nodes. Some additional small delays were observed as expected to account for intermediate data processing as the data moves through the system.

DISCUSSION

Nordic Semiconductor's nRF52840 SoC was used to study the relationships between power consumption, the number of supported peripheral connections, and latency for different BLE configurations. In applications where power is constrained, longer connection intervals are recommended — when latency concerns permit. If aiming to maximize the number of peripheral sensors in the network, smaller event lengths allow for more data transfers to occur in each connection interval. This assumes the selected event length provides sufficient time for the data to be transferred. Overall system latency scales directly with connection interval, thus low latency requires short connection intervals. It is important to note that results may vary between different manufacturer's devices, firmware, software development kits (SDK) and the specific implementation of the biopotential application. 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 [8]. Future work could focus on developing software optimized for power savings, such as implementing our patented power savings technique (U.S. patent #11,154,408, 2021) which reduces wireless transmissions during intervals of bio-signal inactivity to improve battery life.

CONCLUSION

The release of BLE 5.x has allowed for the development of larger and lower power wireless, biopotential sensor networks. It is critical to understand how selection of BLE parameters such as connection interval and event length influence power consumption, number of peripheral devices that the sensor network can reliably support, and latency. This experimental work tested different BLE configurations to study their influences on sensor network performance to guide application development. It was observed that power consumption decreased by as much as 18% by increasing connection interval from 10 to 100 ms. To increase the number of supported peripheral sensor nodes, designers should select the minimum event length required to successfully transmit their data. Finally, when looking at latency, it was found that on average, 1.14 connection intervals lapse between the application of a step response on the peripheral node and when it is detected in the received BLE data by the central node. 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.

ACKNOWLEDGEMENTS

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