

EE209AS – Spring 2011:  
*Special Topics in Wireless Communications*  
*System Design*  
**Prof. Danijela Cabric**

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Final Project Report:

*Lowering System Energy Usage*  
*through Interval Wireless Data*  
*Transfer*

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## **I. Abstract**

This paper presents a new metric to determining the energy usage of wireless protocols through the use of interval wireless data transfer. This paper shows that through the use of hold periods in which data is accumulated and subsequently transferred in a single burst, energy savings is realized. Furthermore, four wireless protocols (Bluetooth, Bluetooth Low Energy, Wi-Fi and ZigBee) have been compared on the basis of their interval energy usage as an example of how the introduced metric can help improve a systems energy efficiency.

## **II. Introduction**

The rapid shrinking of the transistor has ushered in a new era of portable devices that are both powerful and complex. But, inherent in the design of a portable device is a limited energy supply. Thus, particular emphasis is placed on energy efficiency with innovations being made to address energy bottlenecks.

This paper presents a novel solution to address the bottleneck associated with the wireless transmission through the use of interval wireless data transfers. The process involves the accumulation of data in a buffer before data transmission. During the accumulation phase, incoming data is routed to a temporary onboard storage location and the wireless chip is placed into a low power state. Following the accumulation phase is the transmission phase, which involves the sending of the previously accumulated data. By utilizing interval wireless data transfer the amount of time the chip is sending data is minimized as the full speed of its protocol capability is utilized. Conversely, the amount of time the chip spends in low power mode is maximized. This paper theorizes that such operation can greatly save energy associated with the wireless data transfer portion of the system.

## **III. Wireless Protocols**

This section provides an introduction to the basics of the wireless protocols compared in this paper, namely: Bluetooth, Bluetooth Low Energy, Wi-Fi, and ZigBee. The protocols listed are all based on IEEE standards, which define the physical and MAC layers. Further standardization is done by respective groups or industry alliances to improve interoperability and consumer adoption.

### **a. Bluetooth**

Bluetooth is an open wireless technology standard built atop the IEEE 802.15.1 specification and managed by the Bluetooth Special Interest Group (SIG). Originally created to replace wired connections of computer peripherals; Bluetooth has gained in popularity and is used in many devices that require short range exchange of data.

Bluetooth abides by the master/slave model which allows for both point-to-point and point-to-multipoint connections where a physical channel is shared among several devices and managed by the master (figure 1). This architecture forms a piconet with a maximum of 7 devices active at once. Separate piconets which share devices are termed scatternets.

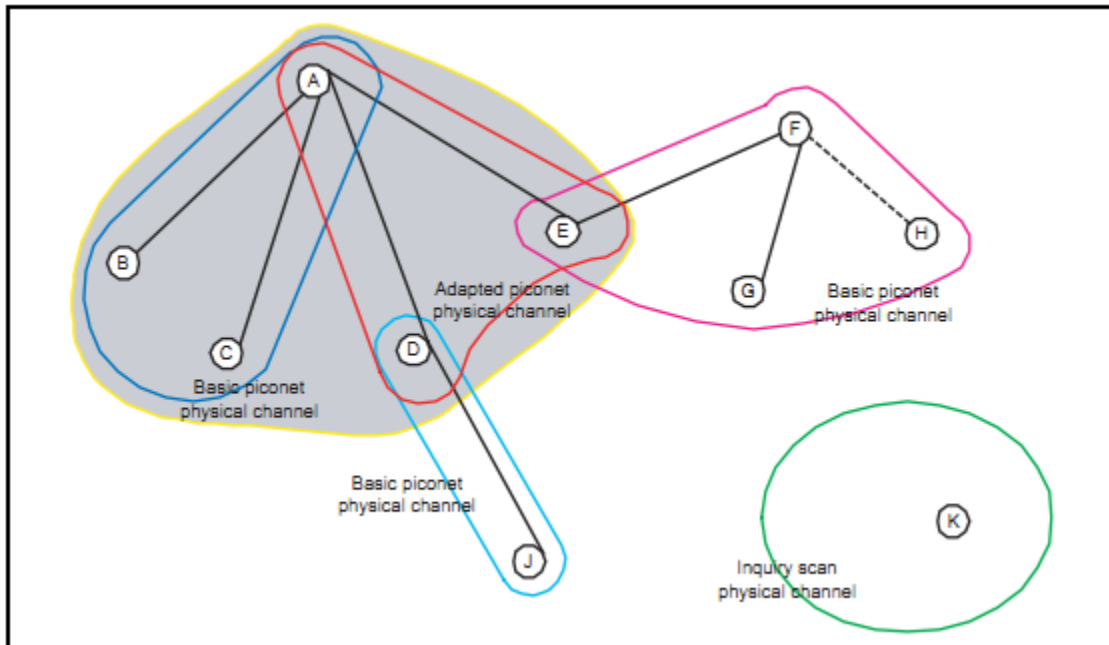


Figure 1: Graphical representation of Bluetooth connectivity architecture. [1]

In Version 1.2 of the Bluetooth specifications, data transmission occurs through the use of GFSK modulation and adaptive frequency hopping, allowing for theoretical data rates of 1 Mb/s with maximum real world throughputs being closer to 0.7 Mbits/s. Data is sent in the form of packets which include an initial access code, a header, and the payload. The access code, CRC code, packet header, and payload header are considered the “overhead” with the actual data being transmitted comprising the greater portion of the payload.

Access Code	Header	Data Unit
72 bits	18 bits	2780 bits

Figure 2: Bluetooth packet format.

### b. Bluetooth Low Energy

In the latest revision of the Bluetooth specifications, Version 4.0, a new feature termed Bluetooth Low Energy was added to facilitate a wider range of applications aimed at devices with increased portability. Target changes were made to reduce low data rate energy usage. Critical

changes include: a larger frequency modulation band, a smaller overhead, and a stricter limit on transmission power.

The result is a dramatic decrease in transmission latency which combined with a lower duty cycle improves on the overall power consumption.

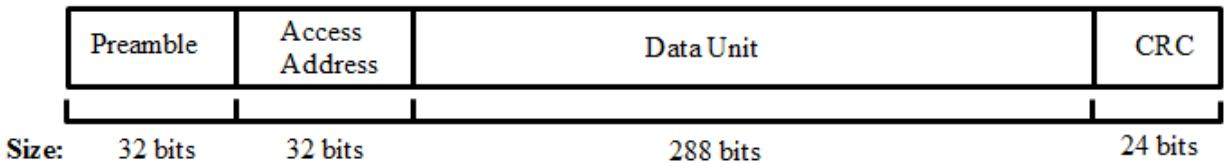


Figure 3: BLE packet format.

### c. 802.11g Wi-Fi

IEEE 802.11 is a standard with the main intention of enabling a wireless local area network. The term Wi-Fi is a trademark of the Wi-Fi Alliance and was created to help maintain the standard and improve interoperability between the 802.11 devices. As a superset of the IEEE 802.11 multitude of specifications, Wi-Fi comes in a variety of flavors. The technology tested in this paper is the IEEE 802.11g standard released in June of 2003.

Wi-Fi provides two popular styles for network connectivity. One is termed the Independent Basic Service Set (IBSS) or “ad-hoc” mode in which two devices are able to communicate directly without the need of an access point. Another is the Extended Service Set (ESS) which consists of one or more access point controlled service sets, termed Basic Service Sets (BSS) that are combined through the use of a common distribution system.

IEEE 802.11g utilizes orthogonal frequency-division multiplexing (OFDM) modulation with dynamic frequency selection to obtain theoretical transmission speeds of up to 54 Mb/s. Packet formation in the 802.11 specifications is outlined in figure 4. An important differentiator of IEEE 802.11 from the other standard compared in this paper is a larger payload size as listed in table 1.

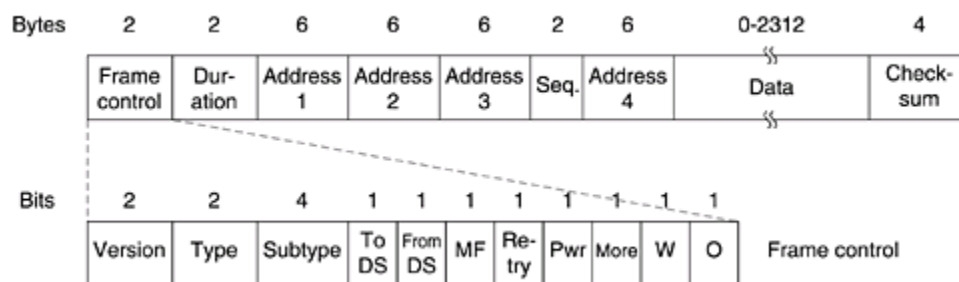


Figure 4: Wi-Fi packet format. [2]

#### d. ZigBee

ZigBee is the final transmission protocol being compared. It is aimed at low cost, low data rate, and low power networks. ZigBee is a registered trademark of the ZigBee Alliance which defines the network layer and application layers on top of the IEEE 802.15.4-2003 defined physical and MAC layers.

ZigBee offers flexible network topologies which consist of star, tree, and generic mesh networks. It also utilizes offset quadrature phase-shift keying (OQPSK) with frequency selection to achieve speeds near 250 kb/s at short distances. Packet formation is outlined in figure 5 with payload and header size listed in table 1.

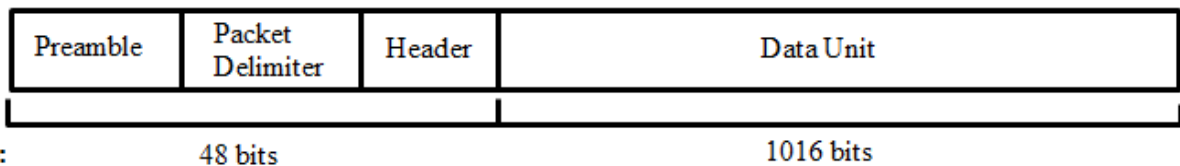


Figure 5: ZigBee packet format.

Protocol	Standard	Transmission Speed (kbps)	Max Data Payload Length (bits)	Max Overhead Length (bits)
<b>BLE</b>	IEEE 802.15.1	256	264	112
<b>Bluetooth</b>	IEEE 802.15.1	723.2	2712	158
<b>WiFi</b>	IEEE 802.11g	54000	18496	272
<b>Zigbee</b>	IEEE 802.15.4	250	816	248

Table 1: Transmission speed and packet characteristics of wireless transmission protocols

## IV. Hardware

Chips representative of each wireless transmission protocol was chosen based on the amount of information available in their respective datasheets. The information critical for energy usage analysis is listed in table 2 and 3, below:

Protocol	Name	Voltage (V)	Transmission Speed (kbps)	Tbit (us)	Delay, Low Power -> Active (us)	Delay, Active -> Transmit (us)
<b>BLE</b>	CC2540	3	256	3.91	4	160
<b>Bluetooth</b>	RN-42	3.3	723.2	1.38	5000	0
<b>WiFi</b>	XG-180M	3.3	54000	0.02	75000	210
<b>Zigbee</b>	CC2520	3	250	4.00	200	192

Table 2: Chip information for each transmission protocol.

<b>Protocol</b>	<b>Low Power Current Usage (mA)</b>	<b>Active Current Usage (mA)</b>	<b>Transmit Current Usage (mA)</b>
<b>BLE</b>	0.235	19.6	27
<b>Bluetooth</b>	0.026	40	40
<b>WiFi</b>	0.2	10	450
<b>Zigbee</b>	0.175	1.6	25.8

Table 3: Further chip information for each transmission protocol.

## V. Comparisons

To determine the final metric for energy savings of interval wireless data transfer, several prior derivations are required. First, the size of the payload will be calculated from the delay interval. With this, the total time required for sending of the payload (transmission time) is determined for each respective wireless protocol. Finally, data from table 2 and table 3 as well as the transmission time is combined to determine the total energy expended by the wireless chip during the given interval.

### a. Payload Size

The payload size is the product of the data incoming to the wireless chip and the interval hold time. As data throughput cannot be measured in fractions of a bit, the total payload size must to rounded down to the nearest whole bit.

$$Payload\ Size = N_{data} = ROUND\ DOWN(Incoming\ Data\ Rate * Hold\ Period)$$

### b. Transmission Time [3]

To calculate the transmission time, the packet format for each wireless protocol must by analyzed. The transmission time is the product of the total time required to transmit one bit ( $T_{bit}$ ) and the total number of bits required to transmit the payload, including the added overhead costs. The overhead is the additional bits required for identification, security, and error correction which are added to each payload. Additional overhead costs must be paid for each transmission that surpasses the maximum payload. Finally, it is assumed that the transmitter and receiver are close, thus, the propagation time is negligible. The resulting equation is described below:

$$T_{tx} = \left( N_{data} + ROUND\ UP\left( \frac{N_{data}}{N_{maxPld}} \right) \times N_{ovhd} \right) \times T_{bit} + T_{prop}$$

$N_{maxPld}$  – Maximum Payload

$N_{ovhd}$  – Overhead Size

$T_{bit}$  – Bit Time

$T_{prop}$  – Propagation Time

Figure 6 shows the transmission time required to transmit the data accumulated at a rate of 6 kbps during the hold time. A smaller transmission time helps to decrease the overall system energy usage as the chip spends a shorter interval in the transmit mode. It is also interesting to note how BLE eventually overtakes Zigbee in total transmission time. This is due to the BLE's smaller maximum payload size which requires a second overhead once a hold time of 44 seconds (264 bit payload size) is reached.

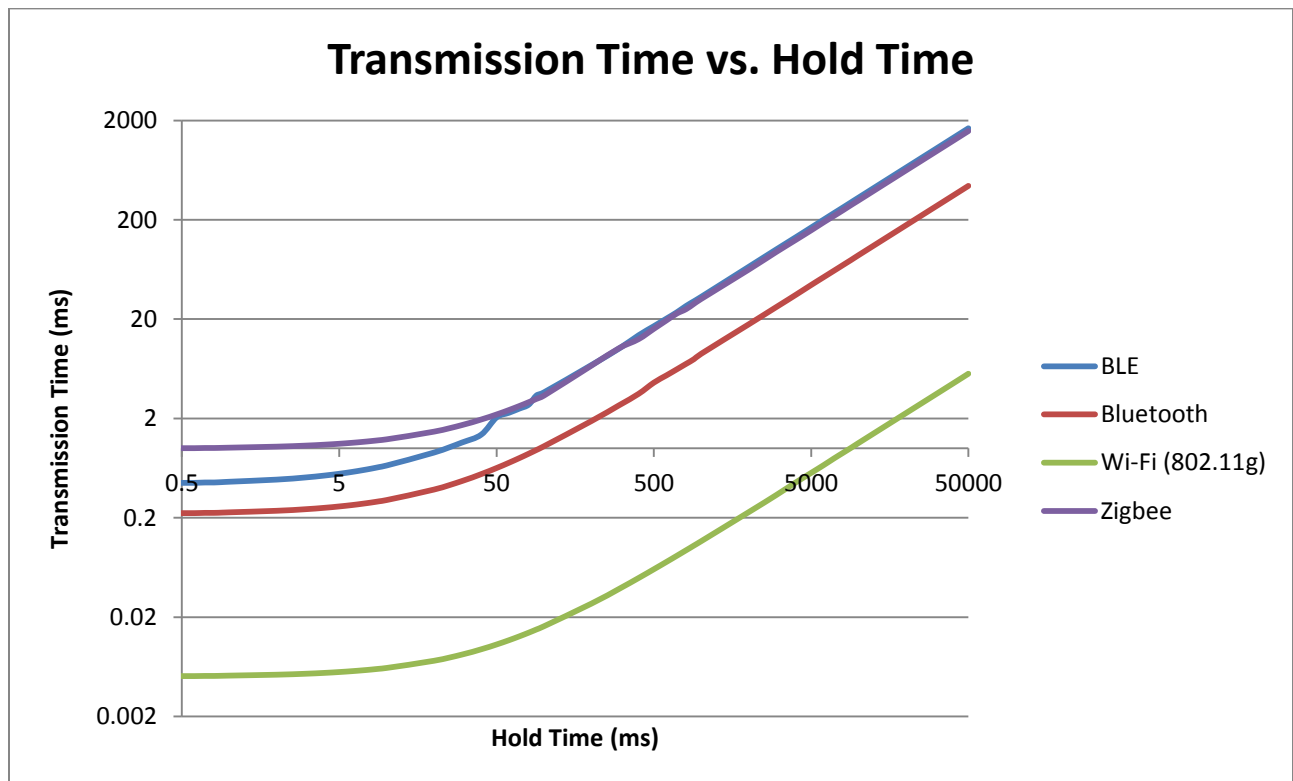


Figure 6: Comparison of transmission times at an incoming data rate of 6 kbps.

Increasing the incoming data rate to 100 kbps proportionally increases each protocols transmission time as shown in figure 7.

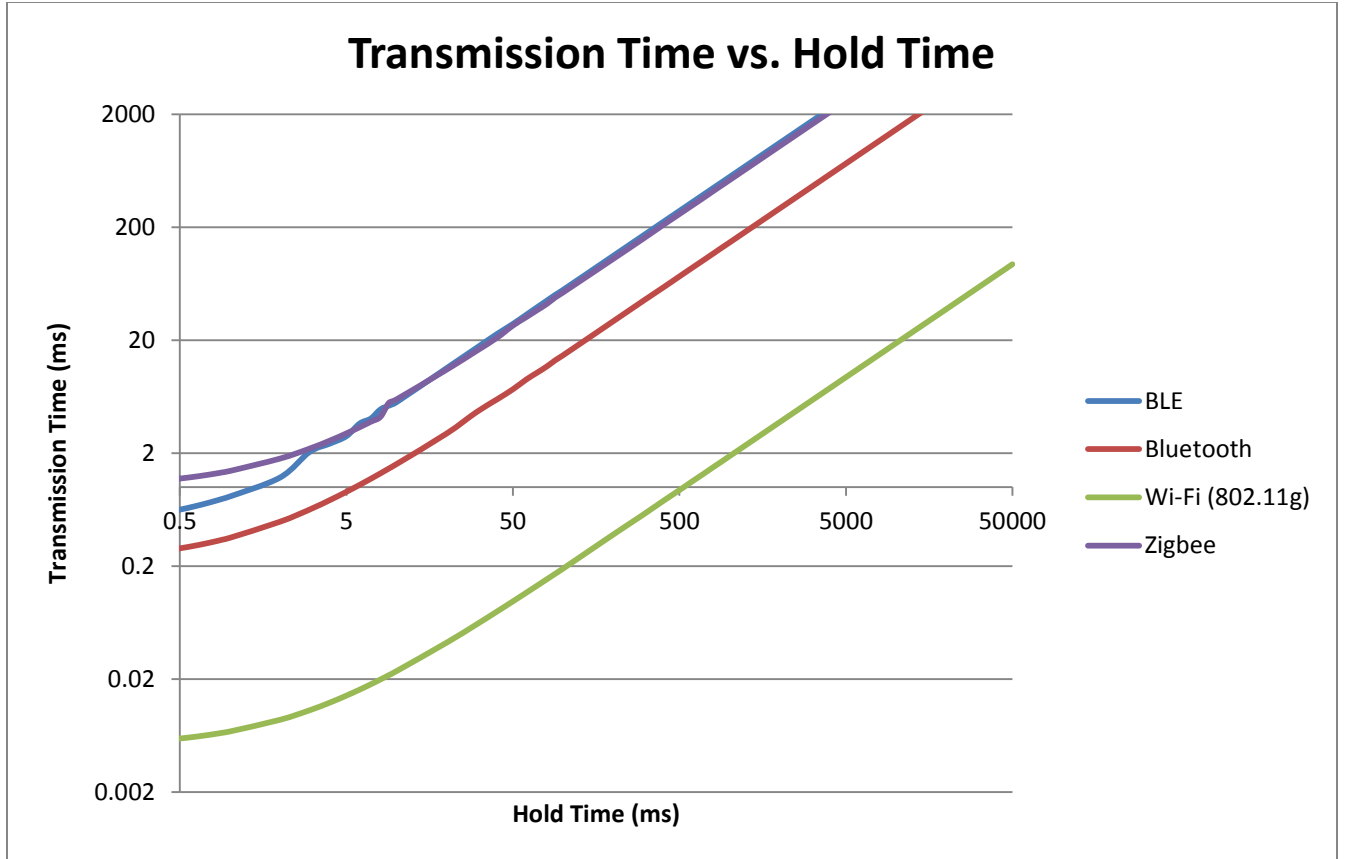


Figure 7: Comparison of transmission times at an incoming data rate of 100 kbps.

### c. Energy Expenditure

The energy expenditure is the sum of total time the wireless chip is in the low power, active, and transmission modes. Since the total hold time is known, the system power usage can be further minimized by preparing the chip to transmit as soon as the hold period is complete. As a result, the total time the chip spends in low power mode is not the full hold time, but is shortened by the total chip delay while changing from low power to transmit mode. A consequence of interval wireless data transfer is that transmission times cannot exceed the hold time. A system that violates this rule will either continue to accumulate data till all memory space is consumed, causing a system crash, or, the hold time is extended which changes the energy characteristics.

To simplify analysis, the rate of power change is considered to be linear as the chip switches from low power to active and from active to transmit mode. Thus, the total energy consumed by the chip during each transition is the product of the average power between the initial and final states and the delay of each transition. The resulting equation is described below:

$$E = [A_{lp}(T_{hold} - T_{lp-active} - T_{active-TX}) + AVG(A_{lp}, A_{active}) * T_{lp-active} + AVG(A_{active}, A_{TX}) * T_{active-TX} + A_{TX} * T_{TX}] * V_{cc}$$

- $A_{lp}$  – Low power current consumption
- $A_{active}$  – Active current consumption
- $A_{TX}$  – Transmission current consumption
- $T_{hold}$  – Hold time
- $T_{lp-active}$  – Low power to active transition delay
- $T_{active-TX}$  – Active to transmit transition delay
- $T_{TX}$  – Transmission time
- $V_{cc}$  – Source voltage of the chip

It is important to note that the total energy usage is affected by chip specifications as much as the wireless protocol they represent. None-the-less, figure 8 provides good insight on how each wireless protocol is affected as the hold time is varied. The aim is to minimize energy, thus, the smallest energy usage for each hold time is the protocol of choice for a more efficient system. It is interesting to see that each protocol has an interval, however brief, that it becomes the most efficient solution. Figure 9 shows the energy usage for an increased data rate of 100 kbps. The increase data rate favors the protocols with a higher transmission speed. This can be noticed by how much earlier Wi-Fi becomes the most energy efficient protocol. It can also be seen that BLE with its small payload size and slow transmission speed no longer is the recommended protocol across all hold times.

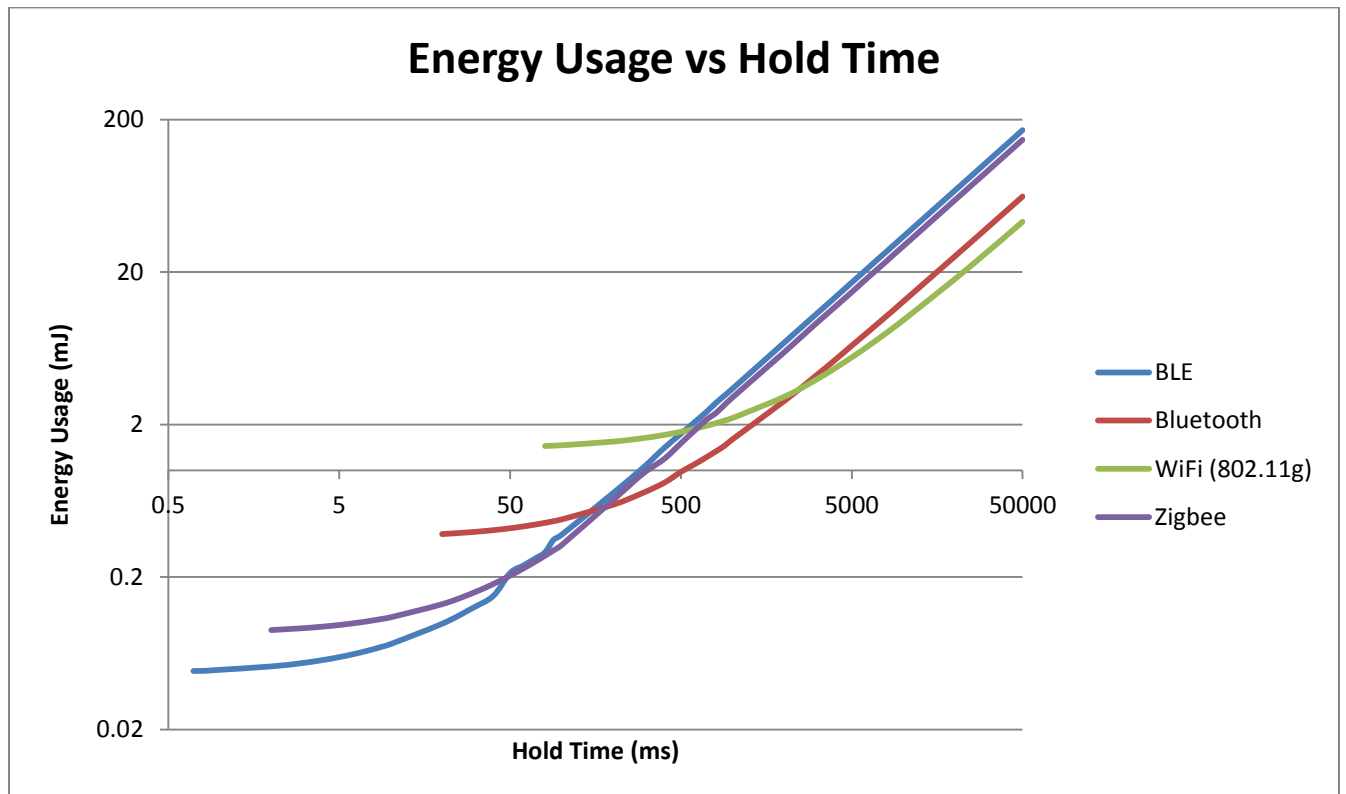


Figure 8: A comparison of energy usage at an incoming data rate of 6 kbps.

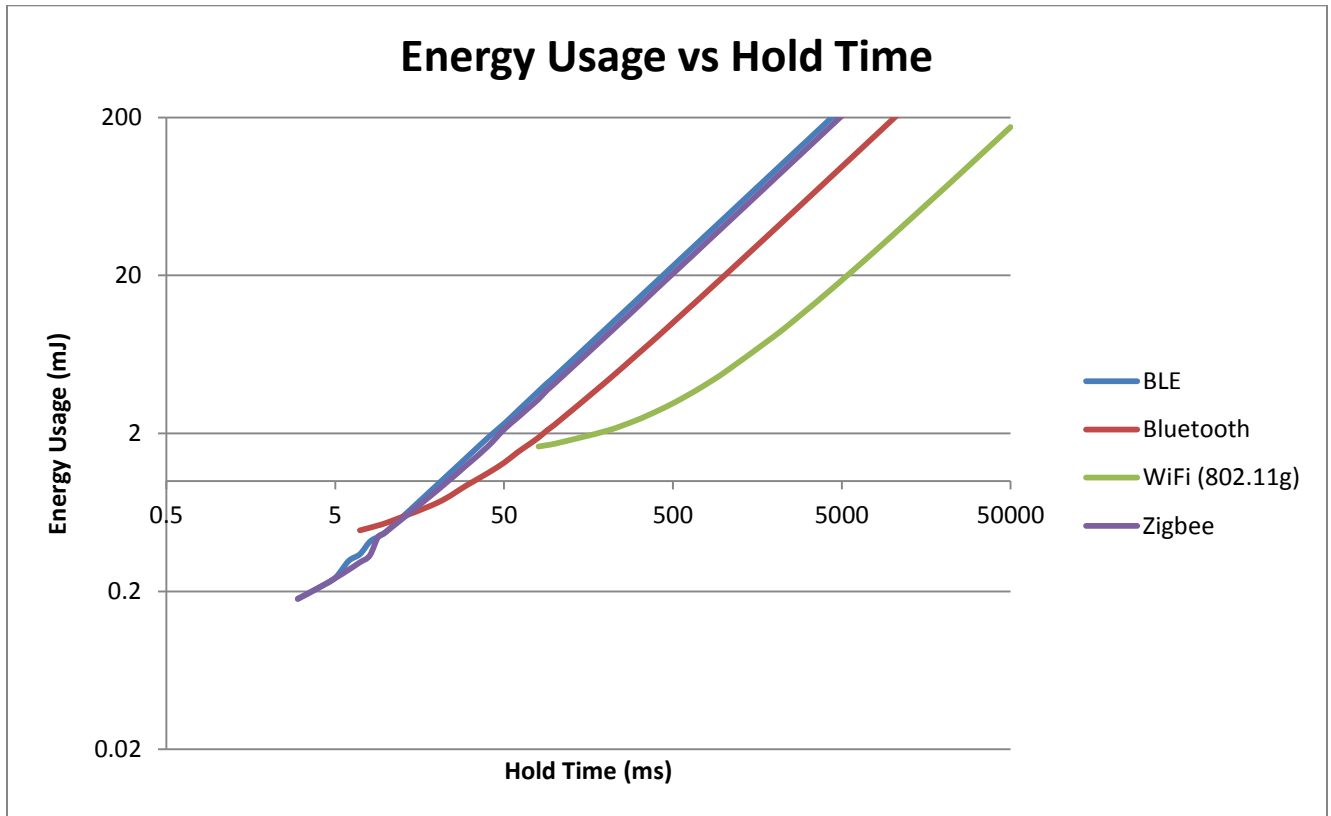


Figure 9: A comparison of energy usage at an incoming data rate of 100 kbps.

Figure 10 shows a graph for each wireless protocols energy usage per data bit transmitted versus the hold time. As the hold time increases the normalized energy usage decreases as a result of increased data transfer efficiency. Some small spikes can be seen which result from the added overhead cost once the data size surpasses the payload, thus lowering the systems efficiency. None-the-less, the overall trend is downward, with the wireless chips with the lowest transfer speeds saturating sooner. This graph conclusively shows the benefits of interval wireless data transfer

Figure 11 shows a similar conclusion but at an increased incoming data rate of 100 kbps. With the increase of incoming data rate, the wireless protocols with low transmission speeds saturate much sooner. Yet, even at low hold times the increase of data rate results in a higher overall energy efficiency as seen by the lower normalized energy usage.

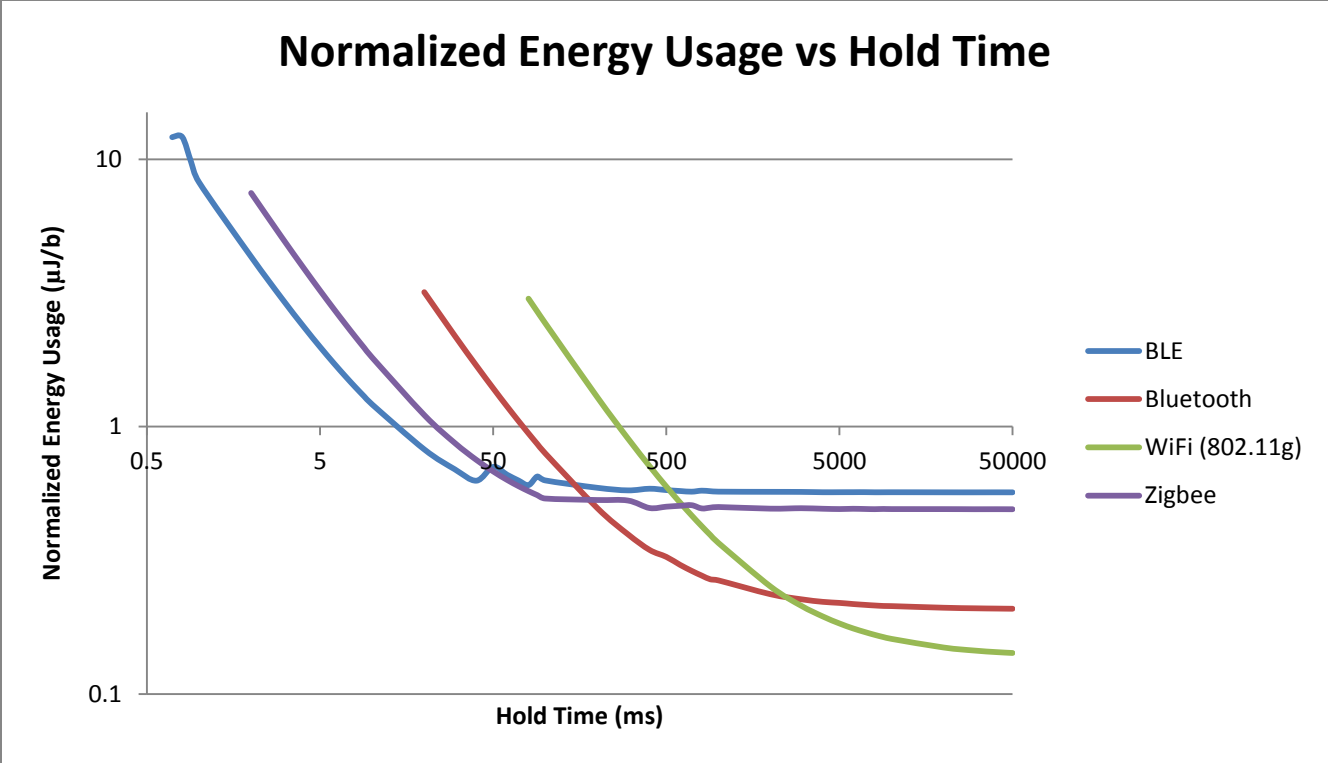


Figure 10: A comparison of normalized energy usage at an incoming data rate of 6 kbps.

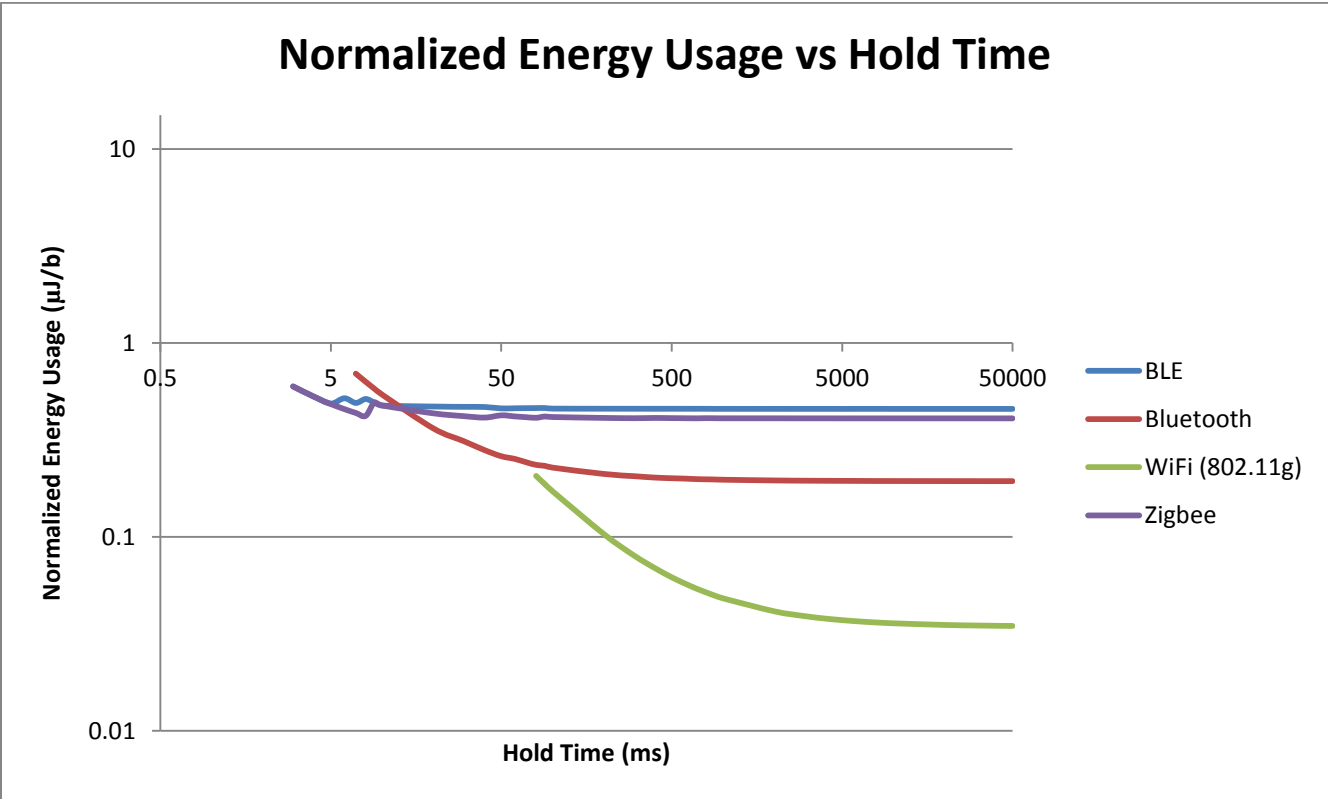


Figure 11: A comparison of normalized energy usage at an incoming data rate of 100 kbps.

## VI. Energy Usage Comparison MATLAB GUI

A graphical user interface was built to simplify the exploration of different wireless chips to determine the best solution that meets the needs of the end user. This GUI can be used to compare different chips that a product designer would integrate into a system. Or, the GUI can be used by chip manufacturers and IC designers to determine if a new chip improves upon the energy efficiency of a previous iteration or another competitors chip.

The following section outlines the usage of the GUI:

Launching the GUI, the user is initially greeted with the following screen:

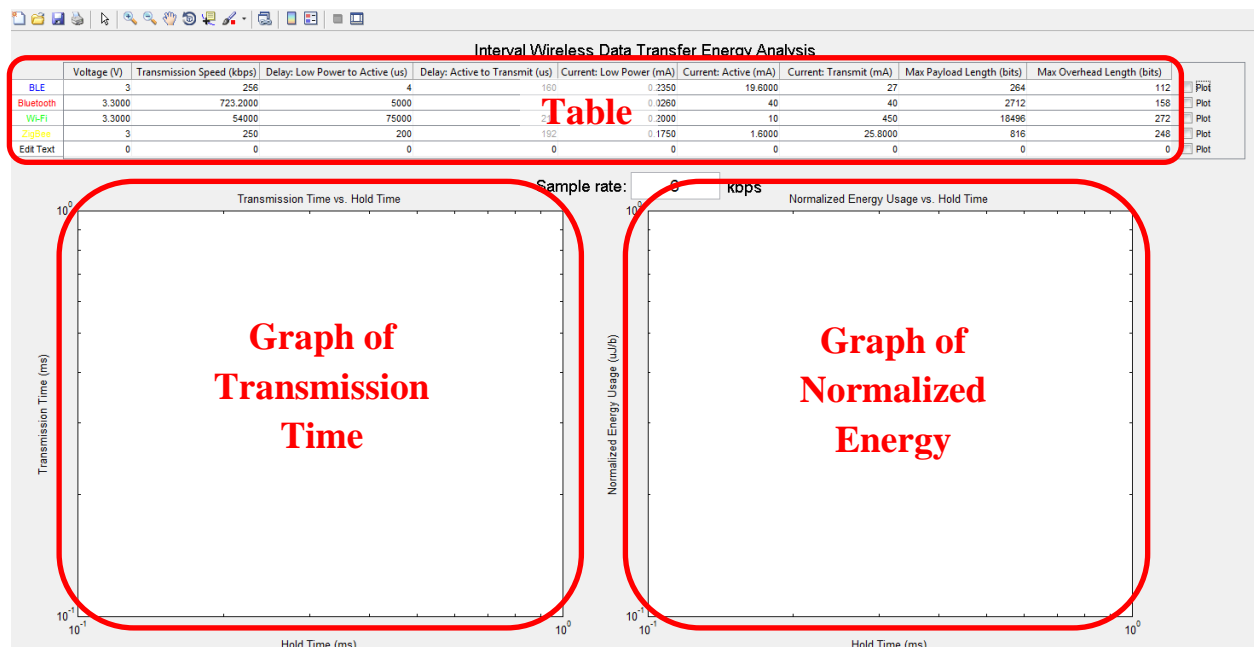


Figure 12: Initially start screen of GUI.

A table near the top lists the specifications required to derive an accurate assessment of the energy usage of the chip being analyzed. The table is partially filled with 4 representatives of each wireless protocol that have been previously discussed. The fifth row is purposely left blank as a space for the user to add an additional chip. For increased flexibility, the entire table is editable, so modifications can be made to all chips listed in the table.

Below the table is an input which determines the data sample rate of the system, the initial rate is set at 6 kbps but can be modified by the user to meet their systems specifications.



Figure 13: Sample rate input.

Below the sample rate input are two plots with the left showing the transmission time vs. hold time and the right showing the normalized energy usage vs. hold time.

The graphs are initially blank until a plot checkbox, to the right of the characteristic table, is checked. The plot checkbox's can be checked and unchecked to assist the user with accurately comparing different wireless chips.

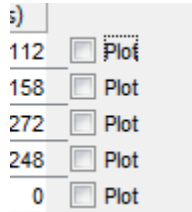


Figure 14: Plot checkboxes.

An additional feature of the GUI is the real time updating of the graphs. Changing individual chip characteristics or the sample rate will immediately change each plot.

The toolbox on top allows the user to zoom into specific areas of each plot to enable the user a better view of critical areas.



Figure 15: GUI toolbox.

The figure below shows the GUI with plots enabled. Notice that they compare favorably with Figures 7 and 8 in section V.

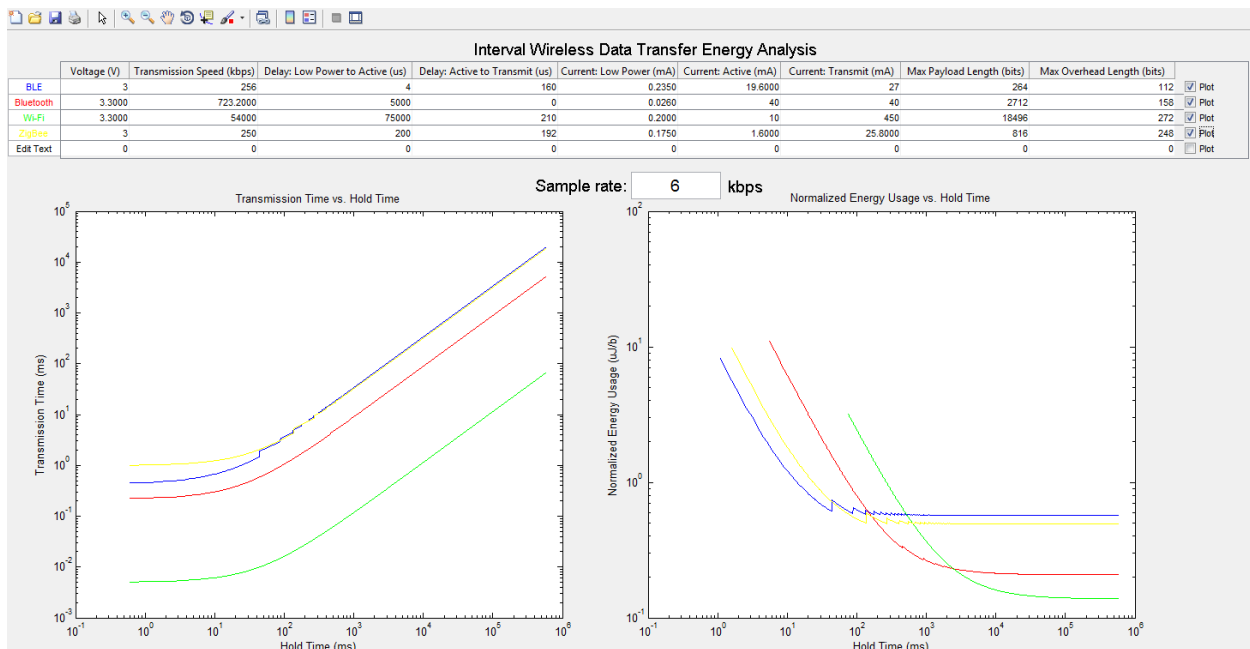


Figure 16: GUI showing plots for the initial list of wireless protocols.

## VII. Conclusion

This paper presented a method to compare energy expenditure of several popular wireless protocols when the data was transferred intermittently. From the information presented in figure 10 and 11 it was determined that interval data transfer does indeed improve energy savings. The figure also allowed a visual comparison of each protocol and as a result, the most efficient protocol corresponding to a specific hold time can be seen. Furthermore, this paper introduced a GUI interface which assists engineers and manufacturers alike to quickly determine the energy efficiency of their respective products. With the increase importance of energy savings it is critical to continue exploration of novel methods to improve the efficiency of the entire system. This paper provides one metric to aid in this exploration.

## VIII. Acknowledgements

I would like to thank Professor Danijela Cabric for her guidance on the project and the suggestion to create an interactive GUI aimed at both engineers and manufacturers.

## IX. Bibliography

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