Bluetooth Energy Characteristics in Wireless Sensor Networks

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Abstract— In this paper a measurement system to create an experimental model and a tool box for simulations concerning both the energy consumption and the time aspect when creating wireless sensor networks using Bluetooth 2.0 + Enhanced Data Rate has been developed. Further energy and time characteristics for critical events when using Bluetooth 2.0 in Wireless Sensor Networks are investigated experimentally, with the main events; create connection, send data, receive data, and idle state. Results show that when allowing higher latencies for the connection in the Wireless Sensor Networks the power consumption drops drastically when using low power mode as sniff.

Index Terms— **Wireless Sensor Networks, Bluetooth, Energy Characteristics, Scatternet, Measurement System**

I. Introduction

Wireless Sensor Networks (WSN) consist of a large number of sensor nodes that are deployed within or near the phenomena to be sensed. The fundamentals of WSN are well described in [1] and [2] where design challenges are highlighted such as hardware constraints, scalability and power consumption. Power consumption is a main issue since the sensor nodes typically are battery powered, thus low power consumption is directly related to the lifetime of the sensor network. Usually the most power consuming component in a sensor node is the radio and research on power efficiency in communication is a main issue. This includes routing, clustering and synchronization [3].

Bluetooth [4] is a leading radio standard for short-range wireless data communication. It was initially designed for low power consumption cable replacement but the radio interface can also be used to create multi-hop ad hoc networks called scatternets. This makes it possible to create wireless sensor networks with Bluetooth technology although its use as a large scale ad hoc networking technology has some problems as described in [5]. Most of the scatternet studies rely on simulations based on Bluetooth models.

The fundamental problem is addressed in [6] where it is stated; *"BT-models studies employ rather old and inadequate power-models that were derived for other wireless systems"*. Thus most power models used are oversimplified and not based upon experimental measurements.

To develop a model of wireless sensor network using Bluetooth, several characteristics need to be extracted. These include power consumption, the time for each event and overall performance. Extracting these characteristics for Bluetooth 2.0 will provide information for enhancement of the overall performance in terms of battery life time depending on data rate, distance between nodes and sampling rate. A Network Simulator [7] can be used as a simulation tool and helps to develop WSN using Bluetooth regarding efficient ways to communicate in terms of time and energy consumption. A first step for enabling the use of Bluetooth in WSN is presented in [6] and describes a power model for Bluetooth 1.2 in complex Scatternet scenarios. A more complex node analysis of the power characteristics is presented in [8]

A step towards automatic measurement system of the Bluetooth 1.2 power consumption for single events when creating a connection and sending data with different settings is presented in [9] and [10], however based on a point to point scenario.

Accurate energy characteristics are essential for network simulation tools in order to predict WSN behaviour. These energy characteristics combined with other WSN parameters such as latency and network topology help the designer to develop efficient algorithms for overall network energy consumption.

The focus in this study is to create a tool box to enable simulations concerning both energy consumption and the time aspect when creating WSN using Bluetooth 2.0 + Enhanced Data Rate (EDR). Energy and time characteristics for critical events when using Bluetooth 2.0 in WSN are investigated experimentally, with the main events; create connection, discover devices, send data, receive data, idle and disconnect.

II. Energy Affecting parameters in bluetooth

The energy consumption for a Bluetooth radio module depends on which role/roles the device has, how many and what kind of connections to other devices it has and how these are configured.

Transmit (TX) power affects the power consumption and Bluetooth has three classes and their respective maximum output power are +20 dBm, +4 dBm and 0 dBm respectively. The minimum output power is at maximum power setting 0 dBm for class 1 and -6 dBm for class 2. For class one devices power control is mandatory. For class two and three it is optional. A device with power control compares the received signal with a preferred value and can, based on this comparison, request that the other device decreases or increases its TX power. The sensitivity of the radio also effects energy consumption during reception and a Bluetooth radio has a sensitivity level of -70 dBm or lower with one bit error rate (BER) of 0.1%.

The Synchronous Connection-Oriented (SCO), Extended Synchronous Connection-Oriented (eSCO) and Asynchronous

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Connection-Oriented logical transports (ACL) each has different parameters which influence the power consumption.

How much power an ACL connection drains depends, apart from TX power, on its quality of service (QoS) settings, amount of data transferred, quality of physical link, e.g. retransmissions, and what kind of package type is used. The QoS setting dictates how often POLL and NULL packages are sent from the master to slave i.e. latency.

SCO and eSCO transports duty cycle, and thus power consumption, is configurable by the parameters transmit and receive bandwidth, max latency, retransmission effort and packet type.

Bluetooth has two low duty cycle modes which potentially lower the power consumption; sniff and hold. Each of these modes has duty cycle affecting parameters which in turn influence power consumption. In sniff mode an ACL connected slave device listens for a specified amount of time, depending on the parameters $N_{sniff\_attempt}$ and $N_{sniff\_timeout}$, regularly with a period depending on T_{sniff}. When a device places an ACL connection in hold mode traffic for that connection are suspended for a specified time, holdTO.

When a device is discoverable and/or connectable the device, with regular intervals, listens for incoming inquiry or page packets. The duration and interval for these scans is configurable, and thus the impact on the energy consumption, with the parameters inquiry scan window, inquiry scan interval, page scan window and page scan interval.

III. Measurement Setup

The goal of the measurement setup is to be able to measure the energy and time characteristics of a Bluetooth radio for different scenarios. The measurement setup is divided into three parts, sensor node, instrumentation system and Bluetooth sniffer, each part is described as an individual part but all parts are centred to work with the sensor node.

A. Sensor Node

The sensor node consists of a Bluetooth radio module, a microcontroller, a current measurement circuit and I/O interfaces. The radio modules which have been used are Mitsumi WML-C46 and CSR BC4 external modules which have been programmed with HCI firmware. The microcontroller is a dsPIC in which HCI upper layer and transport plus a reduced L2CAP layer to send data have been implemented. An UART connection, with a baud rate 115.2 kbaud/s, between the host and the controller has been used as a H4 host controller transport layer.

B. Instrumentation system

The instrumentation system consists of a Tektronix TDS 3012 oscilloscope that communicates via an IEEE 488.2 -bus with a computer providing a Graphical User Interface (GUI) developed in LabView 8.2 that uses the CPU internal clock for high precision timestamp. The energy consumption of the nodes and time for the single events can be monitored through the GUI.

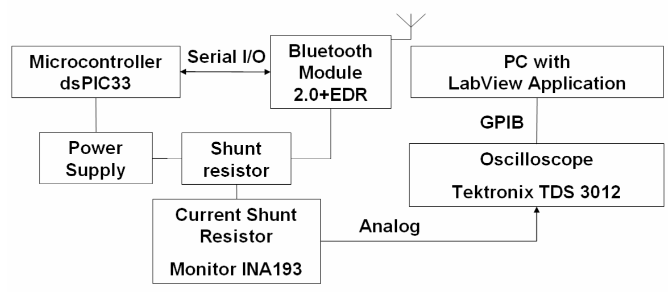

Figure 1 Instrumental system

Using a current shunt monitor, Texas instrument INA193, with an inbuilt gain of 20 V/V gives a higher resolution and reduces noise to signal ratio compared to measuring directly over the shunt resistor as depicted in figure 2.

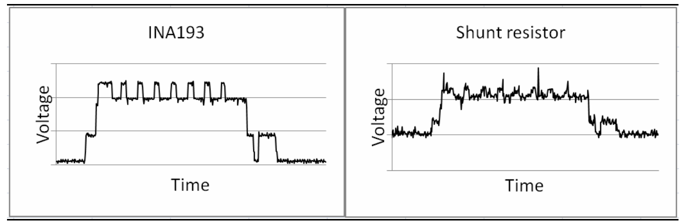

Figure 2 Voltage measuring with TI INA193 compared to shunt resistor

In table 1 the specifications of the instrumental system are declared.

Table 1 Specification of instrumental system

Sample Frequency	25kHz
ADC Resolution	8-bit
Gain INA193	20 V/V
Resolution Oscilloscope	7.8mA
System Resolution	0,39mA
Supply Voltage	3.3 V
Time Stamp Resolution	1µs

1) Calibration of instrumental system

A measurement calibration has been performed with a reference current measured with a FLUKE 45 dual display multimeter and the following formula has been extracted to calculate the current, I, for each digital value produced with the LabView application:

$$I = \text{Res} \cdot (D - Z) \cdot k_i$$

Res is the system resolution, D is the digital value obtained from the oscilloscope, Z the value obtained at zero current and k_i is a correlation term depending on the interval.

C. FTS4BT Sniffer

For verification and monitoring of the data traffic between the sensor nodes, a FTS4BT sniffer from Frontline [11] has been used. This gives the instrumentation system full control of time of events and what is being sent. To complement the HCI air sniffer the commands sent from the controller to the Bluetooth module are forwarded to the sniffer program via serial cable by HCI serial H4 protocol for data logging of the communication between the controller and Bluetooth module.

IV. EXPERIMENT SETUP

Measurements on the time and energy characteristics of each event have been performed in this study. Further the result has been used to develop energy consumption models for sensor network simulations for overall performance such as; battery lifetime expectancy or system latency.

In the measurement of energy consumption during a device discovery, also known as inquiry, the measurement starts when the Bluetooth module has received the HCI "Inquiry" command and stops when the module has sent the HCI "Inquiry Complete" event to the host.

The device discovery scan and page scan measurement begins when the Bluetooth module power up for the inquiry scan or page scan and ends when the module has returned to idle state.

With the concept "Create Connection" the measurement starts on the master device(s) when the HCI command "Create Connection" has been sent from the host to the controller to the time when all initial message exchanges has been completed by the master and slave device. On the slave device the measurement begins when the controller has received the page packet from the master and ends when the initial message exchange has been completed.

The data send measurements starts when the microcontroller begins transmitting the packet to the module and ends when the module has confirmed that the packet has been sent with a "Number of completed packets" event packet. For the receive measurement the average current over time is measured together with the number of received packets. In the idle measurements, the average current over time is measured and the disconnect measurement begins when the module has received the command the time when it has sent the disconnection complete event to the microcontroller.

V. EXPERIMENTAL RESULTS

Results for the events described in IV are presented below with the specific settings that affect the energy and time characteristics for each event. The radio transmission power has been set to +4 dBm for all measurements and all connection types are ACL.

A. *Characteristics for create connection events*

The default setting for "create connection" is; a page scan interval of 2.56 s and a time window of 11.25 ms. Whereas the settings for fast has an interval of 160 ms and a time window of 100 ms. The results presented in table 2 are for creating an ACL connection as a function of number of slaves.

TABLE 2 CREATE CONNECTION

Number of Slaves	Default		Fast	
	Time [s]	Power [mW]	Time [s]	Power [mW]
1	3.529	11.3	0.148	0.5
2	10.407	33.3	0.309	1.0
3	14.085	45.0	0.501	1.6
4	18.716	59.8	0.689	2.2
5	23.152	74.0	0.976	3.1
6	26.382	84.3	1.256	4.0
7	33.018	105.5	0.163	5.3

B. *Characteristics for send events*

Table 3 shows the energy consumption when transmitting on a default ACL connection (the default latency for one ACL connection is set to 25 ms) for roles master and slave and master broadcasting.

TABLE 3 SEND WITH DEFAULT SETTINGS

Packet size [bytes]	Master		Slave		Broadcast	
	Time [s]	Power [mW]	Time [s]	Power [mW]	Time [s]	Power [mW]
2	0.013	50.8	0.019	81.3	0.012	55.4
10	0.013	52.5	0.020	81.5	0.013	51.1
50	0.017	40.9	0.024	82.4	0.023	51.4
250	0.037	34.3	0.042	82.8	0.073	67.4

In table 4 the latency parameter has been varied for one ACL connection and the measurements is for a master device. Table 5 shows the same type of measurement as table 4 with the difference that the ACL connection has been configured to sniff mode with different sniff intervals and with sniff attempt set to one.

TABLE 4 SEND AS MASTER WITH ALTERING QOS SETTINGS

Packet size [bytes]	QoS Latency 13.75ms		QoS Latency 51.25ms		QoS Latency 101.25ms	
	Time [s]	Power [mW]	Time [s]	Power [mW]	Time [s]	Power [mW]
2	0.012	86.2	0.029	35.9	0.050	25.5
10	0.013	84.0	0.027	35.9	0.046	27.9
50	0.015	74.3	0.033	35.1	0.047	29.2
250	0.035	61.8	0.051	29.0	0.070	21.2

TABLE 5 SEND AS MASTER WITH SNIFF MODE

Packet size [bytes]	Sniff Interval 12.5ms		Sniff Interval 512.5ms		Sniff Interval 912.5ms	
	Time [s]	Power [mW]	Time [s]	Power [mW]	Time [s]	Power [mW]
2	0.012	54.5	0.268	7.2	0.473	8.0
10	0.012	52.7	0.254	9.3	0.505	6.0
50	0.017	45.3	0.295	7.3	0.546	6.0
250	0.037	47.1	0.273	10.5	0.555	7.2

In table 6 the latency parameter has been varied for one ACL connection and the measurements is for a slave device. Table 7 shows the same type of measurement as table 6 with the difference that the ACL connection has been configured to sniff mode with different sniff intervals and with sniff attempt set to one.

TABLE 6 SEND AS SLAVE WITH ALTERING QOS SETTINGS

Packet size [bytes]	QoS Latency 13.75ms		QoS Latency 51.25ms		QoS Latency 101.25ms	
	Time [s]	Power [mW]	Time [s]	Power [mW]	Time [s]	Power [mW]
2	0.014	84.0	0.057	95.7	0.009	74.2
10	0.015	86.0	0.056	106.2	0.013	74.5
50	0.018	85.5	0.060	106.4	0.013	74.7
250	0.037	84.1	0.079	98.1	0.033	75.8

TABLE 7 SEND AS SLAVE WITH SNIFF MODE

Packet size [bytes]	Sniff Interval 12.5ms		Sniff Interval 512.5ms		Sniff Interval 912.5ms	
	Time [s]	Power [mW]	Time [s]	Power [mW]	Time [s]	Power [mW]
2	0.012	45.6	0.252	7.1	0.495	7.0
10	0.013	42.3	0.255	9.9	0.471	5.4
50	0.016	40.2	0.298	7.6	0.403	7.0
250	0.037	44.7	0.281	10.0	0.558	6.6

C. Characteristics for receive

Table 8 shows the power consumption when receiving data of different specific sizes over a default ACL connection with a packet frequency specified in the table.

TABLE 8 RECEIVE DATA

Packet size [bytes]	Master		Slave	
	Power [mW]	Packets/ second	Power [mW]	Packets/ second
2	19.5	2.00	74.9	1.99
10	19.6	1.99	75.0	1.99
50	19.5	1.96	75.1	1.96
250	19.7	1.84	75.2	1.83

D. Characteristics for idle

The measurements in table 9 show the power consumption of a slave device for an idle sniff configured ACL connection to one master. The sniff parameters number of attempts and sniff interval has been varied.

TABLE 9 IDLE STATE AS SLAVE WITH SNIFF MODE

Interval [ms]	Number of attempts			
	1	2	5	10
	Power [mw]	Power [mw]	Power [mw]	Power [mw]
12.5	20.3	29.5	53.0	81.7
112.5	7.1	8.1	10.9	15.2
212.5	6.2	6.7	7.9	10.1
412.5	5.2	5.3	6.1	7.2
612.5	4.7	5.0	5.5	6.2
812.5	4.3	4.5	4.8	5.4
1000	4.1	4.2	4.5	5.1
5000	3.2	3.3	3.3	3.4
10000	3.1	3.0	3.0	3.1

Table 10 presents the power consumption for a master device with different number of idle default ACL connections. In column three the master device also has an idle ACL connection to another master.

TABLE 10 IDLE STATE AS MASTER WITH DEFAULT ACL CONNECTIONS

Number of Slaves	Master	Being Master and Slave
	Power [mW]	Power [mW]
1	17.6	80.5
2	29.1	82.3
3	40.1	83.2
4	40.9	83.7
5	41.9	84.7
6	42.8	85.4
7	43.2	-

In table 11 the power consumption for a slave with one and two ACL connected masters is presented. The sniff and QoS measurements are for one idle ACL connection.

TABLE 11 IDLE

Settings	Being Master	Being Slave
	Power [mW]	Power [mW]
No Role or Scans	3.1	
1 master connected	-	75.3
2 masters connected	-	80.7
Sniff interval 12.5ms	25.3	20.3
Sniff interval 512.5ms	5.3	5.1
Sniff interval 1000ms	4.0	4.1
QoS 1.25ms	98.8	78.1
QoS 26.25ms	16.9	75.5
QoS 101.25ms	7.8	75.7

VI. CONCLUSIONS

When comparing the results in this study with previous results of Bluetooth power consumption [6] it becomes clear that the enhancements made in Bluetooth make it possible to use it for WSNs in terms of energy consumption. E.g. is the power consumption for Bluetooth 1.2 when having no role or as described in [6] as P_{stby} is 44.58 mW and for Bluetooth 2.0 the same activity consumes 3.1 mW as shown in table 10.

When creating a network with Bluetooth 2.0 the settings for the communication are critical both for power consumption and time delays in the WSN. A typical example of how the settings are affecting the power consumption is sending data; as shown in tables 3-7. Comparing a master sending 250 bytes over a default ACL connection with a sniff configured ACL connection with the latency 12.5 ms and one attempt it takes the same time but the sniff mode consumes about 40% more power. With the same settings for a slave sending 250 bytes the opposite occurs when comparing power consumption.

However for a slave in idle state with the same settings compared above there is a vast difference in power consumption; whereas the slave in sniff mode only consumes around 25% of what a slave with the default setting consumes. Lower power consumption is achieved if the latency in sniff mode for the connection is higher as shown in table 9.

When creating a connection the settings for page scan and time window affect both time and power consumption as is shown in table 2, a faster and more power efficient connection is achieved when allowing a shorter interval between scans and longer time window.

Receiving data for a slave when using default settings shows no increase of power consumption and the master shows an increase of about 2 mW when sending two packets per second as shown in table 8 when comparing the result in table 10.

The results show a great versatility when using Bluetooth were a higher latency in the WSN can be used with the energy consumption going to be lower, if using sniff mode.

The results in this study in combination with the enhancement of Bluetooth 2.0 + EDR make it possible to configure advanced WSN using Bluetooth 2.0 + EDR with known performance concerning energy, time and bandwidth.

VII. Future Work And Outlook

The results presented in this study will be used as an aid in simulations of WSN where the energy consumption and latency is studied. In the future it is planned to provide a model for the energy consumption depending on selected bandwidth, latency, distance and number of connections. It is planned to include the upcoming Ultra Low Power Bluetooth in the model.

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