Time-Slot-Based Analysis of Bluetooth Energy Consumption for Page and Inquiry States

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1. Introduction

Bluetooth technology is sometimes rated as "low power" and sometimes as "high power" depending on the observer's point of view. In the ad-hoc network domain Bluetooth is often classified as a technology that consumes low power, e.g. compared to WLAN. From a sensor network researcher's point of view Bluetooth may have a power consumption that is too high [1]. However, Bluetooth power or energy consumption on the one hand depends on many technology-specific parameters and therefore varies according to the selection of these parameters. On the other hand there are manufacturer-dependent differences and measurement results for the Bluetooth device of a specific manufacturer cannot simply be transferred to devices of other manufacturers.

This work is based on analytical results by Joel Linsky. In [2] Linsky presents time-slot-based equations for the energy consumption of synchronous Bluetooth connections and for the page state. Our work in progress is the extension of his system of equations in order to include all Bluetooth states. In this paper we present analytical results for the following states: page, page scan, inquiry, and inquiry scan. These equations can serve as a tool for a manufacturer-independent evaluation of the energy consumption of Bluetooth technology in general and of Bluetooth-based communication protocols such as scatternet formation protocols.

2. Energy consumption for page state and page scan state

During page scan state a Bluetooth devices waits for page requests of other devices. This state consists of alternating scan- and sleep-phases (Fig. 1). Two parameters define the page scan state: the page scan interval T_{page_scan} specifies the time between two consecutive scan phases and the page scan window $T_{page\_scan\_window}$ determines the duration of a scan phase. The average energy consumption per slot of a Bluetooth device in the page scan state then accounts for

$$E_{ps} = \frac{T_{page\_scan\_window} E_{rx\_idle} + (T_{page\_scan} - T_{page\_scan\_window}) E_{sb}}{T_{page\_scan}} \quad \textbf{(1)}$$

with E_{rx_idle} as energy consumption per time slot during scan phases and E_{sb} as energy consumption per time slot during sleep phases. The page scan interval has to be 11.25 ms at least and 2.56 s at most (default: 1.28 s) [3]. The page scan window has to be at least 10.625 ms and must not be longer than the page scan interval (default: 11.25 ms) [1]. With the given default values and the default Bluetooth slot length of 625 µs, the average energy consumption per time slot during page scan substantiates to

$$E_{ps} = \frac{18 E_{rx\_idle} + (2048 - 18) E_{sb}}{2048} \quad \textbf{(2)}$$

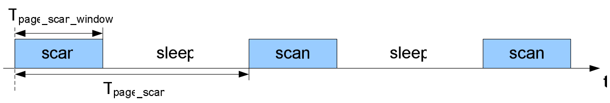

Fig. 1: Bluetooth page scan state with alternating scan and sleep phases

During page state a Bluetooth device attempts to create a connection to other devices in page scan state. The specification of the Bluetooth technology defines the paging device as master and the corresponding device in page scan state as slave [3]. In order to create a connection, the master transmits ID-packets using an increased hop rate of 3200 hops/s. ID-packets contain the device access code of the paged slave. During each odd 625-µs-time-slot the master transmits two ID-packets on consecutive frequencies of the page hop sequence and waits for replies in each even time slot (on the same frequencies used in the preceding odd time slot, see Fig. 2, step 1). If the page frequency of the master and the page scan frequency of the slave match, the connection will be established (see Fig. 2, step 2-4). The master calculates its page hop sequence based on the slave's device address and clock estimate (which the master must have obtained before by an inquiry). The estimation of the slave's clock may be inaccurate due to clock drift of master and slave. Therefore the time for connection establishment may vary. The master's energy consumption per time slot for connection establishment then accounts for

$$E_{page_{Master}} = \frac{1}{n+3}\left(\begin{matrix}\frac{n}{2}E_{rx\_idle} + \frac{n}{2}E_{1-slot-ID*2-tx} + \\ 2E_{1-slot-ID-rx} + E_{1-slot-FHS-tx}\end{matrix}\right) \quad (3)$$

where E_{rx_idle} is the energy consumption for each time slot the master waits for the slave's reply, $E_{1\text{-}slot\text{-}ID*2\text{-}tx}$ is the energy consumption for transmitting two ID-packets, $E_{1\text{-}slot\text{-}ID\text{-}rx}$ is the energy consumption for receiving one ID-packet and $E_{1\text{-}slot\text{-}FHS\text{-}tx}$ is the energy consumption for transmitting one FHS-packet which is used for frequency hopping synchronization. The parameter n specifies the number of time slots the master needs to find a corresponding slave frequency. The slave's energy consumption for connection establishment then accounts for

$$E_{page_{Slave}} = \frac{1}{3}\left(2E_{1-slot-ID-tx} + E_{1-slot-FHS-rx}\right) \quad (4)$$

The parameter $E_{1\text{-}slot\text{-}ID\text{-}tx}$ determines the energy consumption for transmitting one ID-packet within a time slot, $E_{1\text{-}slot\text{-}FHS\text{-}rx}$ specifies the energy consumption for receiving one FHS-packet. Straight before connection establishment, the slave's energy consumption is the same as given in equation (1) for page scan state.

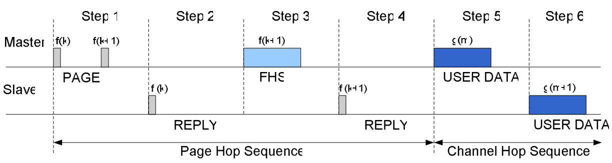

Fig. 2: Connection establishment of two Bluetooth devices (master in page state and slave in page scan state).

3. Energy consumption for inquiry state and inquiry scan state

The inquiry scan state is similar to the page scan state and consists of scan- and sleep-phases. Two parameters define the inquiry scan state: the inquiry scan interval $T_{inquiry\_scan}$ specifies the time between two consecutive scan phases and the inquiry scan window T_{iscan_window} determines the duration of a scan phase. The average slot-based energy consumption of a Bluetooth device in inquiry scan state without active connections then accounts for

$$E_{inquiry\_scan} = \frac{T_{iscan\_window}E_{rx\_idle} + \left(T_{inquiry\_scan} - T_{iscan\_window}\right)E_{sb}}{T_{inquiry\_scan}} \quad (5)$$

where E_{rx_idle} is the energy consumption per time slot during scan phases and E_{sb} is the energy consumption per time slot during sleep phases. The inquiry scan interval has to be at least 11.25 ms and must not be longer than 2.56 s (default 2.56 s) [3]. The inquiry scan window has to be at least 10.625 ms and must not be longer than the inquiry scan interval (default: 11.25 ms) [3]. With the given default values and the default Bluetooth slot length of 625 µs, the average energy consumption per time slot during inquiry scan accounts for

$$E_{inquiry\_scan} = \frac{18E_{rx\_idle} + (4096-18)E_{sb}}{4096} \quad (6)$$

A Bluetooth device in inquiry states searches for other Bluetooth devices in the vicinity. The timing of the inquiry state is similar to the page state. An inquiring device transmits during each odd 625-µs-time-slot two ID-packets on consecutive frequencies of the inquiry hop sequence and waits for replies in each even time slot (on the same frequencies used in the preceding odd time slot). Discovered devices will reply to an inquiry with an FHS-packet. Let k be the number of received FHS-packets as replies to an inquiry. The average energy consumption per time slot of the inquiry state is then:

$$E_{inquiry} = \frac{1}{n}\left(\frac{n}{2}E_{1-Slot-ID*2-tx} + \left(\frac{n}{2} - k\right)E_{rx\_idle} + kE_{1-Slot-FHS-rx}\right) \quad (7)$$

4. Conclusion

We presented parts of a system of equations that enables developers to evaluate Bluetooth power consumption independent of a specific device manufacturer. With these equations, communication protocols using Bluetooth can be compared objectively. If developers are interested in manufacturer-dependent results, time-slot-based energy consumption values can be measured and integrated into our equations.

5. References

[1] Leopold, M., Dydensborg, M., Bonnet, P., „Bluetooth and sensor networks: a reality check“, in *Proc. of SenSys 2003*, Los Angeles, USA, November 2003.

[2] Linsky, J., „Bluetooth and power consumption: issues and answers“, *RF-Design*, November 2001, pp. 74-95.

[3] Specification of the Bluetooth System, Version 2.0, November 2004.