The Power Consumption of Bluetooth Scatternets

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Abstract

Low power has become a primary concern in the field of ad–hoc and personal area networks. As manufacturers start endowing their designs with scatternet support, Bluetooth is emerging as a key enabling technology. Although this is driving research on Bluetooth power optimization, most proposals in the literature are based on either over–simplified, fully theoretical, or old and inadequate power models. We present a real–world power model of a Bluetooth device supporting scatternets and sniff–mode, and validate it experimentally for the BTnode, an ad–hoc and sensor network prototyping platform developed at ETH Zurich. Whilst guaranteeing a low computational complexity, the model achieves a 4% RMS error.

1 Introduction

Low power consumption has become a primary goal in the design of electronic devices, on the wave of ubiquitous computing applications requiring smaller, cooler and longer–lasting portable devices. Two complementary approaches to the problem exist: *power optimized designs*, to endow devices with power/performance tradeoffs, and *power management* techniques, to fully exploit these tradeoffs. To enable effective power management, an abstraction describing the power behavior of the device along tradeoff curves is required: such abstraction is called a *power model*.

A challenging problem is posed by wireless ad–hoc networks, where devices are most likely mobile, and thus battery powered, and where communication often accounts for a relevant power contribution [12]. Moreover, when multiple devices form a network, the power state of a single device might not be independent of that of its neighboring nodes. Power–optimized design and power management map to wireless networks too, with specific power/performance tradeoffs such as modulation scaling [14] and power control [13], as well as power management policies to exploit them [5]. The work in [7] presents a survey of *power–aware protocols*, a broad term which can stand for a protocol that (i) manages hardware–level power/performance tradeoffs (e.g. power control), (ii) exposes further tradeoffs to the application layer (e.g. low–power modes in Bluetooth), or (iii) both. In (ii) and (iii) a *power model* of the protocol becomes crucial to the upper layers to exploit the exposed tradeoffs.

Bluetooth (BT) is the leading standard for short–range ad–hoc connectivity in the Personal Area Networks (PAN) field. It was initially designed for simple point–to–multipoint cable replacement applications but seems also very appealing to build multi–hop ad–hoc networks (called *scatternets*) [8] and even for certain types of sensor networks with high bandwidth demands [9]. BT provides three low–power modes to applications: hold, sniff and park, which trade throughput and latency for power. Nevertheless, to take advantage of these features, applications need a *power model* of the device, describing power behavior in all possible states (number of links, active, sniff, etc.).

There is indeed a lack of such a model in the literature to date. Many Bluetooth power–related proposals, such as [4] and [15], are based on over–simplified power models, not considering number and role (master vs. slave) of links. Also, such models are normally not based on experimental measurements, but rather on theoretical assumptions. Even worse, other BT–related studies employ rather old and inadequate power models that were derived for other wireless systems [1]. Finally, the few power measurements for Bluetooth in the literature (see [10] and [9]) do not cover BT low–power modes and scatternet configurations.

In this paper we present a full power model of Bluetooth in a complex *scatternet scenario* where each link can be in active or low–power *sniff* mode The model is experimentally characterized and validated (RMS error below 4%) for the *BTnode*, a BT–based ad–hoc network prototyping platform developed at ETH Zurich [3]. However, the whole modeling process is based on a methodology which can be easily re–applied to other BT implementations. Moreover, the model can be easily extended to cover additional low–power modes, i.e. hold and park.

Section 2 recalls some important characteristics of BT, whereas Section 3 describes the BTnode platform and Section 4 discusses our previous point–to–point power model of BT. Section 5 presents the core of our work, that is the extension and subsequent characterization and validation of the model. Section 6 concludes the paper, outlining possible extensions and usages of the model.

2 Bluetooth

Bluetooth is based on 79 independent channels working at 1 Mbit/s ($1\mu s$ symbols) selected thorough a *frequency hopping* algorithm. The MAC layer is based on a TDMA (Time Division Multiple Access) scheme using slots of $625\mu s$ each, and supports up to 8 devices within the same *piconet* (set of nodes sharing the same hopping sequence), one of them being the *master* of the piconet and polling the other *slave* devices. Master/slave communication is handled in a TDD (Time Division Duplexing) fashion, where the master uses even slots and the polled slaves respond in the odd ones. Nodes are allowed to participate in more than one piconet in a time–sharing fashion, to form a *scatternet*.

During normal piconet operation (*active* mode), a master regularly polls its attached slaves every T_{poll} slots. However, slaves are completely unaware of the polling algorithm and are required to listen to the channel at the beginning of each master slot, to find out whether a packet is sent to them. *Sniff* mode allows for a lower duty cycle on both sides, with a master polling its slaves at regularly spaced beacon instants. Since beacon spacing can be in the range of seconds, rather than tens of slots (as for T_{poll}), this mode allows for power savings. More precisely, sniff mode is regulated by three parameters called Sniff Interval (SI), Sniff Attempt (SA) and Sniff Timeout (ST), which are specified in number of slot pairs[1]. SI is the time between beacons. At each beacon the slave listens to its master for SA slot pairs, during which it is allowed to send data if polled. The slave continues then listening for an extra ST slot pairs after the last packet received from the master.

3 The BTnode

The BTnode is a versatile, lightweight, autonomous platform based on a Bluetooth radio, a low-power radio and a microcontroller [2]. The device is designed for fast prototyping [3] of ad-hoc and wireless sensor network applications and is well suited to investigate different protocols, operation parameter tradeoffs and radio alternatives. The Bluetooth radio is a Bluetooth 1.2 compliant device (Zeevo ZV4002) with radio circuits, baseband, MAC and link controller and an ARM7 core integrated on a single system-on-chip. The Atmel ATmega128l microcontroller serves as Bluetooth host controller and interfaces to the Host Controller Interface of the ZV4002 via UART. Embedded applications are integrated into BTnut, a custom C-based threaded operating system that offers drivers for the peripherals as well as communication protocol stacks for the radios. Benefits of this platform are a small form factor of 5x3 cm and comfortable programmability while maintaining interoperability through its standardized wireless interface. Simple sensors and actuators can be attached and powered through generic interfaces. Three direct current access points are available where *in-situ* measurements of the power consumption of the radios and the microcontroller core can be performed (see Figure 1). This allows for very fine grained and subsystem-specific power consumption measurements in the live system under standard operating conditions as opposed to an artificial lab setup with developer boards only.

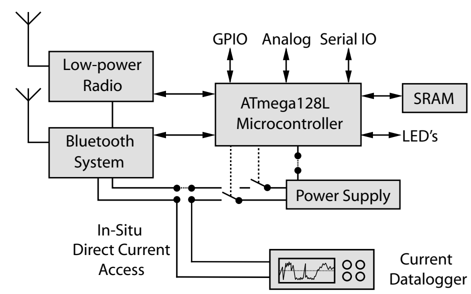

Figure 1. The BTnode rev3 system with a current datalogger connected for Bluetooth power consumption measurements.

In particular, all measurements related to this work were performed on the Zeevo BT chip access point, hence whenever "power consumption of the BTnode" is mentioned this shall be interpreted as "power consumption of the Bluetooth chip of the BTnode". The choice is in line with our protocol–level approach to power measurement and also supported by the fact that the BT chip is the most power–hungry component on a BTnode [10].

4 Previous Work: Point to Point Model

The TDMA, connection–oriented nature of Bluetooth makes it substantially different from other wireless systems employing contention–based random MAC protocols (e.g. 802.11). This reflects in a different power model, where power contributions also exist to merely keep links alive, even when no data transfer is ongoing. In [11] we presented a complete power model of BT for the *point–to–point* case, i.e. limited to a device being master or slave of a single

[1] However they are often specified in second in this document.

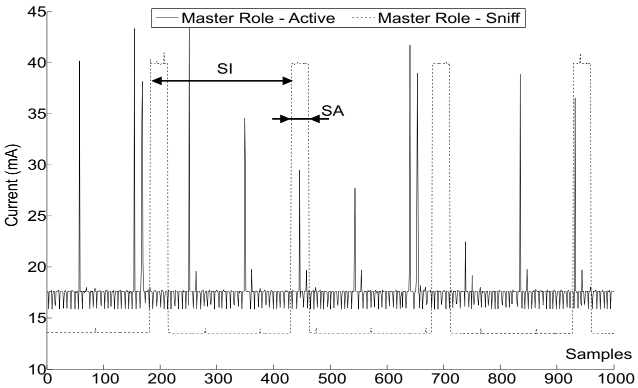

Figure 2. Current in active and sniff mode on a master (SI=5.12 s, SA=ST=0.64 s).

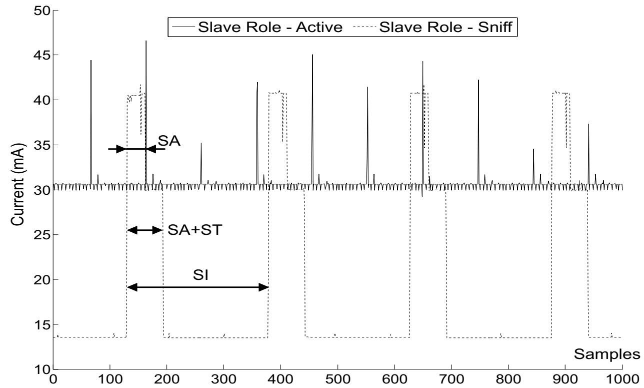

Figure 3. Current in active and sniff mode on a slave (SI=5.12 s, SA=ST=0.64 s).

link. Such model highlights three major contributions to the power consumption of a BT module:

- A *standby* power consumption P_{stby}, always present, which is the one measured when the device is switched on, idle, and all scanning activities are disabled.
- A *Link Controller* (LC) power consumption which varies if the device is master (P_{master}) or slave (P_{slave}) of the link, or if it is not connected at all.
- An additional *data* level consumption for transmission (P_{tx}) and/or reception (P_{rx}) of data over the link.

In the model 'stby', 'master', 'slave', 'tx' and 'rx' are called *logical activities*, and the model is said to be *characterized* for a specific BT implementation once a value has been assigned to the correspondent P_{stby}, P_{master}, etc.

5 Scatternet and Sniff–Mode Extensions

The work in [11] showed that the modelling abstraction of summing up power related to useful data transmissions and to link maintenance activities holds well for the point–to–point case when validating the model for a real BT device. In this section we assume the same property to hold for a multi–point scenario[2] and *extend* the Link Controller layer model to the *piconet* and *scatternet* cases, allowing for an arbitrary number of master/slave, active/sniff connections (within the limits of BT specifications).

5.1 Experimental Phase

We have run a set of roughly 100 experiments on BTnodes. Each experiment consisted of tracing the current draw of the Zeevo BT chip on the BTnode (see Section 3) for 20 seconds via a bench multimeter. The voltage, which we assumed constant during the experiments, was previously measured at 3.3 V and the multimeter was set to operate at 50 samples/s (integration time 20 mS). Among different experiments, the following parameters were changed: (i) *number* of nodes connected to the device under test and *role* of these connections (maximum 7 slaves and 3 masters supported by the Zeevo chip) (ii) *mode* of these connections (active vs. sniff). In sniff mode, Sniff Interval (SI), Sniff Attempt (SA) and Sniff Timeout (ST) were also varied, according to hardware limitations that impose *equal SI* for links belonging to the same piconet.

Figure 2 and Figure 3 compare the current consumption curve in active and sniff mode, for a master and slave role connection respectively. For the sake of clarity, we denote with *master role connection* a connection to a slave and with *slave role connection* a connection to a master. The active–mode slave role curve (around 30 mA) is significantly *higher* than the master one (just above 15 mA); we believe this is due to the continuous listening activity a slave is required to perform.

Figure 2 and Figure 3 also highlight the bursty behavior of sniff mode, with periodic peaks every SI slot pairs. The baseline value is lower than the active master and active slave ones, and is equal to the *standby* current, which had been previously measured at 13.51 mA. Conversely, the height of the peaks surpasses both active master and slave values, reaching 40 mA; this indeed suggest an interesting *tradeoff* between active and sniff mode as SI is varied. Peak duration is SA slot pairs on the master side and $SA + ST$ slot pairs on the slave one, however here current drops to the normal active level (30 mA) after SA slot pairs. The higher current during the Sniff Attempt (SA) stems from the increased frequency of POLL packets sent by the master, which also causes higher power consumption on the slave

[2]Our preliminary tests show that the property holds within a reasonable error margin, especially for low duty cycle or bursty traffic patterns.

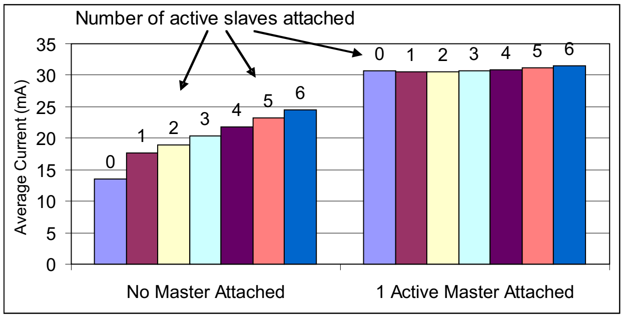

Figure 4. Average current with sole active–mode links. Left cluster: 0 to 6 slaves attached (piconet mode); right cluster: 0 to 6 slaves plus one master (scatternet mode).

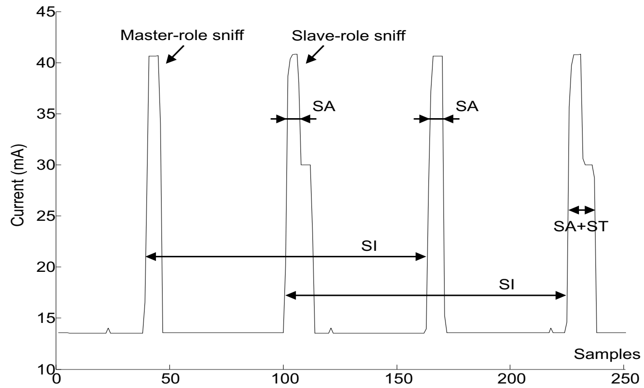

Figure 5. Current with mixed master (one) and slave (one) sniff–mode links (SI=2.56 s, SA=ST=0.16 s)

receiving them; this is most likely done to give the slave better chances of sending data during the (possibly short) SA window. According to BT specs, the slave continues then listening for an extra ST slot pairs, and this justifies the wider peaks in Figure 3.

Figure 4 concentrates on the effects of multiple active–mode connections on the total power consumption. The left cluster of bars represents the *average* current in *piconet* mode, with an increasing number of connections to slaves (0 to 6), but no master attached. These values exhibit the interesting property that each additional slave after the first one brings a nearly *constant* power penalty.

The right cluster of bars in Figure 4 is the average current when an increasing number of slaves are attached (0 to 6, as before) but when the device also has a *master*; in this situation the BTnode is in *scatternet* mode. The values are higher than in than in piconet mode, and all lie in the neighborhood of 30 mA, which is the *slave role* consumption as discussed for Figure 2. This can be explained as follows: with no data transfers, the only duty of the node in its piconet (as a master) is to poll its slaves, which accounts for a small time fraction; hence, the node spends far more time in slave mode, listening in the second piconet, and its current consumption is then much closer to the slave than to the master one. A second interesting property emerges: the total power is only slightly affected by the number of active slaves attached if an active master is present. In one word, the slave role *dominates* the master one.

Figure 5 refers to scatternet mode, but where all links are in *sniff mode*; more specifically, one master and one slave role links are present here. The exhibited behavior is a simple extension of that with a single link in sniff mode (as in Figure 2 and Figure 3), with the BT module scheduling each sniff attempt as far away as possible from the others.

Figure 6 shows the current plots in the case of multiple coexisting links in active and sniff mode; all links are here towards slaves (master roles) and the device is not in scatternet mode. The graph represents a single period of the 20 seconds experiments, whose waveforms are periodic with SI, namely 2.56 seconds or 128 samples. The first curve (dashed) represents the case of 3 active slaves, and shows no major peaks. The second curve (solid, 2 active and 1 sniff slaves) has a lower baseline average value but exhibits one peak of width SA. The third curve (solid with dots, 1 active and 2 sniff slaves) presents an even lower baseline value but features two peaks of width SA, according to what said for Figure 5. Finally, the fourth curve (solid with squares) has a baseline value equal to *standby* but contains three sniff attempts, two of which are clustered together in a peak of width $2 \cdot SA$; this behavior is in line with the fact that all links are now in sniff mode. The rules emerging from Figure 6 are the following: (i) outside sniff attempt peaks power consumption is determined by the number of active–mode links; (ii) the height of the sniffing peaks is not influenced by the number of active links.

A set of experiments similar to that of Figure 6 has been performed on coexisting slave–role active and sniff–mode links (not shown here). The behavior in this case is slightly different: although there are still a baseline value and regular peaks due to sniff, the baseline value shows only *marginal fluctuations* around the value of active slave power consumption (circa 30 mA), regardless of the number of active slave roles (1, 2 or 3). The same holds true if active master roles (connections to slaves) are added, and confirms the rule of the slave role dominance introduced earlier when discussing Figure 4.

5.2 Model Characterization and Validation

The point–to–point model of the LC presented in Section 4 only contains two logical activities, namely being mas-

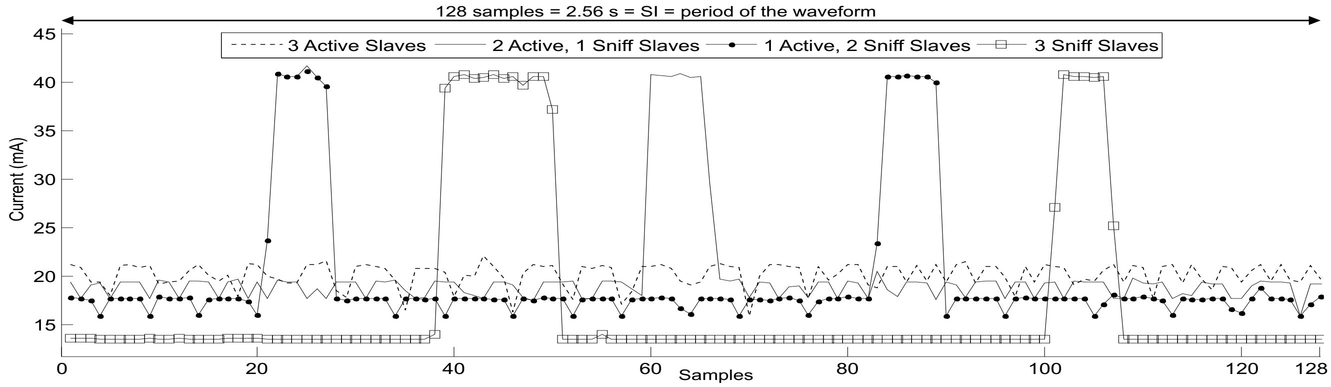

Figure 6. Current with mixed active and sniff master roles: three slaves attached, switched from active to sniff mode one after the other in a sequence (SI=2.56 s, SA=ST=0.16 s)

ter (power consumption P_{master}) and being slave (power consumption P_{slave}). We extend here such model to handle multiple connections and sniff mode. Since it would be unfeasible to measure and record power individually for each possible combination of number, type (master/slave) and mode (active/sniff) of links, we seek a compact set of *logical activities* A_i, each with power consumption P_i, whose *linear combination* approximates with a reasonable error the actual consumption of the device in all possible cases.

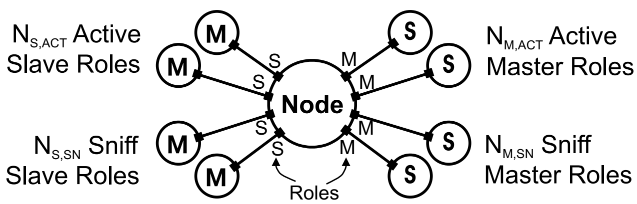

Figure 7. The four main degrees of freedom of Link Controller state including multiple master/slave and active/sniff links.

Figure 7 shows the four main degrees of freedom of the LC state when an arbitrary number of connections are open: number of active master–role and slave–role links, number of sniff master–role and slave–role links, which we denote respectively with $N_{M,ACT}$, $N_{S,ACT}$, $N_{M,SN}$ and $N_{S,SN}$. Our choice of logical activities is then driven by the knowledge gained in the experimental phase, which can be summarized in the following rules:

1. Power consumption is the sum of three terms: (i) a *standby* term (P_{stby}) always present, (ii) a *baseline* power value on top of standby due to active connections and (iii) periodic *peaks* due to sniff links.

2. When an *active slave role* connection exists, this fixes the baseline value at P_{slave}, regardless of additional active masters and/or slaves attached.

3. When *no active slave role* connection exists, the baseline value is determined by number of active master roles, with the first slave attached contributing P_{master} and each additional one contributing P_{add_slv} (with $P_{add\_slv} < P_{master}$).

4. On top of the previously determined baseline value, which shall be called P_{BAS}, contributions from sniff–mode peaks are added as follows, respectively for master roles (1) and slave roles (2):

$$P_{M,SN} = (P_{sniff} - P_{BAS}) \cdot (\frac{SA}{SI}) \quad (1)$$

$$\begin{aligned} P_{S,SN} &= (P_{sniff} - P_{BAS}) \cdot (\frac{SA}{SI}) + \quad (2) \\ &+ (P_{slave} - P_{BAS})(\frac{ST}{SI}) \end{aligned}$$

where P_{sniff} is the peak value during sniff attempts. Putting the rules together, the prediction of the model is:

$$\hat{P} = P_{stby} + P_{BAS} + N_{M,SN} \cdot P_{M,SN} + N_{S,SN} \cdot P_{S,SN} \quad (3)$$

where P_{BAS} is calculated as follows:

$$P_{BAS} = \begin{cases} P_{slave} & \text{if} \quad N_{S,ACT} > 0 \\ P_{master} + & \text{if} \quad N_{S,ACT} = 0, \\ +(N_{M,ACT} - 1)P_{add\_slv} & \quad N_{M,ACT} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

Note that the model is *linear* w.r.t. the power consumption of the logical activities P_{stby}, P_{master}, P_{slave}, P_{add_slv}, P_{sniff} but *not* linear w.r.t. other parameters, such as the number of links in a certain mode Y and role X $N_{X,Y}$ or the Sniff Interval SI.

We present now the numerical results that characterize the model for the BTnode. These are obtained following the characterization and validation methodology fully described in [11]. For each experiment, a power equation like (3) is written. In this equation, the left hand side is *not a power estimate*, but rather the *average power measured* during the experiment, obtained multiplying the average current and the fixed voltage of 3.3 V. Conversely, the right hand side is the prediction of the model, where the activity power consumptions (P_{stby}, P_{master}, $\ldots$) are the unknowns. Since the equations are linear w.r.t. the unknowns, and since the number of experiments is significantly higher than the number of unknowns, the equations form a strongly over–constrained linear system, which can be solved reliably with the Least Squares method. Doing so yields the values that best fit the experimental data, shown in Table 1.

Activity	Description	Value
P_{stby}	Always present	44.58 mW
P_{master}	Being master of 1 slave	12.97 mW
P_{add_slv}	Having additional slaves	4.55 mW
P_{slave}	Being slave	56.63 mW
P_{sniff}	Peak value in sniff mode	86.96 mW

Table 1. Numerical model for the BTnode.

We have validated the linear regression model using the *LOO* (Leave One Out) technique [6]. RMS error on the predicted power consumption of a generic LC mode is at 3.7%, whereas the maximum LOO validation error among all experiments is around 10%.

6 Conclusions and Outlook

We have presented a high–level power model of a Bluetooth device in a generic piconet or scatternet scenario, including sniff mode. Unlike most Bluetooth power abstractions employed in the literature, the model has been experimentally validated on a real device, the BTnode platform. Power consumption with an arbitrary number of active or sniffing, master or slave links is predicted within a 4% average error for the BTnode. Moreover, preliminary tests show that the model fits well most BT modules, and suggest an easy characterization for other BT implementations via new experimental measurements.

The proposed model can be a precious aid in the ad–hoc and personal area networking community, providing researchers with an abstraction that is much more realistic than datasheets figures and fully theoretical models, whilst guaranteeing a low computational complexity to empower their simulations and optimizations. Ongoing and future work includes the extension to hold and park modes, as well as the cross–validation on different Bluetooth implementations and the usage of the model for selected power optimization problems in personal area networks.

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