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 are based on 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 on a real implementation. Whilst guaranteeing a low computational complexity, the model achieves a 4% RMS error and can be a precious aid in the design and implementation of power–critical Bluetooth applications.

1. Introduction

Power consumption is one of the chief issues in wireless ad–hoc networks, where devices are mobile and battery powered, and where communication often accounts for a relevant power contribution [13]. Moreover, when multiple devices form a network, the power state of a single device might not be independent of that of its neighboring nodes. Two complementary approaches to the problem exist: *power–optimized design*, to endow devices and protocols with power/performance tradeoffs such as modulation scaling [15] and power control [14], and *power management* policies to exploit such tradeoffs [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 all cases, an abstraction describing power behavior along tradeoff curves is required: such abstraction is called a *power model*.

Bluetooth (BT) is the leading standard for short–range ad–hoc connectivity in the Personal Area Networks (PAN) field. Although initially designed for simple point–to–multipoint cable replacement applications, it seems also very appealing to build multi–hop ad–hoc networks (called *scatternets*) [8] enabling a whole range of new consumer applications, such as home automation [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 states.

There is indeed a lack of such a model in the literature to date. Many Bluetooth power–related proposals, such as [4] and [16], 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 [11] and [10]) 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.

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

2. Bluetooth and the BTnode

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

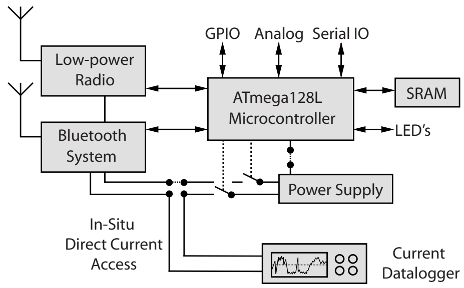

Figure 1. Experimental setup.

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, which are completely unaware of the polling scheme employed. Nodes are allowed to participate in more than one piconet in a time–sharing fashion, to form a *scatternet*. Low power *Sniff* mode allows for a lower duty cycle on both sides, with a master polling its slaves at regularly spaced beacon instants; more precisely, it is regulated by three parameters called Sniff Interval (SI), Sniff Attempt (SA) and Sniff Timeout (ST). 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.

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. 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. In particular, all measurements related to this work were performed on the Zeevo BT chip access point. 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 [11].

3. 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 [12] 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 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.

4. Scatternet and Sniff–Mode Extensions

The work in [12] showed that the modelling abstraction of summing up power related to 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[1] and *extend* the LC layer model to the *piconet* and *scatternet* cases, allowing for an arbitrary number of master/slave, active/sniff connections.

4.1. Experimental Phase

We have run a set of roughly 100 experiments on BTnodes, measuring average current consumption and varying: (i) *number* and *role* of connections (maximum 7 slaves and 3 masters supported by the Zeevo chip) (ii) *mode* of these connections (active vs. sniff). In sniff mode, SI, SA and ST were also varied, according to hardware limitations that impose *equal SI* for links belonging to the same piconet. We show here a restricted set of significant plots.

Figure 2 and Figure 3 compare current consumption in active and sniff mode, for a master and slave role connection respectively. We denote with *master role connection* a

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

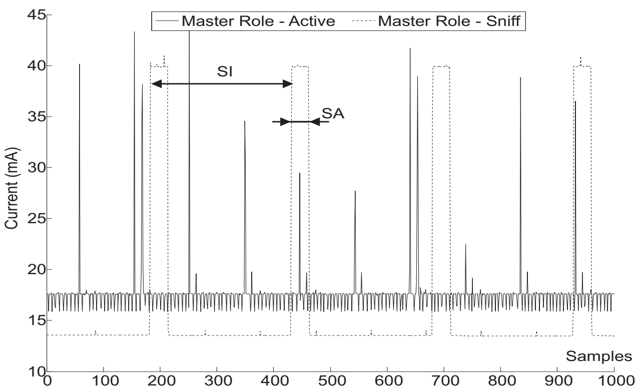

Figure 2. Current in active and sniff mode on a master (SI=5.12 s, SA=ST=0.64 s).

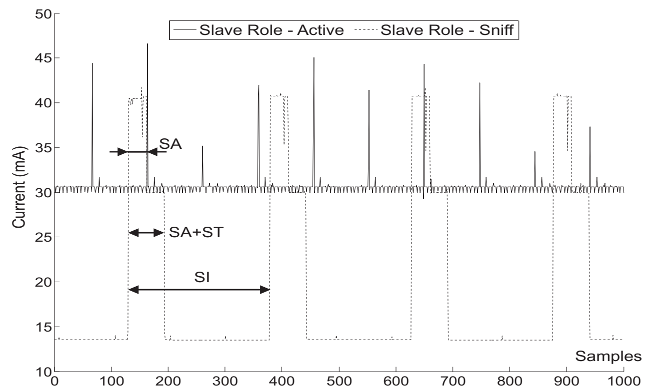

Figure 3. Current in active and sniff mode on a slave (SI=5.12 s, SA=ST=0.64 s).

connection to a slave and viceversa. 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. The figures 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.

In Figure 4, multiple active connections are present. 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. On the right is the average current when an increasing number of slaves are attached but when the device also has a *master* (*scatternet* mode). 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. Another property emerges: total power is 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 in Figure 2 and Figure 3.

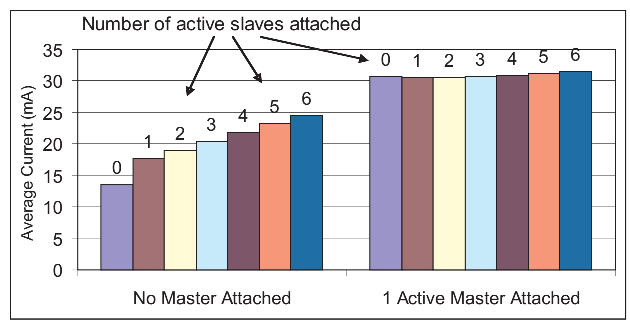

Figure 4. Active links; left cluster: 0 to 6 slaves attached (piconet); right cluster: 0 to 6 slaves plus 1 master (scatternet).

Figure 6 mixes active and sniff links towards slaves (device is not in scatternet mode). The graph represents a single period of the waveforms, periodic with SI (2.56 seconds). 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) has a lower baseline average value but exhibits one peak of width SA. The third curve (solid with dots, 1 active and 2 sniff) presents an even lower baseline value but features two peaks of width SA, according to 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 $2 \cdot SA$. Hence: (i) outside sniff attempt peaks power consumption is determined by the number of active links; (ii) the height of the sniffing peaks is constant.

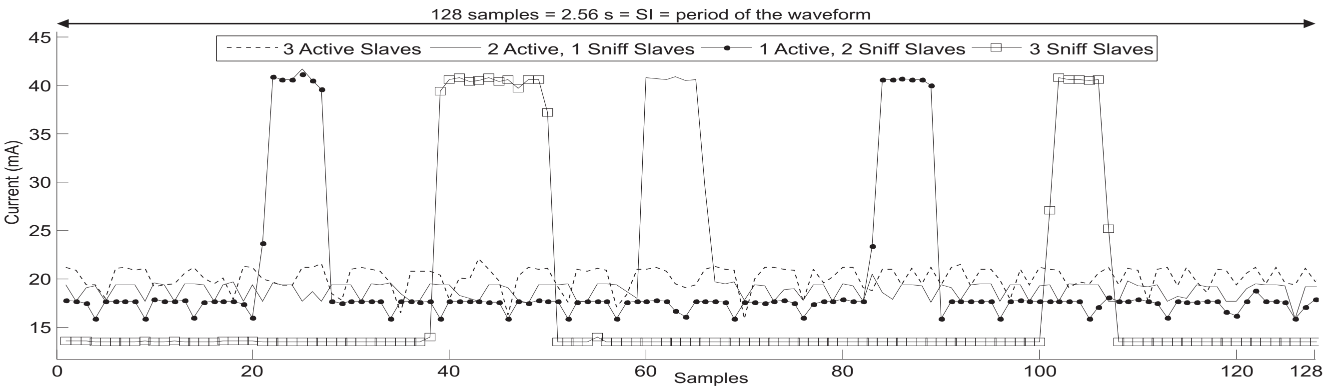

Figure 6. Current with mixed active and sniff master roles: three slaves attached, switched from active to sniff mode one after the other in a sequence (SI=2.56 s, SA=ST=0.16 s).

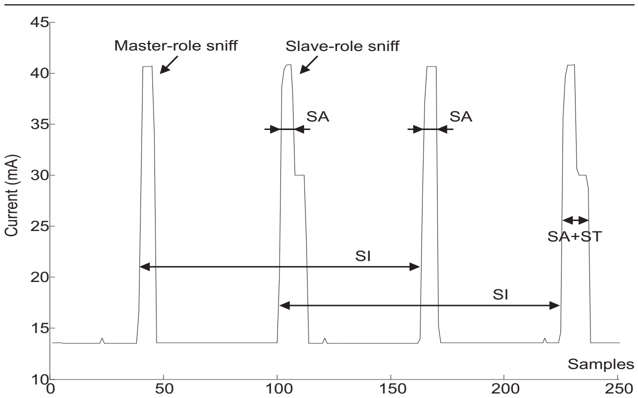

Figure 5. Mixed master and slave sniff links (SI=2.56 s, SA=ST=0.16 s).

4.2. Model Characterization and Validation

The point–to–point model of the LC presented in Section 3 only contains two logical activities, namely being master (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 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

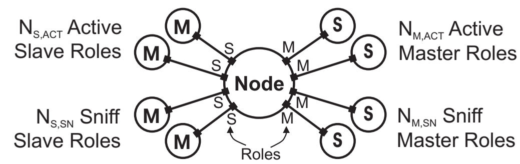

Figure 7. Degrees of freedom of LC state.

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 is the sum of 3 terms: (i) *standby* (P_{stby}) always present, (ii) a *baseline* power value 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}.
3. When *no active slave role* connection exists, the baseline value is determined by the number of active master roles (first P_{master}, additional ones P_{add_slv}).
4. On top of the previously determined baseline value, which shall be called P_{BAS}, contributions from sniff–mode peaks are (for master and slave roles):

$$
\begin{aligned}
P_{M,SN} &= (P_{sniff} - P_{BAS}) \cdot (\frac{SA}{SI}) \qquad (1)\\
P_{S,SN} &= (P_{sniff} - P_{BAS}) \cdot (\frac{SA}{SI}) + (P_{slave} - P_{BAS})(\frac{ST}{SI})
\end{aligned}
$$

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

$$\hat{P} = P_{stby} + P_{BAS} + N_{M,SN} \cdot P_{M,SN} + N_{S,SN} \cdot P_{S,SN} \quad (2)$$

$$P_{BAS} = \begin{cases} P_{slave} & \text{if} \quad N_{S,ACT} > 0 \\ P_{master} + & \text{if} \quad N_{S,ACT} = 0, \\ +(N_{M,ACT} - 1)P_{add\_slv} & \quad\quad N_{M,ACT} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

We characterize now the model for the BTnode, following the methodology described in [12]. For each experiment, a power equation like (2) is written, substituting the left hand side with the average power *measured* during the experiment. Conversely, the right hand side is the prediction of the model, with P_{stby}, P_{master}, ... as unknowns. Since the equations are linear w.r.t. the unknowns, and 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. We have validated the model using the *LOO* (Leave One Out) technique [6]. RMS error is at 3.7%, maximum error around 10%.

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.

5. Conclusions and Outlook

We have presented a power model of a Bluetooth device in a generic piconet or scatternet scenario, including sniff mode. Unlike most abstractions employed in the literature, the model has been experimentally validated on a real device. The 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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