Energy Performance of High Data Rate and Low Power Transceiver based Wireless Body Area Networks

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Abstract: Emerging Wireless Body Area Networks (WBANs) are receiving increasing interest from researchers and designers. Specific requirements for small-scale dimensions, low-latency, lightweight and limited power capacity mean that the key challenge in WBANs design is in the adoption of energy-efficient strategies for better system performance, and in the efficient use of high data-rate and ultra-low-power transceivers. This paper presents a high-level energy-aware SystemC-based model and simulation of Nordic's Enhanced ShockBurst (ESB) and ShockBurst (SB) baseband protocol engine. The model includes data from Energy consumption experiments using nRF24L01+ transceiver, enabling detailed exploration of energy conversation strategies. With this model, we show that a high data-rate ESB and SB transmission at 2Mbps can save more than 60% and 80% energy respectively, and it has 3x higher lifetime expectancy than the 250Kbps low data-rate communication with a payload collecting strategy.

1 INTRODUCTION

In recent years, a new type of network known as wireless body area networks (Chen et al., 2011); (Latré et al., 2011) has attracted increasing interest from academia and industry alike. Generally, a WBAN node consists of ultra-low-power, small-size, lightweight sensors coupled to RF transceiver for wireless communication as well as microcontroller for processing. WBANs are usually used in patient monitoring, sports and fitness applications. With the wearable and implantable features, the design of a WBAN sensor node is strictly constrained to small dimensions and low weight. Batteries which account for a significant part of these metrics in the overall system, are consequently limited in size and weight, which in turn results in reduced energy capacity. For implanted devices which must operate over a lifetime of months or more typically years, the battery replacement or recharging is inconvenient and costly. Hence, energy-efficient devices and sensing/communication strategies are crucial considerations for the design of a WBAN sensor node.

The focus on energy consumption optimization is mainly on the radio transceiver, since wireless communication is typically the most power consuming part (Latré et al., 2011); (Weder, 2010). With high energy consumption, existing Bluetooth-based device is not suitable for WBANs while ZigBee-based device cannot satisfy latency requirements of some WBAN scenarios because of its low data-rate. High data rate and ultra-low-power transceiver can be a good solution.

The Nordic nRF24L transceiver series (Nordic homepage) can support up to 1Mbps/2Mbps high data rate and they are ultra-low-power compared with other frequently used devices (Zhu et al., 2011), and its built-in MultiCeiver function (nRF24L01+ datasheet) supports a simple star network topology, which is typically preferred by most WBAN applications.

In order to predict in an accurate way of the system behavior and network performance of the designed WBAN in an application context, and to further explore energy-efficient communication strategies, it is necessary to build a high-level and energy-aware model of such a transceiver. We first present a SystemC-based simulation models for both Enhanced ShockBurst (ESB) and ShockBurst (SB) mode (nRF24L01+ datasheet), which are the Nordic

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embedded protocol engines for its 2.4GHz transceivers. Then we use this SystemC based model to simulate the energy consumption of various WBAN scenarios and extract a detailed analysis of energy performance.

The organization of the rest of the paper is as follows. In section 2, some related works are described. In section 3, we first briefly present the modeling concept and then show some experimental simulation results with detailed analysis. Finally, we conclude in section 4.

2 RELATED WORKS

Nordic's ESB- and SB-based nRF24L transceiver series are widely used in WBAN application scenarios by many research communities.

By using nRF24L01, (Sonavane et al., 2009) propose an adaptive power control algorithm by simply configuring the programmable output power on transceiver.

A CSMA/CA based MAC protocol (Zhurong et al., 2008) is proposed and tested in a nRF24L01-based pulse oximetry sensor with some experimental results, however no energy consumption data.

(Weder, 2010) presents a system level simulation model of nRF24L01 in MiXiM, and simulation results on energy consumption are given only at 1Mbps data rate and 0dBm power scenario.

In this work, our experimental results provide a comprehensive energy consumption analysis in both ESB- and SB-modes.

3 MODELING AND CASE STUDY

To the best of our knowledge, this paper is the first to propose a SystemC-based simulation model for Nordic high data-rate and ultra-low-power nRF transceivers as used in WBANs. We extend Nordic nRF24L transceiver series module to a SystemC-based simulator (Wan Du et al., 2011), our transceiver module supports both ESB and SB-modes and as the ESB-supported transceiver (e.g. nRF24L01) model is backward-compatible with SB-based transceiver (e.g. nRF24E1) models, so heterogeneous simulations can be handled.

In SystemC simulation, *SC_THREAD* process (Black and Donovan, 2009) is used to model ESB- and SB-modes in the finite state machine. Figure 1 shows a brief state diagram.

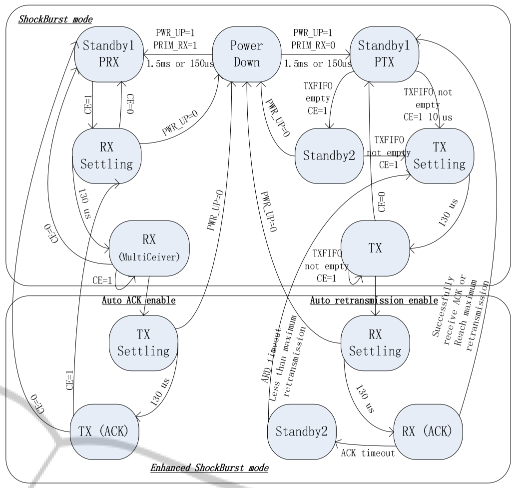

Figure 1: Brief State Diagram ESB and SB Mode.

Another feature of the transceiver module is that the register configuration method is used, so different nodes objects could maintain individual settings during simulation.

In this section, an ECG monitoring application is studied to analyze the energy consumption, and some optimization strategies are proposed. The energy performance is focused on the use of the Nordic hardware embedded ESB- and SB- modes. The sensor node of the ECG monitoring application is equipped with an ECG lead sampling at 200 Hz, and the size of each data is set to 2 bytes. While the nRF24L01-based platform is widely used in WBANs for ECG applications (Weder, 2010); (Zhurong et al., 2008), we base our experiments on the more recent nRF24L01+ due to its drop-in device compatibility and improved RF performance.

3.1 Energy Consumption of ESB and SB Mode

This experiment analyzes energy consumption with ESB- and SB- modes for varying output power and data rate values. Based on our ECG application scenario, a packet containing 2 bytes of payload data is transmitted every 5ms by PTX (Primary Transmitter) and the simulation runs for a transmission of 500 packets. The PRX (Primary Receiver) is configured in continuous RX mode, and default values are used for all other packet parameters (1 byte preamble, 5 bytes address, 1 byte CRC, power supply of 3.3 V). Figure 2 shows the simulation results and the energy consumptions are compared in Table 1.

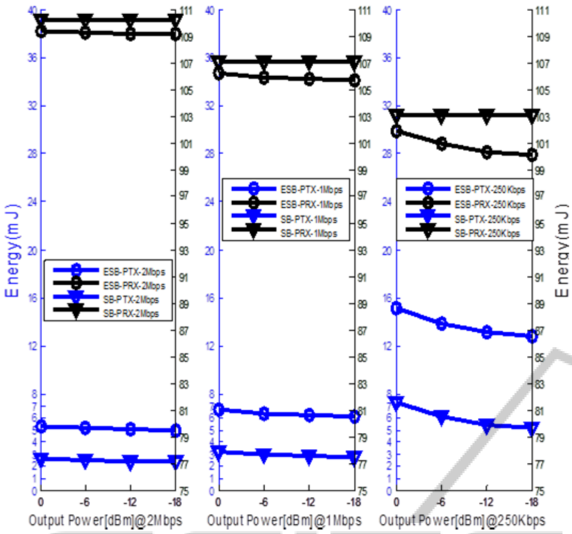

Figure 2: Energy Consumption of ESB and SB Mode.

Table 1: Energy Consumption of ESB and SB.

Data Rate	ESB (PTX) 0dBm VS -18dBm	SB (PTX) 0dBm VS -18dBm
2Mbps	5.35% higher	9.84% higher
1Mbps	8.45% higher	15.65% higher
250Kbps	15.02% higher	28.06% higher

Data Rate	ESB (PTX)	SB (PTX)
2Mbps@PTX (Energy efficient)	65% total energy is saved in 2Mbps	83% total energy is saved in 2Mbps
250Kbps@PTX (Energy Consumption)		

3.2 Detailed Consumption and Radio Task Profiling

By using the same application as in part A, Table 2 shows the detailed energy consumption information and radio task time profiling.

Table 2: Energy Consumption and Task Time.

Detailed Energy Consumption (mJ) @2Mbps/0dBm				
	ESB-PTX	ESB-PRX	SB-PTX	SB-PRX
Standy1	0.20	0	0.21	0
RX_settling	1.91	1.91	0	1.91
TX_settling	1.72	1.73	1.72	0
TX	0.75	0.60	0.67	0
RX	0.74	105.14	0	108.32
Task Profiling (ms) @2Mbps/0dBm				
Standy1	2339.8	0	2423.2	0
RX_settling	65	65	0	65
TX_settling	65	65	65	0
TX	20	16	18	0
RX	16	2360	0	2431.3

For PTX devices in ESB- and SB- modes, large amount of energy can be saved in low-power Standby1 mode (less than 4% total energy, over 90% task time). For PRX devices in ESB- and SB- modes, the RX mode takes over 90% task time and also consumes over 95% total energy. The total energy consumption of PRX in ESB-mode is about 20x that of PTX, while in SB- mode, it rises to about 42x.

3.3 Energy Consumption, Packet Payload and Lifetime

The first part of Figure 3 shows the relationship between energy consumption and packet payload. When compared with (Weder, 2010), our simulation results provide more information on different transceiver data rate scenarios (all in ESB-mode): transmission of packet with 2 bytes payload every 5ms, then 4 bytes every 10ms until 30 bytes every 75ms. The total payload during transmission is the same (0.4 bytes/ms), and all the simulations are launched for the same duration. For implanted devices, WBANs are likely to have higher packet error rate (PER) due to the impact of cutaneous and subcutaneous tissue, as well as body movement (Chen et al., 2011); (Latré et al., 2011). Hence, PER is necessary for energy profiling. In the second part of Figure 3, 5% PER and 10% PER are used respectively in the channel module.

Finally, in Figure 4, we analyze the radio lifetime expectancy by using a Li-ion battery with a capacity of 160mAh and coin cell size, which is used by Generic Wireless Node of Human++ BANs platform (Huang et al., 2009). The lifetime estimation is calculated as follows:

$$LT = (SimT * 160) / Total\_mAh / 1000 / 3600 / 24 \quad (1)$$

Where LT is lifetime, $SimT$ represents the simulation time and $Total\_mAh$ denotes the total current consumption during the simulation period.

To sum up, results in Figure 4 show that 2Mbps scenario is the most energy-efficient way of using payload collecting strategy for PTX, which can save from 64.9% (2 bytes) to 70.3% (30 bytes) energy when compared to 250Kbps, and for 1Mbps scenario the ratio are from 21.0% to 25.3%. Even with the introduced PER, high data-rate (2Mbps) scenario can still provide better energy performance than the other two data-rate scenarios, when considering 5% PER, 6.6% (30 bytes) to 12.1% (2 bytes) more energy is consumed compared with the ideal 2Mbps scenario, and with 10% PER, the ratio rises to 17.7%

to 23.9%.

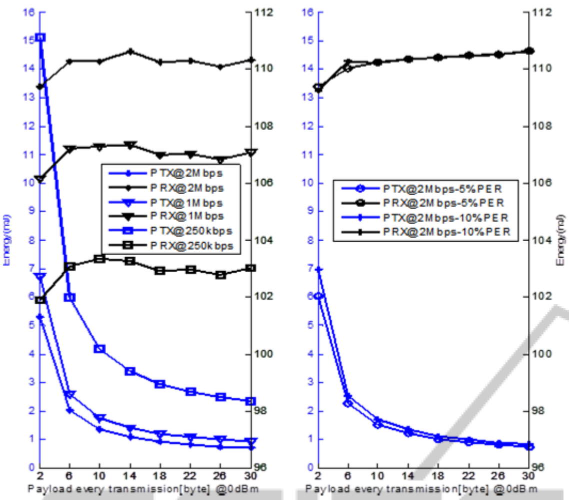

Figure 3: Energy Consumption, Payload Size and PER@ESB mode.

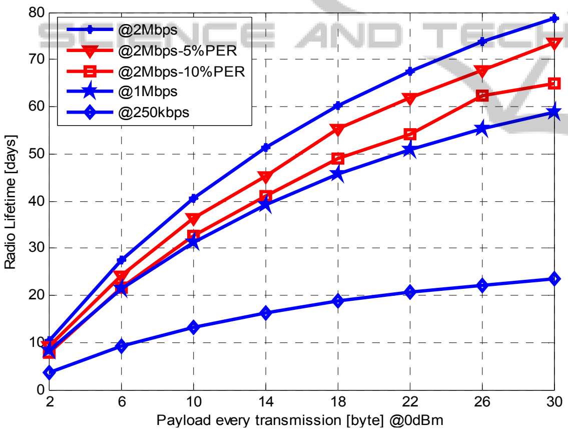

Figure 4: Lifetime Estimation of Payload Collecting Strategy.

On the other hand, lifetime estimation shows that with low data rate (250kbps), the PTX radio cannot last for one month, while with the high data rate (2Mbps), the radio can run for nearly 3 three months. Therefore high data rate based transmission is suggested for lower energy consumption, besides it can also provide much better latency and less over-the-air collisions.

4 CONCLUSIONS

In this paper, a SystemC structured ESB/SB based nRF transceiver simulation model is presented, with high data rate and low power features. Then nRF24L01+ transceiver is selected for performance analysis of energy consumption in a WBANs scenario. Results demonstrate that more than 60% and 80% energy are consumed respectively in ESB- and SB- mode in low data rate (250Kbps) transmission compared to 2Mbps high data rate transmission, besides high data rate will be more energy-efficient in payload collecting strategy, and can last for about 3 months with a coin cell size battery. These results can provide valuable information for WBANs application designers.

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