Average Power Consumption Model For Wireless Sensor Networks

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***Abstract*— This paper presents the evaluation of a model for estimating the power consumption for Zigbee devices in wireless sensor networks. The model is adjusted based on measurements of real devices. It is intended to be used alone or as a improvement for simulator softwares.**

***Index Terms*— Sensor networks, ZigBee, wireless, batteries.**

I. Introduction

Wireless sensor networks are used in low-power consumption applications, usually requiring embedded power source to supply the devices. As batteries are the most used type of power supply, the power consumption becomes a very important issue in the development of these networks [1].

ZigBee networks operate in the ISM (Instrumentation, Scientific and Medical) frequency band that are reserved for industrial, scientific and medical use and do not require operating licenses. There are three types of devices in a wireless network: end devices, routers and coordinators. The network function of these three types is different and because of this their power consumption is not the same. Another factor that influences the energy consumption is network topology. The Zigbee standard defines three types for the topology: tree, star and mesh [1].

To optimize the design of a wireless sensor network, an accurate power consumption model is desired. Most published articles use software simulators to evaluate the power consumption behavior. However these simulators require many calculations resulting in a time-consuming solution.

An important reason for the development of a power consumption model is that the implementation of parameters setups in real devices would benefit from the knowledge of corresponding power use for those parameters which allow a good forecast of battery lifetime of the network devices.

The objective of this paper was to evaluate a simple mathematical model for predicting the power consumption of devices in wireless sensor networks. The comparison between the measured and theoretical values allows to understand the behavior of real devices and to evaluate the causes of eventual differences. Based on this comparison the theoretical mathematical model can be adjusted for a specific device. The majority of commercial devices are composed of the same types of components, microcontrollers and radio transmitters, so the behavior of these devices will be very similar and there is no need to change the entire model because only the numerical results will be different.

A common use of sensor networks is the monitoring of some measured quantities over time. Typicaly a constant interval is used to collect those measurements from all sensors. In this paper, this type of application was considered when calculating average power of devices.

Some simulation softwares are capable of modeling Zigbee networks but the power consumption predictions are based on ideal devices and not on real ones. The software Network Simulator 2 (NS-2) was used to simulate an IEEE 802.15.4 network and the results obtained for the power consumption were not in the range of values expected for real devices. Wireless network devices are composed of several components and if the power consumption is calculated based only on datasheet specifications the values may be far from the real ones. This difference between calculated and measured values shows that a theoretical improvement for the network may not have the same effect when applied to real devices. The measurements of current consumption showed that data processing and radio transmission influence on consumption are different depending on network parameters such as data transmission interval. A change in the network parameters for the improvement of battery life that only takes in consideration the radio transmission consumption may not be effective in real devices if the time and complexity of the data processing required to implement these changes is ignored. Devices like the Texas Instruments CC2530 use microcontrollers for data processing and they have a large influence on power consumption that is ignored when a theoretical model is based only on the network standards. For example, if the data transmission interval is very high most of the current consumption will be done by the microcontroller and the data processing will be more important than the radio transmission.

A. *Related work*

Jain e Braathen [2] measured the energy consumption of the Texas Instruments CC2530 kit. They used a 10 Ohms in series with the end device. An end device and a coordinator were programmed with the simplest example supplied

Mfr.	Product	ROM (kB)	RAM	Transmission Power	Receiver Sensitivity	Transmission Current	Reception Current	Sleep Mode Current
Atmel	AT86RF230	–	–	3dBm	-101dBm	16.5mA	15.5mA	20nA
	ATmega128 RZAV	128	8kB	3dBm	-101dBm	26.5mA	25.5mA	1.02uA
Meshnetics	MNZB-24-A2	128	8kB	3dBm	-101dBm	18mA	19mA	6uA
	MNZBA24-UFL	128	8kB	20dBm	-104dBm	50mA	23mA	6uA
Chipcon (Texas)	CC2430	128	8kB	0dBm	-95dBm	26.9mA	26.7mA	0.5uA
	CC2420	–	–	0dBm	-95dB	17.4mA	18.8mA	20nA
Microchip	MRF24J40	–	–	0dBm	-95dBm	23mA	19mA	2uA

TABLE I: Manufacturers comparison.[3]

by the manufacturer. This example does not implement the ZigBee Device Object ZDO and Application Framework (AF) interfaces making the idle current consumption lower but it limits the practical applications because most of the real applications need these interfaces to work. An oscilloscope was used to measure the current generating very accurate measurements that can be used to visualize all the steps of the data transmission, as shown in Fig. 1. They estimated the batteries life. The calculations were based on operating details of the devices that were used and a generic model for other manufacturers was not developed. Many task can be seen on

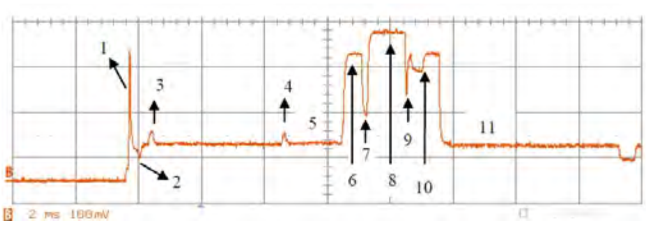

Fig. 1: Data transmission consumption details [2]

each transmission cycle:
1. Startup of the internal 16 MHz RC oscillator and the 32 kHz crystal.
2. The MSP430 sends the data and appropriate command over to the CC2530 so that it can start the transmission.
3. The CC2530 starts the 32 MHz crystal and sets it up as the core clock.
4. CC2530 wakes up the MSP430, such that it can read out the return value for the command that was invoked.
5. CC2530 sets up the radio and churns the packet through the ZigBee stack, preparing it for transmission.
6. CC2530 starts the Carrier Sense Multiple Access Collision Avoidance (CSMA-CA) algorithm.
7. Switch from RX to TX.
8. The packet is sent over the air.
9. Switch from TX to RX.
10. CC2530 receives the MAC ACK from the associated device in the network.
11. CC2530 enters an IDLE state, waiting to request the APS ACK from the recipient.

Prince-Pike [3] measured the energy consumption of the Texas Instruments CC2431BB and compared the batteries life of different network setups. The measured values were also compared with simulations results of Network Simulator 2 and showed the limitations of the consumption model of this simulator. Using the measured values the simulator model can be adjusted to become more accurate. Table I shows a comparison they did for devices from different manufacturers.
Zheng e Lee [4] developed the first simulation model of the IEEE 802.15.4 standard for the NS-2 simulator. They do not explain how the power consumption is calculated but it can be understood by analyzing the energy model code. In the code three functions are used: "DecrIdleEnergy()", "DecrRcvEnergy()" and "DecrTxEnergy()" that are generic functions for wireless devices and were not developed exclusively for the IEEE 802.15.4 standard. These functions estimate the power consumption by multiplying the transmission, reception and idle times by their corresponding the power.
Landsiedel [5] developed the AEON tool for the AVRORA environment to simulate with precision a wireless sensor network. This model is based on Mica2 devices. The results show that this model can estimate the power consumption of a network. This model is very accurate but it runs in a specific environment.
Jie [6] developed a new version of the AODV protocol to improve the power consumption. He used the NS-2 simulator without any modifications to compare the new version of the protocol with the standard one. This shows the importance of an accurate power consumption model.
Konstantakos e Laopoulos [7] made several measurements using devices based on the Texas Instruments CC2480 transceiver. They obtained detailed information of the power consumption for all the steps of operation of the devices.

II. Experimental Setup

The measurements presented in this paper were done using the Texas Instruments CC2530 Mini Kit, a National Instruments PCI-6014 data acquisition board and the software Labview. A 1.3 Ohm resistor connected in series with the devices was used to measure the consumed current, as shown in Fig. 2. The voltage used to power the devices was 3.1V. The distance between the devices during testing was of less than 30cm to avoid signal interference. A ten thousand samples per second data acquisition rate and a decimation factor of ten were used. The Texas Instruments CC2531DK USB

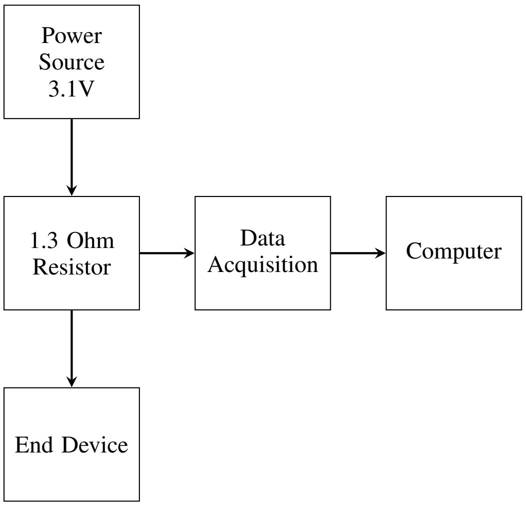

Fig. 2: Experimental setup block diagram.

Dongle device and SmartRF Packet Sniffer software were used to monitor the data transmitted through the wireless network.

III. Theoretical Model

The total power consumption of a device is a result of all the steps of operation: radio initialization, transmission and data processing. It would very complex to develop a model that considers all these details. The measurement of the total consumption can be used to model the characteristics of a device operation and it requires much less time than a detailed study of all the components of a sensor network device. The model uses the packet length, transmission speed and transmission power information to calculate the average power consumption. Fig. 3 shows the time intervals considered for the basic model.

Root mean square value of current is

$C_{RMS} = \sqrt{\frac{1}{T}\int_0^T C\left(t\right)^2 \; dt}$

$= mP_t + nP_t + (1 - (1 - m) - (1 - n))P_b$

where,

C = consumed current

T = time interval

$T_f = \frac{L8}{250kbps}$

$T_r = \frac{L_r 8}{250kbps}$

$m = \frac{1}{T_f}$

P_t = transmission current

$n = \frac{1}{T_r}$

P_b = idle current

L = frame size (bytes)

T_f = transmission time

L_r = "data request" frame size.

The theoretical basic model was modified to consider the power consumed during the initialization and data processing times. Estimated power consumption was not close enough to measured values. The root mean square error (RMSE) between measured values and model prediction was used to find a

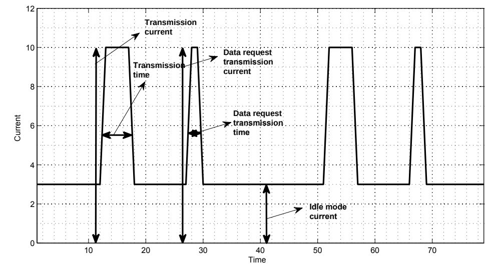

Fig. 3: Basic theoretical model.

Router		Coordinator		End device	
AVG	28,40 mA	AVG	28,66 mA	AVG	5,41 mA
STD	0,14 mA	STD	0,41 mA	STG	0,23 mA
Min.	28,07 mA	Min.	27,84 mA	Min.	4,93 mA
Max.	28,76 mA	Max.	29,40 mA	Max.	5,90 mA

TABLE II: Measured values.

larger interval for data transmission in order to account for initialization of transmission hardware. The minimum error was obtained by multiplying the theoretical frame size by 2.92. The error for the basic model was 1.4233 and for the improved model 0.8388. Fig. 4 shows the root mean square error curve for the adjustment values. The root mean square error without

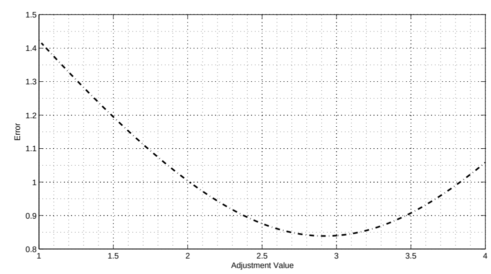

Fig. 4: Adjustment Values vs. RMSE.

the data request transmission was 0.7377 and with it 0.7036.

IV. Experimental Results

Table II presents the measured current consumption values for the three types of devices, for a data transmission interval of 0,8s. Sensor device presents lower consumption (5mA) compared to router (28mA). Low standard deviation of measurements indicates good precision of the obtained values. Fig. 5 was obtained with a lower decimation factor in order to make all the steps of the data transmission identifiable.

The measured consumed current of end device generated a curve similar to $\frac{1}{x} + c$. Using the measured values without the data request frames transmission the root mean square error (RMSE) for the basic model was 2.9340. Fig. 6 shows the comparison with the basic model for measurements where the transmission of data request frames were disabled. A $\frac{1}{x} + c$ model was plotted for comparison using curve fitting. RMSE for the $\frac{1}{x} + c$ model was 2.7455. Fig. 7 shows the data request packets obtained by a sniffer. In practical applications

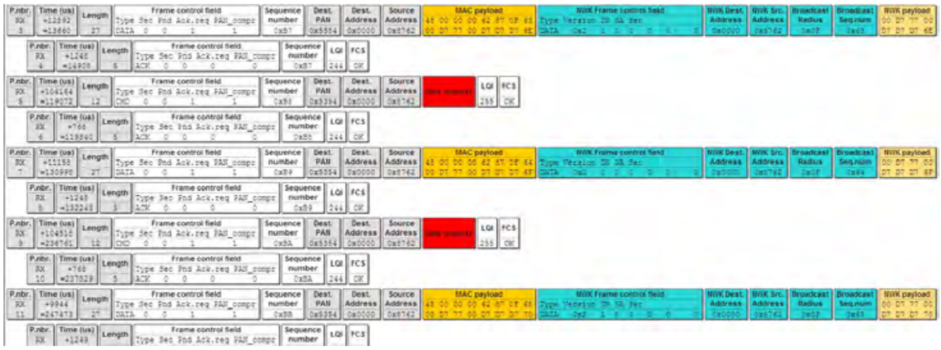

Fig. 7: Packet content captured by sniffer device.

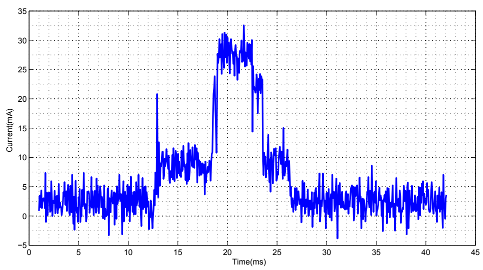

Fig. 5: Measured current consumption during one frame transmission.

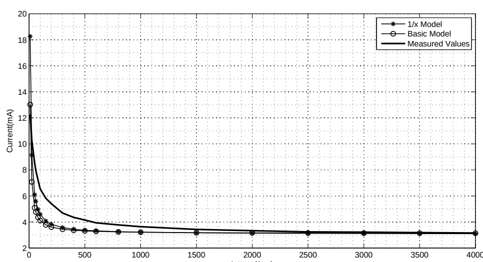

Fig. 6: Average current versus transmission interval. Data request frames deactivated.

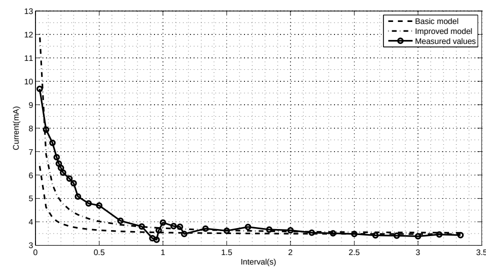

Fig. 8: Basic and Improved Models vs. Measured Values.

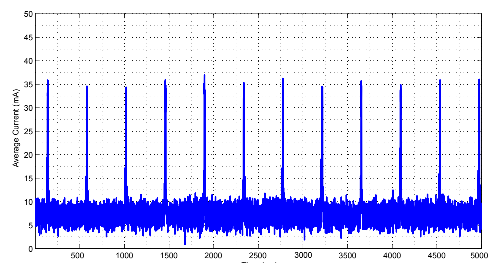

Fig. 9: Digi International end device consumed current.

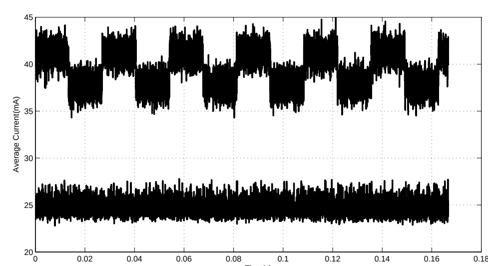

Fig. 10: Digi International and Texas Instruments routers consumed current.

data request frames transmission is necessary for this reason the next comparisons use the measured values with the data request frames transmission. Fig. 8 shows the comparison of the improved model and the measured values demonstrating that this model is very close to the real values. Fig. 8 shows the comparison between the improved and basic models with the measured values. The measured values for the Digi International XBee S2 [8] devices were similar to the measured values of the Texas Instruments devices. Fig. 9 shows measured current over time for a 0,5s data transmission interval. Fig. 10 shows Digi International (XBee) and Texas Instruments routers current consumptions for the same situations. Texas Instruments device has the lower average consumption, 25mA compared to 40mA. It is interesting to note that for these router devices the current level is higher and almost constant because reception radio is probably turned on all time.

V. Conclusion

It was verified how close the theoretical model can estimate the average power consumption of wireless sensor devices transmitting in constant intervals. The model presented in this paper could be used to improve the standard energy consumption model of simulator making the estimations more reliable. The model can be used for different manufactures by changing the values of the transmission, reception and idle mode power consumption. These values can be usually found on the devices documentation or determined by direct measurements.

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