Behavior Modeling of Networked Wireless Sensors for Energy Consumption Using Petri Nets

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***Abstract*— Energy efficiency is a critical design issue in wireless sensor networks. In order to analyze the energy consumption of a single node, a system model of networked wireless sensors is thus required. Based on a Petri net framework, this paper is proposing a systematic approach to the modeling and measurement of energy consumption for ZigBee-equipped sensors. Moreover, an experiment has been conducted to measure the real power consumption and to provide input parameters to the Petri net model. The comparative results show that the Petri net model could approximate the real measurement under the assumed scenarios. It is believed that the technique presented in this paper could be further applied to complex and non-periodic operations in wireless sensor networks.**

Keywords-energy consumption; Petri nets; sensor models; wireless sensor networks; ZigBee.

I. INTRODUCTION

Recently, there has been an increasing emphasis on developing distributed Wireless Sensor Networks (WSNs) with self-organization capabilities to cope with device failures, changing environmental conditions, and different sensing and measurement applications [1]-[4]. WSNs consist of hundreds or even thousands of networked wireless sensors which are linked by radio frequencies to perform distributed sensing tasks. In general, since these wireless sensors are equipped with batteries, energy consumption is a major design issue. Researchers have attempted to determine the best topology, the optimal way of routing, or whether the sensor node should aggregate data or not. All these topics are investigated with the intention of prolonging network lifetime from a global networking point of view [5]-[7].

On the other hand, from a single node point of view, the energy conservation could be achieved by applying some power management techniques. However, in order to propose methods by which power consumption can be minimized in networked wireless sensors, it is first necessary to gain an accurate understanding of their energy consumption characteristics. Thus, a system model of wireless sensors is required so as to analyze the energy consumption of a single node.

Starting from measurements carried out on the off-the-shelf radio, Bougard *et al.* [8] evaluated the potential of an IEEE 802.15.4 radio for use in an ultra-low power sensor node operating in a dense network. Their resulting model has been used to optimize the parameters of both the physical and medium access control layers in a dense sensor network scenario. Also, based on the empirical energy consumption measurements of Bluetooth modules, Ekstrom *et al.* [9] presented a realistic model of the radio energy consumption for Bluetooth-equipped sensor nodes used in a low-duty-cycle network. Their model gives users the possibility to optimize their radio communication with respect to energy consumption while sustaining the data rate. From a hybrid system point of view, Sousa *et al.* [10] modeled and analyzed the power consumption of a wireless sensor node in sensor networks using differential hybrid Petri Nets (PNs). With the discrete event evolution, the continuous battery discharge profile is updated and the remaining battery capacity is estimated. Moreover, their Petri net model was further applied to the design and evaluation of several dynamic power management solutions [11]. Based on Petri nets, Shareef *et al.* [12] also developed a model of a wireless sensor node that can accurately estimate the energy consumption. They used this model to identify an optimal threshold for powering down a sensor node of a specific wireless sensor application.

Most of the previous work focused on developing a conceptual sensor model and provided limited results on realistic measurement or comparative experiments. By applying our previously proposed Petri net framework in [13], this work has modeled the energy consumption of a ZigBee-equipped sensor node. Furthermore, an experiment has been conducted to measure the real power consumption and provide input parameters to the PN model, which could be applied to further simulations of ZigBee-based WSNs. This is the sense to use the PN model to describe the power consumption of sensor nodes.

The rest of this paper is organized as follows. Section II introduces the Petri net model of a wireless sensor. Then, experimental results are provided in Section III. Finally, Section IV concludes this paper.

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II. PETRI NET MODELING OF WIRELESS SENSORS

This section will introduce the MultiParadigm Modeling (MPaM) methodology, and then show the behavior modeling of networked wireless sensors.

A. MultiParadigm Modeling (MPaM)

To deal with specific and complicated problems, we have to integrate heterogeneous modeling arts, thereby resulting in the MPaM methodology. It is based on a proposition of giving different entities of a complex system the most appropriate modeling abstractions [13]. From a viewpoint of MPaM, the PN is adopted to design and analyze coordination controllers in a discrete-event domain. The primary motivation for employing PN as hybrid models is the situation that all those good characteristics that make discrete PN a valuable discrete-event model still be available to hybrid systems. Examples of these characteristics include: PN does not need the exhaustive enumeration of the state space at the design stage and can finitely model systems with an infinite state space. Moreover, PN provides a modular description where the structure of each module is maintained in the composed model. Furthermore, discrete states of PN are modeled by a vector and not by a symbolic label, thus linear algebraic techniques may be adopted for system analysis.

Figure 1 represents the previously proposed PN framework for modeling a system in discrete-event and discrete-time domains [13]. Each operation is modeled with a *command* transition to start the operation, a progressive *working* place, a *response* transition to end the operation, and a *completed* place. Note that the start transition (drawn with a dark symbol) is a controllable event as "command" input, while the end transition is an uncontrollable event as "response" output. The working place is a Hierarchical Hybrid Place (HHP, drawn with a triple circle), in which the state equations of the systems to be controlled are contained and interacted through the boundary interface. The interaction between event-driven and time-driven domains is realized in the following way: a token put into the working place triggers a discrete (or continuous) time process with the corresponding equations. Thresholds are monitored concurrently. Each threshold is corresponding to a transition, that is, the response transitions. When the threshold is reached or crossed, it indicates that the associated event is happening, and the corresponding transition is fired. Next, a new marking is evaluated, and the combination of the hybrid system restarts.

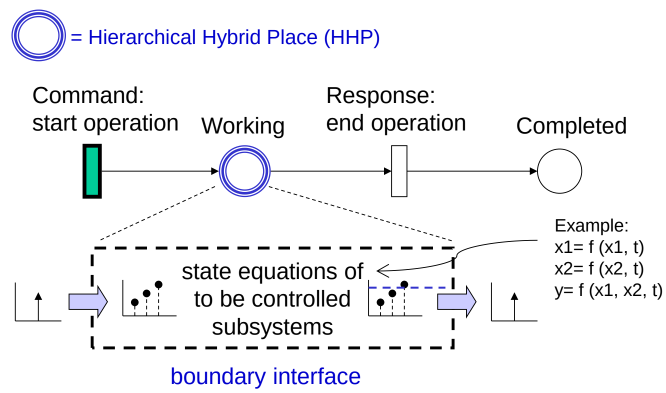

Figure 1. Multiparadigm modeling within a Petri net framework [13].

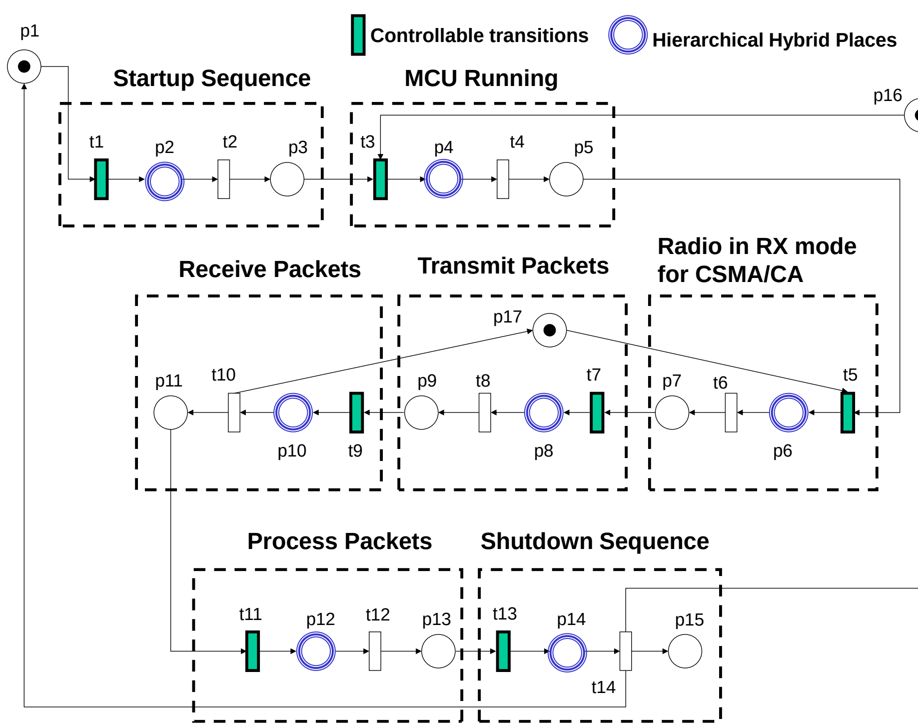

Figure 2. Petri net model of a networked wireless sensor.

TABLE I.
NOTATION FOR PETRI NET OF A WIRELESS SENSOR IN FIGURE 1

Place	Description	Transition	Description
p1	Node in sleep mode	t1	Cmd: start startup sequence
p2	MCU running at 16MHz	t2	Re: end startup sequence
p3	Startup sequence completed	t3	Cmd: start running MCU at 32MHz
p4	MCU running at 32MHz	t4	Re: end running MCU
p5	MCU running completed	t5	Cmd: start CSMA/CA operation
p6	Radio in RX mode	t6	Re: end CSMA/CA operation
p7	CSMA/CA operation completed	t7	Cmd: start transmitting packets
p8	Radio in TX mode	t8	Re: end transmitting packets
p9	Packet transmission completed	t9	Cmd: start receiving packets
p10	Radio in RX mode	t10	Re: end receiving packets
p11	Packet reception completed	t11	Cmd: start processing packets
p12	Processing packets	t12	Re: end processing packets
p13	Processing packets completed	t13	Cmd: start shutdown sequence
p14	MCU running at 16MHz	t14	Re: end shutdown sequence
p15	Shutdown sequence completed		
p16	MCU is available		
p17	Radio is available		

B. *Behavior Modeling of Networked Wireless Sensors*

In general, the radio communication is the most energy consuming part of a wireless sensor as compared with its sensing and computation tasks. Hence, our model focuses on the operations of packet transmission and reception. By applying the design procedure in [13], the PN model of a networked wireless sensor is constructed as shown in Figure 2, which consists of 17 places and 14 transitions, respectively. The corresponding notations are described in Table I. The model is based on a scenario where a sensor node periodically transmits and receives some data towards, for example, a base station.

III. EXPERIMENT AND RESULTS

This section will firstly show the measurement setup and experimental results. Then, the comparisons between the measurement and PN model will be described.

A. *Measurement Setup*

In this section, the energy consumption of a wireless sensor as computed via its Petri net model will be compared against real measurements collected from a ZigBee-equipped sensor node. The measurement setup in [14] has been adopted as shown in Figure 3 (a), in which a ZigBee End Device is the Device Under Test (DUT) and powered by a power supply. The energy consumption measurements are performed at the End Device, which periodically (every 0.5 sec in our measurement) wakes up and sends data to the coordinator (base station). The voltage across a 10 Ohm resistor is monitored to determine the current draw of the system. The measurement system has been calibrated with both a digital oscilloscope and a digital multimeter to ensure an accurate measurement. Figure 3 (b) shows the hardware setup during energy consumption measurement.

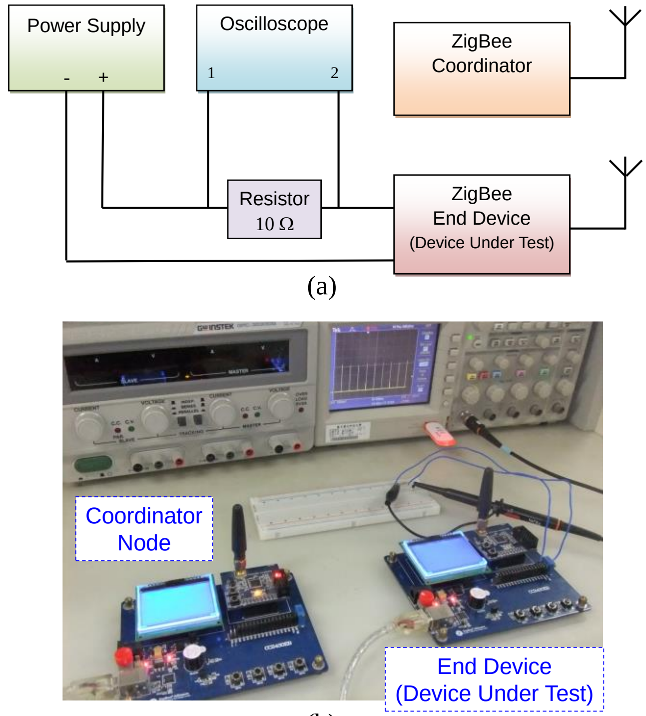

Figure 3. (a) Measurement configuration and (b) hardware setup during energy consumption measurement.

B. *Measurement Results*

Figure 4 (a) shows the power consumption during sleep and awake states. The time base on the oscilloscope is set to 500 ms per division, and it can be seen that it is about 0.5 sec among each current peak, showing the power consumption when the device is awake to send the data to the coordinator. Figure 4 (b) is a zoomed version of Figure 4 (a) and shows the current consumption during the active modes in more details. This snapshot has a time base of 1 ms per division. The duration of the active mode is about 7 ms. According to the measurement results, the consumed energy and duration of each operation can be estimated.

C. *Comparisons between Measurement and Petri Net Model*

With the measured sets of consumed current and duration for each transition as the inputs to the Petri net model, the energy consumption can be obtained as shown in Figure 5. In general, the energy consumption of the Petri net model is close to the practical measurement with a mean difference of around 0.9%. However, several peak currents appear during the state transitions, especially the startup sequence t1. Moreover, note that between transitions t7 and t9, there are two V-shaped gullies, which present the transceiver turnaround operations (RX to TX and TX to RX). Future work would attempt to model such detailed behaviors.

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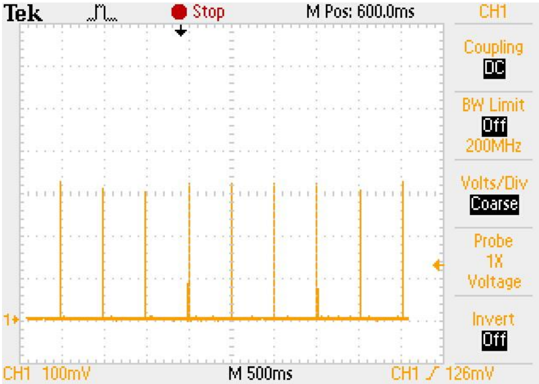

(a)

(b)

Figure 4. Measurement results for the division scale at (a) 500 ms and (b) 1 ms.

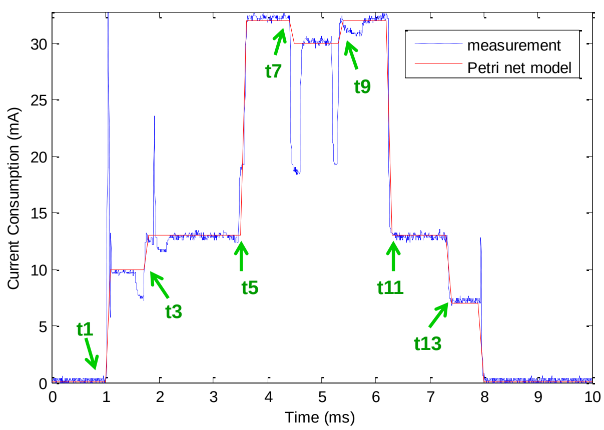

Figure 5. Comparison of energy consumption between measurement and Petri net model.

Obviously, the description of the power consumption of a single node during a standard RX/TX procedure is a very isolated scenario. For example, the power consumption of a node would significantly change when a collision is happening during transmission with a subsequent packet loss which requires a repeated transmission. Future work would consider more practical interactions between the nodes so as to simulate the power consumption of a whole sensor network for different scenarios.

IV. CONCLUSION AND FUTURE WORK

In this paper, a systematic approach to modeling and measurement of energy consumption for wireless sensors has been presented. The sensor operation is modeled using the Petri nets. Then, an experiment has been conducted to measure the real power consumption and provide input parameters to the Petri net model. The comparative results indicate the Petri net model has approximated the real measurement under the assumed scenarios. Besides the periodical operations demonstrated in this paper, the measurement scheme is also useful for other specific applications and could be fed back to the Petri net model as a calibration source.

Since the proposed Petri net model in this paper is mainly designed for packet transmission and reception, as a future work, operations of sensing and computation tasks could be further considered so as to make the model much more realistic. Moreover, with a given battery, the proposed model could be further applied to the lifetime estimation for periodical operations.

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REFERENCES

[1] J. S. Lee and Y. C. Lee, “An application of grey prediction to transmission power control in mobile sensor networks,” *IEEE Internet of Things J.*, vol. 5, no. 3, pp. 2154-2162, Jun. 2018.

[2] W. Q. Guo, W. M. Healy, and M. C. Zhou, “Impacts of 2.4-GHz ISM band interference on IEEE 802.15.4 wireless sensor network reliability in buildings,” *IEEE Trans. Instrum. Meas.*, vol. 61, no. 9, pp. 2533-2544, Sep. 2012.

[3] J. S. Lee and W. L. Cheng, “A fuzzy-logic-based clustering approach for wireless sensor networks using energy predication,” *IEEE Sensors J.*, vol. 12, no. 9, pp. 2891-2897, Sep. 2012.

[4] J. S. Lee, “A Petri net design of command filters for semi-autonomous mobile sensor networks,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, pp. 1835-1841, Apr. 2008.

[5] G. Anastasi, M. Conti, M. D. Francesco, and A. Passarella, “Energy conservation in wireless sensor networks: A survey,” *Ad Hoc Netw.*, vol. 7, no. 3, pp. 537-568, May 2009.

[6] J. S. Lee and T. Y. Kao, “An improved three-layer low-energy adaptive clustering hierarchy for wireless sensor networks,” *IEEE Internet of Things J.*, vol. 3, no. 6, pp. 951-958, Dec. 2016.

[7] J. S. Lee and C. L. Teng, “An enhanced hierarchical clustering approach for mobile sensor networks using fuzzy inference systems,” *IEEE Internet of Things J.*, vol. 4, no. 4, pp. 1095-1103, Aug. 2017.

[8] B. Bougard, F. Catthoor, D. C. Daly, A. Chandrakasan, and W. Dehaene, “Energy efficiency of the IEEE 802.15.4 standard in dense wireless microsensor networks: Modeling and improvement perspectives,” in *Proc. of Design, Automation and Test in Europe Conference and Exhibition (DATE)*, Munich, Germany, Mar. 2005, pp. 196-201.

[9] M. C. Ekstrom, M. Bergblomma, M. Linden, M. Bjorkman, and M. Ekstrom, “A Bluetooth radio energy consumption model for low-duty-cycle applications,” *IEEE Trans. Instrum. Meas.*, vol. 61, no. 3, pp. 609-617, Mar. 2012.

[10] J. R. B. Sousa, A. M. N. Lima, and A. Perkusich, “Modeling and analyzing power consumption in sensor networks nodes based on differential hybrid

Petri nets," in *Proc. The Annual Conf. IEEE Industrial Electronics Society (IECON)*, Raleigh, NC, Nov. 2005, pp. 389-394.
[11] P. S. Sausen, J. R. B. Sousa, M. A. Spohn, A. Perkusich, and A. M. N. Lima, "Dynamic power management with scheduled switching modes," *Comput. Commun.*, vol. 31, pp. 3625-3637, Sep. 2008.
[12] A. Shareef and Y. F. Zhu, "Power modeling of wireless sensor nodes based on Petri net," in *Proc. The 39th Int. Conf. Parallel Processing*, San Diego, CA, Sep. 2010, pp. 101-110.
[13] J. S. Lee, M. C. Zhou, and P. L. Hsu, "Multiparadigm modeling for hybrid dynamic systems using a Petri net framework," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 38, no. 2, pp. 493-498, Mar. 2008.
[14] B. Selvig, "Measuring power consumption with CC2430 & Z-Stack," Application Note AN053, Texas Instruments. Jul. 2007.