Energy Measurements and Evaluations on High Data Rate and Ultra Low Power WSN Node

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Abstract—Due to reliance on batteries, energy consumption has always been of significant concern for sensor node networks. While many energy efficient protocols and energy-aware application scenarios have been proposed in recent years, most are based on unrealistic theoretical model analyses or simple simulations due to the lack of real-world energy measurement tools, which leads to erroneous energy consumption prediction. Therefore, the energy source of sensor networks may be exhausted before completion of the required task. This paper presents our experimental platform named iWEEP_HW, which consists of Multichannel Energy Measurement Device (MEMD), Energy Data Management Software Platform (EDMSP) and a Testbed node. By using MEMD and EDMSP, real-world measurements and corresponding analyses are provided based on our high data-rate and ultra low-power testbed iHop Node. Such measurements, as well as the measurement protocol, could be valuable for other researchers focusing on energy efficiency in WSNs, and the provided measurements can also be used as a simulated energy model.

Keywords—WSNs; iWEEP_HW; MEMD; EDMSP; Testbed Node; Measurements; nRF24L01+; PIC16/18; Current Consumption

I. INTRODUCTION

With the widespread development of embedded systems and wireless communication technologies, wireless sensor networks (WSNs) have gained the attention of industrial and research groups all over the world in recent years. A typical WSN sensor node consists of different sub-modules to perform various tasks such as data processing, packet sending/receiving and channel listening/sensing. Since most sensor nodes are battery driven, energy efficiency is a crucial characteristic for WSN design. Despite proposals of plenty of energy effective MAC protocols, routing protocols and application scenarios, the lack of tools for measuring real-world hardware energy consumption means that these protocols and applications are often based on coarse energy estimations such as theoretical models for energy analysis. With such simple and unrealistic models, the prediction of the energy consumption is inaccurate. The use of simulators for energy estimation is another possibility, but results depend on simulator parameter settings, the simulator operation mechanism and energy models which have no basis in real world hardware - all of which leads to rather untrustworthy simulation results.

The main contribution of this work is to present an experimental platform named iWEEP_HW (INL WSNs Energy Evaluation Platform Hardware) that is composed of three parts. Multichannel Energy Measurement Device (MEMD) and Energy Data Management Software Platform (EDMSP) are used for the energy consumption measurements of iHop@Node (INL build High data-rate and ultra low-power testbed Node). Since the sensor node is component-structured, so the decomposition [6] and measurement of energy consumption on separate functional modules can provide a detailed and clear information to the overall node consumption. Detailed current consumption measurements on the MCU and transceiver are given and analyzed in this paper, as both components are the most energy-consuming parts of a sensor node.

The organization of the rest paper is as follows. In section II, some related works are described. In section III, we present our experimental platform both on hardware and software aspects. Then section IV shows some experimental measurements. Finally, we conclude in section V.

II. RELATED WORKS

In recent years, an increasing number of research works have focused on energy consumption in real-world sensor nodes. [16] presents a detailed energy consumption analysis based on the MicaZ mote, several benchmarks are used for energy estimation, and the battery charge effect and battery lifetime are also considered. Authors in [17] present AEON (Accurate Prediction of Power Consumption) and evaluate detailed energy profiling on a MicaZ sensor node. [6] provides very detailed energy consumption data on the TelosB mote based on the authors’ measuring methodology and power consumption measuring system (PCMS). [9] and [18] present their Sensor Node Management Devices (SNMD) with detailed performance parameters for the energy data measurements. For these research works, costly measurement equipments (high-performance oscilloscope [16–17], acquisition cards [6] [19]) limit deployment beyond the lab environment. In addition, the measurements of these works are based on low data rate WSN motes.

Nowadays, many applications require high data-rate and ultra low-power WSN nodes. In particular, for newly developed fields such as WBANs (Wireless Body Area Networks) [21], high data-rates are needed to reduce the
latency and delay of packet transmission to inform medical staff of the latest status of patients in real time. On the other hand, for implanted sensor nodes in WBANs, these sensor nodes are of very small size and lightweight, such that the attached battery module is limited in capacity. Consequently, there is a great need for these nodes to be ultra low-power, and to be able to run for months or even years, since frequent battery change is not envisageable. Nordic’s nRF24L01(+) [3] transceiver based node seems to be a good solution for above high data-rate and low-power scenario, as it can provide up to 2Mbps packet-based data-rate and consume less energy compared to other widely used RF radios, shown in Table I. However, for this transceiver based node, very limited research works can be found. Partial results of measured energy consumption data on nRF24L01 based nodes are presented in [5] [20], however, [5] mainly focuses on an Adaptive Power Control Algorithm, while [20] presents a simulation model in MxSIM.

III. EXPERIMENTAL PLATFORM

A. iHop@Node Testbed Design

For experimental testbed design in the lab, we used Microchip PIC16LF88 [2] and Nordic nRF24L01+ module [14] as the main part of the node with a size of 4.1" * 2.4" shown in Fig. 1, it can be used as a wearable node for WBANs and a generic WSN node. The key features of this testbed are ultra low-power and high data-rate. PIC16LF88 is very power efficient with current load of 0.93–1.30mA in active mode and 0.30–0.5uA in sleep mode [2], and Nordic nRF24L01+ [3] is also designed as ultra low-power shown in Table I. Besides, nRF24L01+ is also embedded with Nordic Enhanced ShockBurst and ShockBurst modes [3] which can provide up to 2Mbps packet based high data-rate, and support the following features:

- Configurable packet format: Length of address, CRC, payload and packet control field
- Configurable output power: 0, -6, -12, -18dBm
- Configurable data rate: 250kbps, 1Mbps, 2Mbps
- Configurable carrier frequency: 2.4GHz–2.525GHz
- Configurable automatic retransmission: 0–15 times
- Automatic retransmission delay: 250us–4000us
- Automatic packet assembly and disassembly
- MultiCeiver function: a star network topology with one primary receiver (PRX) device and six primary transmitter (PTX) devices

In addition, nRF24L01+ provides a true full-duplex SPI interface with four pins CSN, SCK, MISO, MOSI for simultaneous data transmission and reception between microcontrollers (masters). Our testbed supports hardware SPI communication, and on the other hand by using GPIOs to emulate SPI communication for the generic purpose, a software SPI library is also built, which is hardware independent and able to be used with any related PIC MCUs. The time for software SPI communication can be accurately estimated by MPLAB IDE stopwatch function, which can provide useful information for WSN simulations such as network throughput [1], energy consumption, etc. However software SPI is limited by its speed when compared with hardware. In this work we use hardware SPI communication between transceiver and microcontroller for our measurements.

| Table I. Overview of RF Radios and their Main Parameters |
|------------|-------------|-----------------|-----------------|-----------------|---------|---------|
| Radio      | Data rate (kbps) | Band (MHz) | Buffer (Byte) | Sleep (µA) | RX (mA) | TX (mA) |
| MRF24J40 (IEEE 802.15.4) | 250 | 2400 | 128 | 2 | 18 | 22 |
| nRF2401A (Nordic SB) | 1000 | 2400 | 32 | 0.9 | 19 | 13 |
| nRF24L01+ (Nordic ESB) | 250/1000/2400 | 2400 | 32 | 0.9 | 13.5 | 11.3 |
| TI CC2420 (IEEE 802.15.4) | 250 | 2400 | 128 | 1 | 18.8 | 17.4 |
| CX72303 (Bluetooth) | 1000 | 2400 | no | 1 | 14.4 | 11.4 |

Most research works [5–8] use a current sensor circuit [4] test method by placing a shunt resistor between the voltage source and supply pin of the node, with the voltage across the shunt resistor being then amplified and measured. In these works, MCU and transceiver are considered as a whole for energy data measurements, because both components are usually integrated onto a board and supplied by the same power source, so energy measurements are the combination of both of them, even if the isolated measuring methodology presented in [6] is used. Our experimental testbed uses a multi-layers architecture design, such that the MCU layer, transceiver layer and sensor layer are powered by different energy sources. In this way, detailed energy data can be measured respectively and accurately on different components at the same time.

Fig. 1. iHop@Node Testbed.

B. Multichannel Energy Measurement Device (MEMD)

As previously mentioned, by using a shunt resistor (Rsense) of known value between supply and sensor node for energy consumption measurements, the voltage drop (Vsense) across the resistor will be amplified and measured by oscilloscope or acquisition card. This method has been used by many studies [5–8] and can be seen as the cleanest method of energy
measurement, since no side-effects will be introduced to the sensor node hardware or software [9]. However, measurement equipment such as oscilloscope and acquisition card [6] can be costly and real world experiments are time-consuming. To overcome these problems, a dedicated Multichannel Energy Measurement Device (MEMD) is designed and implemented to measure and retrieve node energy consumption. A 10-bit ADC chip [10] is employed to sample the energy usage data (Vout), and then the sampled value can be stored in the buffer of PIC18 [11]. The sampled data can be saved continuously in the whole buffer and then sent out in a buffered sampling mode; alternatively, the data can be sent out immediately after each sampling, in an unbuffered sampling mode. To simplify the development, we use commercial virtual COM port module UR232R [12] for the communication between PIC18 and PC, serial UART signals generated by the MCU is able to be sent over UB232R to PC for later evaluation and analysis. However, a large amount of raw measurements are likely to cause memory problem if the experiments run for a long time. Fig. 2 shows the architecture of one channel of MEMD.

In addition, the multi energy measurement channel design is able to sample the energy consumption of different components on the testbed simultaneously, which can provide much more accurate and detailed information. As shown in Fig. 3, due to the multilayers architecture testbed, channel 1 of MEMD is used for nRF24L01+ energy measurement while channel 2 is for PIC16. Both channels run the sampling at the same time and measurements are stored in respective PIC18 MCUs via buffered sampling for high speed, and then these data are sent to the PC according to channel number for later evaluation. Finally, the cost of this Multichannel Energy Measurement Device is much lower than an oscilloscope, an acquisition card and even SNMD [9] [18].

The following lists the detailed features of MEMD:

- Four channels for sampling energy usage data
- Synchronous energy usage data sampling
- 10-bit resolution for each ADC value
- 1900 samples buffered saving (each channel)
- Configurable Gain
- 150KHz buffered sampling rate
- 5.5KHz unbuffered sampling rate
- Measurement range 0–40mA
- Virtual COM port interface (UB232R module)

C. Energy Data Management Software Platform (EDMSP)

As large amount of raw measurements are sampled and sent to the PC for later evaluation, we design an Energy Data Management Software Platform (EDMSP) called SCOMPRT to receive and manage energy measurements. For EDMSP, it is based on the well-known CSerialPort class [13] which is developed by MFC and Windows API, and then we build a GUI-based platform with various configurable settings as shown in Fig. 4. The settings of COM port such as port number, baud rate, data bit, stop bit and this platform has a multi-types display function for the received data in decimal value, hex value, voltage value, current value and even power consumption value. Besides, these energy data values can also be printed out into a file at the same time for the convenience of later evaluation.

![Fig. 2. Architecture of MEMD (One channel).](image)

![Fig. 3. Multichannel Energy Measurement Device (MEMD).](image)

![Fig. 4. GUI based EDMSP.](image)
IV. MEASUREMENT RESULTS AND DISCUSSION

In this section, we present the obtained measurements of current consumption for both PTX (Primary Transmitter) device and PRX (Primary Receiver) device.

Fig. 5 represents the process of PTX device under Enhanced ShockBurst mode [3], where measurements are sampled by MEMD (Testbed is configured as 2Mbps and 0dBm output power).

![Fig. 5. PTX Current Consumption.](image)

Interval 1: MCU is in active mode, while the transceiver works under power down mode [3]. MCU demands about 1.4mA current consumption, and about 0.8–0.9mA current is required by nRF24L01+ module.

Intervals 2 and 4: during interval 2, MCU sends commands to nRF transceiver to configure it from power down mode to standby mode [3] by SPI communication. For interval 4, by SPI communication, MCU sends 10 bytes payload to the TXFIFO of nRF24L01+. Both intervals show that SPI communication will not increase current consumption of PIC16.

Interval 3: after receiving SPI commands from the MCU, the nRF transceiver crystal starts up, and the transceiver enters into standby mode from power down. The maximum current consumption for this interval can reach about 1.83mA.

Interval 5: the CE (Chip Enable) signal [3] is set high for at least 10us which triggers nRF first into the TX_Setting mode, and then automatically to TX mode after a 130us period. Based on the specification [3], an average current consumption is given for the 130us settling state. According to our measurements, during the first 50us, the current consumption increase rate is slower than in the last 80us, because internal components which are needed for packet sending, are turned on during the later 80us, which leads to a rapid increase in current consumption.

Interval 6: nRF transceiver automatically enters the RX_ACK mode waiting for acknowledgement packet according to ESB mode, as RX_Setting state is needed before entering into RX_ACK mode. Therefore current consumption will first reduce and then increase.

Interval 7 and 8: after successfully receiving ACK frame, nRF transceiver automatically goes back to standby mode and during interval 8, MCU sends command via SPI to configure transceiver into power down.

![Fig. 6. PRX Current Consumption.](image)

TABLE II. CURRENT CONSUMPTION OF iHOP@NODE TESTBED

<table>
<thead>
<tr>
<th>Hardware Components</th>
<th>Current (MEMD)(mA)</th>
<th>Current (Scope)(mA)</th>
<th>Current (Datasheet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCU(sleep)</td>
<td>0.12</td>
<td>0.13</td>
<td>0.5uA</td>
</tr>
<tr>
<td>MCU(active)</td>
<td>1.34</td>
<td>1.399</td>
<td>1.2mA</td>
</tr>
<tr>
<td>MCU(SPI)</td>
<td>1.34</td>
<td>1.399</td>
<td>N/A</td>
</tr>
<tr>
<td>MCU(UART)</td>
<td>1.34</td>
<td>1.399</td>
<td>N/A</td>
</tr>
<tr>
<td>MCU (Instruction)</td>
<td>1.34</td>
<td>1.399</td>
<td>N/A</td>
</tr>
<tr>
<td>nRF(Power Down)</td>
<td>0.82</td>
<td>0.89</td>
<td>0.9uA</td>
</tr>
<tr>
<td>nRF(Standby1)</td>
<td>0.85</td>
<td>0.93</td>
<td>26uA</td>
</tr>
<tr>
<td>nRF(Startup)</td>
<td>1.83(max)</td>
<td>1.86(max)</td>
<td>0.4mA(ave)</td>
</tr>
<tr>
<td>nRF(TX_Settings)</td>
<td>8.66(max)</td>
<td>8.70(max)</td>
<td>8.0mA(ave)</td>
</tr>
<tr>
<td>nRF(TX@0dBm)</td>
<td>10.88</td>
<td>11.03</td>
<td>11.5mA</td>
</tr>
<tr>
<td>nRF(TX_Settings)</td>
<td>10.68(max)</td>
<td>10.72(max)</td>
<td>8.9mA(ave)</td>
</tr>
<tr>
<td>nRF(RX@2MHzps)</td>
<td>14.84mA</td>
<td>14.96mA</td>
<td>13.5mA</td>
</tr>
</tbody>
</table>

As the nRF24L01+ we use is a module [14] with an onboard 3.3V regulator, RP-SMA 2.4GHz antenna and some peripherals circuits. So as shown in above Table II, the measured current consumption values are much bigger compared to the values which are listed in the product specification of nRF24L01+. This is especially true in power down and standby modes, because significant current loads are required by other hardware components on the module except for the nRF24L01+ device.
As shown in Table II, SPI and UART communications in MCU do not consume extra energy. So do the instruction executions of MCU, the instructions under investigation are AND, OR, XOR, ADD, DIV, MUL, WHILE and FOR loop [6]. The measured current consumption in the sleep mode of MCU is found to be significantly different from the values in the datasheet, this could be due to the vertical resolution of the oscilloscope and the low value of the shunt resistor, which do not permit an accurate estimation of the current [7]. In addition, we also find that 1) by disabling interrupt, SPI, ADC and Timer functions on the MCU chip, about 0.2mA current consumption can be saved. 2) no more extra current will be consumed with watchdog function enabled. 3) I/O port settings are related to current consumption.

With the feature of easy to use, MEMD and EDMSP experimental platforms not only provide accurate energy measurements on each component of our testbed node because of the simultaneous tests at run-time, but also simplify the decomposition process, as no extra codes are needed to disable the modules that are not required in the experiments.

For the other nodes, such as TelosB, MicaZ and Mica2, the measurement range of our platform is available, buffered sampling mode is fast enough for the collecting of energy usage data, meanwhile multichannel can provide accurate and detailed energy measurements of several nodes simultaneously. Apparently, MEMD and EDMSP are of very generic use in the energy measurements of WSN mote.

V. CONCLUSION

This paper presents the design and implementation of an efficient and low-cost experimental platform iWEEP_HW for sensor node energy measurement. In addition, detailed and accurate measurements concerning the current consumption of our high data-rate and ultra low-power iHop@Node testbed are provided. Due to the proposed MEMD and EDMSP, the measurements of different functional modules are tested at run-time simultaneously. Although real-world hardware measurements is time consuming, complex and repetitive with large amounts of raw measurements, we find the accurate results from real measurements are worth the efforts and time. To sum up, these measurements can be valuable for designers, developers and researchers who focus on energy efficient protocol design, power saving applications development and optimization of network lifetime.

REFERENCES


