Protocol assessment issues in low duty cycle sensor networks: The switching energy

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Abstract

Energy assessment of MAC protocols for wireless sensor networks is generally based on the times of transmit, receive and sleep modes. The switching energy between two consecutive states is generally considered negligible with respect to them. Although such an assumption is valid for traditional wireless ad hoc networks, is this assumption valid also for low duty cycle wireless sensor networks? The primary objective of this work is to shed some light on relationships between node switching energy and node duty cycle over the total energy consumption. In order to achieve the target, initially, we revisit the energy spent in each state and transitions of three widespread hardware platforms for wireless sensor networks by direct measurements on the EYES node. Successively, we apply the values obtained to the SMAC protocol by using the OmNet++ simulator. The main reason for using SMAC is that it is the protocol normally used as a benchmark against other architectures proposed.

keywords: access control, switching energy, MAC, wireless, sensor networks, energy-efficient, protocol assessment, duty cycle.

1 Introduction

Wireless sensor networks consist of an ensemble of tiny devices that are dispersed in an area where they operate for one or more tasks of long unattended operations. Requirements demand an active cooperation of nodes to ensure autonomy, self-organization and a long life of the network. As a result, energy consumption is the primary concern and minimizing such is a key objective. The transceiver activity is one of the most energy hungry processes especially for long haul transmission. Therefore, communication takes place in multi-hop fashion. Moreover, sensors have limitations in cost, size, processing capability and storage capacity. Such characteristics lead to a direct impact over the software design guidelines, as it is remarked in [8, 16]. Within this context, a significant increase of energy-efficiency can be achieved by an effective protocol of Medium Access Control (MAC). A successful approach taken has been the introduction of the wakeup concept in which node transceivers alternate periods of activity and inactivity. The node duty cycle is reduced as a result.

From the communications energy point of view, a sensor node consumes energy in four states: sleeping, receiving, transmitting, and switching between the three former states. It is common to merely consider the receiving, transmitting, and sleeping energy of nodes. Although, the switching energy in high throughput ad-hoc networks is negligible with respect to other sources of energy wastage, can the same be assumed in energy-efficient systems such as low duty-cycle sensor networks?

In this paper, we seek to clarify the significance of such a source of energy consumption over the total for three different WSNs hardware by means of direct measurements. Subsequently we address the variability of energy consumption composition in conjunction with a MAC protocol, SMAC. Such a protocol has been chosen as it is the one commonly used for benchmarking.

The final objective of the paper is to observe the impact of different energy consumption sources over the total when different network conditions apply. It represents one of the first attempts to critically assess the sources of energy consumption of three dominant hardware boards when used in conjunction with a MAC protocol, specifically with SMAC. Results can improve the MAC protocol evaluation process together with empowering decisions relating to the judicious protocol/hardware choice for a given specific set of WSN applications.

2 Related works

The large number of applications for a WSN leads to different requirements for sensor node hardware. Some aspects to consider are number and type of electronic peripherals used, type and number of sensors, rate of measurements, communication or storage of information collected, etc.[1]. Studies on WSN protocols in [2] have taken into account the sources of power consumption in a WSN simulation model. The literature proposes many protocols for WSNs [23, 6, 19, 18, 13, 7, 21, 9, 11], which are claimed to offer low energy consumption. They have been simulated and assessed under certain parameters and scenarios. In such protocols the energy consumption is evaluated by taking into account the energy spent in transmitting, receiving an sleeping states of nodes. Such evaluations do not consider the energy consumed in switching from one state to another.

In [2], the switching energy is mentioned as an open research issue. Studies like [17] refer to the switching energy since significant amount of power is consumed for starting up the transmitter itself. Other works, e.g. [13], state that the overhead of the switching is likely to be small. In general, it is a common practice to assume the switching energy to be negligible.

The energy spent in state transactions is insignificant for wireless ad-hoc protocols like in [10]. Such protocols do not apply any low duty cycle concept which leads to an increased energy consumption. On the other hand, energy efficient protocol that apply the wake up concept can reduce the node duty cycle to less than 1% for example, in [15].

3 Analysis of the sensor node

The analysis of the sensor node has been obtained through an investigation of different EYES sensor node prototypes [12]. All boards have been equipped with temperature sensing devices and presented comparable components. The main differences consisted in the different transceivers they mounted. In particular, processor and radio transceiver of TR1001 [14] transceiver, CC1000[5] and CC1010 [4] stand-alone chipcon modules have been used. The CC1010 had a μprocessor built in and therefore the CPU on that board could be put into sleep mode. Another difference is the higher sensitivity of the CC chipcon class than TR1001. Tables 1 and 2 show a resume of the specification and configurations of boards used, respectively.

For simplicity, *boards are categorized based upon transceiver type*. The rest of the section focuses upon the approach used to obtain energy measurements plotted at the oscilloscope by means of a measuring circuit.

3.1 The Experimental Model

The objective of manual measurements is to build an accurate experimental model of the energy composition. The parameters recorded are steady-state current consumption, switching times and switching energy. Therefore, we measured the CC1010 and TR1001 boards, so that we could derive the CC1000 information based on the information on its data-sheet [5]. Sections 3.1.1 and 3.1.2 give details for correct reproducibility of the experiment.

3.1.1 The approach

The measurements followed a simple approach. The voltage drop is gauged across a known high-side series resistor placed between the positive terminal of the battery and the sensor node input power connector. Current consumption, power and energy consumption are then derived from this voltage. In order to collect the information, we have connected the hardware to an oscilloscope then repetitive cycle of node switching between states has been performed. Figure 1 shows command cycle snapshot on the CC1010 and the TR1001 boards.

The measuring circuit adopts the following design guidelines:

- Do not sink or enter current over the DUT or the sensing resistor while measuring;
- Chose a series resistor keeping the voltage drop across it in a low level;
- Use a measuring circuit fast enough to follow switches at a rate of 30 Hz, with steps of 3 V in 10 μs;
- Avoid the connection of a high capacitance in parallel to the DUT or sensing resistor to be able to measure accurately during the switches.

3.1.2 The circuit

The measuring circuit is based on the *INA110 instrumentation amplifier* fast settling time and high slew rate device. It has high common mode rejection ratio (CMRR) and very low input currents, due to its very high input impedance both in common and differential modes. It also has a very low input capacitance as required.

Table 1. Sensor node hardware investigated

	CC1010	**C1000**	**TR1001**
CPU	8051 core	MSP 430F149	MSP 430F149
Prog. mem.(KB)	32	60	60
Data mem.(KB)	2	2	2
Clock (Hz)	32 KHz & 15 MHz	32 KHz & 4 MHz	32 KHz & 4 MHz
RF transceiver	CC1010	CC1000	TR1001
Radio(MHz)	868	868	868
Modulation	FSK	FSK	ASK
Data rate (bps)	76800	76800	115200
Radio Encoding	Manchester	Manchester	None

Table 2. Boards configurations investigated

Test-bed	Radio	Processor
TR1001	Manchester, output power 0 dBm, 115200 bps, 10 Bytes preamble	32 kHz in low power mode (LPM3) and 800 kHz in active mode.
CC1000	Manchester, output power -7 dBm, 76800 bps, 5 Bytes preamble, low power mode: oscillator ON, bias OFF, synthesizer OFF bias OFF	32 kHz in low power mode (LPM3) and 800 kHz in active mode.
CC1010	Manchester, output power -7 dBm, 76800 bps, 5 Bytes preamble, low power mode: oscillator ON, bias OFF, synthesizer OFF bias OFF	Main oscillator ON in low power mode (Idle from 32 kHz oscillator), RTC ON in active mode (14.7 MHz), FLASH reduced energy mode

We identified two ranges of current to measure: low power mode and Tx/Rx mode. As a result, it was necessary to incorporate two sensing resistors. The chosen values are the following:

- **Low power mode:** Imax = 200 μA, Rsense1 = 50 Ω $\Rightarrow$ VRsense1 = 10 mV, Gain = 100 $\Rightarrow$ Vout = 1 V

- **TX/RX mode:** Imax = 1 to 30 mA, Rsense2 = 0.33 Ω $\Rightarrow$ V = 0.3 to 10 mV, Gain = 100 $\Rightarrow$ Vout = (30 to 1000) mV.

The test was performed by choosing a square waveform of 1 kHz and of 5 V amplitude at the input of the INA 110 connected through an attenuating resistive divider circuit. The circuit offered good precision allowing us to conduct measurements at the edges with a very low distortion.

3.2 Measurement results

Tables 3 ,4 show the values of the current and power consumption, switching times, and switching energy derived from measurements on the sensor board through the circuit described in section 3.1.2. We assumed three possible modes of the node: receiving, sleeping or transmitting. The measurements have been conducted by applying the consideration derived from the standard board configuration in [14, 5, 4] in conjunction with the protocol requirements, as follow:

- The energy consumption in the sleeping mode of the CC1000 and CC1010 boards is due to leaving the transceiver oscillator ON in low power mode. The consumption in sleeping mode is of about 5-8 mA. Such a configuration avoids 2 ms wake-up time that the oscillator would need to wake from sleep. The faster wake-up scheme does not compensate for the extra energy spent during the sleeping mode. The choice of the proper configuration is chosen by taking into account several factors like SLOT length, number of neighbors, maximum delay, clock drift, etc.

- The switching energy time from any state to TX/RX computes time and energy spent during the PREAMBLE transmission/reception, as part of the process required to switch between states. The PREAMBLE adopted, is based on the longest time elapsed before the first data bit left the transceiver output port. This time is variable, and depends on the signal strength at the antenna of the receiver.

- In the case of the CC1010, the wake-up time includes: time for the processor to wake up from idle to low power mode; time to Switch the CPU oscillator source. Time to switch the transceiver ON once in high-speed mode. Time needed for the transceiver to deliver the first data bit.

- The CC1010 and CC1000 TX power consumption is based on a -7 dBm configuration. We chose that value based on the results on MOTES [3]. The aim is to use values that lead to a similar reception rate along the message length range simulated for the three transceivers.

The measurements results obtained are then applied on the Sensor-MAC protocol (SMAC) described in the following section.

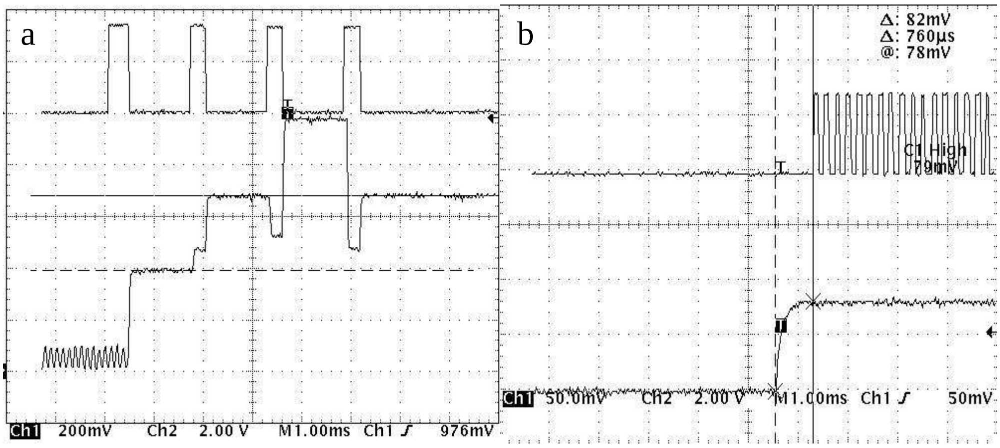

Figure 1. Screen-shots of the oscilloscope when measuring the current consumption of the CC1010 and TR1001 boards. Lower traces show the voltage across the measuring resistor. (a)Upper traces draw the commands performed: Low speed → high speed → Rx → Tx → Rx. (b)Upper trace shows incoming bits: TR1001 switching from sleep to Rx;

Table 3. Measured boards current and power consumption

	current [mA]			power [mW]		
	Sl	Rx	Tx	Sl	Rx	Tx
TR1001	0.005	4.8	12	0.015	14.4	36
CC1000	0.11	10	11	0.33	30	33
CC1010	0.15	26	26	0.45	78	78

Table 4. Switching time and switching energy of measured boards

	switching time [μs]					
	Sl to Rx	Sl to Tx	Rx to Sl	Tx to Sl	Rx to Tx	Tx to Rx
TR1001	700	700	10	10	700	700
CC1000	850	850	10	10	850	850
CC1010	1600	1600	10	10	850	850
	switching energy [μJ]					
TR1001	8.82	25.2	0.116	2.83	25.2	8.85
CC1000	19	20.5	0.7	0.75	22.4	21.4
CC1010	45.8	47.75	1.83	1.93	61.43	61.61

4 The Sensor-MAC protocol

The section gives a brief overview of the SMAC protocol. For a complete description, refer to [23].

SMAC divides the time in two periods: active time and sleeping time. This cycle is repeated periodically on a fixed scheme, so that after every sleeping period nodes either wake up and listen to the channel for messages addressed to them, or transmit their information if they obtain access to the channel. For establishing a communication, neighboring nodes have to synchronize to the start of the active period. Bordering nodes have to keep synchronized with all their neighbors to allow communications between zones. Therefore, they have to follow two or more synchronizations simultaneously with an increase of node activity and hence energy consumption. Active period is also divided into three contention based access sections: the SYNC period dedicated to node synchronization update and the Request To Send (RTS) period and the CTS period. SYNC packets are sent periodically by nodes to keep the network synchronized; nodes willing to access the channel and nodes that are free to receive the packet send RTS/CTS packets. As a result, the exchange of data messages follows the RTS/CTS/DATA/ACK handshake mechanism; therefore, nodes switch between different states periodically. Nodes with the same synchronization have to wake up at the beginning of the active period, which correspond to the start of the SYNC section. If there is no information to transmit, they keep on listening until the end of the RTS section, or until they listen to a RTS message not addressed to them then go to sleep. Every packet has a field that contain the duration of the remaining transmission. Therefore, a node that receives a packet destined to another node knows how long it has to refrain from transmitting. In order to improve the latency of messages, SMAC adopts an adaptive listening technique. Nodes that listen to a RTS or CTS not destined to them take up at the end of the transmission so allowing the supposed neighbour to pass the message immediately.

The SMAC protocol has been coded at the simulator by means of a framework of wireless sensor networks that included the measurements obtained in section 3.2. Simulation results are presented in the following section.

5 The Simulation

SMAC has been implemented in Omnet++ [20] discrete event network simulator. The framework is based on earlier work at the EU Eyes project, co-design template in [22]. The work is part of a larger set destined to study the composition of the total communications energy when different parameter values of protocols, applications and hardware are used.

5.1 Performance evaluation

The metrics used for a specific evaluation of the switching process relevance are the following:

Energy TX It is the energy spent by one node per every bit transmitted;

Energy Switch: It is the energy spent per node for the total number of transitions of two consecutive states;

Energy Sleep: It is the energy spent by one node during the time of inactivity referred to as sleeping state; The energy spent for state transactions is based on earlier measured values in table 4;

Total energy consumption: It is the total energy consumption calculated per node. It includes all previous metrics together with the energy spent for receiving and idle listening. Such sources of energy wastage have not been taken into account separately as they are not central thrust of the paper. Percentage of previous metrics is calculated with respect to the total energy consumption.

5.2 Simulation setup

The selected scenario consists of three nodes and one gateway arranged in a line as shown in figure 2. The node transmitting range allows nodes communicating with direct neighbours only. Secondary effects such as node interferences and routing issues are excluded as they are not the main aim of the paper. Consequently, a separate evaluation of source (node3), forwarders (node2 node1), and destination (gateway) could be estimated. The simulation aimed to evaluate the switching energy with a minimal number of transactions. In fact, more complex topologies could introduce node collisions, retransmissions, multiple attempts to access the channel etc. so increasing the amount of switching thus distorting the bare relevance of switching energy.

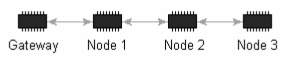

Figure 2. Scenario in which node3 is the source and node2 and node1 are forwarders.

Each graph has been obtained by running 13 independent simulations of 20 minutes each. Percentages of switching, sleeping and transmitting energies are calculated over the total energy consumption simulated. The physical model included clock skew and offset inaccuracies obtained by randomly choosing among 10 independent seeds for each simulation. The results are averaged between node2 and node1 values as they are the nodes that are subjected to more switching activity due to message forwarding. The generation of data begins after 20s of simulation. Such a time has been considered sufficient for network initialization purposes.

5.3 Simulated results

Variation of the duty cycle has been obtained by fixing the frametime to 0.25s then tuning the contention window from 25ms to 4.2ms. The message length has been chosen to be 16 bytes of data since it is considered a typical value for sensor network payload (e.g. sensed temperature value). The model includes preamble (5 bytes), header (6 bytes), modulation factor (2 bytes) and coding (Manchester), these are identified as message overhead. The final size of the message is 45 bytes. Different network loads have been simulated by varying the message generation period of node 3, the source.

The transceivers TR1001, CC1000 and CC1010 have been evaluated under low and high traffic loads by variation of the packet generation period. In particular, traffic load is regulated by Node3 that generates one message of 16 bytes in length every 60s (low traffic) and 2s (high traffic). In line with the latter SMAC evaluation in [23], a synchronization packet of 2 bytes (plus message overhead) is transmitted every 10s. The final length of the sync packet is 17 bytes.

At first glance, all graphs in figures from 3 to 5 show an increase of switching energy as the duty cycle decreases. In fact, fewer messages that are generated the lower the total energy consumption is, hence a higher switching energy as a percentage of.

For TR1001 in figure 3 , the maximum switching value is just above 6% that has been obtained for 1.7% duty cycle in low traffic condition. The motivation for choosing a lower bound of 1.7% for the duty cycle is due to an intrinsic operational limit of SMAC given the chosen contention window size together with data rate of the investigated transceivers.

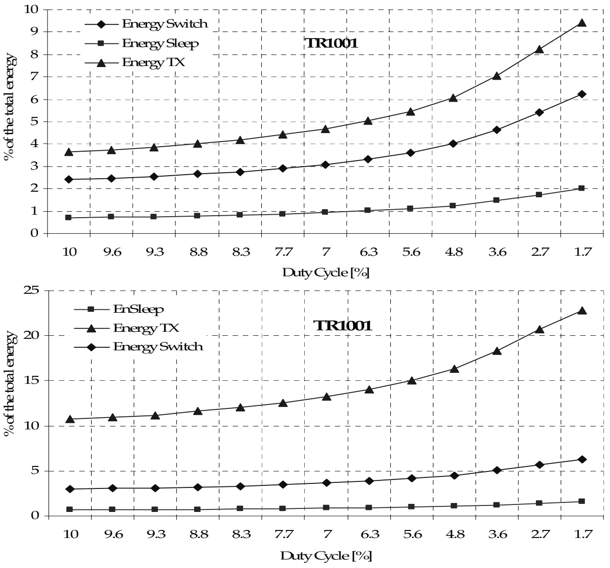

Figure 3. Energy composition for Tr1001 under low and hight traffic load respectively (60s and 2s message generation periods)

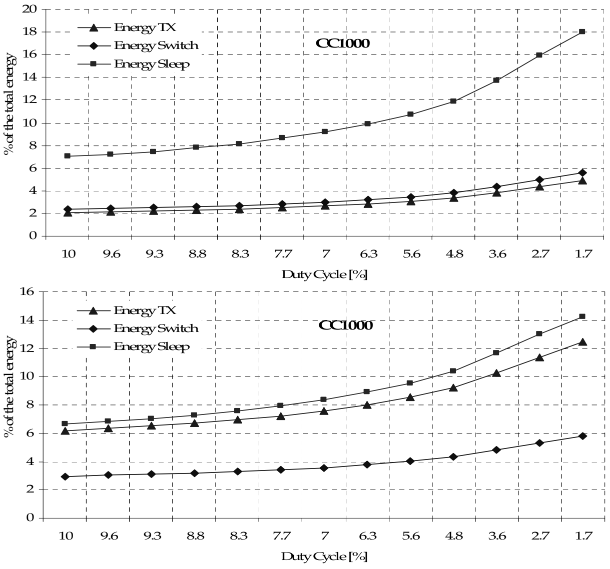

Figure 4. Energy composition for CC1000 under low and hight traffic load respectively (60s and 2s message generation periods)

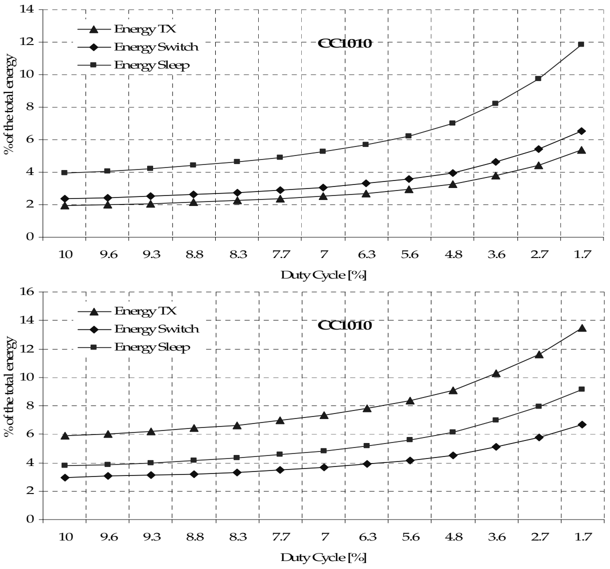

Figure 5. Energy composition for CC1010 under low and hight traffic load respectively (60s and 2s message generation periods)

It is interesting to notice that for any duty cycles, both graphs show the sleeping energy positioned well beneath the switching energy, meaning switching energy can be more important than sleeping energy when evaluating low duty cycle MAC protocols.

The two graphs in figure 4 show the energy composition trends of the CC1000 transceiver for 60s and 2s message generation period. As in the previous graphs, the switching energy has its maximum at about 6% for the lowest duty cycle simulated, 1.7%. It is remarkable the fact that in low data traffic conditions, the switching energy is higher than the transmitting energy.

Figure 5 shows results of the CC1010 chipcon. The graphs show a trend that is in line with the ones obtained for the previous transceivers. The switching energy has its maximum of just below 7% at 1.7% duty cycle. As for TR1001 and CC1000 in low traffic load, the CC1010 show the switching energy above the transmitting energy for all simulated duty cycles. As the traffic load becomes high, both CC1000 and CC1010 show the percentages of transmitting energy that lie above the switching energy. The effect is not in accordance with TR1001. The reason is mainly due to the lower data rate of CC1000 and CC1010 chipcons than the TR1001 as shown in table 2 with a consequence larger traffic load sensitivity of the class CC of chipcons.

It should be noted the higher sleeping energy of CC1000 and CC1010 with respect to TR1001. The main reason for this is mainly due to leaving the oscillator ON in low power mode of CC1000 and CC1010. In fact, if the oscillator is configured to power down in low power mode then it could take more than 2 ms (with more than 5 mA of current consumption) from sleeping mode to an active mode.

Moreover, the PLL takes around 300 μs to lock. Therefore, sleeping energy could be reduced only with a large increase of wake-up time together with the energy spent for switching. The best configuration to select is strictly dependent on the MAC protocol characteristics together with application features such as data generation rate, average number of neighbours etc. In our set of experiments, the oscillator was set to ON as it showed less total energy consumption with respect to the other option.

Finally, figure 6 illustrates the trend of the total energy consumption for the time simulated. The graphs show a very little variation with respect to the high and low traffic load albeit they generate a very different energy composition as showed in previous graphs.

6 Discussion

In general, neglecting the switching energy when evaluating protocols for wireless sensor networks can lead to significant errors that is accentuated as the duty cycle is reduced. As previously mentioned, long unattended applications make the network life expectancy one of the most important performances metric. For example, an error of 6% of the energy consumption can lead to a decrease of network life expectancy of more than 2 months over a 3 years expected operational time.

Graphs showed that the energy consumption composition is both transceiver and application dependent. If we assume 5% to be the lower bound of energy consumption significance then the following guidelines can be derived:

- For TR1001 and CC1010, the switching energy needs to be computed if the node duty cycle is equal or lower than 3% and 3.6% in case of low and high traffic load respectively;
- For CC1000, the switching energy needs to be computed if the node duty cycle is equal or lower than 2.7% and 3.6% in case of low and high traffic load respectively;
- Sleeping energy consumption of TR1001 can be neglected in any case simulated as less than 2%;
- For CC1000 and CC1010 in low traffic load conditions, the transmitting energy starts being significant at 2.5% duty cycle or lower.

Our simulated lower bound duty cycle of 1.7%, due to SMAC protocol limitations, is in contrast with existing works on low power listening, for example BMAC [15], which can facilitate effective operation down to a duty cycle as low as 1%. Extrapolating from our existing results in this paper, we expect switching energy to cover an even more significant percentage of the total power consumed as the duty cycle get closer to 1% such as in BMAC. On the other hand, BMAC may exhibit a different energy consumption composition which may alter the significance of the switching energy. A further extension to be investigated is the importance of the energy consumed in state transitions with regard to TDMA based protocols, for example [18, 19], as they can reduce the node duty cycle to a greater extent.

The simulation showed results of only a very simple network topology. A natural extension of this work could be the investigation of more complex topologies and scenarios such as augmented channel contention within more nodes between the same transmitting range, different message flow directions, presence of hidden and exposed terminals, random node placements etc. Additional extensions could also include the effect of handshake mechanisms on the switching energy.

The effect of such situations could be two fold: on one hand, circumstances can lead to an increase of the amount of switching due to multiple channel access attempts. On the other hand, the total per node energy consumption could increase consequently reducing the switching energy as a percentage of total energy.

7 Conclusion

The switching energy is in general not considered when MAC protocols for wireless sensor networks are evaluated. The work presented sheds some light on the real negligibility of the energy spent for transceiver state transactions. Initially, the paper focused on manual measurements of the switching energy on the EYES sensor node hardware. Measurements involved the TR1001, CC1000 and CC1010 transceivers for wireless sensor networks. Successively, such results were utilized at the simulator to evaluate the impact of the switching energy at the MAC layer. Simulated results were carried out by using the Sensor-MAC protocol since it is the one normally used for benchmarking novel architectures. In the case of low traffic load and short messages, the switching energy can also be higher than the energy spent for transmission. Given a 5% lower bound of energy consumption significance, we derived some guidelines for protocols evaluated against SMAC that are expected to be used at a duty cycle of less than 10%. In general switching energy should not be neglected but computed together with transmitting, receiving and sleeping energies. The obtained results improve the MAC protocol evaluation process together with empowering decisions relating to the judicious protocol/hardware choice for an aimed set of WSN applications.

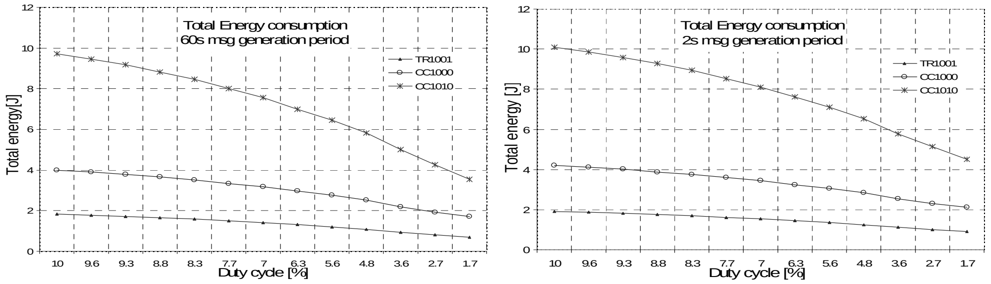

Figure 6. Total energy consumption for different transceivers under low and high traffic loads

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References

[1] Croosbow data sheets. Technical report, RF Monolithics, Dallas, TX, USA.

[2] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: A survey. *Computer Networks*, 38:393–422, 2002.

[3] N. B. Alberto Cerpa and D. Estrin. Scale: A tool for simple connectivity assessment in lossy environments. Technical report, in CENS Technical Report 21, September 2005.

[4] C. AS. CC1010 datasheet. Technical report, Chipcon AS, Oslo, Norway, May 2005.

[5] ChipconAS. CC1000 datasheet. Technical report, Chipcon AS, Oslo, Norway, May 2005.

[6] T. V. Dam and K. Langendoen. An adaptive energy efficient mac protocol for wireless sensor networks. *ACM Sensys*, November 2003.

[7] A. El-Hoiydi and J.-D. Decotignie. WiseMAC: An Ultra Low Power MAC Protocol for the Downlink of Infrastructure Wireless Sensor Networks. In *Proceedings of the International Symposium on Computers and Communications ISCC*, pages 244–251, Alexandria, Egypt, June 2004. WiseMAC.

[8] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. E. Culler, and K. S. J. Pister. System architecture directions for networked sensors. In *Architectural Support for Programming Languages and Operating Systems*, pages 93–104, 2000.

[9] L. V. Hoesel, S. Chatterjea, and P. Havinga. An energy efficient medium access protocol for wireless sensor networks. *proRISC 2003*, November 2003.

[10] IEEE. Wireless lan medium access control and physical layer specification. *ANSI/IEEE Standard 802.11*, 1999.

[11] Kalidindi, Kannan, Iyengar, and Ray. Distributed energy aware mac layer protocol for wireless sensor networks. *International conference on Wireless Networks*, pages 282–286, 2003.

[12] P. J. H. H. J. K. Lodewijk F.W. van Hoesel, Stefan O. Dulman. Design of a low-power testbed forwireless sensor networks and verification. Technical report, University of Twente and Nedap N.V., The Netherlands, May 2003.

[13] G. Lu, B. Krishnamachari, Cauligi, and S. Raghavendra. An adaptive energy-efficient and low-latency mac for data gathering in sensor networks. *International workshop on Alghoritms for Wireless, Mobile, ad Hoc Sensor Networks (WMAN 04)*, April 2004.

[14] R. Monolithics. TR1001 datasheet. Technical report, RF Monolithics, Dallas, TX, USA, July 2003.

[15] J. Polastre, J. Hill, and D. Culler. Versatile low power media access for wireless sensor networks. In *SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems*, pages 95–107. ACM Press, 2004.

[16] G. J. Pottie and W. J. Kaiser. Wireless integrated sensor networks. *Communications of the ACM*, 43:51–58, 2000.

[17] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava. Energy-aware wireless microsensor networks. *IEEE Signal Processing Magazine*, pages 40–50, Mar. 2002.

[18] Rajendran, Obrazka, and Garcia-Luna-Aceves. Energy-efficient, collision-free medium access control for wireless sensor netwoks. *Conference on Embedded Networked Sensor System*, pages 181–192, November 2003.

[19] A. Ruzzelli, M. O'Grady, G. O'Hare, and R. Tynan. An energy-efficient and low-latency routing protocol forwireless sensor networks. *In proceeding of the Advanced Industrial Conference on Wireless Technologies SENET 2005, Montreal, Canada, IEEE Press,*, Agoust 2005.

[20] A. Varga. The OMNet++ discrete event simulation system. In *European Simulation Multiconference*, Prague, Czech Republic, June 2002. http://www.omnetpp.org.

[21] A. Woo and D. Culler. A transmission control scheme for media access in sensor networks. *Mobicom Rome*, pages 221–235, 2001.

[22] E. WSN. The codesign project. University of Twente, The Netherlands, 2003. http://wwwhome.cs.utwente.nl/ mader/Codesign/.

[23] W. Ye, J. Heidemann, and D. Estrin. Medium access control with coordinated adaptive sleeping for wireless sensor networks. *IEEE/ACM Transactions on Networking*, 3:493–506, 2004.