Impact of Switching Latency Times in Energy Consumption of IEEE 802.15.4 Radio Transceivers

Norberto Barroca, Paulo T. Gouveia and Fernando J. Velez

Instituto de Telecomunicações - DEM

Universidade da Beira Interior

Covilhã, Portugal

Email: nbarroca@lx.it.pt, paulotorresgouveia@gmail.com, fjv@ubi.pt

Abstract—The energy efficiency of wireless sensor networks medium access control protocols depends on the adopted radio transceiver. This paper addresses the influence of the switching latency times in the energy consumption of IEEE 802.15.4 radio transceivers. Three different radio transceivers have been considered operating in the 2.4 GHz band. Simulation results performed in OMNET++ show that the radio transceiver with the shortest latency switching time has better performance in terms of energy consumption.

Index Terms—Wireless Sensor Networks, Switching Latency Time, Energy Optimization.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are used in a wide range of scenarios and applications [1]. With the recent technological advances, miniaturization becomes a reality allowing the creation of tiny, autonomous sensor devices with wireless communication capabilities. These devices are restricted in terms of energy since batteries have limited lifetime. Moreover, in most of the cases, there is no valid solution that allows the batteries to recharge. These limitations are directly affected by the power consumption of the radio transceiver.

Energy-efficient medium access control (MAC) protocols [2] are responsible for timing the transmissions allowing for multiple sensor nodes to share the same communication medium, as well as to determine and change the operation mode of the radio transceiver. Furthermore, devices must co-operate among themselves in order to efficiently exchange data by using multi-hop to possibly save energy. As a consequence, an efficient management of transmission, reception and sleep modes should be implemented in each individual WSN device. Nodes must remain in the sleep mode whenever they do not have to receive/process/transmit data packets. Efficient energy-aware protocols are therefore crucial to ensure error free packet delivery, whilst minimizing power consumption. However, MAC protocols are always restricted by hardware constraints. Moreover, long periods for switching the radio between the radio states (i.e., RX, TX and SLEEP) could result in significant energy spent.

The remainder of this paper is organized as follows. Section II presents the timing model to evaluate the impact of the switching latency times in the energy consumption. Section III addresses the simulation results for three different radio transceivers operating in the 2.4 GHz band. Finally, Section IV presents the conclusion.

II. TIMING MODEL TO EVALUATE THE IMPACT OF THE SWITCHING LATENCY TIMES

IEEE 802.15.4 radio transceivers have strict hardware timing constraints that influence the energy performance of the MAC protocols. In this work we propose a model to evaluate all the times involved in IEEE 802.15.4 nonbeacon-enabled multi-hop WSNs. Our model accounts all the timing constraints of IEEE 802.15.4 standard, plus the hardware constraints of typical transceivers.

A. IEEE 802.15.4 timing requirements

According to IEEE 802.15.4, a sensor node that sends data or a MAC command frame with its ACK request subfield set to one shall wait for at most *macAckWaitDuration* symbols (*symbol period* = 16 μs) for the corresponding acknowledgment frame to be received. The *macAckWaitDuration* already includes the time for the ACK frame itself (acording to Section 7.5.6.4.2 from [3]). The value is determined as follows:

$$
\begin{aligned}
macAckWaitDuration = {} & LastSymbol + \\
& aTurnaroundTime + \\
& phySHRDuration + \\
& 6 \times phySymbolsPerOctet
\end{aligned}
\tag{1}
$$

At 2.4 GHz, the PHY *macAckWaitDuration* is given by:

$$
macAckWaitDuration = 1 + 12 + 10 + (6 \times 2) = 35 \tag{2}
$$

$$
\begin{aligned}
macAckWaitDuration \quad & = 35 \; symbols \times 16 \; \mu s \\
& = 560 \; \mu s
\end{aligned}
\tag{3}
$$

Figure 1 shows the timing of the acknowledgement process considering IEEE 802.15.4 radio compliant transceivers. The *aTurnaroundTime* (192 μs) is the time for IEEE 802.15.4 compliant radio transceivers to switch from TX/RX or RX/TX.
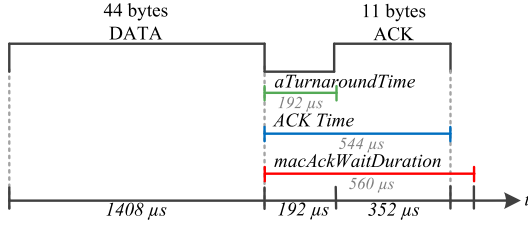
Fig. 1. DATA/ACK handshake from IEEE 802.15.4.

IEEE 802.15.4 radio compliant transceivers use CSMA/CA to access the medium for their data transmissions. The algorithm is implemented in units of time called backoff periods. One backoff period is equal to $aUnitBackoffPeriod$ symbols (i.e, 20 symbols, for IEEE 802.15.4). Before trying to sense the channel, a device shall wait for a specified number of backoff periods, determined by the backoff exponent (BE). The transceiver randomly selects a backoff time from a number between 0 and $2^{BE}-1$. Each device considers a $macMinBE$ time value before starting a new transmission and increments it after every failure to access the channel.

The $Initialbackoff Period$ is given as follows:

$$Initialbackoff Period = (2^{BE}-1)\times \qquad (4)$$
$$aUnitBackoff Period$$

When a node is in the RX state and the backoff timer expires, node perform the CCA before transmitting a packet. This time delay, due to CCA, is given by:

$$ccaTime = rxSetupTime + ccaDetectionTime \qquad (5)$$

The $rxSetupTime$ is the time to switch the radio between the different states and must be taken from the datasheet of the radio transceiver. During the $ccaDetectionTime$, the radio transceiver must determine the channel state within the duration of 8 symbols (i.e, 128 μs) as defined in the IEEE 802.15.4 standard. Figure 2 presents the timing for transmitting a data packet by considering CC2420 [4].
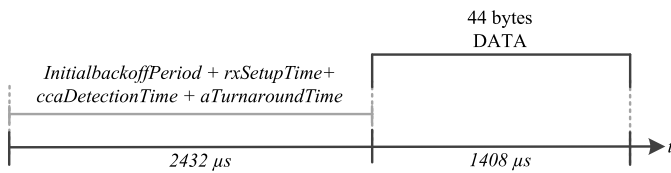

Fig. 2. Timing for transmitting a data packet.

Besides, for every data packet transmitted, there is a random deferral period of time before transmitting that is given by:

$$D_T = Initialbackoff Period + rxSetupTime \qquad (6)$$
$$+ccaDetectionTime + aTurnaroundTime$$

B. Energy Consumption

In order to know how much energy is spent by the radio transceivers on each state, an analytical model was conceived. A two-hop network, with two sources, one relay and two sinks, has been considered. Figure 3 shows the multi-hop star topology OMNeT++ [5] simulation setup. The packets from source node A flow, through node C, to sink node D, while the packets originated by source node B flow, through node C, to reach sink node E.
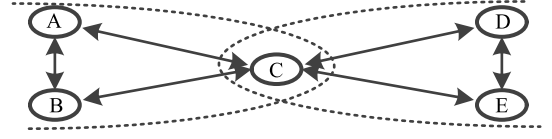

Fig. 3. Multi-hop star topology simulation scenario.

The star network topology is challenging because there are abundant overhearing opportunities between neighbouring nodes. A node acting as the coordinator may therefore take advantage of these opportunities to seek network optimization. The star topology may also be viewed as a part of a larger network. Therefore, this type of network can be viewed as a building block for larger scale wireless networks [6].

The analysis of the sensor nodes performance is done through simulation by considering three different radio transceivers operating at 2.4 GHz. The CC2420, CC2520 [7] and AT86RF231 [8] transceivers.

Table I shows the specifications of the radio transceivers, where P indicates the power consumed in each state (a supply voltage of 3V is considered).

TABLE I
SPECIFICATIONS OF THE CONSIDERED TRANSCEIVERS.

Parameter	CC2420	CC2520	AT86RF231
P_{Sleep} [μA]	0.02	0.03	0.02
$P_{Receive}$ [mA]	18.8	18.5	12.3
$P_{Transmit}$ [mA]	17.4	25.8	11.6
$Transmit\ rate$ [kb/s]	250	250	250
$aTurnaroundTime$ [μs]	192	192	192
$ccaDetectionTime$ [μs]	128	128	128
$rxSetupTime$ [μs]	1792	1792	400
$ccaTime$ [μs]	1920	1920	528

In this research, we have created an energy model based in [9]. The energy consumption over a period of time t is given as follows:

$$E(t) = [T_{TX} \times P_{TX}] + [T_{RX} \times P_{RX}] \qquad (7)$$
$$+[T_{Sleep} \times P_{Sleep}] + [T_I \times P_I]$$

The meaning of each variable is presented in Table II. We assume that for all radio transceivers the energy consumption is equal for both IDLE and RX states.

As shown in Table I, the transmission power is significantly different for each IEEE 802.15.4 transceivers. Besides, the time for the $rxSetupTime$ of the AT86RF231 transceiver is considerably lower than for the CC2420 and CC2520 transceivers. By analyzing equation (6), we can conclude that the $rxSetupTime$ (the node switching delay time) has a higher impact in the CCA of the IEEE 802.15.4 radio transceivers. Hence, with longer warm-up times the energy

TABLE II
NOTATIONS FOR THE ESTIMATION OF THE ENERGY.

Notation	Parameter
T_{TX}	The amount of time the node has spent in TX state
P_{TX}	Power consumption in the TX state
T_{RX}	The amount of time the node has spent in RX state
P_{RX}	Power consumption in the RX state
T_{Sleep}	The amount of time the node has spent in SLEEP state
P_{Sleep}	Power consumption in the SLEEP state
T_I	The amount of time the node has spent in IDLE state
P_I	Power consumption in the IDLE state

spent by each node is augmented, since it has direct influence in the total time a node is consuming power.

Figure 4 presents the conceptual profile energy of a sensor node that switches the radio transceiver between the IDLE and SLEEP states, given by $\tau_{i,s}$ and $\tau_{s,i}$, which also corresponds to the $rxSetupTime$ value presented in the datasheets of the IEEE 802.15.4 compliant transceivers.
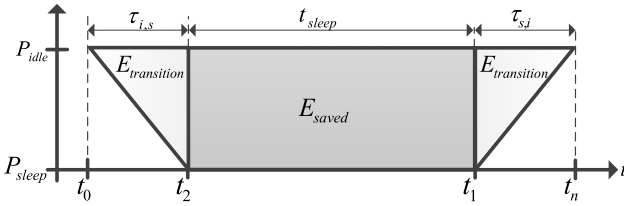

Fig. 4. Energy savings and transitions for sleep modes.

By considering different switching latency times, the expected results for the energy consumption on each state are the following:

- Every time a node performs CCA, it is in RX mode. Since CC2420 and CC2520 have the longest switching delay times, it is expected that they spend longer time in the RX mode than the AT86RF231 radio transceiver;
- CC2420 has the highest power consumption in the RX state, it is expected to have the worst performance in terms of energy consumption;
- The AT86RF231 transceiver is the one with the lowest power consumption in the RX state, so it is expected to have a better energy performance when compared with CC2420 and CC2520;
- In the TX state, the radio transceiver with the worst energy performance is the CC2520, while AT86RF231 is the one with the best performance, so it should always outperforms the CC2520 transceiver in this state;
- The switching delay times from IDLE to SLEEP and SLEEP to IDLE must be considered (this value is given by the $rxSetupTime$). Longer wake-up means longer delay but more energy is saved.
- During the SLEEP state, the radio transceiver with the worst performance is CC2520, however the impact of this state always depends on the duty cycle conditions.

III. RESULTS

To evaluate the impact of the switching delay times ($rxSetupTime$) imposed by the hardware in the network

performance we have implemented IEEE 802.15.4 for the nonbeacon-enabled mode by using the OMNeT++ component-based C++ simulation library with the MiXiM framework. We have included a RTS/CTS exchange mechanism in order to avoid the hidden terminal problem for the nonbeacon-enabled multi-hop wireless networks, which may significantly degrade their performance [10], [11]. Nodes that hear either the RTS, CTS, data or acknowledgment packet, set an internal timer called Network Allocation Vector (NAV) to the remaining duration indicated in the respective frame, and go to the sleep mode until the timer expires. This way, interference is avoided, and energy usage is improved. Table III presents the key parameters considered in our simulations.

TABLE III
SIMULATION PARAMETERS.

Parameter	Value
Channel bitrate	250 kb/s
Operating frequency	2.4 GHz
Bandwidth	2 MHz
Modulation	O-QPSK
Transmission power	0 dBm (1 mW)
Channel model	Free-space path loss
Minimum path loss coefficient	2.5
Data packet size	44 bytes
Control packet size (ACK/RTS/CTS)	11 bytes
Duty cycle	12 %
Listen Period	0.15642 s
Retransmission limit	2
Number of runs	5
Maximum simulation time	100 s
Packet inter-arrival time	from 1 to 10 s

The simulations have been performed by considering the multi-hop star topology simulation scenario presented in Fig. 3, with a duty cycle of 12%. Each source node sends 100 data packets, with a data generation interval between 1 and 10 s. Simulations have been run five times for each seed. Figure 5 shows the average energy consumption of the nodes for each packet inter-arrival time for the CC2420, CC2520 and AT86RF231 radio transceivers. The achieved 95 % confidence intervals are negligible.
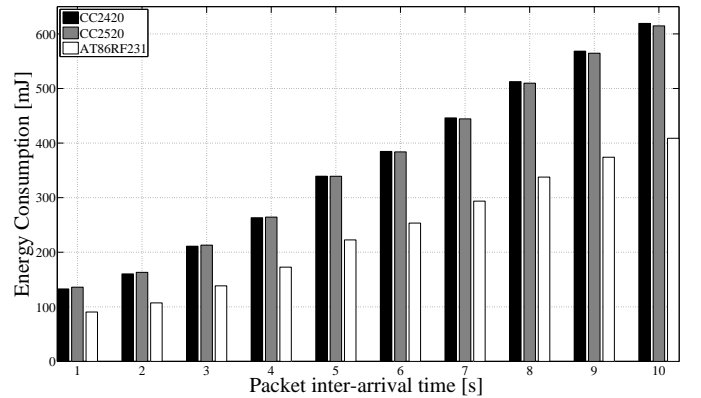

Fig. 5. Energy consumption for the CC2420, CC2520 and AT86RF231 transceivers.

As shown in Fig. 5, when the packet inter-arrival time

increases, the energy consumption of all radio transceivers also increases. The AT86RF231 transceiver has always the best performance, followed by CC2520, and by CC2420, which has the worst performance. As shown in Table I, the CC2420 and CC2520 transceivers have the same switching delay time ($rxSetupTime$), leading to a equal random deferral period of time before transmitting. Hence, in these cases the energy consumption does not depend on the direct comparison of the switching latency time, being only influenced by the power spent in the TX/RX/SLEEP states. For a packet inter-arrival time between 1 and 4 s, CC2520 has worst performance in terms of energy consumption than CC2420, since the amount of time spent in TX state is longer than the time spent in RX or SLEEP states.

For a packet inter-arrival time between 5 and 10 s, since the nodes spend more time in the RX or SLEEP states, CC2520 has always the best performance when compared with the CC2420 transceiver. The AT86RF231 transceiver spends around 3.64 times less time in the CCA procedure than CC2420 and CC2520. Besides, it has the best performance in terms of energy consumption in the RX/TX states. Since in most of the active time period the node is in the RX or TX state, the AT86RF231 has got the best results in terms of energy consumption. The energy spent on each state by CC2420, CC2520 and AT86RF231 is presented in Fig. 6. The energy spent on the SLEEP state is negligible, when compared with the RX/TX states.
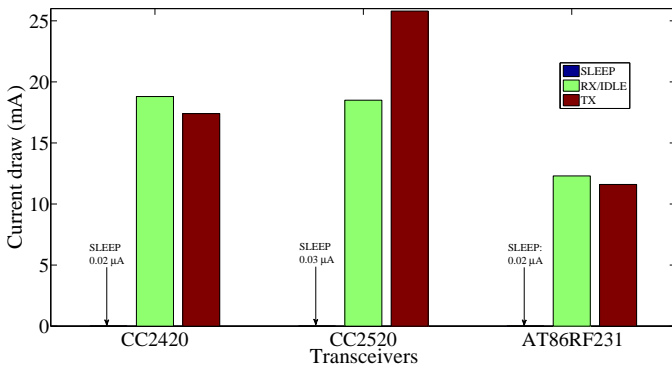

Fig. 6. Power consumption in each state for the CC2420, CC2520 and AT86RF231 transceivers.

By comparing the results for the energy consumption from Fig. 5 with the power consumption on each state, from Fig. 6, one concludes that the energy consumption mainly depends on the RX/TX states duration. Moreover, by comparing the energy profile from Fig. 4 with the ones presented in Fig. 5, we conclude that the energy spent in the switching delay times, from SLEEP to IDLE and IDLE to SLEEP, which corresponds to the $rxSetupTime$ in the datasheets of the radio transceivers impacts on the overall energy consumption

Besides, the energy consumption results for the CC2420, CC2520 and AT86RF231 transceivers from Fig. 5 have the same trend of the results presented in Fig. 6 for the RX/IDLE states. The CC2520 consumes approximately 1.5% less energy

than CC2420 in the RX/IDLE states, while the AT86RF231 transceiver consumes approximately 35% less energy than the CC2420 transceiver in the RX/IDLE states.

IV. Conclusion

In this paper, we have analyzed the influence of the switching delay times imposed by the hardware constraints of the IEEE 802.15.4 compliant radio transceivers. Three radio transceivers have been considered, operating in the 2.4 GHz band, with different switching delay times and values for the energy consumption. A star topology network in which nodes communicate using the central node as a relay, was simulated in the MiXiM framework of OMNeT++. Results show that the radio transceiver with lower switching delay time (i.e., AT86RF231) has the lowest global energy consumption, as it spends less time performing the CCA procedure. For radio transceivers with the same switching delay time (i.e., CC2420 and CC2520), for high traffic loads (i.e, packet inter-arrival time between 1 and 4 s) the one which spends less energy in the transmitting state (i.e., CC2420) has the lowest energy consumption, since this is the state more frequently used by the radio. For light traffic loads (i.e., packet inter-arrival time between 5 and 10 s), since a node spends more time in the RX or SLEEP states, CC2520 has always the best performance when compared with CC2420. The range of values for the switching delay times is not defined by the IEEE 802.15.4 standard itself but by the hardware of the radio transceiver. Since WSN are very restricted in terms of available energy, the radio transceivers with the shortest switching delay time can maximize the network lifetime whilst decreasing the time for switching between states (i.e., RX, TX and SLEEP).

References

[1] H.-P. Tsai, D.-N. Yang, and M.-S. Chen, "Mining Group Movement Patterns for Tracking Moving Objects Efficiently," *IEEE Transactions on Knowledge and Data Engineering*, vol. 23, no. 11, pp. 266–281, Feb. 2011.

[2] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung, "MAC Essentials for Wireless Sensor Networks," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 2, pp. 222–248, Second Quarter 2010.

[3] *Part 15.4: Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks*, IEEE Std. 802.15.4, Sep. 2006.

[4] "CC2420 datasheet." http://www.ti.com/lit/ds/symlink/cc2420.pdf, Apr. 2012.

[5] "OMNET++," Website, Apr. 2012, http://www.omnetpp.org/.

[6] Y. Kim and G. de Veciana, "Is rate adaptation beneficial for inter-session network coding?" *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 5, pp. 635–646, Jun. 2009.

[7] "CC2520 datasheet." http://www.ti.com/lit/ds/symlink/cc2520.pdf, Apr. 2012.

[8] "AT86RF231 datasheet." http://www.atmel.com/Images/doc8111.pdf, Apr. 2012.

[9] H.-W. Tseng, S.-H. Yang, P.-Y. Chuang, E. H.-K. Wu, and G.-H. Chen, "An Energy Consumption Analytic Model for A Wireless Sensor MAC Protocol," in *Proc. of IEEE 60th Vehicular Technology Conference*, Los Angeles, California, USA, Sep. 2004.

[10] M. T. Hansen and E. Biagioni, "BTP: a Block Transfer Protocol for Delay Tolerant Wireless Sensor Networks," in *Proc. of IEEE International Workshop on Practical Issues in Building Sensor Network Applications*, Denver, Colorado, USA, Oct. 2010.

[11] M. Sun, K. Sun, and Y. Zou, "Analysis and Improvement for 802.15.4 Multi-hop Network," in *Proc. of International Conference on Communications and Mobile Computing*, Kunming, Yunnan, China, Jan. 2009.