IEEE 802.15.4 Performance on a Hierarchical Hybrid Sensor Network Platform

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Abstract

A Wireless Sensor Network (WSN) consists of a large number of sensor nodes designed to collect information about an environment and transmit the accumulated data using a wireless technology to a base station known as Sink. In this way, the wireless technology is an important factor in the design of a sensor network. Several wireless technologies are available, but IEEE 802.15.4 is the most commonly used for WSN since this MAC protocol is designed for low data rate, short distance, and low power consumption communication applications in conformity with WSN constraints. However, the complexity of novel applications has resulted in WSN driven by two conflicting criteria which are energy consumption and delay. In this article, we study energy consumption and delay using 802.15.4 on a new generic hybrid wireless sensor network platform based on Fox board and low power sensor nodes such as Tmote Sky or Crossbow motes. We analyse different scenarios at each layer of the hybrid architecture. This paper evaluate the strengh of the antagonism between energy and delay in IEEE 802.15.4.

Keywords: wireless sensor network, IEEE 802.15.4, hierachical architecture

1 Introduction

The improvements in Micro-Electro-Mechanical Systems (MEMS) and wireless communication technologies have enabled the development of distributed autonomous devices able to sense, compute and create wireless communication: Wireless Sensor Networks [1]. This MEMS's advancement leads to a pragmatic vision of WSN which can operate in remote or hostile environments. However, the limited sensor battery power has brought up power managment as a critical point. This crucial point has fostered the development of several different platforms of wireless sensor networks with low power consumption hardwares which use, in most cases, IEEE 802.15.4 to communicate. The IEEE 802.15.4 Medium Acess Control (MAC) protocol is designed for low data rate, short distance and low power consumption communication applications in conformity with WSN constraints. In order to improve energy saving in IEEE 802.15.4, researchers explore scheduling sensor states: this technique decides which sensor may change its state (transmit, receive, idle, sleep), according to the current and anticipated communications needs.

The best known technique for saving energy is the use of sleep mode where significant parts of the sensor transceiver is switched off. However, when the transceiver is switched off, a sensor cannot communicate with its neighbor, yielding communication latency increases in the network. In the proposed wakeup schedule [2, 3], the energy saving and delay are not simultaneously considered. Consequently, focusing on the antagonistic behaviour between delay and energy saving is significant.

There exist two main kinds of sensor network applications which are demand-driven and event-driven applications. In event-driven applications such as forest fire detection or earthquake monitoring where the nodes detect an event and report it to the Sink, the delay is an important criterion. The complexity of the previous applications, in which the users could be able to estimate the strength of the fire, for example, by using multimedia is not possible with low power devices. Indeed, the requirements and the constraints of sensors, like energy management, have resulted in the design of several different platforms with low power hardware which are not adapted for complex applications. Hence, one solution is the use of hybrid platforms where the nodes of the first level detect events and the high level sensor nodes perform complex tasks.

In this paper, a new architecture with different layers of sensor nodes will be illustrated. This new structure is a hybrid platform of wireless sensor networks adapted for several areas. The hybrid wireless sensor platform presented in [4] with various sensors uses different wireless technologies for each type.

Unlike our platform, based on Fox board [5] and low power sensor nodes such as Tmote sky [6] or Crossbow motes [7] , it uses the same wireless technology at each level of the architecture to avoid interferences in the network. In general, the wireless technology used for low power sensor like Tmote sky or Crossbow motes is IEEE 802.15.4/Zigbee except for BTnode [8] which uses Bluetooth.

However, the network architecture of Bluetooth is not flexible enough to comply with the network scaling requirement of WSN. In this work, we have adapted the Fox board wireless interface to IEEE 802.15.4 and compared energy comsumption *v.s.* delay at each level of our generic hybrid architecture. This paper is organized as follows: the next section is the Related work, the description of the system is presented in the Section 3 and experimental results are given in Section 4.

2 Related work

The recent advancement in MEMS has enabled several platforms of wireless networks with different characteristics. In [9], hierarchical deployment of wireless sensor network has been defined with different types of sensing. The second level of this architecture is based on the most popular sensor platform today manufactured by Crossbow [7] such as Mica2, Telos, and MicaZ for generic sensing. The high level is based on Stargate platform for high-bandwith sensing, communications, aggregation and gateway.

The platforms MicaZ and Stargate presented above have formed a hierarchical hybrid platform for the surveillance and monitoring of an archaeological site [4]. However, in this platform, two wireless technologies are simultaneously used: IEEE 802.15.4 for both Stargate-MicaZ and MicaZ-MicaZ communications and IEEE 802.11b/WiFi for intra-Stargate backbone communications. However, using two wireless technologies simultaneously causes interferences in the network since IEEE 802.15.4, IEEE 802.11 and Bluetooth operate in the same 2.4 GHz frequency band.

In this paper, we present a new hierarchical hybrid platform using the same wireless technology at each layer of its architecture. The IEEE 802.15.4, which is generally used for low power sensor nodes, has been chosen and adapted to the flexible Fox board which is the high-level sensors of this new hybrid platform. That is why we defined this platform as a generic platform adapted for many areas.

The IEEE 802.15.4 protocol offers Medium Access Control (MAC) sublayer and the Physical Layer (PHY) specification for Low-Rate Wireless Personal Area Networks (LR-WPAN). Low rate and power consumption are the key features of Wireless Sensor Network as required by our application. Because IEEE defines only Medium Access Control (MAC) sublayer and the Physical Layer (PHY) on the standard, alliances of companies named ZigBee Alliance have specified network and application layers which formed ZigBee. This standard specifies two operational modes: the beacon-enabled and non-beacon network modes. In this work, we have focused on the beacon-enabled network mode where the communication is guaranteed by a special network communication architecture for time division multiplexing named superframe. The superframe is divided in two main portions which are active and inactive portions. Nodes interact during the active portion and enter in sleep mode to save energy during the inactive portion. The active portion is composed of Contention Access Period (CAP) and Contention Free Period (CFP). Two important values, Beacon Order (BO) and Superframe Order (SO), determined by the coordinator, control respectively the length of the superframe and the length of the Contention Access Period.

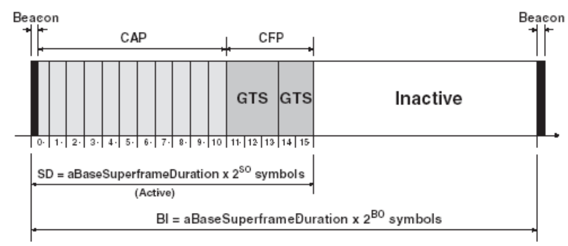

Figure 1. An example of the superframe structure [11]

In [10], the performance of IEEE 802.15.4 is evaluated by the modification of the BO value. The authors in [11] do not use the modification of the Beacon Order (BO) to increase the performance of IEEE 802.15.4 but they simulate a data fragmentation scheme for small beacon interval situations by reducing inevitable collision caused by these situations. Beyond these simulations, the evaluation has been performed analytically [10]. In this work, we experimentally evaluate IEEE 802.15.4 performance at each layer of a real hierarchical platform by modifiying the BO value using (1) and (2).

$BI = aBaseSuperframeDuration * 2^{BO}$, (1)
$SD = aBaseSuperframeDuration * 2^{SO}$, (2)
and $0 \leq SO \leq BO \leq 14$

3 System Description

In this section, we present our hybrid wireless sensor network platform based on the Tmote Sky and Fox board. The ACME Fox Board has some required features to support our sensor networks. The version of the Fox Board used is the LX 416 with 4 MB FLASH memory and 16 MB RAM.

It runs the GNU/Linux operating system on a 100 MIPS RISC CPU. The board includes two USB host interfaces to which peripherals such as webcams, Wi-Fi, Bluetooth or IEEE 802.15.4/Zigbee dongles can be connected.

The Tmote Sky is an ultra low power wireless module manufactured by Sentilla for use in sensor networks. It belongs to the family of Telos motes which are USB devices. The Tmote Sky is an IEEE 802.15.4 compliant device using the Chipcon CC2420 radio (250kbps), providing reliable wireless communication. It consists of TI MSP430 ultra low power microcontrollers, 10 kB RAM, 48 kB Flash memory, 1 MB storage and integrated Humidity, Temperature, and Light sensors. It runs the TinyOS operating system. 802.15.4 seems to be an interesting wireless technology which responds to WSN requirements. The Fox board is a generic platform and with its two USB hosts, we can adapt it to 802.15.4 by using 802.15.4/Zigbee dongle made by Silicon Labs [12]. Then, we used on the Tmote Sky an open-source implementation of the 802.15.4 protocol stack on TinyOS named Open-ZB [13]. In this way, our hybrid platform specifies three levels of genericity:

1. *Communication level*: the flexibility of the Fox board permits it to adapt to several wireless technologies,

2. *Software level*: Open-ZB which is a TinyOS implementation can adapt to several low power sensor nodes platform running TinyOS, using the same program files,

3. *Application level*: the hierarchical architecture of our platform, in which the low level sensor nodes detect events and the high level make complex tasks, permit it to adapt to severals areas.

There exist two types of devices defined on the 802.15.4 specification: the first one is the Full Function Device (FFD) which requires a lot of processing power. The other one is the Reduced Function Device (RFD) which is an extremely simple device with very modest resource requirement that can only communicate with one FFD. This previous description is in conformity with our hierarchical hybrid wireless sensor network where the Fox board will be a FFD, PAN coordinator, and the Tmote Sky, a RFD. In Fig. 2, we show our architecure with its two levels of sensors. The first one is the Tmote Sky which senses environmental data. The second one is the Fox board platform, with high power processing unit, for more complex actions.

The hierarchical hybrid platform defined here facilitates data aggregation when the Fox board receives information from the Tmote Sky and also allows efficient routing from the Fox board communication backbone to the Base station. We have designed a hybrid wireless sensor network with several levels of sensors adapted to several applications. However, because the coexistence of several wireless technologies yields network problems such as packet errors, we only used 802.15.4 at each layer of our architecture.

The dilemma is summarized as: is 802.15.4 always more advantageous than other wireless technologies ? What about the delay when energy saving increases ? We propose an analysis of the trade-off between energy consumption and delay at each level of our hybrid wireless sensor network platform.

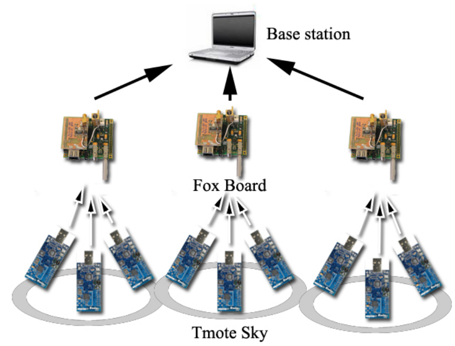

Figure 2. Hierarchical hybrid platform of a Wireless Sensor Network

4 Experimental results

In this section, we describe the results obtained during the transmission of test data using 802.15.4. We focused on energy consumption and transmission delay. We added an energy analyser on our experimental Fox board (Fig. 3) to report current energy consumption.

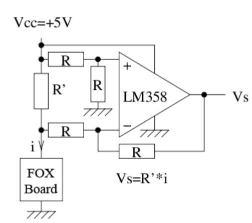

Figure 3. Energy analyser schematic

The Fig. 4 shows the energy consumption of the Fox board when it continuously sends and receives test data of 4 bytes long without any sleep period. This experiment has been done in order to estimate the energy consumption gain when we later use the sleep mode. Indeed, the procedure best known for saving energy is the sleep mode. Nevertheless, using the sleep mode during a long period of time increases the latency in the network: that is why we have decided to observe energy consumption within very short inactive period. Fig. 5 shows the energy consumption of the Fox board with a short inactive period. We adjust the beacon order (BO) to 6 and the superframe order SO to 4.

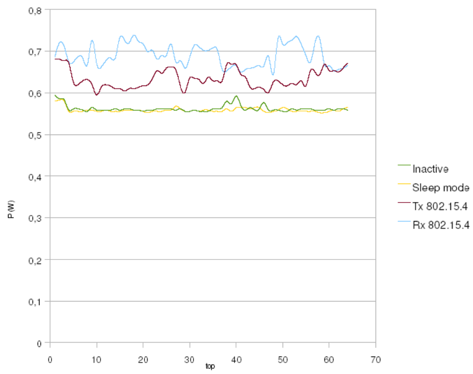

Figure 4. Energy consumption of Fox board in active mode

In applying equations (1) and (2), we can determine the inactive period (BI-SD) of the Fox board which is about 0.73 s.

In this graph, we compare 802.15.4 and Bluetooth energy consumption when the Fox board continuously receives data streams of 4 bytes from the Tmote Sky, as well as a laptop using respectively, 802.15.4 and Bluetooth. We have used the first level of genericity of our platform to adapt the Fox board to Bluetooth.

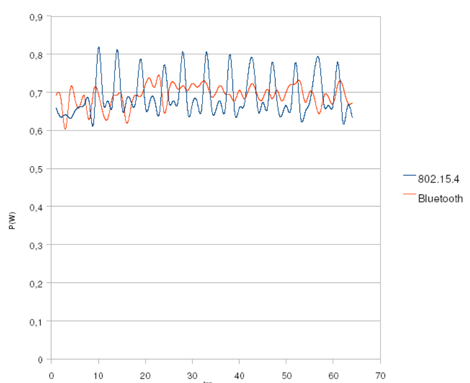

Figure 5. Energy consumption of Fox board with a short inactive period of 0.73 s

The comparison between Bluetooth and 802.15.4 energy consumption (Fig. 5) shows that Bluetooth consumption is constant of about 0.7 W, while IEEE 802.15.4 uses more energy with powerful peaks about 0.8 W to rapidly go down (about 0.6 W). The average energy consumption between the two wireless technologies used in this experiment is the same of about 0.7 W.

These results show that continuous data stream transmission using 802.15.4 is not better than Bluetooth. We can conclude that it is not only by choosing 802.15.4 wireless technology that energy is saved, but also the way the different modes are used. Indeed, energy consumption without any sleep period (Fig. 4) has no powerful peaks from 0.6 W to 0.8 W (Fig. 5). 802.15.4 devices need to be on sleep mode most of the time to save energy. However, the wakeup scheme is very important. In this experiment we have continuously changed the sleep mode to active mode with a very short inactive period.

Considering these results in which the inactivity period is very short with no energy gain compared to Bluetooth, we increase the sleep period and observe the variation of the energy and the delay. These previous experiments emphasize the importance of the sleep mode in 802.15.4. In the next part of our experiment, we used the second level of genericity of our generic hybrid platform on one hand to validate the second level of genericity of our platform, and on the other hand because it is easier to plug an energy analyser on MicaZ because of its hardware architecture. MicaZ, which is manufacured by Crowsbow, is based on Atmel AVR microcontroller and uses the same Chipcon CC2420 transceiver, compliant with 802.15.4.

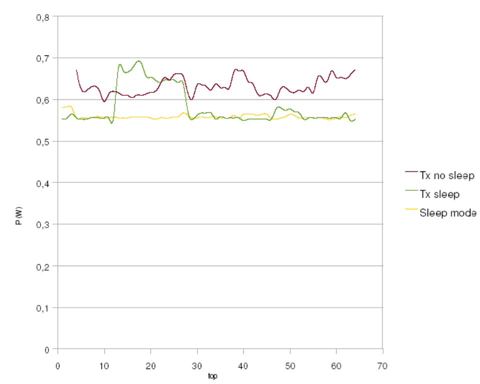

Figure 6. Energy consumption of the Fox board with inactive period of 1,7 s

In this way, we compare on Fig. 6 and Fig. 7 respectively, the Fox board and MicaZ energy consumption gain with an inactive period during transmission of a test data set of 4 bytes. We have adjusted BO to 7 and SO to 4 on the Fox board and on micaZ. In applying (1) and (2), we obtain an inactive period of 1.7 s. The variation of energy is the same on both platforms. The transmission without sleep mode is constant while the transmission with sleep mode has a peak and goes back.

The consumption of Fox board without sleep mode is about 0.65 W while the consumption with inactive period of 1.7 s is about 0.6 W (Fig. 6): the 0.05 W gain represents an improvement of 8% compared to continuous transmission without sleep mode. The consumption of micaZ without sleep mode is about 9.93 mW while the consumption with an inactive period is about 9.43 mW (Fig. 7): the 0.5 mW gain represent 5%.

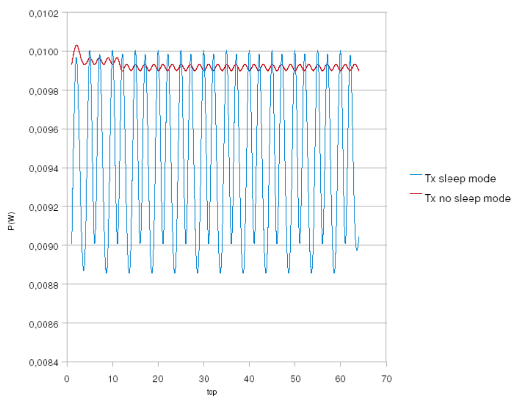

Figure 7. Energy consumption of MicaZ with inactive period of 1.7 s

We notice that there is a great difference of energy consumption between Fox board and micaZ mote. For example when the Fox board and the MicaZ mote are continuously on active mode, the Fox consumption is about 0.65 W while the mote consumption is about 9.93 mW. The difference is about 0.64W. In this way, the mote uses less than 2% of the power consumption of the Fox board for the same activity. For the same sleep period, the energy saving gain of the Fox board is 8% while for the mote it is 5%. The sleep period of 1.7 s is 3% more beneficial for the Fox board than the mote.

As described above, during data transmission of Fox board and MicaZ, we have also focused on transmission delay to study the compromise between energy saving and delay in 802.15.4. Fig. 8 and Fig. 9 show the delay obtained during data transmission with sleep period and without sleep period. Results show that the Fox needs about 15.6 ms to transmit data without inactive period and about 1967 ms for 1.7 s of inactivity. The difference is 1951 ms.

MicaZ uses about 18.6 ms to transmit data without inactive period and about 2139 ms for 1.7 s of inactivity. The difference is 2120 ms. The comparison between Fox and MicaZ shows that on active mode, both need almost the same time to transmit data. Fig. 9 shows that the Fox wakes up and transmits data more quickly than the mote: we notice a difference of about 172 ms between Fox delay and MicaZ delay. The Fox needs 1.96 s for transmiting data during an inactive period of 1.7 s while MicaZ needs 2.13 s. This means that the Fox uses 0.26 s (1.96 - 1.7) to wake up and transmit data while MicaZ uses 0.43 s (2.13 - 1.7). The Fox wakes up faster than the MicaZ after a sleep period.

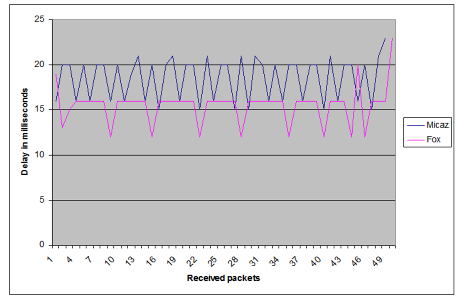

Figure 8. Delay of Fox board and MicaZ without sleep period

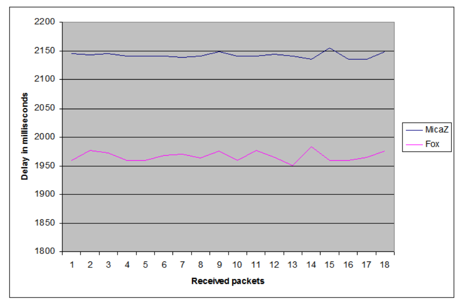

Figure 9. Delay of Fox board and MicaZ with sleep period

For this small number of tests employed, named energy and delay, the Fox board is a clear winner. However, as illustrated on Fig. 10, energy consumption difference between Fox board and mote is very great. Histograms on Fig. 10 and Fig. 11 show the trade-off between energy consumption and delay. We notice that when the energy consumption decreases slowly (Fig. 10), the delay increases very quickly (Fig. 11). As illustrated on Fig. 10, we also note that there is a great difference between the energy consumption of the high level sensor platform and the low level of our architecture.

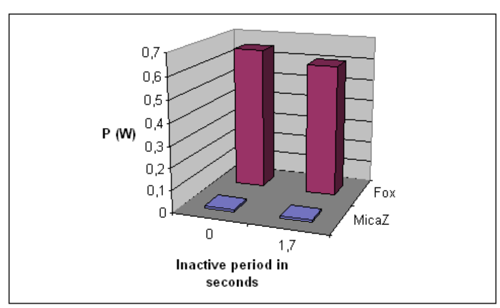

Figure 10. Histogram of Energy consumption

However, Fig. 11 shows that, while the high level sensor platform uses more power, it needs less time to wake up and to transmit data.

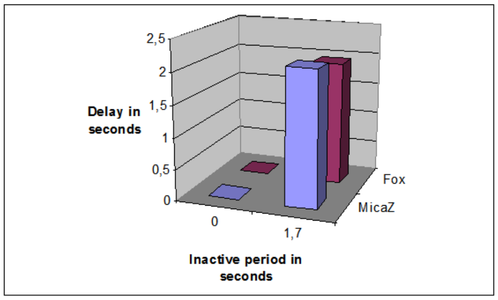

Figure 11. Histogram of Delay

As mentioned above, a trade-off between energy consumption of platforms and performance such as delay also exists. The difference in the variation of energy consumption and delay that varies much more quickly, makes the discovery of an optimal point between energy consumption and delay difficult.

5 Conclusion and Future Work

In this paper, we have shown a new hybrid wireless sensor network platform with three levels of genericity which permits its adaptation to many applications. This hierarchical architecture describes two levels of sensors. The high-level is based on a new high power sensor node named Fox Board platform, while the Tmote Sky or Crossbow motes platform are low-level sensor nodes.

Because of its characteristics, the IEEE 802.15.4 protocol has been chosen to ensure the communication between nodes at each level of our hybrid platform. We have focused on energy, plus delay variation at each level of our hybrid WSN.

Experimental results on realistic and pratical way show that while the energy consumption at each level of our platform decreases by the use of sleep mode, the latency in the network increases. The results obtained for a short inactive period of 0.73 s give no energy consumption gain in average compared to Bluetooth: this shows the importance of wake-up schemes in IEEE 802.15.4. Using a sleep period of 1.7 s, we notice that the Fox board saves 8% of its energy while low power sensor node, MicaZ, saves 5% of its energy. These results also show that MicaZ needs more time than the Fox board to wake up and transmit data after an inactive period.

We note that for a very little energy consumption gain about 8% and 5% respectively for the Fox board and MicaZ, the delay between two messages increases by 1951 ms for the Fox and 2120 ms for the micaZ. The interaction of the Fox board with the sleep mode is better than MicaZ, even if MicaZ's energy consumption represents only 2% of Fox's energy consumption.

Consequently, we can conclude that it is important to consider energy and delay in WSN applications, since these two antagonistic criteria influence each other. This paper has demonstrated the difficulty in simultaneously considering energy consumption and delay in wireless sensor networks which use IEEE 802.15.4 as a wireless technology.

Future work will focus on finding a wakeup scheme which will give an optimal point between energy consumption and delay.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks*, 38(4):393–422, 2002.

[2] M. Nosovic and T. Todd. Low power rendezvous and rfid wakeup for embedded wireless networks. In *In Annual IEEE Computer Communications Workshop*, pages 3325–3329, 2000.

[3] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava. Topology management for sensor networks: Exploiting latency and density. In *In Proceedings of The Third ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pages 135–145, 2002.

[4] E. Ardizzone, M. L. Cascia, G. L. Re, and M. Ortolani. An integrated architecture for surveillance and monitoring in an archaeological site. In *VSSN '05: Proceedings of the third ACM international workshop on Video surveillance & sensor networks*, pages 79–86, New York, NY, USA, 2005.

[5] The Acme Systems website. Available: http://www.acmesystems.it.

[6] (2007-2009) The Sentilla Corporation website. [Online]. Available: http://www.sentilla.com/

[7] (2008) The Crossbow website. [Online]. Available: http://www.xbow.com

[8] J. Beutel, O. Kasten, F. Mattern, K. Römer, F. Siegemund, and L. Thiele. Prototyping wireless sensor network applications with btnodes. In *EWSN*, pages 323–338, 2004.

[9] J. L. Hill, M. Horton, R. Kling, and L. Krishnamurthy. The platforms enabling wireless sensor networks. *Commun. ACM*, 47(6):41–46, 2004.

[10] M. Neugebauer, J. Plonnigs, and K. Kabitzsch. A new beacon order adaptation algorithm for ieee 802.15.4 networks. *Wireless Sensor Networks, 2005. Proceeedings of the Second European Workshop on*, pages 302–311, 2005.

[11] J. Yoon, H. Kim, and J.-G. Ko. Data fragmentation scheme in ieee 802.15.4 wireless sensor networks. In *VTC Spring*, pages 26–30, 2007.

[12] (2008) The Silicon Labs Home. [Online]. Available: https://www.silabs.com.

[13] A. Cunha, A. Koubaa, R. Severino, and M. Alves. Open-zb: an open-source implementation of the ieee 802.15.4/zigbee protocol stack on tinyos. *Mobile Adhoc and Sensor Systems, 2007. MASS 2007. IEEE Internatonal Conference on*, pages 1–12, Oct. 2007.