IEEE 802.15.4: a wireless communication technology for large-scale ubiquitous computing applications

Anis Koubâa, Mario Alves, Eduardo Tovar

PP-HURRAY! Research Group, Polytechnic Institute of Porto
Rua Dr. Antonio Bernardino de Almeida, 431, 4200-072 Porto, PORTUGAL
{akoubaa, emt}@dei.isep.ipp.pt, mjf@isep.ipp.pt

Abstract. Wireless Sensor Networks (WSNs) have been attracting increasing interest for supporting a new generation of ubiquitous computing systems with great potential for many applications such as surveillance, environmental monitoring, health care monitoring or home automation. However, the communication paradigms in WSNs differ from the ones associated to traditional wireless networks, triggering the need for new communication protocols. In this context, the IEEE 802.15.4 protocol presents some potentially interesting features for supporting large-scale ubiquitous computing applications, namely power-efficiency, timeliness and scalability. Nevertheless, when addressing applications with (soft/hard) timing requirements some inherent paradoxes emerge, such as power-efficiency versus timeliness. Consequently, there is the need of engineering solutions for an efficient deployment of IEEE 802.15.4 in such scenarios. In this paper, we present some of the most important results on the IEEE 802.15.4 protocol that have been achieved within the context of wireless sensor networks. The paper outlines the most relevant characteristics of the IEEE 802.15.4 protocol and presents the most important research challenges regarding time-sensitive WSN-based applications. Then, it presents some timing performance analysis that unveils some directions for resolving the previously mentioned paradoxes.

1. Introduction

Wireless Sensor Networks (WSNs) have revolutionized the design of emerging embedded systems and triggered a new set of potential applications. This particular form of distributed and ubiquitous computing raises many challenges in terms of real-time communication and coordination due to the large number of constraints that must be simultaneously satisfied, including limited power, CPU speed, storage capacity and bandwidth. These constraints trigger the need for new paradigms in terms of node/sensor design and network communication/coordination mechanisms. The design of wireless sensor networks is mainly concerned with power-efficiency issues, due to the severe limitation in terms of energy consumption (Aykildiz *et al.* 2002; Stankovic *et al.* 2003). However, the design complexity is even more significant when applications have, in addition, real-time and/or scalability requirements (Stankovic *et al.* 2003).

Several research initiatives, aiming at providing different design solutions for WSNs protocols, have recently emerged (Lu *et al.* 2002; Bandyopadhyay and Coyle 2003; He *et* *al*. 2003; Ye *et al.* 2004; Bacco *et al.* 2004). However, we believe that the use of standard technologies pushed forward by commercial manufacturers can speed-up a wider utilization of WSNs. In this context, the IEEE 802.15.4 protocol (IEEE 802.15.4 Standard 2003), recently adopted as a communication standard for Low-Rate Wireless Local Area Networks (LR-WPANs), shows up itself as a potential candidate for such a deployment. This protocol provides enough flexibility for fitting different requirements of WSN applications by adequately tuning its parameters, even though it was not specifically designed for WSNs. In fact, low-rate, low-power consumption and low-cost wireless networking are the key features of the IEEE 802.15.4 protocol, which typically fit the requirements of WSNs. Moreover, the ZigBee specification (ZigBee Alliance 2005) relies on the IEEE 802.15.4 Physical and Data Link Layers, building up the Network and Application Layer, thus defining a full protocol stack for LR-WPANs (refer to Section 2.1).

More specifically, the IEEE 802.15.4 Medium Access Control (MAC) protocol has the ability to provide very low duty cycles (from 100% to 0.1 %), which is particularly interesting for WSN applications, where energy consumption and network lifetime are main concerns. Additionally, the IEEE 802.15.4 protocol may also provide timeliness guarantees by using the Guaranteed-Time Slot (GTS) mechanism, which is quite attractive for time-sensitive WSNs. In fact, when operating in beacon-enabled mode, i.e. beacon frames are transmitted periodically by a central node called the *PAN Coordinator* for synchronizing the network, the IEEE 802.15.4 protocol allows the allocation/deallocation of GTSs in a superframe for applications with real-time constraints. Hence, the GTS mechanism provides a minimum service guarantee for the corresponding nodes, thus enabling the prediction of the worst-case performance for each node's application.

In this paper, we describe the most important features of the IEEE 802.15.4 protocol that are relevant for WSNs and we discuss the ability of this protocol to fulfill the different requirements of WSNs and to resolve inherent paradoxes involving power-efficiency and timeliness guarantees.

2. Overview of the IEEE 802.15.4 protocol

2.1. Physical Layer (PHY)

IEEE 802.15.4 offers three operational frequency bands: 2.4 GHz, 915 MHz and 868 MHz. There is a single channel between 868 and 868.6 MHz, 10 channels between 902 and 928 MHz, and 16 channels between 2.4 and 2.4835 GHz.

The data rates are 250 kbps at 2.4 GHz, 40 kbps at 915 MHZ and 20 kbps at 868 MHz. Lower frequencies are more suitable for longer transmission ranges due to lower propagation losses. However, the advantage of high data rate transmission is the provision of higher throughput, lower latency or lower duty cycles. All these frequency bands are based on the *Direct Sequence Spread Spectrum* (DSSS) spreading technique.

IEEE 802.15.4/IEEE 802.11b coexistence problem. The deployment of IEEE 802.15.4 WPANs in the presence IEEE 802.11b WLANs (IEEE 802.11 Specification 1999) triggers some inherent problems since they both operate in the 2.4 GHz frequency band. Coexistence between both technologies has become an important issue after the proposal of the IEEE 802.15.4 standard and has been subject of recent research works. In (Howitt and Gutierrez 2003), the authors analyzed the impact of an IEEE 802.15.4 network composed of several clusters on an IEEE 802.11b station communicating with a WLAN access point. An expression of the probability of an IEEE 802.11b packet collision due to the interference with IEEE 802.15.4 has been proposed. The authors conclude that the IEEE 802.15.4 network has little to no impact on the performance of IEEE 802.11b, unless the IEEE 802.11b station is very close to an IEEE 802.15.4 cluster with high activity level. A later work in (Shin *et al.* 2005) analyzed the packet error rate of IEEE 802.15.4 WPANs under the interference of IEEE 802.11b WLAN and proposed some coexistence criteria for both standards. The results of this work show that the interference caused by the IEEE 802.11b WLAN does not affect the performance of an IEEE 802.15.4 WPAN if the distance between the IEEE 802.15.4 nodes and the IEEE 802.11b WLAN is larger than 8 m. Moreover, if the frequency offset is larger than 7 MHz, the interference of IEEE 802.11b has negligible effect on the performance of the IEEE 802.15.4. Another experimental work by Crossbow Tech. (Crossbow Tech. 2005) considered a set of three experiments using the MICAz motes, which implement the physical layer of the IEEE 802.15.4 and the Stargate single board computer compliant with IEEE 802.11b. The first experiment run with no WiFi interference and the other experiments run under IEEE 802.11 interference with two different power levels (standard level and 23 dBm). The packet delivery rate was analyzed. The experiment shows that high power transmissions of IEEE 802.11b packet reduce the packet delivery rate up to 80% for 23 dBm Wifi cards.

In general, these results state that the coexistence of both IEEE 802.15.4 and IEEE 802.11b networks is generally possible with an acceptable performance, when nodes are not in a close proximity of each other and channels are adequately selected to prevent overlapping.

2.2. Medium Access Control Sub-Layer

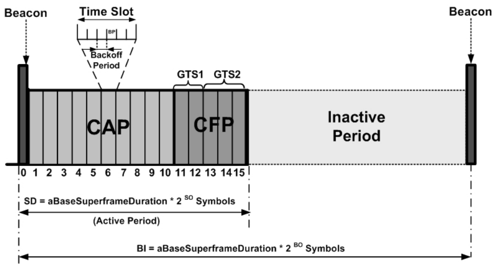
The MAC protocol supports two operational modes that may be selected by the PAN Coordinator, the master node that creates and manages the WPAN.

- The *non beacon-enabled mode*, in which MAC is simply ruled by non-slotted CSMA/CA.
- The *beacon-enabled mode*, in which beacons are periodically sent by the PAN Coordinator to synchronize nodes that are associated with it, and to identify the PAN.

Due to its importance in the context of this paper, we address next the main characteristics of the beacon-enabled operational mode.

In beacon-enabled mode, beacon frames are periodically sent by the PAN Coordinator to identify its PAN and synchronize nodes that are associated with it. The *Beacon Interval* (BI) defines the time between two consecutive beacon frames. It includes an active period and, optionally, an inactive period (Fig. 1). The active period, called *superframe*, is divided into 16 equally-sized time slots, during which frame transmissions are allowed. During the inactive period (if it exists), all nodes may enter into a sleep mode, thus saving energy. The Beacon Interval and the *Superframe Duration* (*SD*) are determined by two parameters, the *Beacon Order* (*BO*) and the *Superframe Order* (*SO*), respectively. The Beacon Interval is defined as follows:

$$BI = aBaseSuperframeDuration \cdot 2^{BO}, \quad for\ 0 \le BO \le 14 \qquad \textbf{(1)}$$



The Superframe Duration, which corresponds to the active period, is defined as follows:

$$SD = aBaseSuperframeDuration \cdot 2^{SO}, \quad for\ 0 \le SO \le BO \le 14 \qquad \textbf{(2)}$$

In Eqs.(1) and (2), *aBaseSuperframeDuration* denotes the minimum duration of the superframe, corresponding to $SO = 0$.

By default, nodes compete for medium access using slotted CSMA/CA during the *Contention Access Period* (CAP). A node computes its backoff delay based on a random number of backoff periods, and performs two CCAs before transmitting. The IEEE 802.15.4 protocol also offers the possibility of defining a *Contention-Free Period* (CFP) within the superframe (Fig. 1). The CFP, being optional, is activated upon request from a node to the PAN Coordinator for allocating *Guaranteed Time Slots* (GTS) depending on the node's requirements.

In this paper, we present some results on the performance of the GTS allocation mechanism and slotted CSMA/CA and discuss their adequacy for WSNs.

3. IEEE 802.15.4 for time-sensitive WSN applications

3.1. Tackling the power/timing efficiency paradox

With the emergence of new WSN applications under reliability and timing constraints, the provision of real-time guarantees may be more crucial than saving energy during critical situations. The IEEE 802.15.4 protocol presents the advantage to fit different requirements of potential applications by adequately setting its parameters. Real-time guarantees can be achieved by using the GTS mechanism in beacon-enabled mode. The allocation of a GTS by a node provides it with a minimum service guarantee, enabling the prediction of the worst-case timing performance of the network. On the other hand, power-efficiency can be achieved by operating at low duty cycles (down to 0.1%). However, power-efficiency and timeliness guarantees are often two antagonistic requirements in wireless sensor networks.

This issue has been addressed in (Koubâa *et al.* 2006a). The authors have analyzed and proposed a methodology for setting the relevant parameters of IEEE 802.15.4-compliant WSNs taking into account an optimal trade-off between power-efficiency and delay bound guarantees. To tackle this challenge, the authors have proposed an accurate model of the service curve provided by a GTS allocation as a function of the IEEE 802.15.4 parameters, using Network Calculus formalism. They then evaluated the delay bound guaranteed by a GTS allocation and expressed it as a function of the duty cycle. Based on the relation between the delay requirement and the duty cycle, the paper proposed a power-efficient superframe selection method that simultaneously reduces power consumption and enables meeting the delay requirements of real-time flows allocating GTSs. In what follows, we present the most relevant results presented in (Koubâa *et al.* 2006a) for showing a potential solution of the power/timing efficiency paradox.

The main challenge is the following. *Given a set of data flows within an IEEE 802.15.4 cluster, where each data flow has a delay requirement D, what is the most efficient network setting (BO and SO pair) that satisfies the delay requirement of each data flow, allocating one time slot GTS, and minimizes the energy consumption?*

An IEEE 802.15.4 cluster with a unique PAN Coordinator, and a set of nodes within its radio coverage have been considered. The network operates in beacon-enabled mode, thus the PAN Coordinator periodically sends beacon frames. The Beacon Interval (*BI*) and the Superframe Duration (*SD*) are defined by Eq. (1) and Eq. (2), respectively. *Ts* is the duration of the time slot equal to *SD*/16. *C* denotes the total data rate of the channel. In our case, the data rate is fixed to $C = 250$ kbps. It is also assumed that each node generates a data flow that has a cumulative arrival function $R(t)$ upper bounded by the linear arrival curve $\alpha(t) = b + r.t$, with b denoting the maximum burst size, and r denoting the average arrival rate.

It has been shown that the delay bound experienced by a data flow with an arrival curve $\alpha(t) = b + r.t$, which has allocated one time slot GTS, is computed as follows:

$$D_{\max} = \frac{b}{\frac{T_{data}}{BI} \cdot C} + \left(BI - Ts\right) \qquad \textbf{(3)}$$

with T_{data} is the portion of time into a time slot effectively used for data transmission (without overheads like acknowledgement frames and Inter-Frame Spacing). As a result, based on Eqs. (1), (2) and (3), it has been shown that the duty cycle can be expressed as a function of the delay requirement as follows:

$$DC = 2^{IO} = \frac{SD}{BI} \quad \textbf{where} \quad IO = \left\lfloor \log_2\left(\frac{SD}{D - \lambda \cdot SD} \cdot \left(\frac{b}{T_{data} \cdot C} + 1 \right) \right) + 1 \right\rfloor \qquad \textbf{(4)}$$

where $\lambda = 1/16$ and D is the delay requirement of the flow.

Based on the aforementioned analysis, it is possible to evaluate the performance of a GTS allocation and capture the energy/delay trade-off.

Our problem is to evaluate the impact of the delay bound on the duty cycle for a given superframe order *SO* and a given burst *b*. Fig. 2 shows the variation of the duty cycle as a function of the delay bound for different values of *SO*. The burst size is equal to 200 bits.

Observe in Fig. 2 that decreasing the delay requirement does not automatically increase the duty cycle. For instance, delay values in the range of [600, 1000] ms have the same 6.25% duty cycle for $SO = 0$. This fact is due to the slotted behavior of the superframe structure defined in Eqs. (1) and (2). Hence, in some cases, relaxing the delay requirement will not automatically lead to a lower duty cycle for some IEEE 802.15.4 superframes. It is also observed from Fig. 2 that the number of possible superframe structure configurations (alternatives for *BO* and *SO*) increases with the delay. Hence, for low delay requirements, only the lower superframe orders (*for low burst size*) can meet these delay bounds, if it is possible, due to the increased latency for large *SO* values.

Another interesting problem is to determine the adequate superframe order reducing the duty cycle and still meeting a delay bound *D* for a given burst *b*. Fig. 3 shows the variation of the duty cycle as a function of the superframe order for different values of the burst size. The delay bound requirement is assumed to be 3 seconds.

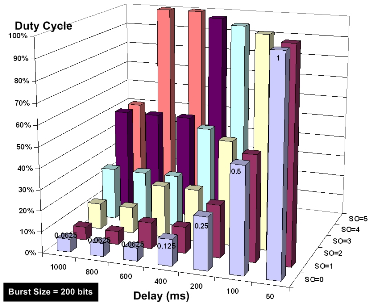


Fig. 2. Duty cycle versus delay bound

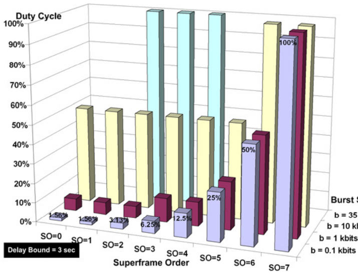


Fig. 3. Duty cycle versus superframe order

Observe that for relatively low burst sizes (0.1 kbits, 1 kbits) the minimum duty cycle required to satisfy the delay bound increases with the superframe order. For a burst size equal to 10 kbits, there is no advantage of using low superframe orders for $SO \in \{0, 1, 2, 3, 4\}$. The duty cycle remains the same, since lower superframe orders have lower latencies, whereas higher superframe orders provide higher guaranteed bandwidths due to the effect on the overheads (inter-frame spacing) for lower *SO* values. However, for a burst size $b = 35$ kbps, only superframe orders $SO \in \{2, 3, 4\}$ can satisfy the delay bound of 3 s, with a full duty cycle. This is because the guaranteed bandwidth has the most significant impact on the delay bound.

3.2. Performance limits of the slotted CSMA/CA mechanism

The performance of the slotted CSMA/CA mechanism in IEEE 802.15.4 was recently evaluated using discrete time Markov chain models (Mišic and Mišic 2005a, Mišic *et al.* 2005b, Park *et al.* 2005, Pollin *et al.* 2005). Those works provided analytic models of the slotted CSMA/CA mechanism in both saturation and non saturation modes, and also provided steady state solutions. These analytical models are interesting for capturing the behavior of the protocol in terms of throughput and access delays.

In (Koubâa *et al.* 2006b), the authors have evaluated the performance of slotted CSMA/CA using simulations. It also presents results without doing restrictive assumptions and taking into account some realistic features of the physical layer (propagation delays, fading, noise effect, etc.).

In (Koubâa *et al.* 2006b), it has been considered a typical wireless sensor network in a (100 m x 100 m) surface with one PAN Coordinator and 100 identical nodes (randomly spread) generating Poisson distributed arrivals, with the same mean arrival rate. Note that the Poisson distribution is typically adopted by most simulation and analytical studies on CSMA/CA. The frame size is equal to 404 bits corresponding to 300 bits of data payload and 104 bits of the MAC header according to the standard.

The PAN Coordinator periodically generates beacon frames according to the *BO* and *SO* parameters. Unless it is mentioned differently, *BO* and *SO* are both equal to 3. In this study the authors considered unacknowledged transmissions, since WSNs typically use broadcast transmissions which do not use acknowledgements. In order to focus on the performance analysis of the slotted CSMA/CA algorithm, it is assumed that the network is fully connected, i.e. all nodes hear each other (no hidden-node problem).

In this simulation study, two performance metrics was considered: (1) The ***Network Throughput*** (*S*) is the fraction of traffic correctly received by the network analyzer (a device in promiscuous mode hearing all the traffic in the network) normalized to the overall capacity of the network (250 kbps). (2) The ***Average delay*** (*D*) is the average delay experienced by a data frame from the start of its generation by the application layer to the end of its reception by the analyzer.

First, Figs. 4 and 5 present the impact of *BO* and *SO* values on the network throughput and the average delay, respectively. Observe that, as expected, low *SO* values produce lower network throughput. This is basically due to two factors. First, the overhead of the beacon frame is more significant for lower *SO* values, since beacons are more frequent. Second, CCA deference is also more frequent with lower *SO* values, leading to more collisions at the start of each superframe.

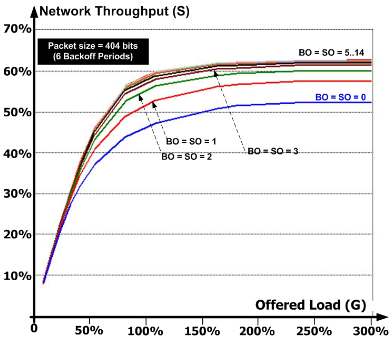


Fig. 4. The network throughput as a function of the offered load for different (BO, SO) values

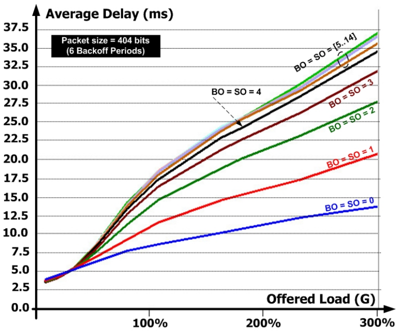


Fig. 5. The average delay as a function of the offered load for different (BO, SO) values

Note that the increase in the superframe order, from *SO* equal to 5 until 14, has a reduced impact on the network throughput. In fact, for high *SO* values (≥ 5), the probability of deference is quite low, which reduces the amount of collisions due to simultaneous CCA deference in multiple nodes, and thus leads to higher network throughputs.

Fig. 5 shows that the average delays significantly increase with *SO* for a given offered load *G* higher than 50 %, as explained next. In fact, for low *SO* values, the high probability of CCA deference results in having more frequent collisions of data frames at the beginning of a new superframe. Hence, the backoff delays will not increase too much due to this frequent collision in case of low superframe orders. However, for high superframe orders the backoff algorithm will be less exposed to this problem, and then nodes will go into additional and higher backoff delays, since the backoff exponent is increased each time the channel is sensed as busy.

Second, Figs. 6 and 7 present the impact of the initialization value of the backoff exponent *macMinBE* on the network throughput and on the average delay, respectively.

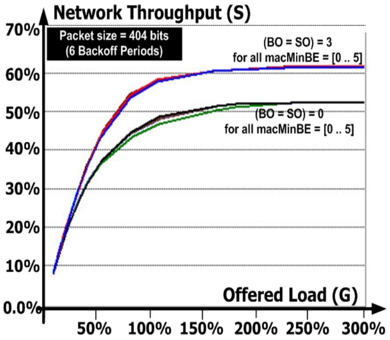


Fig. 6. The network throughput as a function of the offered load for different *macMinBE* values

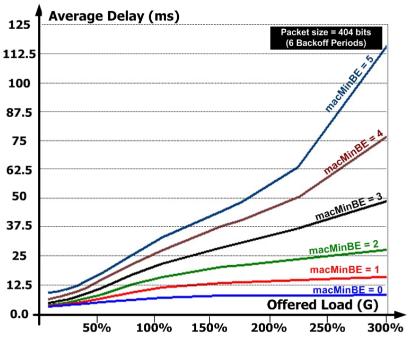


Fig. 7. The average delay as a function of the offered load for different *macMinBE* values

Intuitively, it could be expected that the network throughput would be improved with higher *macMinBE* since the backoff interval would be larger. However, this is not the case in this example. This result is due to the backoff algorithm behavior of slotted CSMA/CA. In fact, for a given *macMinBE*, the interval from which the backoff delay is randomly generated at the first iteration is [0, $2^{macMinBE}$ -1]. Independently from *macMinBE*, the lower limit of the backoff delay interval is always 0 while the upper limit will be incremented each time the channel is sensed busy. Since the number of nodes is high (100 nodes), the probability that a medium is busy is also high, which leads to increasing *BE* for improved collision avoidance in the next iterations. *BE* cannot exceed *aMaxBE* = 5 and this value is reached by the competing nodes at most after 5 transmissions from other nodes. Thus, the backoff interval will tend to [0, 31] in all remaining nodes waiting for medium access and, as a result, the backoff delay distribution will not depend too much on the initialization value of *macMinBE*.

On the other hand, observe that the average delay increases with *macMinBE* for a given offered load (Fig. 7). Lower *macMinBE* values provide lower average delays with the same network throughputs. This is because the average backoff delays are higher for large [0, 2^{BE} -1] intervals. Observe that for low offered loads ($G < 50$ %), the variance of the average delays for different *macMinBE* is not significant (around 10 ms from *macMinBE* from 0 to 5). However, for high offered loads $G \geq 50$ %, the impact of *macMinBE* is significantly more visible. For instance, for $G = 300\%$, the average delay is higher than 110 ms for *macMinBE* = 5, whereas it is does not exceed 8 ms in case of *macMinBE* = 0.

4. Research trends and challenges of the IEEE 802.15.4 protocol

Since its proposal in 2003, the IEEE 802.15.4 protocol has been attracting more and more research work envisaging its deployment in wireless sensor networks. It is expected that many commercial manufacturers of wireless sensor technologies will shift towards this standard solution due to its low-cost and improved performance. However, there are still some challenges that must be addressed to tune this COTS technology for WSN applications. In this section, we present some hints on potential research trends and future challenges for the use of IEEE 802.15.4 in wireless sensor networks.

One of the challenges is the deployment of the beacon-enabled mode in a multi-hop network with several Coordinators. The main problem is to find adequate synchronization schemes for different Coordinators in the same range, to avoid beacon collisions. In such kind of networks, beacon frames of a given Coordinator may collide with beacon frames of other Coordinators (which lead to permanent collisions) or data/control frames (which lead to occasional collisions). Losing beacon frames will lead to synchronization failures of associated nodes in the network. This problem was analyzed in (Ha *et al.* 2005), where the authors derived the probability of beacon frame collisions with other beacons, and the probability of beacon frame collisions with data/control frames. The analytical results and experiments show that, when the starting time of the first beacon frame generated by each Coordinator is uniformly distributed, multi-hop beacon enabled networks are feasible for *BO* values higher than 1, and for evenly distributed Coordinators. In such conditions, they show that synchronization failures may be less that 1%. An interesting extension of this work is to propose improved synchronization schemes for several Coordinators operating with beacon orders equal to 0 and 1, since these modes provides better performances in terms of delay guarantees, as it has been shown in Section 3.3. In addition, it is important to propose a deterministic synchronization scheme that ensures that no collisions will disturb beacon frame transmissions to achieve 0 % of synchronization failure.

Another open issue is to resolve the hidden-node problem in IEEE 802.15.4, since its MAC protocol does not use any RTS/CTS mechanism. This problem may be serious in large-scale wireless sensor networks, which typically use broadcast transmissions to disseminate data. In such conditions, the hidden-node problem would have a negative impact on the network throughput. This issue was addressed in (Hwang *et al.* 2005), in which the authors proposed a grouping strategy to solve the IEEE 802.15.4 hidden-node problem without using the RTS/CTS mechanism. This strategy groups nodes according to their hidden-node relationship such that all nodes in each group are not hidden to each other. Then, this technique allocates guaranteed time slots to each group, in which slotted CSMA/CA is used by different nodes in the group to access the channel. The PAN Coordinator is in charge of detecting the hidden-node situation and performing grouping procedure if necessary. An open problem is to resolve the hidden-node problem for multi-hop cluster-tree networks defined by the Zigbee protocol.

Concerning time-sensitive sensor networks, the improvement of the GTS mechanism is still an open issue. In fact, the protocol only supports explicit GTS allocations, i.e. a node allocates a number of time slots in each superframe for exclusive use. The limitation of the explicit GTS allocation is that GTS resources may quickly disappear, since a maximum of seven GTSs can be allocated in each superframe, preventing other nodes to benefit from guaranteed service. Moreover, the GTSs may be only partially used, resulting in a wasted bandwidth. To overcome this limitation, one possible solution is to share the same GTS between multiple nodes, instead of being exclusively dedicated to one node, if a certain schedule that satisfies the requirements of all requesting nodes exists. Sharing a GTS by several nodes means that the time slots of this GTS are dynamically allocated to different nodes in each superframe, according to a given schedule.

Another important issue regarding the deployment of IEEE 802.15.4 is the adequacy of the Zigbee routing layer for WSN applications. In fact, the IEEE 802.15.4 protocol is intended to operate on the bottom of the Zigbee network/application stack. It is therefore quite important to analyze the suitability of Zigbee solutions, namely in terms of routing protocols and network services, with the requirements of wireless sensor networks, which are typically data centric contrarily to traditional wireless networks.

In conclusion, we believe that the IEEE 802.15.4 protocol is a promising enabling technology for low-cost, low-rate and low-power consumption WSNs due to its flexibility to fulfill different requirements of various application patterns, by adequately tuning its parameters.

References

Akyildiz IF, Su W, Sankarasubramaniam Y, and Cayirci E (2002) Wireless sensor networks: A survey. Journal of Computer Networks, vol. 38, pp.393-422.

Bacco GD, Melodia T, and Cuomo F (2004) A MAC protocol for delay-bounded applications in wireless sensor networks. In Proc. of the Third Annual Mediterranean Ad Hoc Networking Workshop (MedHoc'04), June 27-30.

Bandyopadhyay S, and Coyle EJ (2003) An energy efficient hierarchical clustering algorithm for wireless sensor networks. In Proc. of the Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003), vol. 3, 30 March - 3 April.

Crossbow Tech. (2005) Avoiding RF interference between WiFi and Zigbee, Crossbow Technical Report.

Ha J, Kwon WH, Kim JJ, Kim YH, and Shin YH (2005) Feasibility analysis and implementation of the IEEE 802.15.4 multi-hop beacon-enabled network. In Proc. of the 15th Joint Conference on Communications & Info, Jun. 2005.

He T, Stankovic JA, Lu C, Abdelzaher T (2003) SPEED: A stateless protocol for real-time communication in sensor networkss. In Proc. of the 23rd IEEE International Conference on Distributed Computing Systems (ICDCS'03): 46-55.

Howitt I, and Gutierrez JA (2003) IEEE 802.15.4 low rate-wireless personal area network coexistence issues. IEEE Wireless Communications and Networking Conference (WCNC'03), vol. 3, pp. 1481- 1486, 16-20 Mar. 2003.

Hwang L, Sheu ST, Shih YY, and Cheng YC (2005) Grouping strategy for solving hidden terminal problem in IEEE 802.15.4 LR-WPAN. In Proc. of the 1st International Conference on Wireless Internet (WICON'05), pp. 26-32.

IEEE 802.11 Specification (1999) IEEE Standards for Information Technology, Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Network - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

IEEE 802.15.4 Standard (2003) Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE Standard for Information Technology, IEEE-SA Standards Board, 2003.

Koubâa A, Alves M, and Tovar E (2006a) Energy/Delay trade-off of the GTS allocation mechanism in IEEE 802.15.4 for wireless sensor networks. IPP-HURRAY Technical Report, HURRAY-TR-060103, (*Submitted*), Jan. 2006.

Koubâa A, Alves M, Tovar E, and Song YQ (2006b) On the performance limits of slotted CSMA/CA in IEEE 802.15.4 for broadcast transmissions in wireless sensor networks. Hurray Technical Report, (submitted).

Lu C, Blum BM, Abdelzaher T, Stankovic J, and He T (2002) RAP: A real-time communication architecture for large-scale wireless sensor networks. In IEEE Real-Time and Embedded Technology and Applications (RTAS 2002), Sept. 2002.

MICAz datasheet (2004), http://www.xbow.com

Mišic J, and Mišic B (2005a) Access delay and throughput for uplink transmissions in IEEE 802.15.4 PAN. Elsevier Computer Communications Journal, vol. 28, N.10, pp.1152-1166, Jun. 2005.

Mišic J, Shafi S, and Mišic B (2005b) The impact of MAC parameters on the performance of 802.15.4 PAN. Elsevier Ad hoc Networks Journal, vol. 3, N. 5, pp.509–528, 2005.

Park TR, Kim T, Choi J, Choi S, and Kwon W (2005) Throughput and energy consumption analysis of IEEE 802.15.4 slotted CSMA/CA", IEEE Electronics Letters, vol. 41, issue 18, pp. 1017-1019, Sept. 2005.

Pollin S, *et al.* (2005) Performance analysis of slotted IEEE 802.15.4 medium access layer. Technical Report, DAWN Project, Sep. 2005. http://www.soe.ucsc.edu/research/ccrg/DAWN/papers/ZigBee_MACvPV.pdf

Shin SY, Choi S, Park HS, and Kwon WH (2005) Packet error-rate analysis of IEEE 802.15.4 under IEEE 802.11b interference. In Proc. of Conference on Wired/Wireless Internet Communications (WWIC'2005), Springer LNCS, vol. 3510, Xanthi (Greece), 11-13 May, 2005.

Stankovic J, Abdelzaher T, Lu C, Sha L, and Hou J (2003) Real-Time communication and coordination in embedded sensor networks. Proceedings of IEEE, vol. 91, N. 7, pp.1002-1022.

Ye W, Heidemann J, and Estrin D, (2004) Medium access control with coordinated adaptive sleeping for wireless sensor networks. IEEE/ACM Trans. on Networking, vol. 12 , Iss. 3, pp. 493 - 506 Apr. 2004.

ZigBee Alliance (2005), ZigBee specification – June 2004, http://www.caba.org/standard/zigbee.html