This paper is a preprint (IEEE "accepted" status).

DOI. 10.1109/TELFOR.2013.6716229

Practical Aspects Regarding Implementation of Real Time WSN Applications based on IEEE 802.15.4

Valentin Stangaciu, Dan Pescaru, *Member, IEEE,* Mihai V. Micea, *Member, IEEE*, Vladimir Cretu, *Member, IEEE*

***Abstract* — Nowadays, systems based on Wireless Sensor Networks are intensively used in various fields. However, there are few real time applications employing WSNs. The problem resides in various limitations especially at the level of their communication capabilities. Various researches were conducted in this direction but theoretical models are still far from physical reality. The work presented in this paper aims to identify some hard to modeled aspects using practical measurements on a real time WSN. Experiments were conducted on a network using IEEE 802.15.4 compliant communication modules, including the widespread ZigBee solution.**

***Keywords* — WSN, real time applications, IEEE 802.15.4, ZigBee.**

I. Introduction

Wireless Sensor Networks (WSNs) have been an important subject for the last decade researchers mainly because of their applicability and large number of devices. A wireless sensor network is formed by a large number of low power and low cost intelligent sensors with wireless communication capabilities mainly for monitor and control applications [1]. These systems are currently used in a large number of applications for monitoring, controlling, analyzing and predicting certain environment parameters and also for collaborative activities [2, 3, 4, 5].

A particular case of these wireless sensor networks is when the whole network becomes a real time system. We speak of a real time system when not only the correct result produced by the system is important but also the time spent by the system to generate the result; in such a system time is the essential parameter [6, 7]. In a WSN, communication delays are dominant over in-node processing delays. To achieve real-time constraints in such networks, the communication latency must be managed. Therefore, in real time WSN applications communication implies not only the successful delivery of a message from one node to another but also the meet a time constraint for a message to arrive at its destination. Indeed, this represents the main difference between traditional wireless sensor networks and real time wireless sensor networks: the message delivery deadline is one of the most important parameters in communication between sensor nodes [8].

A largely used communication protocol in wireless sensor networks is the ZigBee protocol [9]. The ZigBee stack uses the IEEE 802.15.4 standard as medium access layer protocol [10]. Drawbacks of this solution for real time WSN applications are represented not only by the cost of hardware but also by some issues regarding communication constraints. Therefore, a practical approach could consider also some less complex IEEE 802.15.4 compliant communication modules in a hybrid network architecture. We investigate in this paper both solutions using physical experiments close to real world applications. The experimental setup was built using XBee Series 2 modules implementing ZigBee protocol and Texas Instruments ChipCon CC2420 based also on IEEE 802.15.4.

Our interest concentrates especially on MAC layer defined by the broader IEEE 802.15.4 standard. As results we aim to identify some setbacks having significant impact on real time applications development.

The paper is structured as following: section II presents some important work regarding the usage of IEEE 802.15.4 in various situations, section III describes some of the main aspects of the IEEE 802.15.4 standard, section IV describes experiments meant to identify some of the main interoperability issues and section V concludes the paper.

II. Related Work

The unreliability problem regarding the MAC specifications of the 802.15.4 standard have been studied by many researchers due to the high popularity of this protocol in the wireless sensor networks areas. An important issue of the standard is emphasized in [11] where the authors found that a communication based on this protocol can suffer high packet loss even in the

Valentin Stangaciu is with Department of Computer and Software Engineering (DCSE), Politehnica University of Timisoara, 2, Vasile Parvan Blvd., 300223 – Timisoara, Romania (e-mail: valys@dsplabs.cs.upt.ro).

Dan Pescaru is with Department of Computer and Software Engineering (DCSE), Politehnica University of Timisoara, 2, Vasile Parvan Blvd., 300223 – Timisoara, Romania (e-mail: dan@cs.upt.ro).

Mihai V. Micea is with Department of Computer and Software Engineering (DCSE), Politehnica University of Timisoara, 2, Vasile Parvan Blvd., 300223 – Timisoara, Romania (e-mail: micha@dsplabs.cs.upt.ro).

Vladimir Cretu is with Department of Computer and Software Engineering (DCSE), Politehnica University of Timisoara, 2, Vasile Parvan Blvd., 300223 – Timisoara, Romania (e-mail: vladimir.cretu@cs.upt.ro).

situation of a network with a small number of nodes. After intense measurements and simulations the main issue seems to be connected to the power saving mechanism offered by the standard. Authors also offer a solution for increasing the packet delivery ratio with the cost of delivery latency which may not be a solution for a real time environment. A similar issue is also found by the authors of [12] regarding the high unreliability and low predictability of a communication based on this standard. Similar solution was offered by modifying some of the CSMA/CA parameters of the standard but also the packet latencies were affected. In both of these papers authors evaluated the protocol using simulation environments but also using real communication platforms mainly because the low predictability of the communication environment is almost impossible to proper simulate.

Other researchers observe that in most cases 802.15.4 is an enabling communication protocol for low rate networks but also recognize that using the small real time capabilities, the GTS mechanism, is not affordable in many situations. Because of the high popularity of the standard a simulator has developed in order to evaluate the aspects of this protocol. [13]

All these observations also apply to the ZigBee networks as the MAC layer of the ZigBee stack is based on the IEEE 802.15.4 standard. Therefore all attempts to improve the ZigBee stack in order to support minimum real time operations has to take into considerations the limitations of the base of the stack, the medium access layer protocol.

III. The IEEE 802.15.4 MAC layer protocol

The IEEE 802.15.4 standard defines the guidelines of a network for low rate networks such as WSNs regarding layer 1, the physical layer and layer 2, the medium access layer. Our studies and observations are only related to the medium access layer.

The standard defines two types of nodes. The first is named Reduced Functional Device (RFD) and the Second is known as Full Functional Devices (FFD). The RFD are nodes with very limited communication capabilities that are mainly used for monitoring and control functions. On the other hand the FFD nodes are used mainly for communications and have no other functions at all. Some ideas in wireless sensor networks are that the number of nodes is extremely high and because of this, the nodes of the network are low-cost and low-power. Also, regarding communication, all the nodes have full communication capabilities in order to increase network reliability, scalability and fault tolerance [14, 15].

The IEEE 802.15.4 standard is highly oriented on cluster based network topologies where a high number of nodes are coordinated by a cluster head which has extended communication capabilities. This is feasable for a static network where the possition of each node is known but cannot satisfy the situation when nodes have mobility capabilities. In this last situation an ad hoc network is much prefered where nodes do not need a coordinator in order to form a network and in this case all nodes have extended communication capabilities [16, 17]. The standard have little or no coverage for this situation.

The standard offers both beacon based communication and non-beacon communication. In a beacon based communication the cluster coordinator, or the network head, send a periodically special broadcast frame, called *beacon*, which synchronizes the entire communication

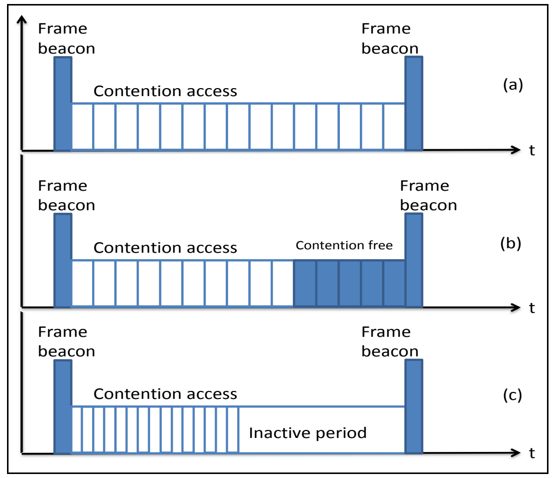

Fig.1 – IEEE 802.15.4 super frame structure (a); with contention free period (b); with inactive period (c).

within the network. If a cluster head fails then all the nodes that were coordinated by it cannot establish communication thus they lack the presence of the beacon. Two consecutive beacons form a super frame which is divided intro 16 equally timeslots where the access into a communication slot by a node is obtained in a CSMA/CA matter, transforming the communication into a timeslotted CSMA/CA mechanism [10].

Fig. 1(a) describes the IEEE 802.15.4 superframe in the first version of the standard.

In the structure of the superframe the access to a timeslot is obtained using the CSMA/CA algorithm. This introduces high unpredictability and make the protocol unusable in real time environment where predictability is a key property. In order to add some real time support the standard defines, besides the contention access period, a number of slots where there is no contention. A node that obtained the slot may use it for a period of time in which the standard guarantees the access of that specific node to its timeslot. The issue is that the standard can offer a maximum of 7 guaranteed time slots and a node obtains this slot, for a limited period of time, in a CSMA/CA matter. Fig. 1(b) shows a super frame with GTS capabilities.

In order to reduce the power consumption of the wireless communication modules the standard introduced an additional period in the superframe called *Inactive Period* where the modules may enter in low power modes [18]. As expected, this solution has a significant impact over the packet latencies [12, 13] and significantly reduce the posibility to use the protocol in a real time environment. The newly introduced capability is depicted by the Fig. 1(c).

Another important aspect of this protocol is the data packetization. A general IEEE 802.15.4 MAC frame is depicted in Table 1. The protocol support the following

TABLE 1: IEEE 802.15.4 GENERAL PACKET

Field size [bytes]	1	2	1	0/2	0/2/8	0/2	0/2/8	n	2
Field description	Frame length	Frame control field	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source Address	Frame payload	Frame checksum

frame types: beacon, data, ack, MAC command, and four other types for future extension.

Depending on the address types used, the maximum overhead that the packetization introduces in a data frame is 26 bytes and the maximum amount of payload data is 229 bytes. This has to be taken unde consideration when using this protocol in an application in order to fit the wireless modules capabilities.

IV. INTEROPERABILITY BETWEEN ZIGBEE AND OTHER IEEE 802.15.4 COMPLIANT DEVICES

Several experiments were conducted in order to decide if ZigBee devices could be used in a simple IEEE 802.15.4 network giving the fact that the ZigBee stack implements the same standard as medium access layer protocol. We were interested only in the MAC specifications of the standard and the PHY specifications were ignored mainly because it is possible to use the MAC protocol defined by the standard on wireless modules that are not compatible with the standard at a PHY level. The experiments were conducted using XBee Series 2 modules [19] as a ZigBee certified module and Texas Instruments ChipCon CC2420 [20] as IEEE 802.15.4 devices capable of carry a ZigBee stack implemented over it. The XBee module was configured as stated in Table 2. It was configured as a network coordinator thus it is responsible for the beacon transmission and the basic forming of the network.

TABLE 2: XBEE MODULE SETTINGS

Serial number	0x0013A20040649EC2
Function set / version	ZigBee Coordinator AT / 1020
Operating channel	0xB
Destination address	Broadcast
Pan ID	0x0234

The other module used in the experiment was set on operating channel B, at 2405 MHz in the 2.4GHz ISM band. In this was this module was able to capture all the packets that were transmitted within a ZigBee network.

Before presenting some frame examples certain clarifications have to be made. The packets within the ZigBee network are indeed complaint to the IEEE 802.15.4 general frame but all the communication inside the ZigBee network is equivalent to data frames in the 802.15.4. An important observation is that the ZigBee stack uses no other frame types. Also the addressing fields of each packet are constant even if the packets are beacons, broadcast data packets or directly addressed packets.

After the modules were powered on the ZigBee coordinator began to transmit a frame every about 2 seconds, this being the ZigBee beacon. An example of this frame is presented in Table 3.

From an IEEE 802.15.4 point of view these 2 captured packets are the same. This later captured packet is a data packet from a ZigBee point of view. Out test payload can be identified in Table 4 in the payload section as the bolded bytes. Also other data can be identified in the ZigBee payload as “13 A2 00 40 64 9E C2” which is the module address as described in Table 2. This address could have been encoded using the specific field described by the IEEE 802.15.4 and in this way increasing the performance and predictability of IEEE 802.15.4 networks and ZigBee networks mainly because most of these compatible wireless modules have address decoding and recognition capabilities.

TABLE 3: ZIGBEE CAPTURED PACKET

ZigBee packet as raw hex data	19 41 88 37 34 02 FF FF 00 00 04 00 FF FF 00 00 01 68 08 F0 80 0E C0 F0 06
Packet decoding according to 802.15.4	
Length	25
Sequence number	57
Frame type	Data
Destination pan	0234
Destination address	FFFF
Source address	0000
Payload length	15
Payload	04 00 FF FF 00 00 01 68 08 F0 80 0E C0 F0 06

TABLE 4: ZIGBEE CAPTURED PACKET

Zigbee packet as raw hex data	27 41 88 73 34 02 FF FF 00 00 04 00 FF FF 00 00 0F A4 08 E8 11 05 C1 E8 21 0A 0B 00 13 A2 00 40 64 9E C2 61 62 63 06
Packet decoding according to 802.15.4	
Length	39
Sequence number	115
Frame type	Data
Destination pan	0234
Destination address	FFFF
Source address	0000
Payload length	29
Payload	04 00 FF FF 00 00 0F A4 08 E8 11 05 C1 E8 21 0A 0B 00 *13 A2 00 40 64 9E C2* **61 62 63** 06

The captured frame is practically a ZigBee beacon frame giving the fact that it is transmitted by the coordinator as broadcast every two seconds. As stated before, the IEEE 802.15.4 module sees this packet as a standard data frame. The ZigBee stack does not use the beacon packet specified by the standard.

This situation can introduce interconnectivity issues when ZigBee devices communicate on the same channel as other IEEE 802.15.4 devices that do not operate on the ZigBee stack.

Another experiment was to observe the data transmitted by the ZigBee device when user data is involved. Our test user payload is "*abc*" (61 62 63). Table 4 describes the captured packet.

Moreover, the overhead introduced by the ZigBee stack in this situation is of 26 bytes making it extremely hard to use for sensors with fewer capabilities for example the Texas Instruments ChipCon CC2500 [21] modules that can only support maximum packets of 64 bytes. Adding the ZigBee overhead to the IEEE 802.15.4 introduces overhead we find a total of 52 bytes of overhead making this protocol hard to use for example on a maximum 64 bytes of packet, leaving a 12 bytes for user specified data.

This overhead problem can be easily solved if the ZigBee stack will use the packet types defined by the standard and the addressing fields. This can not only decrease the overhead but can significantly increase the predictability of the network by using the capabilities of other modules that have to ability to decode IEEE 802.15.4 frames using hardware.

V. Conclusion

The work presented in this paper identifies some communication issues regarding implementation of real time WSN applications. We concentrate on problems related to the MAC layer when using IEEE 802.15.4 compliant devices for the communication infrastructure.

As presented in the paper we identified several problems related to unpredictability of the CSMA/CA mechanism used by the protocol, the weak real time support offered by the GTS and compatibility issues between ZigBee and less complex modules as well as unexpected overhead introduced by the ZigBee higher levels.

As future work we intend to develop solutions to overcome identified drawbacks based on a MAC protocol derived from the IEEE 802.15.4 standard.

References

[1] L. B. Ruiz, J. M. Nogueira, and A. A. F. Loureiro, "Sensor Network Management," in *Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems*, M. Ilyas and I. Mahgoub, Eds., ed Boca Raton, Florida: CRC Press, 2005, ISBN: 0-8493-1968-4, pp. 57-84.

[2] J. V. Capella, A. Bonastre, J. J. Serrano, and R. Ors, "A new robust, energy-efficient and scalable wireless sensor networks architecture applied to a wireless fire detection system," in *International Conference on Wireless Networks and Information Systems WNIS*, 2009, pp. 395-398.

[3] J. V. Capella, A. Bonastre, J. J. Serrano, and R. Ors, "A pollution monitoring system based on an energy efficient Wireless Sensor Networks architecture," in *17th Telecommunications forum TELFOR*, Serbia, Belgrade, 2009, pp. 1145-1148.

[4] M. Marcu, C. Stangaciu, A. Topirceanu, D. Volcinschi, and V. Stangaciu, "Wireless Sensors Solution for Energy Monitoring, Analyzing, Controlling and Predicting Sensor Systems and Software." vol. 57, G. Par and P. Morrow, Eds., ed: Springer Berlin Heidelberg, 2011, ISBN: 978-3-642-23583-2, pp. 1-19.

[5] P. N. N. Reddy, P. I. Basarkod, and S. S. Manvi, "Wireless Sensor Network based Fire Monitoring and Extinguishing System in Real Time Environment," *International Journal Advanced Networking And Application,* vol. 3, no. 2, pp. 1070-1075, 2011.

[6] J. A. Stankovic, K. Ramamritham, M. Spuri, and G. C. Buttazzo, *Deadline Scheduling for Real-Time Systems: EDF and Related Algorithms*. MA, USA: Kluwer Academic Publishers Norwell, 1998, ISBN: 079238.

[7] G. Butazzo and P. Gai, "Efficient EDF Implementation for Small Embedded Systems," in *orkshop on Operating Systems Platforms for Embedded Real-Time applications OSPERT*, Dresden, Germany, 2006.

[8] K. K. Z. Teng, "A Survey on Real-Time MAC Protocols in Wireless Sensor Networks," *Communications and Network,* vol. 2, no. 2, pp. 104-112, 2010.

[9] ZigBee Alliance, "ZigBee Specifications," version 1.0 r13 Dec 2006.

[10] IEEE Computer Society, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless personal Area Networks (LR-WPANs)," in *802.15.4*, ed: Institute of Electrical and Electronics Engineers, Inc., 2003.

[11] G. Anastasi, M. Conti, and M. D. Francesco, "The MAC unreliability problem in IEEE 802.15.4 wireless sensor networks," presented at the Proceedings of the 12th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems, Tenerife, Canary Islands, Spain, 2009.

[12] G. Anastasi, M. Conti, and M. Di Francesco, "A Comprehensive Analysis of the MAC Unreliability Problem in IEEE 802.15.4 Wireless Sensor Networks," *Industrial Informatics, IEEE Transactions on,* vol. 7, no. 1, pp. 52-65, 2011.

[13] M. J. L. J. Zheng, "A comprehensive performance study of IEEE 802.15.4," in *Sensor Network Operations*, I. Press, Ed., ed: Wiley Interscience, 2006, ISBN: 0-471-71976-5, pp. 218-237.

[14] G. Sudha Anil Kumar, G. Manimaran, and Z. Wang, "Energy-Aware Scheduling of Real-Time Tasks in Wireless Networked Embedded Systems," in *Real-Time Systems Symposium (RTSS). 28th IEEE International*, Tucson, AZ, 2007, pp. 15-24.

[15] G. Sudha Anil Kumar, G. Manimaran, and Z. Wang, "Energy-aware scheduling with deadline and reliability constraints in wireless networks," in *Broadband Communications, Networks and Systems (BROADNETS). Fourth International Conference on*, Raleigh, NC, USA, 2007, pp. 95-105.

[16] B. S. Manoj and R. R. Rao, "Wireless Mesh Networks: Issues And Sollutions," in *Wireless Mesh Networking - Architectures, Protocols and Standards*, Y. Zhang, J. Luo, and H. Hu, Eds., ed Boca Raton, New York, USA: Auerbach Publications, Taylor & Francis Group, 2006, ISBN: 978-0-8493-7399-2, pp. 4-46.

[17] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Comput. Netw. ISDN Syst.,* vol. 47, no. 4, pp. 445-487, 2005.

[18] IEEE Computer Society, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless personal Area Networks (LR-WPANs)," in *802.15.4*, ed: Institute of Electrical and Electronics Engineers, Inc., 2006.

[19] Digi International, "XBeeTM/XBee-PROTM OEM RF Modules. Product manual v1.xAx - 802.15.4 protocol," Digi International Inc. 2007.

[20] Texas Instruments, "CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver," ChipCon Products from Texas Instruments, Texas Instruments Press 2012.

[21] Texas Instruments, "CC2500 Low-Cost Low-Power 2.4 GHz RF Transceiver," ChipCon Products from Texas Instruments, Texas Instruments Press 2011.