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

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***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-be-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 to 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 the 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 application development.

The paper is structured as following: section II discusses relevant 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 presents a set of 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]

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where the authors found that a communication based on this protocol can suffer high packet loss even in the 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 featured by the standard. Authors also propose 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. The authors propose to modify some of the CSMA/CA parameters of the standard, but on the other hand, this solution also modifies the packet latencies. In both of these papers the protocol has been evaluated in simulation environments and also using real communication platforms, mainly because it is almost impossible to properly simulate the low predictability of the communication environment.

Other researchers observed that in most cases 802.15.4 is a suitable communication protocol for low rate networks, while also recognizing that using its small real-time capability, the GTS mechanism, is not affordable in many situations. Because of the high popularity of the standard, a simulator has been 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 consideration 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 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 denotes nodes with very limited communication capabilities, 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 feasible for a static network where the position 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 preferred, where nodes do not need a coordinator to form a network and in this case all nodes have extended communication capabilities [16, 17]. The standard has little or no coverage of this situation, at all.

The standard provides both beacon based and non-beacon communication. In a beacon based communication the cluster coordinator, or the network head, sends periodically a special broadcast frame, called *beacon*, which synchronizes the entire communication within the network. If a cluster head fails then all the nodes that were coordinated by it cannot establish communication due to the absence of the beacon. Two consecutive beacons form a super frame which is divided into 16 equal timeslots. The access of a node into a communication slot is obtained in a CSMA/CA matter, transforming the communication into a time-slotted 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 makes the protocol unusable in real-time environments 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 which obtained this slot may use it for a period of time, in which the standard guarantees the access of that specific node to its timeslot. The problem is that the standard can offer a maximum of 7 guaranteed time slots and that 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 introduces 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], which significantly reduces the possibility to use the protocol in a real-time environment. The newly introduced capability is depicted by the Fig. 1(c).

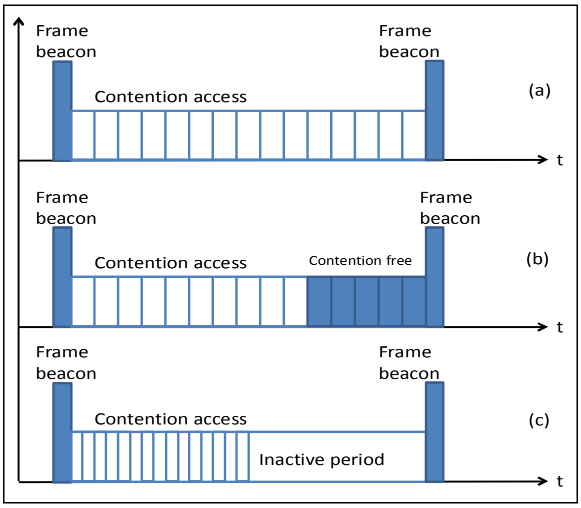

Fig.1 – IEEE 802.15.4 super frame structure (a); with contention free period (b); with inactive period (c).

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

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

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

IV. INTEROPERABILITY BETWEEN ZIGBEE AND OTHER IEEE 802.15.4 COMPLIANT DEVICES

A set of 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 medium access layer protocol. We were interested only in the MAC specifications of the standard; 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 the PHY level. The experiments were conducted using XBee Series 2 modules [19], as ZigBee certified modules, and Texas Instruments ChipCon CC2420 [20] as devices capable of hosting a ZigBee stack implemented over the IEEE 802.15.4. The XBee module was configured as described in Table 2. It was configured as a network coordinator, thus being responsible for the beacon transmission and for the initial network setup.

The other module used in the experiments was set to operate on channel B, at 2405 MHz in the 2.4GHz ISM band. This way, the module was able to capture all the packets transmitted within the ZigBee network.

Before presenting some frame examples, certain clarifications have to be made. 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.

TABLE 2: XBEE MODULE SETTINGS

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

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 such frame is presented in Table 3.

From the IEEE 802.15.4 point of view, the two captured packets, presented in Tables 3 and 4, are the same. The latter captured packet is a data packet from a ZigBee point of view. Out test payload has been identified with bold fonts in Table 4, at the payload section. Other data can also be identified in the ZigBee payload as the sequence “13 A2 00 40 64 9E C2”, which is the module address described in Table 2. This address could have been encoded using the specific field provided by the IEEE 802.15.4, to increase in this way the performance and predictability of IEEE 802.15.4 and ZigBee networks, as most of these compatible wireless modules have address decoding and recognition capabilities.

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 set of experiments were conducted 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 26 bytes, making it extremely hard to use for sensors with fewer capabilities, which is the case of the Texas Instruments ChipCon CC2500 [21] modules that can only support maximum packets of 64 bytes. Adding the ZigBee overhead to the one introduced by the IEEE 802.15.4, we find a total of 52 bytes of overhead. This leaves a maximum of 12 bytes for user specified data out of a 64-byte packet, making this protocol hard to use.

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 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 the unpredictability of the CSMA/CA mechanism used by the protocol, the weak real-time support offered by the GTS mechanism, compatibility issues between ZigBee and other less complex modules, as well as the unexpected overhead introduced by the higher protocol levels of ZigBee.

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

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