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PERFORMANCE ANALYSIS OF IEEE 802.15.4 CONTENTION FREE PERIOD THROUGH REAL-TIME INDUSTRIAL MAINTENANCE APPLICATIONS

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Abstract: Nowadays, a growing number of societies are looking for industrial wireless network solutions. However, industrial communications induce real-time constraints and those networks should at least fulfil those requirements. In this paper, we study IEEE 802.15.4 performances in order to support real-time traffic. This analysis brings out some limitations of that standard concerning cycle duration and amount of messages per cycle.

Keywords: IEEE 802.15.4, industrial wireless, performance analysis, real-time.

1. INTRODUCTION

Over the past few years, intensive wireless networks developments have been done and their usage for industrial cases appear more and more possible. In fact, wireless networks provide noticeable advantages in terms of mobility and costs reduction. Nevertheless, transmission errors may occur and are not negligible. So wireless communications are not advisable for control-command systems forasmuch as hard real-time systems. Nonetheless, they may be used for subsystems like monitoring and e-maintenance applications (Ramamurthy *et al.*, 2007) where a loss of a few information will not be a major inconvenience (i.e. an operator provided with an handled device).

IEEE 802.15.4 (IEEE Computer Society, 2006), one of the most recent wireless standard, is quite interesting due to its “ultra-low complexity, low-cost and extremely low-power wireless connectivity” (Gutiérrez *et al.*, 2003). That protocol provides two different access methods to the medium. The mandatory one is CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) which is not deterministic by design (possible infinite re-

missions). This mechanism may provide a deterministic medium access by the use of an application layer based on a master/slave protocol. The second medium access method is optional and achieves a mechanism of time reservation called GTS (Guaranteed Time Slots). These time allocations may allow periodic unidirectional transmissions within a bounded time delay between a device and its coordinator. Such reservations are bounded to seven GTS's in a duty cycle. So their use are restricted to periodical pooling applications by a coordinator device of a limited number of equipments.

In this paper, we present a performance analysis between the two medium access mechanism provided by IEEE 802.15.4. We will present therefore some advantages and inconveniences for both methods.

This paper is organised as follow. In Section 2 we overview the IEEE 802.15.4 specification. Section 3 comments on network configuration. Section 4, through two different network topologies, focuses on performance analysis of GTS mechanism based on an industrial case. Then it is

compared to a CSMA/CA based medium access in Section 5. Section 6 relates our contribution with previous works on performance analysis of industrial wireless communications. Finally, this paper concludes in Section 7.

2. IEEE 802.15.4 OVERVIEW

2.1 Network design

IEEE 802.15.4 defines two different device types; a full-function device (FFD) and a reduced-function device (RFD). So an FFD is able to communicate with either type of devices, whereas an RFD can only discuss with an FFD.

FFD can operate in three modes serving as a personal area network (PAN) coordinator, a coordinator, or a device. Differences between PAN coordinator and coordinator lie on their range of action. A PAN coordinator controls every coordinator in its PAN whereas a coordinator takes only care of directly connected devices. Later, we won't make any differences as our examples consider only one coordinator (PAN coordinator).

An RFD is intended for simple applications, such as a sensor, it does not need to send large amount of data and may only be associated with an FFD at a time. So, RFD may use low resources and memory capacity and may be cheaper than FFD. On a plant floor, we consider most of sensors are RFDs.

IEEE 802.15.4 standard defines two types of topologies (fig. 1).

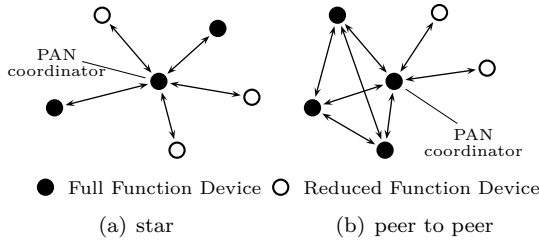


Figure 1. IEEE 802.15.4 network topologies

Star topology restricts every device to communicate only with their PAN coordinator whereas peer-to-peer one allows communication between devices if they are able to. Star topology may result in use of a mains powered coordinator and battery powered nodes. This paper focuses on star topology through a study case based on an European Integrated Project (*DYNAMITE — Dynamic Decisions in Maintenance*, 2005–2009).

2.2 Medium access control

IEEE 802.15.4 medium access may be synchronised or not through a beacon frame. So the stan-

dard specifies the use of a periodic beacon frame to synchronise devices in beacon-enabled mode whereas it is also possible to communicate without any synchronisation in non-beacon-enabled mode.

Both modes provides medium access within a Contention Access Period (CAP). Beacon-enabled mode provides in addition a Contention Free Period (CFP). Therefore, we focus on beacon-enabled mode.

Between beacons, access to the medium is part in two (see fig. 2). The first part, called “super-frame”, represents time allocated by the coordinator for communication whereas the second one corresponds to network inactivity for every node related to that coordinator.

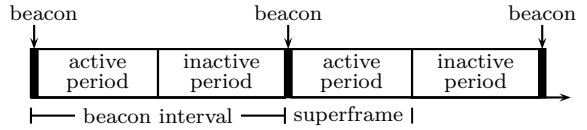


Figure 2. Beacon-enabled access mode

Beacon interval (BI) and superframe (SD) durations are defined by the coordinator through the two parameters Beacon Order (BO) and Superframe Order (SO) as follow:

$$BI = aBSFD \times 2^{BO} \quad (1)$$

$$SD = aBSFD \times 2^{SO} \quad (2)$$

$$0 \leq SO \leq BO \leq 14 \quad (3)$$

Period of network inactivity purposes some power-saving sought by IEEE 802.15.4 standard. In our study, we consider the shortest inactive period, as we are looking for communication performances without considering energy consumption contrary to (Koubâa *et al.*, 2006a).

As the inactive period may not exist ($SO = BO$), we only consider the active period, superframe, composed of a beacon frame, Contention Access Period (CAP) and a Contention Free Period (CFP) (see fig. 3). Then we consider cycle duration is equivalent to superframe duration.

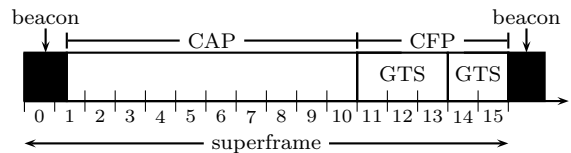


Figure 3. Superframe composition

2.3 Contention Free Period

By definition, a superframe is divided into 16 equals slots which may be allocated to a device by the coordinator for dedicate communication.

Those kind of reservations are called Guaranteed Time Slots (GTS) and may include an integer number of these slots. Any device can ask for such a reservation as long as there are no more than 7 GTS's and CAP duration is at least $aMinCAPLength$ long.

2.4 Superframe duration

Superframe duration SD is defined by the standard by (2) and (3) where $aBSFD = aBSD \times aNSFD$. $aBSD$ and $aNSFD$ parameters are defined by the standard.

So, it is possible to determine, every superframe duration depending on the network parameters set by the coordinator (channel/frequency, modulation and superframe order). we figure out that most efficient network parameters implies the use of a O-QPSK modulation in association with a frequency in the range either 902–928 MHz or 2400–2483.5 MHz. The use of such a configuration results in superframe duration included between 15.36 *ms* and 251.6 *s*. Due to the fact the first range of frequencies is optional for standard specification while the second one is mandatory, we only take care of the use of band 2400–2483.5 MHz in that paper. So the remaining parameter the coordinator has to define, is the superframe order.

3. NETWORK CONFIGURATION

In order to evaluate a superframe duration, we have to know how a network is configured. So we need to specify the value of the undefined parameter, superframe order SO . More the superframe order is low, more the superframe duration is low and so more the cycle duration is accurate for real-time communications. Choice of superframe order must be as low as possible also it respects constraints concerning standard specification and usage of the network. In the next two subsections, we focus on those two constraints.

3.1 Specification constraints

CFP usage implies the respect of the transmission of the beacon frame as well as the minimum CAP duration, $aMinCAPLength$. Then in order to evaluate the impact of a superframe order value, we must consider the mandatory slots M_{slots} required by these two transmissions. CAP length is defined by the coordinator and so it is considered as the minimum required by the standard $aMinCAPLength$. In contrary, beacon frame size, which is application dependent, is considered as its maximum size $Beacon_{max} = 133$ bytes headers

included. Thereby, we determine (4),(5) the maximum CFP length in terms of remaining slots R_{slots} depending on the superframe order (see fig. 4).

$$M_{slots} = \left\lceil \frac{aMinCAPLength + Beacon_{max}}{aBaseSlotDuration \times 2^{SO}} \right\rceil \quad (4)$$

$$R_{slots} = 16 - M_{slots} \quad (5)$$

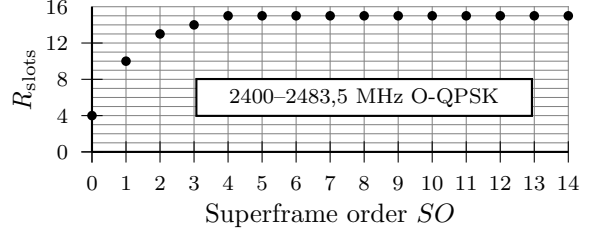


Figure 4. Maximum available slots for CFP

So, choice of a superframe can be checked over the minimum required by the specification. For example, if CFP has to be 5 slots long, it may be impossible to satisfy all requirements with $SO = 0$. In such a case, superframe order must be chosen at least equal to 1.

3.2 Usage constraints

In order to evaluate the choice of a superframe order, we must define how many slots are needed for CFP. In that part, we deal with CFP slots requirements depending on data transmission. We consider a unidirectional transmission between two devices of *Data* bytes in one GTS. That amount of data is considered at the application layer and will be encapsulated by the two IEEE 802.15.4 layers in order to form a network packet. For a communication in a GTS, we consider $PHY_{headers} = 6$ bytes and $MAC_{headers} = 23$ bytes. $MAC_{headers}$ is defined considering the maximum value for auxiliary security field as we can't control the use of such a parameter in industrial environments.

For 1 byte of payload data, we send at least 30 bytes over the network including 29 bytes corresponding to encapsulation. In addition, we should also take care of transmission scheme specified by the standard and notably of interframe spaces (IFS) which should be part of GTS. Figure 5 explains that mechanism which should follow every packets send over the network. It depends size of transmitted packets and acknowledgement configuration.

Short frames correspond to packets which length is lower or equal to 24 bytes. Due to the encapsulation considered in that paper, we doesn't develop what concerns short frames and only consider transmission of long frames in either case of acknowledgement. So, we define in (6), the total amount of bytes $Data_{transmitted}$ transmitted over the network considering minimum fragmentation.

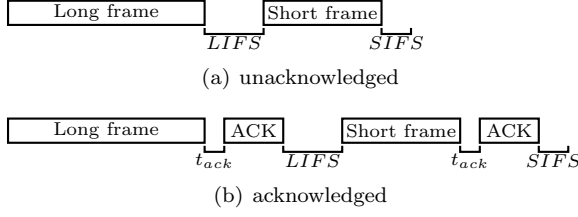


Figure 5. IEEE 802.15.4 interframes spaces

$$Data_{\text{transmitted}} = Data + \left\lceil \frac{Data}{MSDU_{\text{max}}} \right\rceil \times LH \quad (6)$$

$$LH = \begin{cases} Headers & \text{unacknowledged} \\ Headers + t_{\text{ACK}} + ACK & \text{acknowledged} \end{cases}$$

$$Headers = MAC_{\text{headers}} + PHY_{\text{headers}} + LIFS$$

Then we look for the slots needed by transmission of data payload of $Data$ bytes in a GTS. The number N of slots is provided by (7) and represented on figure 6.

$$N_{\text{slots}} = \left\lceil \frac{Data_{\text{transmitted}}}{aBaseSlotDuration \times 2^{SO}} \right\rceil \quad (7)$$

Slots needed for a transmission can be evaluate and bring face to face with specification requirements (8).

$$\sum_i N_{\text{slots}_i} \leq R_{\text{slots}} \quad (8)$$

As an example, if we want to send 60 unacknowledged bytes on the network, we may select $SO = 0$, $N_{\text{slots}} = 4$ slots with (7) which satisfy the maximum R_{slots} (5). But in the case data need to be acknowledged superframe order set to 0 induces $N_{\text{slots}} = 5$ slots and it contradicts the maximum $R_{\text{slots}} = 4$ slots obtained by (5). So in that case, a solution may be $SO = 1$ which induces ($N_{\text{slots}} = 3$ slots) \leq ($R_{\text{slots}} = 4$ slots).

4. INDUSTRIAL CASE

Now we are able to set network parameters in order to satisfy the minimum requirements of such a network, we look for available real-time abilities based on an industrial case. Our study case is based on maintenance of industrial plants. On a plant floor, we want to provide to maintenance teams with direct access to machines' sensors in order to know in real-time how they progress. Maintenance people carries a mobile device (PDA) which is able to communicate with plant's sensors using wireless networks.

That paper studies such capacities regarding the use of IEEE 802.15.4 standard.

4.1 Simple infrastructure

As a first evaluation, we study a network based on a star topology (fig. 1(a)) where PAN coordinator is a PDA and other devices are only RFDs.

In such a configuration every sensor in PDA's range of action are able to send data for maintenance purpose to the PDA after a small time of auto-configuration (negotiation, association, ...). Our interest is to specify what would be the minimum cycle duration to ensure communication of every devices with the PDA in relation with network's requirements.

For that study, we consider a network set up with five industrial sensors transmitting and/or receiving data as described in table 1.

Table 1. Data exchanges

Device	Data send	Data received	Cycle
n°1	1 byte	-	40 ms
n°2	8 bytes	-	40 ms
n°3	4 bytes	-	60 ms
n°4	8 bytes	4 bytes	60 ms
n°5	16 bytes	-	100 ms

Even if sensors doesn't require the same period of cycle, we consider a cycle duration which allows any device to transmit during any superframe. Then the defined set of transmissions induce 6 GTS's; emission and reception implies for node 4 the use of two different GTS's.

Such a configuration lead us to deduce the best network configuration corresponding to that usage. For that purpose, we compute N_i for every node and we evaluate $CFP_{\text{slots}} = \sum_i N_i$. Evaluation of superframe order is given table 2 and 3.

Table 2. Superframe order evaluation, unacknowledgement

SO	0	1	2	3
N_1	2	1	1	1
N_2	2	1	1	1
N_3	2	1	1	1
N_4	2	1	1	1
$N_{4'}$	2	1	1	1
N_5	3	2	1	1
CFP_{slots}	13	7	6	6
CFP_{max}	4	10	13	14
$SD(ms)$	15.36	30.72	61.44	122.88

For that specific case, communications will be insured with the choice of $SO = 2$ with acknowledgement whereas $SO = 1$ is sufficient for unacknowledged communications. $SO = 1$ corresponds to cycle duration equals 30.72 ms which satisfies all requirements (Cycle $\geq 40ms$) whereas superframe duration of 61.44 ms doesn't. So we are able to satisfy sensors' communications in case we set up a network with $SO = 1$ without acknowledgement.

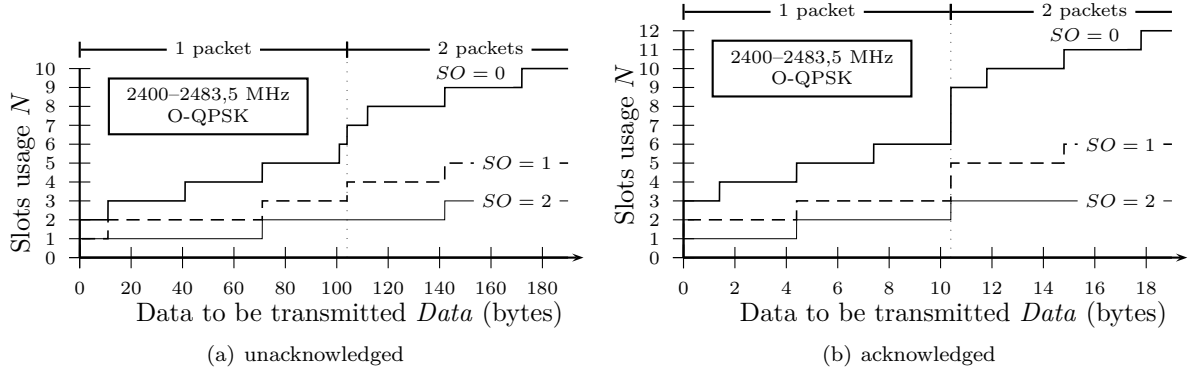


Figure 6. Slots usage in relation with data transmission

Table 3. Superframe order evaluation, acknowledgement

SO	0	1	2	3
N_1	3	2	1	1
N_2	3	2	1	1
N_3	3	2	1	1
N_4	3	2	1	1
$N_{4'}$	3	2	1	1
N_5	4	2	1	1
CFP_{slots}	19	12	6	6
CFP_{max}	4	10	13	14
$SD(ms)$	15.36	30.72	61.44	122.88

That study considers only sporadic communications from sensors to an unique receptor. But in industrial cases, data may be useful for more than one recipient and that is why we should take into account cases with a more permanent structure.

4.2 Permanent infrastructure

Introduction of a fixed coordinator on a plant floor leads to a more permanent infrastructure (see fig. 7). In fact the presence of a coordinator allows communication from the sensors to the coordinator even if there is no maintenance PDA in the area. Moreover, it induces a reduction in time needed for association.

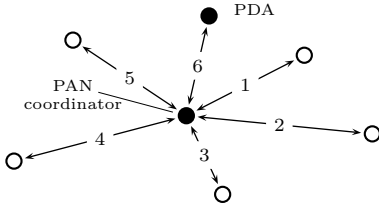


Figure 7. Permanent infrastructure

In terms of performances we consider the example in addition with the communication between coordinator and PDA. This data transmission includes all the previously received frames by the coordinator from sensors. Therefore, this communication includes the same number of frames and we are unable to use (7) with $Data = \sum_{i=1}^5 Data_i$. In order to calculate the number of slots required

for the transmission to PDA, we need to compute $Data_{transmitted_6} = \sum_{i=1}^5 Data_{transmitted_i}$

In our case, all frames are lower than $MPDU_{max}$ (127 bytes), so we reduce the expression to $Data_{transmitted_6} = \sum_{i=1}^5 Data_i + 5 \times LH$. Then we deduces the superframe order corresponding to that network (tables 4 and 5).

Table 4. Superframe order evaluation, unacknowledgement

SO	0	1	2	3
ΣN_{slots}	11	11	8	7
R_{slots}	4	10	13	14
$SD(ms)$	15.36	30.72	61.44	122.88

Table 5. Superframe order evaluation, acknowledgement

SO	0	1	2	3
ΣN_{slots}	30	18	9	8
R_{slots}	4	10	13	14
$SD(ms)$	15.36	30.72	61.44	122.88

In that case, superframe duration is 61.44 ms in either case and we can't satisfy the requirements of all sensors. Moreover we must take into consideration that, with that kind of infrastructure, data arrived at PDA after two superframes and so we should consider cycle duration equals 122.88 ms.

5. METHODS COMPARISON

GTS access method provides a simple polling mechanism for IEEE 802.15.4 devices. It may also be possible to implement a polling protocol through CSMA/CA.

In order to compare use of a CFP with CSMA/CA mechanisms, we consider such a polling protocol requiring an overhead of 1 byte. Coordinator sends poll request to a node and receives one or more poll response messages, depending on size message and needed fragmentation.

Comparison results are represented on figure 8 corresponding to a network with 5 nodes sending the same amount of data.

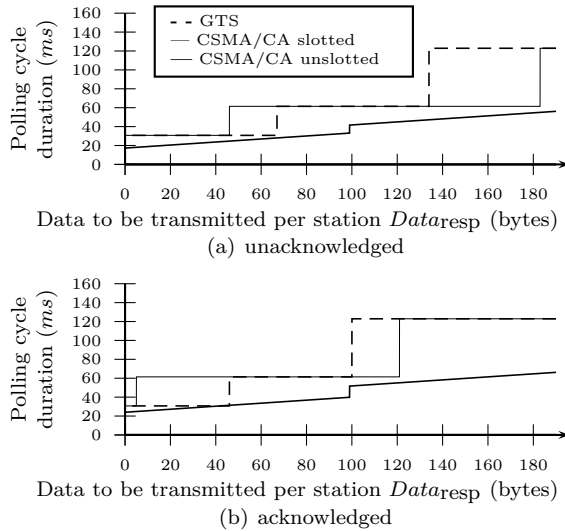


Figure 8. Access methods comparison with a 5 stations polling cycle

We observe that CSMA/CA unslotted provides lower cycle duration than GTS (except on very specific cases). But in what concerns CSMA/CA slotted, results are quite similar. GTS may provide lower cycle duration for low and average size messages whereas CSMA/CA is interesting for long messages, greater than 1 packet.

6. RELATIVE WORKS

Our results focuses on a specific mechanism provided by IEEE 802.15.4 standard. Those results may be completed by (Koubâa *et al.*, 2006b; Mišić and Fung, 2007) who propose simulation results concerning CSMA/CA slotted.

Use of wireless networks for industrial applications may rely on the use of other standard, like IEEE 802.11 or IEEE 802.15.1.

IEEE 802.15.1 was developed in order to unbind equipments from their network wire. Due to some power limitation, its range of action is quite limited (mostly around 10 m). Main applications of that protocol concern computer peripheral devices (printer, keyboard, cell phone, ...). Transmission of real-time traffic over a Bluetooth network has been studied under industrial cases (Lo Bello *et al.*, 2005). Although that protocol is suitable for short range real-time communications, its intricate definition and high energy consumption matter with its use with small mobile devices.

IEEE 802.11, first of them, is currently most used for computer wireless networking. It relies on a CSMA/CA medium access which is not deterministic. A second medium access, named PCF (Point Coordination Function), exists and it allows to assure the transmission of a time constrained traffic. Some publications (Bianchi,

2000; Krommenacker and Lecuire, 2005) focus on IEEE 802.11 performances to support industrial constraints.

7. CONCLUSION

That paper evaluates IEEE 802.15.4 temporal performances aimed to be used by industrial applications. It underlines some heavy limitations concerning cycle duration and number of devices that can communicate within Contention Free Period.

It reveals some difficulties to use IEEE 802.15.4 for heavy time constrained applications. Moreover main commercial products based on that standard are Zigbee ones. Zigbee protocol add more restrictions and it appears very rough to use such a technology for control command applications.

Use of IEEE 802.15.4 for more responsive use than supervision needs at least reconsideration of some standard values. It may also be possible to consider adaptation of some standard rules.

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