Building Industrial Communication Systems based on IEEE 802.11g wireless technology

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Abstract

Industrial Communication Systems (ICS) are specifically designed for deterministic communication between sensors, actuators, programmable logic controllers, monitoring systems, and operator workstations. These networks are traditionally based on wired technology and a deterministic medium access control. Nowadays, the emerging trend is the availability of wireless technology for ICS, since this leads to more flexible and mobile equipments at reduced cost. This article presents a performance analysis of Wireless ICS based on the IEEE 802.11g standardized technology, considering the infrastructure mode with both Distributed and Point Coordination Functions. The time-critical messages are handled during the contention free period. The performance analysis allows to validate the ability of 802.11g technology to support time-critical traffic required by wireless ICS, being given the scheduling and characteristics of the messages. In addition, the configuration parameters of access points can be easily derived from the performance analysis.

1 Introduction

At the lowest level of Industrial Communication Systems (ICS), fieldbuses are able to support time-critical communications between sensors, actuators, programmable logic controllers, monitoring systems, and operator workstations. These networks are traditionally based on wired technology and a deterministic medium access control.

Nowadays, the emerging trend is the deployment of wireless technology in several fields of application. The foundation in 2003 of Wireless Industrial Networking Alliance, a coalition of industrial end-user companies, technology suppliers, and others interested in the advancement of wireless solutions for industry, is a good example of this trend. For industrial networks, wireless technology provides several advantages such as the cabling cost reduction, the installation facility of equipments within hazardous areas (in presence of aggressive chemicals, capable of damaging cables) and the flexibility to perform rapid plant reconfigurations. An other advantage is the potential for truly mobile stations. Human operator needs mobile hand-held device with wireless communication interface and maintenance software for performing bespoke data analysis and early stage diagnosis of faulty conditions on nearest equipments. Moreover, an increasing number of automation systems such as automated warehousing, requires the use of automatic guided vehicles, robots or turntables which benefit from the adoption of wireless communications.

Even if the wireless technologies are a good alternative to the traditional wired technology, they must ideally offer the same services to the users [6]. For instance, wireless channel is error-prone and the packet losses are inevitable. Thus, the use of wireless technologies inside the industrial environment is generally restricted to fault-tolerant applications, mainly in the area of remote data collection.

An additional constraint is the ability to support time-critical communications. It is usually provided by a deterministic medium access mechanism. Among the various wireless technologies at hand, IEEE 802.11 standards family [10][9][8] is already broadly used. They include two protocols at Medium Access Control (MAC) sublayer. The mandatory mechanism to access the medium is called Distributed Coordination Function (DCF). This is a random access scheme, based on carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Although, a large number of QoS enhancement schemes has been proposed using a priority scheme [7] or traffic scheduling and admission control algorithm [12][5]. A recent survey is presented in [15]. It can be easily noticed that legacy DCF cannot fulfil the QoS requirements of fieldbus applications.

IEEE 802.11 MAC sublayer defines also an optional mechanism which provides asynchronous, time-bounded and contention free access control, called Point Coordination Function (PCF). PCF can be only used in infrastruc-

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ture mode, and no in ad hoc mode. This is a polling-based access method using a centralized point coordinator (usually the access point). Since a centralized medium access control is more suitable to support time-bounded traffic than the CSMA/CA protocol, the performance and the combination of DCF and PCF has been studied in several works [3][4][11]. However, such researches concern with the multimedia traffic (e.g., packetized voice and video) and is not well suited for industrial realtime traffic. So, some works have been led to use wireless communications systems for industrial applications. In [2], Willig studies the possibility to create an hybrid wired/wireless PROFIBUS system. He shows that polling-based protocol is better than the existing PROFIBUS MAC protocol which use a token passing scheme. In [1], Alves *et al.* address the timing unpredictability problems due to the co-existence of heterogeneous transmission media in an hybrid wired/wireless PROFIBUS. They propose a solution to provide inter-cell mobility onto such industrial networks. Miorandi [14][13] studied the possibility of implementing a admission control protocol such as master/slave (or producer/consumer), as an upper layer of the Logical Link Control IEEE 802.11.

Although PCF was designed to support time-bounded traffic, several inadequacies have been identified. The first one is the beacon delays resulting in significantly shortened Contention Free Period (CFP). This problem may severely affect the amount of the time remaining for the contention free period. This delay depends of the PHY layer and its maximum value can be computed. The second one is the transmission times of the polled stations. A station that has been polled may transmit frames of variable payload. The Access Point (AP) cannot predict and control the polling schedule for the remainder of the CFP. Whenever the polling list is not completed during the CFP period, stations that have not been polled must wait for the next CFP. Nevertheless, the real-time traffic characteristics are well-known in ICS. This problem can be avoided by determining the worst case runtime of the polling list.

In this paper, we focus on wireless $802.11g$ technology and propose a performance analysis in order to validate its ability to support time-critical traffic. This analysis will also permit to determine the values of MAC manageable parameters in order to the ICS operates as expected. The paper is organized as follows. Section 2 provides an overview of 802.11 MAC Layer protocols. In section 3, we develop the performance analysis of $802.11g$. In particular, we compute the maximum foreshortened CFP delay, the required CFP Duration for poll-based patterns and the DCF throughput. Section 4 provides a numerical application from a Wireless ICS, being given the scheduling and characteristics of its messages.

2 802.11 MAC layer and ICS context

2.1 802.11 MAC layer overview

$IEEE$ 802.11 became the most widely used standards for wireless local area networks. They use a common MAC layer. The MAC Layer provides and maintains communications between 802.11 nodes (stations and access points) by coordinating access to a shared radio channel, which is the wireless medium. Before transmitting frames, a node must first gain access to the medium. To achieve that, a basic access mechanism is employed, the so-called CSMA/CA protocol. It uses 802.11 Physical (PHY) layer to perform the task of carrier sensing. So, each node must check that the channel is idle for some minimum amount of time, before initiating a transmission. This amount of time is called the Distributed Inter-Frame Spacing ($DIFS$) time. Since multiple nodes could have been accessing the medium in the same time, collisions can occur. The Collision Avoidance is ensured by a backoff timer in order to reduce the collision probability. A node computes a random backoff time which is an additional interval beyond the $DIFS$ time. The node that wishes to transmit must verify that the medium is still idle after the elapsed time. To provide reliable data services the 802.11 standard defines an explicit acknowledgment to inform the source node of the outcome of the previous transmission. If the receiving node detects no errors in the received frame, a positive acknowledgment (ACK) must be send to the source after a Short Inter-Frame Spacing ($SIFS$) time. The $SIFS$ time is less long than the $DIFS$ time so that the receiving node is given prioritary over other stations that are attempting to get transmission opportunities. Otherwise, the source node will assume that a collision (or loss) has occured and will retransmit the frame. To reduce collisions, the standard also encompasses an optional RTS/CTS reservation mechanism which implies short control frames exchanges prior to data transmission.

What we described above, is the well-known DCF operation mode. This mode provides a contention period based on a best-effort service, and is not suitable for time-critical applications. To solve this drawback, the standard has defined an optional PCF mode, which is well suited to support time-bounded traffic. The PCF mode relies on a centralized access control which requires the presence of a node that acts as point coordinator. Thus, PCF is used only in infrastructure mode where the AP operates as point coordinator. PCF is built over the DCF mode and provides a Contention Free Period in which nodes may have contention-free access to the channel. Both PCF and DCF alternate within a Contention Free Period repetition interval, as represented in Figure 1, named $Superframe$. The duration of the $Superframe$ and the PCF period are manageable parameters, CFP_rate and $CFP\_Max\_Duration$ respectively, which are maintained by the AP. Both determine the balance between distributed and scheduled medium access and influence on the time reserved to transmit real-time traffic.

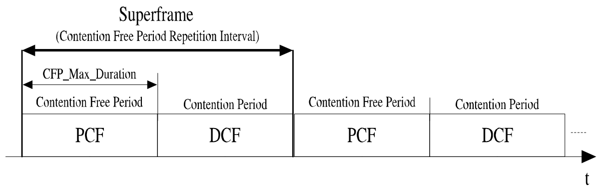

Figure 1. PCF and DCF modes alternation

2.2 PCF mode

PCF provides contention free frame transfer allocating specific time slots for data transmission. For this, a polling-based access mechanism is used with a Round-Robin scheduler. The Point Coordinator polls individual stations to transmit without contending for the channel. At the nominal beginning of each Contention Free Period, the AP senses the medium. If the medium is idle after a Priority Inter-Frame Spacing ($PIFS$) time, a beacon frame including a Delivery Traffic Indication Message is sent. The $PIFS$ time is shorter than $DIFS$ to ensure that PCF is given priority over DCF frame transmission. However, the beacon frame that signals the beginning of the Contention Free Period, may be delayed due to a busy medium. Figure 2 illustrates this. A station with non-real-time traffic starts transmission just before a superframe and lasts longer than the remaining contention period. The AP has to defer the start of its real-time traffic transmission until the medium becomes free for a $PIFS$. Such PCF period is called foreshortened CFP.

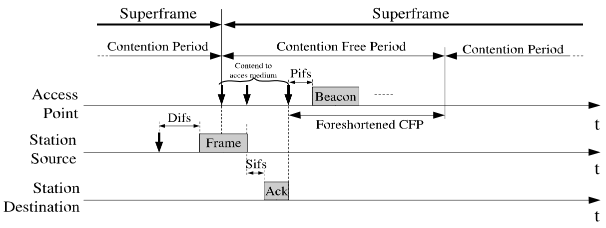

Figure 2. example of Foreshortened CFP

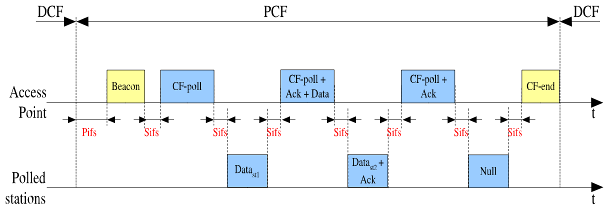

Figure 3. PCF frame transfer

Thereafter, the AP polls each stations, according to a polling list, by sending a CF_Poll frame. The list of all pollable stations is built on the CF-pollable subfield using by stations at the time of the association and reassociation request frames. A typical sequence of frames during PCF is shown in Figure 3. A polled station may only transmit a data frame without contending for the channel. Stations always responds to a poll. If there is no pending transmission, the response is a null frame containing no payload. In case of an unsuccessful transmission, the station retransmits the frame after being repolled or during the next Contention Period. A CF_ACK frame is used to acknowledge receipt of the previous data frame. Note that the efficient medium use is possible to piggyback both the acknowledgement and the CF_Poll onto data frames. All stations will hear the message due to the shared medium, so the acknowledgment is not necessarily for the polled station. This continues for $CFP\_Max\_Duration$. The AP explicitly terminates the Contention Free Period by transmitting a Contention Free (CF_End) frame. A new DCF period starts. If the polling list is empty before the $CFP\_Max\_Duration$, the AP may shorten the period in order to provide the remainder of the repetition interval for the DCF mode.

Others communications may be supported during the Contention Free Period. A polled station can send data either a pollable station or a non-pollable station which does not appear in the polling list. If the data message received by AP is destined to a pollable station, it sends a piggybacked $Data + CF\_Poll$ frame to the destination station at the next round. Otherwise, it will send data message to the non pollable station before continue its normal operations.

2.3 ICS and stations polling list

ICS data traffic consists of time-critical and non time-critical messages. Time-critical traffic is established by short and frequent time-critical messages. In most of cases, it includes periodic variables which require cycle times varying generally between 10 milliseconds and 100 milliseconds, and aperiodic variables upon alarms or device status events. Such variables are typically a few bits long. A periodic message, M_i is exchange at regular intervals P_i with a known and constant length L_i and a deadline D_i. To satisfy the message requirements, scheduling algorithm must be used and gives the timeline of the periodic messages. The microcycles are elementary cycles included within a macrocycle which is the repetition period of the whole sequence. The macrocycle and microcycle durations correspond to the least common multiple and the highest common factor of the required periodicities P_i, respectively. Within a microcycle, each message is generate by a distinct station, so the timeline of the messages correspond to the timeline of stations which must be polled. Thus, the superframe duration must be equal to the microcycle duration and each microcycle pattern must be runned entirely in a PCF period as shown in Figure 4. In addition, the messages deadline constraint will be respected if the maximum PCF duration is lower than the lowest messages deadline, i.e.

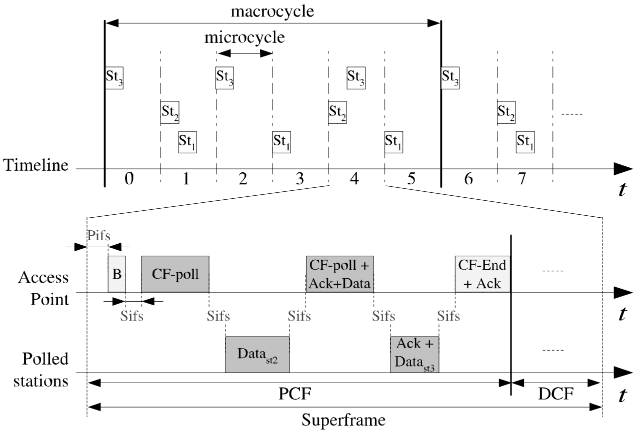

Figure 4. Timeline of pollable stations

$\forall D_i \rightarrow Di \geq CFP\_Max\_Duration$.

Time-critical aperiodic messages have also an hard deadline. To respect their deadline, stations which generate it, are pollable stations and must be also in the polling list. Thus, these messages can be considered as periodic messages with a periodicity equal to their deadline. The perfomance analysis which will be presented in the following section, does not require to distinguish periodic and aperiodic messages.

3 Performance analysis of wireless ICS based on 802.11g

Consider an industrial communication system. Let be $\{M_i\}$ the set of time-critical messages with known properties. We assume that the polling list is established from the timeline produced by an appropriate scheduling algorithm as shown in section 2.3. Let be $\{ST_{ij}\}$ this polling list where ST_{ij} is the i^{th} pollable station of the j^{th} microcycle within macrocycle. ST_{ij} is characterised by (W_{ij}, R_{ij}), where W_{ij} is the size of writing variable (data exchanged from AP to station), R_{ij} is the size of reading variable (data exchanged from station to AP). Both W_{ij} and R_{ij} are expressed in bytes. All stations do not require necessarily writing and reading variables. For instance, the couple $(0, R_{ij})$ represents a station which sends a variable and does not receive any.

Given $\{ST_{ij}\}$ and the set of associated variables, $\{(W_{ij}, R_{ij})\}$,we present below a performance analysis of 802.11g wireless ICS considering that the time-critical messages are handled during the contention free period. This theorical analysis will be used to :

- determinate the maximum delay of the foreshortened CFP,
- determinate the required CFP duration to accomplish properly each of poll-based microcycles,
- determinate the $CFP\_Max\_Duration$ parameter to be configured in the AP so that the effective CFP duration is always sufficient, even if CFP is foreshortened,
- determinate an approximation of the maximum DCF throughput in regard to the non time-critical data traffic.

3.1 Problem of the foreshortened CFP delay

A foreshortened CFP may occur when the access point is prevented from accessing the channel due to busy medium. So, it is necessary to take into account the additional delay involved to determine the $CFP\_Max\_Duration$ parameter. In the worst case, a node starts a transmission of a maximum size frame just before the CFP should start, i.e. just before the AP sends the beacon. Thus, the maximum foreshortened CFP delay is equal to one $PIFS$ more the transmission times for an RTS frame, a CTS frame, a maximum size data frame and one ACK frame, more three $SIFS$ inserted between theses frames.

Since the 802.11 MAC layer can be implemented on a variety of underlying physical (PHY) technologies, the delay computation is dependent of the PHY specification which is used. We present below the case of the Orthogonal Frequency Division Multiplexing (OFDM) PHY defined by 802.11g which supports data rates at up 54 Mbps. Note that 802.11g also supports complementary code keying modulation for backward compatibility with 802.11b.

We will use the notation as specified in Table 1 for the description of the IEEE 802.11 parameters and their values. Note that the MAC header pattern is a 30 bytes long. However, this contains only three address fields when wireless communication from AP to AP is not considered. Thus, we use a 24 bytes long.

Notation	Parameter description	Value
SIFS	*SIFS* time used by OFDM PHY	16 µs
PIFS	*PIFS* time used by OFDM PHY	25 µs
DIFS	*DIFS* time used by OFDM PHY	34 µs
PHY_{Pb}	Preamble time used by OFDM PHY	16 µs
Ts	OFDM symbol time slot	4 µs
SIG	Signal field time with OFDM PHY	$1 * Ts$
SRV	Service field length with OFDM PHY	16 bits
TAIL	Tail field length with OFDM PHY	6 bits
BEACON	*BEACON* frame length with OFDM PHY	852 bits
MAC_{Hd}	Header length of data *MAC* frame	192 bits
MAC_{Fcs}	FCS length of any *MAC* frame	32 bits
RTS	*RTS* frame length	160 bits
CTS	*CTS* frame length	112 bits
ACK	*ACK* frame length	112 bits
END	*END* frame length	160 bits

Table 1. 802.11 parameters notation

OFDM PHY first divides a high-speed binary signal to be transmitted into a number of lower data rate subcarriers. There are 52 subcarriers, of which 48 subcarriers carry actual data and 4 subcarriers are pilots that facilitate phase tracking for coherent demodulation. Each lower data rate bit stream is used to modulate a separate subcarrier from one of the channels in the 2.4 GHz band. OFDM PHY supports eight different data rates, 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. Forward error correction is performed by bit interleaving and convolutional coding, the coding rate depending to the transmission data rate which is selected.

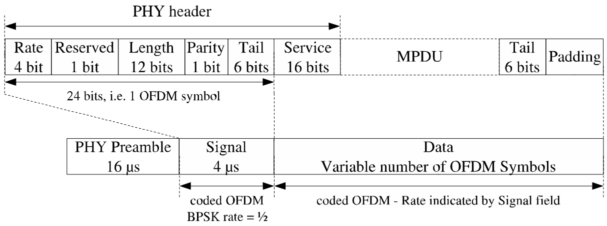

Figure 5. PPDU format with OFDM PHY

The PPDU consists of a PHY preamble, a signal field and a PHY data part as shown in Figure 5. The PHY preamble is used to acquire the incoming signal and train and synchronize the receiver. This is composed of ten repetitions of a short training sequence (0.8 μs) and two repetitions of a long training sequence (0.4 μs). The training of an OFDM is accomplished in 16 μs. The PHY header is divided into two parts, the signal field and the service field. The signal is a 24 bits field, which contains information about the rate and length of the PHY data part. The PHY data part contains a 16 bits service field, the MPDU, 6 tails bits, and a padding field. The tail bits are used to ensure the convolutional encoder is brought back to zero state. The pad bits are used to align data bits into a multiple of OFDM symbols. Each OFDM symbol interval is 4 μs. The PHY preamble and the signal field are always transmitted at 6 Mbps, using BPSK-OFDM modulation and convolutional encoding rate of $1/2$. An OFDM symbol represents, in this case, 6 Mbps $*4$ μs $=$ 24 bits of true data, thus signal field is accomplished in one symbol, i.e. 4 μs. The PHY data part is transmitted at 6, 9, 12, 18, 24, 36, 48 or 54 Mbps as determined by the content in the signal field, using modulation and coding rate in relation with the selected transmission rate. Being given any MPDU, let s be its size, in $bits$ and $r \in R_{OFDM} = \{6, 9, 12, 18, 24, 36, 48, 54\}$ its data transmission rate, in Mbps. The MPDU transmission time, in μs is formulated by the generic function, $\digamma\,(s, r)$ as presented in equation 1 where the notation $\lceil x \rceil$ means "round x to the smallest integer not less than x":

$$\digamma\,(s, r) = Ts * \left(5 + \left\lceil \frac{SRV + s + TAIL}{r * Ts} \right\rceil\right) \qquad (1)$$

In the worst OFDM PHY case, the contention free period will be foreshortened of a time depending to the data rate and the Maximum Transmission Unit (MTU). Let be $D_{CFP}(r, MTU)$ the maximum delay of the foreshortened CFP as a function of the data rate, r and the MTU size. This function is given by the equation 2 :

$$\begin{aligned} D_{CFP}(r, MTU) \quad = \quad & PIFS + 3 * SIFS + \\ & \digamma\,(RTS, r) + \digamma\,(CTS, r) + \\ & \digamma\,(ACK, r) + \digamma(MAC_{Hd} + \\ & MTU + MAC_{Fcs}, r) \qquad (2) \end{aligned}$$

where D_{CFP} is expressed in μs, MTU represents the maximum payload length of the data frame which involves the delay of next CFP, in $bits$, and r is the rate used to transmit the data frame. We assume RTS, CTS and ACK frames are transmitted at the same rate than the data frame[1]. For all data rates supported by OFDM PHY, the computed values of D_{CFP} are shown in Table 2. We have considered two configurations of the MTU. The first one is a 2312 bytes MTU, as defined in the standard. The second one is a 1500 bytes MTU which ensures a seamless frame-compliance between wired and wireless networks.

With a 2312 bytes MTU, an additional delay of approximately 3.4 ms will be possible at 6 Mbps, before time-critical variables are handled. The results are better for higher data rates. In particular, the delay will be lower than 1 ms for data rates varying from 24 to 54 Mbps. A way to decrease the delay is to configure MTU to a smaller value, as shown with 1500 bytes MTU. In this case, the delay is reduced by 23% (at 54 Mbps) and 32% (at 6 Mbps). The assessment of these values must be performed in relation to the ICS requirements. For instance, consider an ICS with microcycles of 20 ms. When the MTU is fixed to 2312 bytes, the foreshortened CFP delay represents 16.8%, 4.8% and 2.6% of the microcycle time respectively at 6, 24 and 54 Mbps. For a MTU of 1500 bytes, its represents 11.5%, 3.5% and 2%. Thus, this delay could be annoying with the lowest data rate.

3.2 Required CFP duration for a poll-based pattern

Given $\{ST_{ij}\}$ and the set of associated variables,$\{(W_{ij}, R_{ij})\}$, the pattern of pool-based frame exchanges in a CFP can be described. It starts with a $PIFS$, followed by a beacon frame. The next frames are transmitted for polling the stations, then the CFP is ended by a CF_End frame. From this pattern, we can compute the minimum CFP duration required to accomplish the whole frames sequence. Let be $T_j\,(r)$, the required CFP duration for the j^{th} microcycle as a function of the data rate. $T_j\,(r)$ is computed by equation 3.

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[1] This hypothesis is valid when r value is preset in BBS basic rate set for all stations in the BSS.

				Maximum foreshortened CFP delay (μs)	
r (Mbps)	Modulation	Coding rate	Coding scheme	MTU = 2312 bytes	MTU = 1500 bytes
6	BPSK	1/2	OFDM	3356	2276
9	BPSK	3/4	OFDM	2288	1568
12	QPSK	1/2	OFDM	1756	1216
18	QPSK	3/4	OFDM	1224	864
24	16-QAM	1/2	OFDM	960	688
36	16-QAM	3/4	OFDM	692	512
48	64-QAM	2/3	OFDM	556	420
54	64-QAM	3/4	OFDM	512	392

Table 2. Maximum foreshortened CFP delay with OFDM PHY

$$\begin{aligned}
T_j(r) &= PIFS + \digamma\,(BEACON, r) + \sum_{i=1}^{n}(SIFS + \\
&\quad \digamma(MAC_{Hd} + W_{ij} + MAC_{Fcs}, r)) + \\
&\quad \sum_{i=1}^{n}(SIFS + \\
&\quad \digamma\,(MAC_{Hd} + R_{ij} + MAC_{Fcs}, r)) + \\
&\quad SIFS + \digamma\,(END, r) \\
&= PIFS + \digamma\,(BEACON, r) + \\
&\quad 2 * (n+1) * SIFS + \\
&\quad \sum_{i=1}^{n}(\digamma\,(MAC_{Hd} + W_{ij} + MAC_{Fcs}, r) + \\
&\quad \digamma\,(MAC_{Hd} + R_{ij} + MAC_{Fcs}, r)) \qquad (3)
\end{aligned}$$

3.3 Determination of $CFP\_Max\_Duration$ parameter

The $CFP\_Max\_Duration$ value which will be configured in the AP corresponds to the addition of two worst values : The first one is the highest CFP duration, $T_j(r)$ required to accomplish each of j poll based cycles issued from $\{ST_{ij}\}$. The second one is the maximum delay of the foreshortened CFP. From equations 2 and 3, the value of $CFP\_Max\_Duration$ is computed by the equation 4

$$CFP\_Max\_Duration = \max_{\substack{j \in [1,m], \\ r \in R_{OFDM}}} \{T_j(r) + D_{CFP}(r, MTU)\} \qquad (4)$$

3.4 Approximation of the DCF throughput

As the duration of the PCF mode is variable from a microcycle to another, the duration of DCF varies also within the constant $Superframe$ interval. The duration of the $Superframe$ is defined by the CFP_Rate manageable parameter. The amount of time allocated to DCF mode can be derived from equation 3 which computes the duration of each PCF period. Let be S_{DCF} defined as the maximum amount of payload bits which can be transmitted by unit of time in DCF mode. Given r in Mbps and MTU in bits, an approximation of S_{DCF} is computed by the equation 5, the probability of collision being ignored.

$$S_{DCF} = \frac{MTU}{m * CFP\_Rate} * \sum_{j=1}^{m} \left\lceil \frac{CFP\_Rate - T_j(r)}{t_{unit}} \right\rceil \qquad (5)$$

with :

$$\begin{aligned}
t_{unit} &= DIFS + 3 * SIFS + \\
&\quad \digamma\,(RTS, r) + \digamma\,(CTS, r) + \\
&\quad \digamma(MAC_{Hd} + MTU + \\
&\quad MAC_{Fcs}, r) + \digamma\,(ACK, r)
\end{aligned}$$

4 Numerical application

In this section, we study an example of a distributed system with 15 stations. These stations generate or receive a set of 17 time-critical messages whose characteristics are known and summarized in Table 3. The data size varies between 1 byte and 16 bytes, and the period from 10 to 100 ms. Note that stations with readable variables will be produced in response to a CF_POLL. Also, writable messages will be conveyed by the AP with biggypacked frame $CF\_POLL + Data$.

Let be a timetable scheduling algorithm providing the timeline of stations which are to be periodically polled. We have obtained a timeline with 20 elementary cycles. The microcycle duration which corresponds to the highest common factor of the required periodicities, is 10 ms. Several microcycles are redondant during the macrocycle and we have distinguish 5 different patterns. They are illustrated in Table 5. From the equation 3, we have computed the required Contention Free Period duration for each pattern, according to the Physical layer used. Figure 6 shows the obtained results with the additional delay due to the foreshortened CFP. This delay has been computed with a MTU of 1500 bytes and added to the required CFP duration. We notice each pattern gives a CFP period (and the $Superframe$) lower than 10 ms (the microcycle). The worst pattern which is the pattern 5, corresponds

Station	Data size ($bytes$)		Period P_i (ms)	Station	Data size ($bytes$)		Period P_i (ms)
	Read	Write			Read	Write	
1	1	–	10	9	4	–	20
2	1	–	10	10	4	–	20
3	8	–	10	11	–	1	40
4	8	–	10	12	–	8	40
5	8	–	10	13	8	–	40
6	16	8	20	14	4	–	100
7	16	8	20	15	4	–	100
8	4	–	20				

Table 3. Data size and period of each message

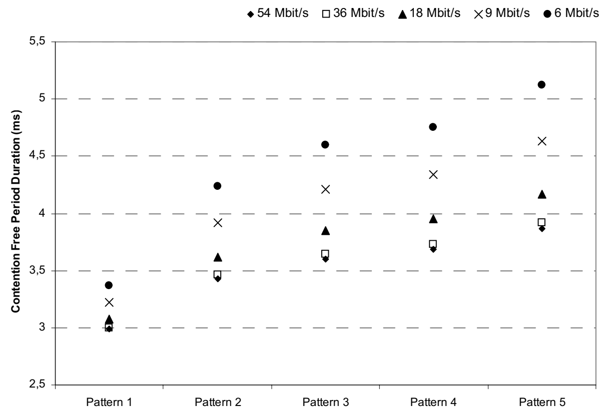

Figure 6. CFP duration for each pattern with a timetable scheduling

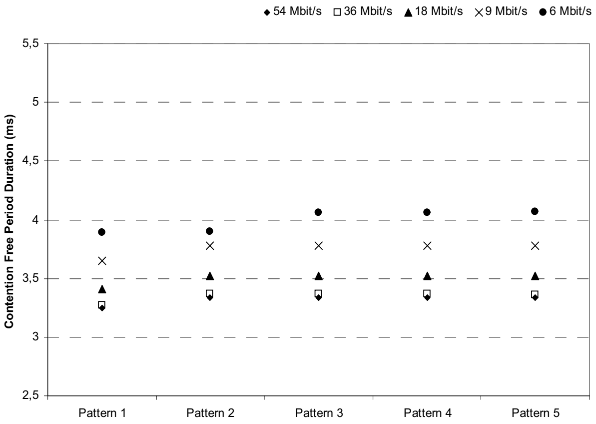

Figure 7. CFP duration for each pattern with an optimized scheduling

to the exchange of all the messages over the network in the same microcycle. In this case, the maximum duration of the PCF period is 5.12 ms at 6 Mbps and 3.87 ms at 54 Mbps. The deadlines of time critical will be never exceeded.

Consider now an optimized scheduling of the same messages. The timeline always provides 5 different patterns within the 20 elementary cycles. However, these patterns which are presented in Table 6 are not similar with the previous case. The obtained results are illustrated in the Figure 7. We can notice that the worst pattern is represented by the pattern 4 and 5 which have different microcycles with the same required Contention Free Period duration.

The Maximum PCF duration has been improve from 5.12 ms to 4.07 ms. This is due to the optimized scheduling which leads to the pattern smoothing within all microcycles. Moreover, the required CFP time is also smoothed. The alloted time for the DCF period will change for each microcycle, but it will not change significantly within the macrocycle. Consequently, the DCF throughput, S_{DCF} do not vary much whatever the scheduling algorithm used, as shown in Table 4. The maximum DCF throughput which will be available to transmit non critical-time traffic, is 0.45 Mbps at the lowest data rate. At 54 Mbps, the maximum DCF throughput is.close to 2, 5 Mbps.

r (Mbps)	timetable algorithm	optimized algorithm
6	0.45	0.45
9	0.68	0.68
12	0.86	0.90
18	1.16	1.20
24	1.46	1.50
36	2.02	1.95
48	2.43	2.40
54	2.58	2.55

Table 4. DCF throughput

5 Conclusions

In this paper, we have stutied the feasability of building wireless industrial communication systems based on IEEE 802.11g technology. According to IEEE 802.11 specifications, we have considered the infrastructure mode with

	Stations														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pattern 1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Pattern 2	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Pattern 3	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1
Pattern 4	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Pattern 5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 5. Microcycle patterns

	Stations														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pattern 1	1	1	1	1	1	1	0	1	0	1	0	0	0	0	0
Pattern 2	1	1	1	1	1	0	1	0	1	0	1	0	0	0	0
Pattern 3	1	1	1	1	1	0	1	0	1	0	0	1	1	0	0
Pattern 4	1	1	1	1	1	1	0	1	0	1	0	0	0	0	1
Pattern 5	1	1	1	1	1	1	0	1	0	1	0	0	0	1	0

Table 6. Microcycle patterns after the optimisation process

both DCF and PCF functions. The periodic and aperiodic messages are handled during the contention free period. The main contribution of this paper is a performance analysis of the contention free period. From this analysis, we can verify that a $802.11g$-based ICS is able to support real-time constraints, being given the messages scheduling. The results show that 802.11g technology offers suitable performances to support time-critical data traffic. The main conditions are the following :

- the higher data rates in BSS basic rate must be set for all stations in the BSS,
- applications with adequate deadlines must be considered (higher than $5ms$),
- the applications are fault-tolerant as the packet losses are inevitable.

If these conditions are respected, the use of $802.11g$ as wireless industrial network is possible and the performance analysis may be used to configure the MIB variables CFP_Rate and $CFP\_Max\_Duration$.

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