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Toni Fernando Flores Pulgar, Jean-Luc Scharbarg, Katia Jaffrès-Runser,
Christian Fraboul

► To cite this version:

Toni Fernando Flores Pulgar, Jean-Luc Scharbarg, Katia Jaffrès-Runser, Christian Fraboul. Extending real-time networks over WiFi: related issues and first developments. 25th Euromicro Conference on Real-Time Systems (ECRTS13), Jul 2013, Paris, France. pp.0. hal-01143765

HAL Id: hal-01143765

<https://hal.science/hal-01143765>

Submitted on 20 Apr 2015

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To cite this version : Pulgar, Tony Flores and Scharbarg, Jean-Luc and Jaffrès-Runser, Katia and Fraboul, Christian Extending real-time networks over WiFi: related issues and first developments. (2013) In: 25th Euromicro Conference on Real-Time Systems (ECRTS13), 9 July 2013 - 12 July 2013 (Paris, France).

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Extending real-time networks over WiFi: related issues and first developments

Tony Flores Pulgar, Jean-Luc Scharbarg, Katia Jaffrès-Runser, Christian Fraboul
University of Toulouse, IRIT / ENSEEIHT
2 Rue Charles Camichel - F-31061, Toulouse, FRANCE
firstname.lastname@enseeiht.fr

Abstract—The flexibility of wireless connectivity is appealing in the context of real-time industrial networks. This paper discusses the use of wireless communication protocols to interconnect remotely located fieldbuses. The focus of this paper is to analyze the feasibility and design issues related to this type of hybrid real-time network architecture. Investigations are presented by addressing an interconnection through the well-mastered WiFi technology. On an example architecture, we discuss the impact of the different distributed medium access protocols available (DCF, EDCA) on the real-time flows. We outline the main design issues related to these choices and illustrate them on a first case study where remotely located CAN buses are interconnected through an IEEE802.11g network in DCF mode. Using this very simple and cost-effective architecture, we show as a first result that transmitting soft real-time data over such an architecture is feasible.

Keywords—Hybrid real-time networks, interconnection, IEEE802.11, DCF, EDCA

I. INTRODUCTION

Industrial fieldbus technologies are widely rolled out to offer real-time communication capabilities on the factory floor. A large set of protocols offer deterministic and timely bounded transmissions using tailored medium access schemes and architectures (e.g. PROFIBUS, PROFINET, TTEthernet, etc.).

Recent developments for industrial communications consider introducing wireless transmissions into the global network architecture [1][2]. First studies have assessed the capabilities of mainstream wireless technologies such as WiFi (IEEE802.11 [3]), Bluetooth or ZigBee (IEEE802.15.4) [2] for real-time communications. In parallel, new real-time wireless protocols have been designed [4][5][6]. Recently, two TDMA-oriented solutions (WirelessHART and ISA100.11a) have been commercialized for factory automation applications [6]. The main pitfall of wireless communications is of course the increased unreliability the medium suffers from due to interference and pathloss compared to shielded wires.

Among others, one of the interesting benefits of wireless transmissions is to provide a cost-effective network to interconnect distant heterogeneous or homogeneous legacy fieldbuses. The focus of this paper is to discuss this use case of wireless communications.

A wireless interconnection will benefit architectures where several fieldbuses, located far from each other, need a backhaul network to exchange data. Depending on the application, this data may be time-sensitive in the hard or in the soft sense. Either legacy wireless technologies such

as WiFi (IEEE802.11 technology) or dedicated wireless protocols such as WirelessHART may be chosen, depending on the nature of the traffic exchanged between the remote buses.

For hard real-time data, a dedicated reliable wireless solution has to be picked, while for soft real-time data, a cheaper and probably less reliable wireless technology can be chosen. This paper focuses on this last case, where off-the-shelf WiFi controllers are used to interconnect remote real-time buses. Several Medium Access Control (MAC) protocols are available with the IEEE802.11 technology. A first discussion presents the benefits and issues related to these MAC protocols to carry soft real-time data on an example hybrid network architecture.

This discussion is then illustrated with a first case study where remotely located CAN buses [7] are interconnected through an IEEE802.11g network using a decentralized MAC protocol relying on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Using this very simple and cost-effective architecture, we show that transmitting soft real-time data over such an architecture is feasible, provided some design issues are correctly accounted for (e.g. gateway policies, wireless network load, interference, ...).

Section II illustrates the hybrid architecture we consider with an example network. Then, Section III discusses the problem of using WiFi to interconnect the remote real-time networks using different distributed IEEE802.11 MAC protocols. Next, Section IV presents the first results of extending CAN networks over IEEE802.11 DCF. Finally, Section V concludes this paper.

II. TARGET INTERCONNECTION ARCHITECTURE

An example of the type of hybrid architecture of interest in this paper is described in Figure 1. In this example, four real-time buses are interconnected through a wireless local area network that follows the mainstream IEEE802.11 standard [3].

To interconnect the real-time buses of Figure 1, four dedicated wireless gateways are implemented composed of a real-time controller and a wireless IEEE802.11 interface. Additional wireless transmitters are represented in this architecture, emitting pure wireless traffic with non real-time guarantees. All wireless transmitters may be connected in ad hoc mode (distributed medium access) or using a central controller localized in an Access Point (AP). Such an AP is not represented in Figure 1 but may be necessary

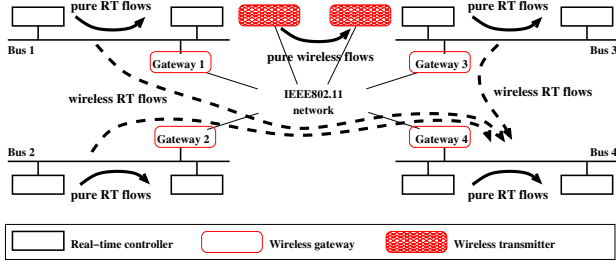


Figure 1. Interconnection architecture overview

for the study of centralized medium access versions of IEEE802.11 or even enhanced distributed ones.

A. Transmitted flows

Three types of flows are depicted in Figure 1:

- **pure RT flows** are periodic real-time flows local to the real-time bus. They *never* transit on the wireless network.
- **pure wireless flows** are *non real-time* Poisson flows local to the wireless network. They are competing for the medium with the wireless real-time flows emitted by the gateways.
- **wireless RT flows** are periodic real-time hybrid flows transmitted between controllers connected to different real-time buses: they transit on both wired and wireless networks via the gateways and are time-constrained.

Unique to pure and wireless RT flows, all frames have a critical delay which is the maximum allowed duration between their generation and reception times at their destination controllers.

III. INTERCONNECTION VIA WiFi

A. IEEE 802.11 MAC protocol overview

IEEE 802.11-2012 [3] defines several standards to offer a wireless connectivity at transmission rates ranging from 11Mbps (e.g. legacy versions such as IEEE802.11b) up to 600Mbps (IEEE802.11n). Bandwidth increase is due to improvements at the physical layer (OFDM, larger bandwidth, MIMO transmissions, etc.). Next generation physical layers are expected to increase data rates beyond 600Mbps (cf. IEEE802.11ac).

The fundamental medium access in IEEE 802.11 is a Distributed Coordination Function (DCF) which is a distributed random access scheme based on CSMA/CA. Additional protocols are defined to meet specific requirements but all use the service provided by DCF as shown on the MAC architecture in Fig. 2. For instance, the Point Coordination Function is a centralized protocol where an Access Point (AP) provides a contention-free medium access. Quality of Service (QoS), where channel access is differentiated for different classes of service, is introduced with the Hybrid Coordination Function (HCF) either in a distributed manner (EDCA protocol) or in a centralized

manner (HCCA protocol). Finally, wireless meshed networks architectures can be handled in a controlled fashion with the MCCA protocol.

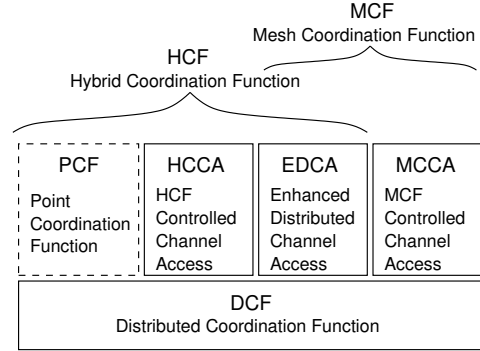


Figure 2. IEEE802.11 MAC (source: [3])

This paper discusses the use of the distributed medium access protocols (DCF and EDCA) since they are widely deployed and available for of-the-shelf designs. Thus, since these access are random based, only soft-real time data can be envisioned on this type of architecture. For more real-time constrained data, it is clear that further studies using centralized HCCA or even MCCA protocols should be performed.

B. Distributed medium access with IEEE802.11

This section introduces the main characteristics of the distributed MAC protocols of IEEE802.11, namely DCF and EDCA protocols. It discusses their implementation aspects in the context of real-time bus interconnection.

In DCF mode: a station performs carrier sensing to detect ongoing communications. If the channel is free for a period of time called Distributed InterFrame Space (*DIFS*), it transmits its frame immediately. If the channel is sensed busy, it defers its transmission until the end of the current transmission. Then, the station selects a random backoff b following an exponential backoff scheme. If the medium is idle for a *DIFS* period of time, the backoff is decremented every *aSlotTime* duration. The backoff interval time is decremented as long as the channel is idle and is frozen as the node detects a transmission. At the end of this transmission, when the channel remains idle during *DIFS*, decrementation resumes. As b reaches zero, the transmission is attempted immediately by the station. After a successful transmission, the receiver sends an ACK after a duration called Short Inter Frame Space (*SIFS*). If no ACK is received by the emitter after an Extended Interframe Space (*EIFS*), the transmission is tried again.

A new backoff b is then uniformly chosen in the range $[0, w - 1]$ where w is the contention window. This window depends on the number of failed attempts experienced by the current transmission. At the first attempt w is equal to the minimum contention window CW_{min} . Each unsuccessful transmission involves the multiplication of w by 2 until a maximum value of CW_{max} is reached.

DCF mode doesn't guarantee any prioritized access for real-time wireless frames. Thus, the real time traffic

created by the gateways is directly competing with the pure wireless flows of non-real time nodes. In order to achieve a soft real-time guaranty, the interconnection policies implemented at the wireless gateways have to be designed with the aim of reducing the number of collisions of RT flows that occur on the wireless medium with DCF mode. This can be arranged by selecting, in a timely manner, the RT frames to be encapsulated in the wireless RT frames as we will investigate in Section IV.

In EDCA mode: QoS is being introduced on top of DCF so as to provide different levels of priority to wireless transmissions. A wireless node requests a transmission opportunity (TXOP) which is an interval of time when a particular quality-of-service (QoS) station (STA) has the right to initiate frame exchange sequences onto the wireless medium. A TXOP is defined by a starting time and a maximum duration. The TXOP is obtained by a station by successfully contending for the channel in EDCA. During an EDCA TXOP, a STA may initiate multiple frame exchange sequences.

EDCA defines four access (or traffic) categories ranging from background (lowest priority), best effort, video to voice traffic (highest priority). All nodes emitting flows in the *same* access category AC contend for TXOPs together using their own set of EDCA parameters which are given by the triplet (AIFS[AC], $CW_{min}[AC]$, $CW_{max}[AC]$). The AC with the highest priority has the lowest parameter values among all ACs so as to have a higher probability to access channel first if contending with lower priority AC data frames. If there are frames with different ACs waiting in the output queue of at the same STA, collisions between them are resolved within the STA so that the data frames of higher priority compete for the channel. Remaining lower priority frames behave as if there was an external collision on the medium.

Interconnecting real-time buses using EDCA will be more challenging than using DCF because several options are available. First, besides defining encapsulation policies, the wireless RT flows have to be properly allocated to ACs. This can be done statically by the gateways. Another more subtle adaptation resides in the development of a dynamic adjustment of the EDCA parameters for each AC based on end-to-end delay statistics and missed-deadline rates, using monitoring. This last issue is an ongoing work which is not further addressed in this paper.

IV. A FIRST STUDY: CAN OVER DCF

Interconnection of a real-time bus with IEEE802.11 in DCF mode is investigated in the following. The real-time bus of interest is the well known Controller Area Network (CAN) [7] standard.

A. Investigated architecture

CAN is one of the mainstream standards for embedded communications. Despite the fact that it has been originally developed for automotive communications, CAN has found its place in factory automation applications to handle sensor-actuator communications because of its

ease of use and the low cost of its controllers. We recall that CAN medium access is based on CSMA/CR (with Collision Resolution): the start of frame transmissions on the bus are synchronous. When two or more stations start a transmission simultaneously, the one with the smallest frame identifier wins and the others stop their transmission. This mechanism guarantees strict priority order on identifiers. It implies limitations on the bandwidth and the maximal length of the bus (e.g. 1 Mbps for 40 meters). Bit-stuffing is used to avoid the transmission of long sequences of bits with identical value. The computation of the frame length has to take into account these additional bits. In this paper, we use the upper bound given in [8]. The length C of a frame carrying x bytes of data is:

$$C = (55 + 10 \times x) \quad (1)$$

In this example, all wireless nodes (gateways, pure wireless emitters) function in ad hoc mode using DCF medium access protocol following the specification of the OFDM-PHY layer of 802.11g (20 MHz channel spacing). Since WiFi access points are static, we can consider that they are located at a distance where they can operate at the highest rate of 54 Mbps. We assume proper channel assignment has been performed so as to mitigate inter-node interference. In this ideal case study, transmissions are error-free and the transmission duration (in μ s) at 54 Mbps of a MPDU of x bytes is derived according to [3]:

$$d(x) = 20 + 4 \left\lceil \frac{22 + 8(34 + x)}{216} \right\rceil \quad (2)$$

Following timing parameters are assumed: $SIFS = 16\mu$ s, $DIFS = 34\mu$ s, $EIFS = 78\mu$ s, $CW_{min} = 16$ and $CW_{max} = 1024$.

B. Wireless gateway policies

As stated earlier, for DCF mode, interconnection policies at the gateway are crucial to ensure a timely distribution of wireless RT frames. Interconnection is done by encapsulating CAN frames of the wireless RT flows into IEEE802.11 frames. Encapsulation is chosen to facilitate the addressing of flows in the global network, and thus a basic static switching table is stored at the gateways to route wireless RT flows.

A gateway encapsulation strategy is characterized by the following parameters:

- The maximum number $N_{\ell,m}$ of CAN frames which can be encapsulated by gateway ℓ for destination gateway m in one IEEE802.11 frame,
- The maximum time W_{max_j} a frame of a wireless RT flow fH_j can wait in its source gateway.

C. Results

Table I summarizes the strategies analyzed in this study on the illustrative configuration of Figure 1. Each CAN bus carries 4 pure RT flows. Each bus 1, 2 and 3 are respectively the source of 8 wireless RT flows each which are all transmitted to bus 4. These wireless RT flows have a period and a critical delay of 10ms each. The size in bytes

for each of these 8 flows are equally distributed between 2, 4, 6 and 8 data bytes.

The encapsulation strategies of Table I are considered, where uniform timers are assigned to the flows. T0 denotes a basic strategy where one CAN frame is encapsulated in exactly one wireless frame. T2, T3 and T4 are purely timed strategies where CAN frames wait for at most 2, 3 and 4ms respectively.

T0	$N_{\ell,m} = 1$	$Wmax_j = 0 ms \forall j$
T2	$N_{\ell,m} = 100$	$Wmax_j = 2 ms \forall j$
T3	$N_{\ell,m} = 100$	$Wmax_j = 3 ms \forall j$
T4	$N_{\ell,m} = 100$	$Wmax_j = 4 ms \forall j$

Table I
SIMULATED STRATEGIES

A quantitative analysis of the proposed bridging strategies has been conducted. This analysis is based on simulations. Therefore, a home-made simulation tool has been developed using QNAP2 [9]. Table II gives results concerning the utilization of the wireless medium. The study is conducted with different numbers of identical pure wireless flows fW (between 4 and 7), all of them with an average period of 2ms and for packets of 200 data bytes.

		T0	T2	T3	T4
$\frac{\sum fW_j}{fW_1}$		4.8	1.9	1.4	1.2
4	% Col	2.2	0.8	0.8	0.7
fW flows	AvgD	250	169	162	158
5	% Col		1.3	1.2	1.1
fW flows	AvgD		199	189	184
6	% Col		2.0	1.8	1.6
fW flows	AvgD		242	227	220
7	% Col			2.7	2.5
fW flows	AvgD			287	274

Table II
IEEE802.11 RESULTS

The first line of the table shows the relative number of IEEE802.11 frames generated by wireless RT flows. The number of IEEE802.11 frames decreases when the value of the timer increases. Indeed, the average number of wireless RT frames encapsulated in an IEEE802.11 frame increases when the timer increases. Table II also shows the percentage of collisions (% Col) and the average delays (AvgD) of pure wireless flows for each strategy and each simulated scenario (i.e. number of pure wireless flows). Empty values mean that the wireless network is saturated and transmission delays diverge. It can be noticed that these percentages of collisions and delays are deeply linked to the number of contending IEEE802.11 frames.

Table III presents the rates of wireless RT frames which miss their deadlines. More precisely, each value in Table III is the average number of wireless RT frames that miss their deadlines when 10^6 of such frames are generated and transmitted. The main result of Table III is that it is still possible to reach a reasonably low value of missed deadlines (up to 200 every 10^6 frames) with the use of DCF when a limited number of pure wireless flows (up to 7) is present in the network.

It can be inferred from these results as well that there is a trade-off between the time spent waiting at the gateway due to $Wmax_j$ and the time spent contending for the wireless medium. In this very simple example, it can be seen that the best trade-off is obtained with T3

nb. of fW flows	T0	T2	T3	T4
4	1	0	0	0
5		0	0	3
6		21	19	20
7			200	200

Table III
MISSED DEADLINES FOR WIRELESS RT FLOWS

V. CONCLUSION

The motivation of this paper is to highlight that IEEE802.11 technology is a credible solution for inter-connecting remote field buses when soft real-time data are exchanged between these buses. Future work needs to discuss the improvements provided by enhanced medium access protocols of IEEE802.11, including QoS capabilities and/or centralized mechanisms. Even though IEEE802.11 is the mainstream wireless technology, it is topical as well to evaluate the benefits of a dedicated wireless real-time protocol such as WirelessHART or ISA100.11a.

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