Handling Real-Time Communication in Infrastructured IEEE 802.11 Wireless Networks: The RT-WiFi Approach

Robson Costa, Jim Lau, Paulo Portugal, Francisco Vasques, and Ricardo Moraes

Abstract: **In this paper, the RT-WiFi architecture is proposed to handle real-time (RT) communication in infrastructured IEEE 802.11 networks operating in high density industrial environments. This architecture is composed of a time division multiple access (TDMA)-based coordination layer that schedules the medium access of RT traffic flows, and an underlying traffic separation mechanism that is able do handle the coexistence of RT and non-RT traffic sources in the same communication environment. The simulation assessment considers an overlapping basic service set (OBSS), where a set of RT and non-RT stations share the same frequency band. The performance assessment compares the behaviour of the RT-WiFi architecture vs. the behaviour of standard distributed coordination function (DCF), point coordination function (PCF), enhanced distributed channel access (EDCA), and hybrid coordination function (HCF) controlled channel access (HCCA) medium access control mechanisms. A realistic error-prone model has been used to measure the impact of message losses in the RT-WiFi architecture. It is shown that the proposed RT-WiFi architecture offers a significantly enhanced behaviour when compared with the use of IEEE 802.11 standard mechanisms, in what concerns average deadline misses and average access delays. Moreover, it also offers an almost constant access delay, which is a relevant characteristic when supporting RT applications.**

Index Terms: **Admission control, IEEE 802.11 networks, OBSS, real-time communication, TDMA communication, wireless networks.**

I. INTRODUCTION

ONE of the major requirements in industrial communication is the support of timely communication services. In the last few years, wireless networks have become a very attractive option for these communication environments. Increased mobility combined with the reduction of cabling costs and deployment time, as well as easy maintenance are the main reasons behind this trend [1]. As a consequence, the demand for high performance wireless networking with real-time (RT) capabilities is a relevant research challenge in this area.

Within this domain, the WiFi technology, which is the preferred term for the IEEE 802.11 family of protocols [2], is one of the main contenders, mainly due to its position as the dominant carrier of wireless traffic [3]. The widely acceptance of WiFi technology is also being supported by the throughput enhancements that have been recently achieved, mainly, due to the use of advanced communication theory mechanisms and to the new radio devices that are able to transparently switch between 2.4 GHz, 5 GHz, and 60 GHz bands, as described in the IEEE 802.11n and two recent approved amendments IEEE 802.11ac [4] and IEEE 802.11ad [5].

It is well known that the IEEE 802.11 standard defines a carrier sense multiple access (CSMA) scheme to manage the communication medium access. It is also well-known that a main drawback of CSMA-based networks is the non-deterministic contention resolution algorithm, which serialises the contending messages whenever a collision occurs. Since the first version of IEEE 802.11 published in 1997, a large number of papers and new IEEE 802.11 amendments were proposed to support quality of service (QoS) and RT guarantees in wireless local area network (WLAN) environments. In [6] is presented an extensive review of IEEE 802.11 WLANs, when dealing with the support of QoS mechanisms.

Currently, the efficient management of radio resources is one of the most challenging issues when deploying WLANs, as in high-density WLAN environments is not possible to avoid basic service set (BSS) overlapping [7]. When the coverage of nearby co-channel BSS overlaps with each other, they are called overlapping BSSs (OBSS). In such an OBSS environment the transmissions from some clients belonging to one BSS affect the transmission capability of stations in other BSSs. There are some recent research works concluding that the degree of overlapping and the number of overlapped BSSs highly degrade the network performance [8], [9]. Accordingly to Bellalta *et al.* [10], it is expected that new access points (APs) will increasingly incorporate dynamic channel allocation mechanisms to deal with this issue, selecting and updating their operating channels at runtime.

It is worth mentioning that very few papers focus on performance analysis and new solutions for OBSSs environments. Additionally, these research works usually consider that all BSSs are under the same management domain, i.e., it is considered that all communicating stations follow the rules established by the new coordinating function proposals.

Within a RT context, we argue that when moving communication systems to the wireless domain, three relevant issues must

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R. Costa is with Federal Institute of Santa Catarina, email: robson.costa@ifsc.edu.br.

J. Lau and R. Moraes are with the Department of Computer Engineering, Federal University of Santa Catarina, email: {jim.lau, ricardo.moraes}@ufsc.br.

P. Portugal and F. Vasques are with INESC–TEC/INEGI, FEUP, University of Porto, email: {pportugal, vasques}@fe.up.pt.

R. Moraes is the corresponding author.

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be considered: **i)** The physical medium becomes an open communication environment, i.e., any alien station can try to access the communication medium at any moment to establish its own communication channels; **ii)** the communication environment is highly susceptible to interferences, whether from systems using the same communication technology (OBSS) or from different technologies that operate at similar communication frequencies [11]; **iii)** the RT infrastructure is shared with non-RT traffic, increasing the non-deterministic characteristics of the medium access. Consequently, solutions that guarantee RT communication through the strict control of every communicating device are hardly applicable in wireless communication domains.

In the present paper the RT-WiFi architecture is proposed and assessed. RT-WiFi has been developed to handle RT communication in infrastructured IEEE 802.11 networks operating in high density industrial environments. It implements a time division multiple access (TDMA)-based coordination layer to handle RT-traffic in infrastructured IEEE 802.11 networks. This coordination layer is backward compatible with the two most important functions defined in the IEEE 802.11 standard, i.e., distributed coordination function (DCF) and enhanced distributed channel access (EDCA) functions. When compared with other research works, the main advantage of the RT-WiFi architecture is that it is able to handle RT-traffic in network topologies operating in OBSSs, without the need to control non-RT (or alien) communicating devices.

The remainder of this paper is organised as follows. Section II details the most relevant aspects of the IEEE 802.11 protocol, in what concerns the support of RT communication in infrastructured wireless networks. Section III describes some relevant solutions to support RT communication in IEEE 802.11 networks. In Section IV the operation mode of the proposed mechanism is presented. In Section V a set of simulation scenarios is defined, and a comparative assessment is made. Finally, the paper is concluded in Section VI.

II. IEEE 802.11 MEDIUM ACCESS MECHANISMS

The medium access control of the IEEE 802.11 protocol relies upon a CSMA with collision avoidance (CSMA/CA) mechanism. The IEEE 802.11 MAC sublayer implements two MAC functions[1]: The mandatory DCF and an optional point coordination function (PCF). DCF is the basic IEEE 802.11 mechanism, where stations perform a backoff procedure before initiating a transmission. That is, when a station wants to transmit, it previously senses the medium carrier sensing; if the medium remains idle during a specific time interval called distributed interframe space (DIFS), it immediately starts the transmission. Otherwise, the station selects a random time called backoff time. The duration of this random interval is multiple of the slot time (ST), which is a system parameter that depends on the characteristics of the physical layer (PHY). The number of slots is an integer in the range of [*0, CW*], where contention window (CW) is initially assigned as $CW_{\min}$. A backoff counter is used to maintain the current value of the backoff time.

[1] An additional mechanism, RTS/CTS, is defined in the IEEE 802.11 standard to solve the hidden terminal problem and to handle adequately the transmission of longer messages. For further details, refer to [2].

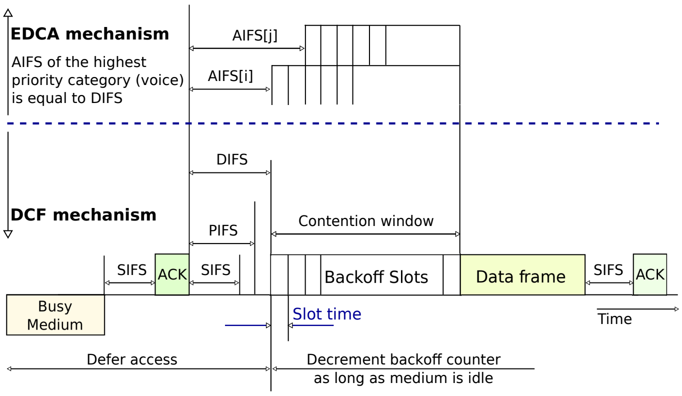


Fig. 1. Interframes spaces in the DCF and EDCA mechanisms.

Thus, after detecting the medium as idle for a DIFS interval, the stations keep sensing the medium (listening) for this additional random time. If the medium gets busy while a station is down-counting its backoff counter, the down-counting stops and the station defers the medium access until it becomes idle for a DIFS interval again. A new independent random backoff value is selected for each new transmission attempt; the CW value is increased by ($CW_{\text{old}} \times 2 + 1$) with an upper bound of $CW_{\max}$, where CW_{old} represents the previous CW value. As soon as the backoff counter reaches zero, the station can retry its transmission (Fig. 1).

The DCF access method imposes an idle interval between two consecutive messages, which is called interframe space (IFS). Different IFS values are defined as following: Short interframe space (SIFS) used for acknowledgements (ACK) and other management messages; PCF interframe space (PIFS) used by PCF stations; DIFS used by DCF stations; and extended interframe space (EIFS) used for communication-error conditions.

The IEEE 802.11e amendment incorporates an additional coordination function called hybrid coordination function (HCF), which is used in QoS network configurations. The HCF mechanism schedules the channel access by allocating transmission opportunities (TXOPs) to each of the stations. Each TXOP is defined by a starting time and a maximum duration, i.e., the TXOP defines a time interval during which the station keeps the medium access control. Consequently, within an acquired TXOP, multiple messages may be transmitted by the station. TXOPs may be allocated through one of two access mechanisms specified by HCF: The EDCA and the HCF controlled channel access (HCCA) mechanisms.

The EDCA mechanism was designed to provide differentiated transmission services with four access categories (ACs). Each message arriving at the MAC sublayer is mapped into one of the four ACs, as follows: Priorities 1 and 2 for background traffic (BK); priorities 0 and 3 for best-effort traffic (BE); priorities 4 and 5 for video traffic (VI); and, finally, priorities 6 and 7 for voice traffic (VO) that is the highest priority level.

Different levels of service are provided to each of the ACs, based on three independent mechanisms: Arbitration interframe space (AIFS), TXOP and CW size. For an EDCA station, each message will wait for an idle medium during an $AIFS_{[AC]}$ interval before contending for the medium access. Such a time

Table 1. Default DCF and EDCA parameter set for IEEE 802.11a.

Parameters		**CWmin**	**CWmax**	**DIFS/AIFSN**
DCF		aCWmin	aCWmax	2
EDCA	Background	aCWmin	aCWmax	7
	Best-effort	aCWmin	aCWmax	3
	Video	(aCWmin+1)/2-1	aCWmin	2
	Voice	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2

interval is given by:

$$AIFS_{[AC]} = AIFSN_{[AC]} \times aSlotTime + SIFS,$$

where $AIFSN_{[AC]}$ is a positive integer that must be greater than or equal to 2 for all QoS stations (QSTA), except for the QoS access points (QAP), where it shall be greater than or equal to 1. The default DCF and EDCA parameters depend on the physical layer. Table 1 shows the default parameters for IEEE 802.11a.

III. RT COMMUNICATION IN IEEE 802.11 NETWORKS

Whenever a CSMA-based network is required to provide timing-related guarantees, there is the need to prioritise specific data messages. This is a critical requirement, whenever the wireless communication environment is shared with external traffic sources, as in the case of an OBSS. More specifically, the access to the shared resource needs to be coordinated, either centrally or in a distributed manner. According to the ISO/OSI model, this coordination procedure must be performed by the MAC protocol. In this section, we briefly describe the state-of-the-art of RT communication in IEEE 802.11 networks.

As regards to the earlier versions of the IEEE 802.11 standard, PCF was the first proposed mechanism to support RT traffic in IEEE 802.11 networks. It has been proposed as an optional access mechanism, implementing a centralised polling scheme to support synchronous data transmissions, where the point coordinator (PC) performs the role of polling master. Between two consecutive beacon frames, PCF defines two periods: The contention free period (CFP) and the contention period (CP). In the CP, DCF is used. In the CFP, the medium access is controlled by a polling scheme, where the PC sends contention-free-poll (CF-Poll) frames to each station, giving them the right to send a frame. The main drawback of the PCF mechanism is that most parts of the network interface cards never implemented it [12] due to complexity reasons.

The HCCA mechanism was proposed to improve the PCF scheme. However, several studies pointed out that it would not be suitable to support the specific requirements of RT applications [13]–[16]. Similarly to the PCF scheme, the PC also polls all the stations in the polling list, even though some stations may have no messages to be transmitted. In this specific case, these stations will transmit a null message. As a consequence, the polling overhead is roughly equal to the time interval from sending the polling message till the end of the corresponding ACK message [17].

The EDCA mechanism, proposed in the IEEE 802.11e ammendment improves the earlier DCF mechanism. It implements four different ACs to provide QoS in wireless communications. The use of the higher priority AC (voice) to transfer RT traffic would be an adequate approach. However, when using the default set of parameters for the voice category, the number of deadline misses may become unacceptable for most RT applications [18]–[20].

According to Kosek-Szott *et al.* [21] the most relevant shortcomings of the last published IEEE 802.11 standard version [2] are the lack of mechanisms for the prioritisation of different audio video streams belonging to the same access category (AC). This is a problem of inter-network interference caused by high-density WLAN environments and the large number of management frame types. To tackle these problems new QoS solutions were introduced in IEEE 802.11aa [22] and IEEE 802.11ae [23] amendments.

The IEEE 802.11aa amendment is intended to improve multimedia streaming support. Basically, it defines two new ACs for the transmission of time-critical voice and video packets, characterised by the requirement of having less than 10 ms delay. Therefore, there are six transmit queues in total. It includes groupcast enhancements and an overlapping basic service set (OBSS) management [22]. This management mechanism is based on two main components: A mechanism for quantifying the load and interference status of each OBSS and signaling this information to neighbour BSSs and; a mechanism for performing channel selection. Load and interference information are distributed in a QLoad report, which are ignored by legacy APs. The IEEE 802.11ae amendment presents a solution to prioritise management frames, where the QoS management service provides a mapping between the management frame types/subtypes and the EDCA Access Categories [21].

In the literature, there are a number of solutions intended to improve the QoS/RT capabilities of IEEE 802.11 networks. Such solutions are, mainly, based on TDMA, Token-Passing, Master-Slave or Polling techniques.

Among the solutions based on Polling schemes, Hamidian and Körner [24] propose a QoS mechanism that allows stations with higher priority traffic to reserve additional time for collision-free access to the medium. Basically, it transfers the HCCA admission control and scheduling algorithms from the HCCA controller to the contending stations.

Wu *et al.* [25] designed the QoS MAC (QMAC) protocol, which defines a new function called quality-of-service point coordination function (Q-PCF) intended to coexist with the earlier DCF function. This protocol is based on a polling scheme, where the CFP is divided into two periods (joining and polling). The joining period guarantees that high-priority stations are always admitted to the polling list earlier than low-priority stations. A NAV-based strategy is used to prevent external interferences from DCF stations.

Gao *et al.* [26] proposed a new admission control framework that replaces the traditional CSMA mechanism to reduce the HCCA polling overhead. It uses the mean data rate and the mean packet size values to evaluate the resources required by each message flow, deriving the delay probability to perform the admission control of new flows. In [27], a modified HCCA mechanism targeting the same problem is defined. This approach uses the beacon frames broadcasted by the AP to determine which stations want to transmit pending data. Basically, the CFP is divided into two phases, where in the former a station can send a transmission request frame after receiving the beacon message from the AP and sensing the medium idle for SIFS. The information from all stations is stored in the scheduling table of the AP. Thus, using this information, the AP can determine a transmission sequence, which is also incorporated into the beacon frame.

Viegas Jr. *et al.* [28] presented a group sequential communication (GSC) approach, based on the Publish-Subscribe paradigm. The main idea is to allow GSC stations to send their messages in a sequential way, using a virtual token passing procedure to coordinate the medium access. This solution does not use polling frames, nor null messages.

Hantrakoon and Phonphoem [29] proposed a simple queue management and admission control called PHCCA. The queue management modifies the HCCA mechanism dividing the queue in three different classes, which can be organised by type or user relevance. Furthermore, a starvation protection for the lower priority queue is implemented, where the admission control provides a bandwidth borrowing algorithm, enabling a high priority queue to borrow bandwidth from lower priority queues.

He and Ma [14] introduced the deterministic backoff (DEB) polling mechanism, enabling CF-poll frame to carry information of distinct backoff counters to the nodes, in order to enable them to access the shared wireless channel at different time slots. Differently from HCCA, where a station is explicitly polled, DEB implement a distributed backoff algorithm to gain control of the channel. This approach intends to improve the communication in OBSS, where the primary cause of network collision is the overlapping backoff counters used by multiple stations. A very strong assumption of this approach is that all stations share a common backoff counter.

Zheng and Hoang [30] proposed a scheme that separates the uplink and downlink transmissions in two periods. The uplink is based on a contention scheme, where all stations in all BSSs become active for uplink transmission, operating under the EDCA rules. The downlink phase is managed by a polling scheme with grouping assignments, using graph colouring techniques, to divide BSSs into groups and time span to avoid downlink collisions. This solution considers that all BSSs in the coordinated OBSS environment would be synchronised and have a unique and coordinated superframe structure.

Among models based on Master-Slave schemes, Bartolomeu *et al.* [31] designed the wireless flexible time triggered (WFTT). This model combines a *bandjacking* approach for gaining prioritised channel access (injecting noise signals during intervals shorter than SIFS) with the FTT paradigm [32] to support RT communications in applications with static and/or dynamic requirements. The Master controls both the injection of noise signals and the permissions of Slave stations to start their own transmissions. The main problem is the need to modify the physical layer of the devices, impairing the use of commercial-off-the-shelf (COTS) network interface cards.

In [12], Seno *et al.* proposed an extension of ethernet powerlink (EPL) [33] to IEEE 802.11. The same principles of EPL are applied. This model operates according to a TDMA scheme implemented upon the MAC sublayer, dividing the cycle in isochronous and asynchronous periods. In the isochronous period, the master defines the start of cycle and broadcasts a message, called start of cycle (SoC), to all slave stations. After this, the master pools each slave with a request message/response message. At the end, the master broadcasts another message, called start of asynchronous (SoA), to notify the beginning of the asynchronous period. An experimental evaluation of this approach was presented in [34].

Among the models based on Token-Passing schemes, Ergen *et al.* [35] proposed the wireless token ring protocol (WTRP), which is a MAC protocol that exchanges special tokens and uses multiple timers to maintain synchronisation among nodes. Each station transmits during a specified time interval and if enough time is left, it invites nodes outside the ring to join it.

In [36], Cheng *et al.* presented a wireless token-passing protocol, named *Ripple*. Basically, *Ripple* modifies the data transmission procedure of 802.11 DCF and employs request-to-send (RTS) and ready-to-receive (RTR) messages as tokens.

There are also approaches that provide QoS guarantees based on forcing collision resolution (FCR) schemes in favour of the RT stations. The most relevant proposal has been made by Sobrinho and Krishnakumar [37], who adapted the EQuB mechanism (Black-Burst) [38] to ad hoc CSMA wireless networks. This scheme requires the shutdown of the standard retransmission scheme. RT stations implementing the EQuB approach contend for the channel access after a medium interframe spacing t_{med}, that is shorter than the long interframe spacing t_{long}, used by standard stations. This EQuB approach also requires the modification of the network interface cards, impairing the use of COTS hardware.

In [39], Sheu *et al.* proposed a priority MAC protocol based on Sobrinho's approach, complemented by a binary tree referred to as contention tree. Basically, the Black-Burst scheme is adapted to distinguish the priorities of stations. Stations with the same priority send messages in a round robin manner. The basic idea is that a station can obtain a unique ID number, which depends on its position in the contention tree.

In [40], a RT-communication approach (VTP-CSMA) has been proposed based on a traffic separation mechanism that prioritises the RT traffic over the non-RT traffic, without directly controlling the latter. The coordination among RT stations is implemented by a Virtual Token Passing procedure that circulates a virtual token among a number of RT devices. This virtual token mechanism ensures that there is no contention conflicts among the RT stations.

Other approaches modify the EDCA mechanism manipulating the CW and $AIFS$ values to improve the QoS guarantees provided to RT applications. The main objective is to avoid collisions and to prioritise the RT traffic.

Villalón *et al.* [41] designed the B-EDCA mechanism. It is backward compatible with legacy DCF-based stations. Basically, it changes the AIFS value of the highest AC to $SIFS + \mathrm{SlotTime}$ when stations are in the backoff state. Moreover, in order to keep the compatibility with the HCCA mechanism, a station implementing the B-EDCA mechanism must wait for an additional SIFS interval when the backoff counter reaches zero, i.e., $2 \times SIFS + \mathrm{SlotTime}$. In [42] there is an assessment of IEEE 802.11e EDCA when it is working in an unsynchronised way. The authors propose the use of AIFS values whose differences are not multiple of the $\mathrm{SlotTime}$. In [19], Cena *et al.* suggest the adoption of a scheme that combines both EDCA and TDMA mechanisms to improve the transmission of urgent frames, independently of the interfering traffic pattern.

Ruscelli *et al.* [43] propose the called overboost scheduler mechanism that combines both the HCCA and EDCA functions. This mechanism assumes the control of the medium at the end of the CAP phase. It checks if the HCCA is empty, in that case it leaves the control to the EDCA function. Otherwise, it moves the data message of HCCA queue to the EDCA function, trying to transfer this message at the highest priority of the EDCA (VO-voice queue). As expected, it reduces the HCCA queue, improving the use of the wireless medium.

In Ji *et al.* [44] is proposed the distributed dense BSS transmission (DDBT) protocol, which allows AP of different BSSs to opportunistically find the bands with the best channel quality to establish the primary channel. It selects the channel according to the quality of different bands. Additionally, it proposes a Space Interference Avoidance Protocol (SIAP) that whenever a station located in OBSS obtains the channel right, it imposes the neighbour stations to set their NAVs and also sends the information of interference avoidance to the interfer AP to partially free the channel access.

Lei and Rhee [8] propose a new scheme to transmit power control information, which enable stations localised in different BSSs, to dynamically adjust their transmission powers. Basically, it proposes that all stations use RTS/CTS procedures, which are exchanged using their maximum power and, all the stations continually monitor the ongoing transmissions, combining with the information recorded in a path loss table, a station can determine whether it is an overlapping area. Then all the stations in these overlapping area adjust their transmit powers to adequate power levels and compete for channel access.

Seno *et al.* [45] presented a technique to ensure RT periodic data exchanges over a wireless network during retransmissions. This approach uses an admission control mechanism. Additionally, the proposed solution takes into account dynamic bandwidth for preallocated retransmissions which reassigns message that have transmission failure.

Cena *et al.* [46] propose an implementation based on a fixed-priority access scheme, that can operate upon commercial Wi-Fi devices. This approach uses a fixed-priority channel access (FPCA), which relies on EDCA. Additionally the duration of interframes spacing is modified, in order to provide fine granularity when allocating priorities to real-time messages.

Seno *et al.* [47] proposed a non-preemptive transmission scheduling scheme, using two retransmission strategies denoted consecutive and preemptable. Consecutive retransmissions are uninterruptedly performed after the first attempt. Preemptable retransmissions are assigned with the same relative deadline as the first attempt and are scheduled according to EDF (i.e., they can be interleaved with other, newly activated instance transmissions with tighter relative deadlines).

Sanabria-Russio and Bellalta [48] designed a scheme called CSMA with enhanced collision avoidance (CSMA/ECA), defining the use of a deterministic backoff, $Bd = CW_{\min}/2-1$ after successful transmissions, where $CW_{\min}$ is the minimum contention window. Basically, contenders that successfully transmitted on a schedule n, will transmit without colliding with other successful nodes in future cycles. This algorithm converge after a number of successful transmission attempts.

In [49] is proposed a CSMA with automatic synchronisation (CSMA/AS) MAC protocol to mitigate the collision problem caused by random access. This approach consider a delay contention feature and a sustained backoff mechanism, setting the initial contention window size to 1. By using CSMA/AS, all the stations can be synchronised without relying on any additional signaling message. Once the network is synchronised. A minimum service rate can be guaranteed for any station, and an end-to-end delay bound can be derived for a given type of traffic.

The research works reported in this state-of-the-art can be classified according to three classification axes: **i)** Scheduling control, **ii)** collision resolution mechanism, and **iii)** compatibility degree. The first axis is related to how the medium access is scheduled and defines two categories: **i) Centralised**, when a central device is used to schedule the medium access, and **ii) distributed**, when the schedule decisions are locally defined by each station.

The second axis defines *how collisions are dealt with*, in order to provide RT communication services, defining three different categories: **i) Avoid collisions**, when the medium access is performed by a contention free service, **ii) solve collisions**, when the traditional backoff algorithm (based on a probabilistic scheme) is replaced by an algorithm that enforces the QoS timing requirements, and **iii) reduce collisions**, when a loosely-coupled distributed algorithm is used.

Finally, the third axis highlights how the RT communication approaches keep or alter the compatibility with IEEE 802.11 compliant devices. Two different compatibility levels have been defined: **i) Open environment**, if the proposed approach is able to ensure the required timing requirements, even in the presence of stations operating in the same frequency channel and coverage area, that are out of sphere-of-control[2] of the RT architecture, and **ii) Commercial-off-the-shelf (COTS)**, if the proposed approach can be implemented using COTS hardware.

Fig. 2 illustrates the behaviour of the reported RT communication proposals according to these three classification axes. Within the context of first axis, it can be concluded that, from an organisational point of view, proposals based on a centralised scheduling would be preferable. This type of scheduling enables the AP to have a global overview of the communication medium status and simplifies the implementation of both admission control and clock synchronisation mechanisms [51]. In what concerns the second classification axis, it can be concluded that proposals focused on solving or avoiding collisions would be preferable, since they both try to create temporal boundaries for the collision resolution. Finally, in what concerns the third classification axis, it can also be concluded that with the large dissemination of IEEE 802.11 deployments, it is of paramount importance that any new real-time wireless communication ap-

[2]The concept "inside/outside" sphere-of-control was defined by Kopetz [50]. Whenever a real-time entity is in the sphere-of-control of a subsystem, it belongs to a subsystem that has the authority to change all the value of this real-time entity. Outside its sphere-of-control, the value of the entity can be observed, but cannot be modified.

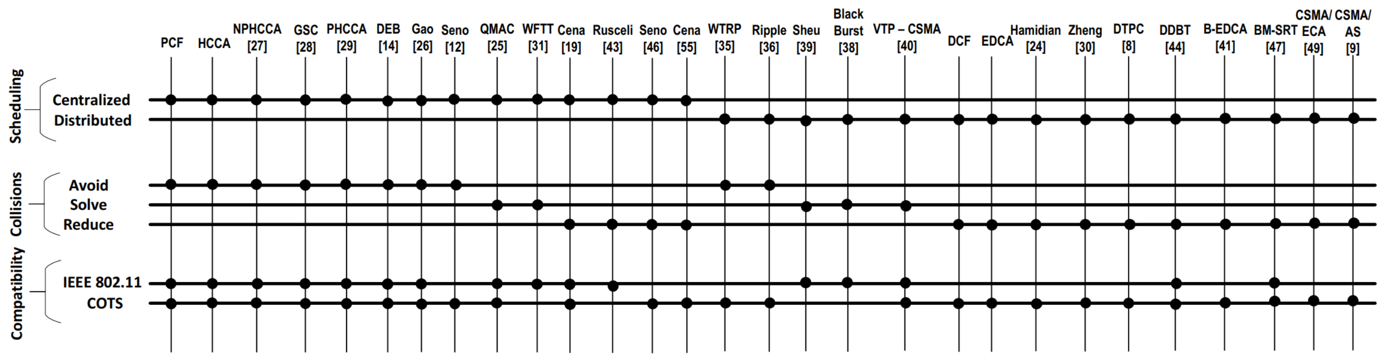


Fig. 2. State-of-the-art comparison.

proach is able to deal with the presence of traffic generated by third stations (alien stations or non-RT statios). Also, it is desirable that this solution can be implemented using COTS hardware.

With exception of PCF and HCCA, a common characteristic of most part of these RT communication approaches is that a QoS-enabled station is unable to support RT communication in the presence of unconstrained IEEE 802.11 stations (e.g. alien stations), unless these unconstrained stations do not initiate any communication. Furthermore, most part of the above mentioned proposals consider that all BSS in the overlapping area are under the same management domain, which is a strong assumption in high density WLANs areas. A relevant and recent study that consider this assumption is presented in [52], where fairness between close WiFi access points is improved. We agree with Bianchi *et al.* [53], who claim that a service differentiation mechanism must be compulsory as a MAC sublayer extension. Within this context, relevant exceptions that are able to deal with open communication environments are those based on the Black-Burst scheme [37] and VTP-CSMA approach [40].

Based on this set of assumptions, any RT communication architecture must consider that the wireless communication medium may be accessed at any instant by any third station. We propose in this paper the use of a coordination layer to manage the medium access, which is able to deal with this issue. Unlike the VTP-CSMA scheme, which uses a virtual token-ring to schedule the RT-station access to the medium, the approach proposed in this paper employs a TDMA scheme to schedule the RT-traffic, combined with the use of an underlying forcing collision resolution (FCR) scheme [54] that prioritises the RT traffic. The use a TDMA scheme results in an almost constant delay for the RT traffic, which is a desirable behaviour for RT systems. The proposed scheme extends the TDMA-based mechanism that was earlier presented in [55].

IV. THE RT-WIFI ARCHITECTURE

The RT-WiFi architecture is primarily composed of two layers: Medium Access Control (MAC) and Admission Control Mechanism (ACM)–Fig 3. At the lower layer, the MAC mechanism combines a FCR MAC [54] with a TDMA mechanism. The FCR (forcing collision resolution) MAC prioritises RT traffic over non-RT traffic, being the TDMA mechanism responsible for the serialisation of the access of RT stations to the communication medium. At the upper layer, an admission control mechanism manages the admission of RT traffic streams (TS) and is responsible for the scheduling tasks. As it is assumed an infrastructured network interconnecting a set of RT stations through a central coordinator (AP_{RT}), the lower layer mechanism must be implemented in both the RT stations and the AP_{RT}. The upper layer mechanism must be just partially implemented on RT stations and fully implemented on the AP_{RT}. All the other stations, supporting just non-RT traffic, do not need to implement any of the proposed mechanisms. These implementations can be done using an open source wireless driver (e.g.: ath5k).

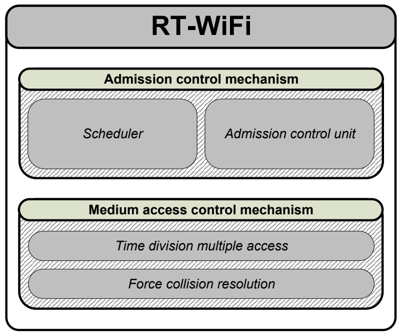


Fig. 3. RT-WiFi architecture.

Additionally, the following conditions must be assumed:
1. RT stations are under the coverage area of the AP_{RT}, so that there are no hidden or exposed terminals;
2. RT stations are operating in an OBSS environment;
3. non-RT devices are outside the *sphere-of-control* of RT architecture and operate according to the IEEE 802.11 standard.

The main objective of the RT-WiFi architecture is to enable the provision of RT QoS in OBSS environments. Within this context, non-RT stations will share the communication medium with the set of RT stations and the AP_{RT}. RT stations can handle the transfer of multiple TS. In this paper all defined TSs will be mapped in the RT category as HIGH priority messages.

A. *Medium Access Control (MAC) Mechanism*

The RT-WiFi architecture defines, at the lowest level, the use of a FCR MAC [54], which ensures the highest priority level to the RT stations by managing the AIFS/CW parameters of both the RT stations and the AP_{RT}. Basically, whenever a collision

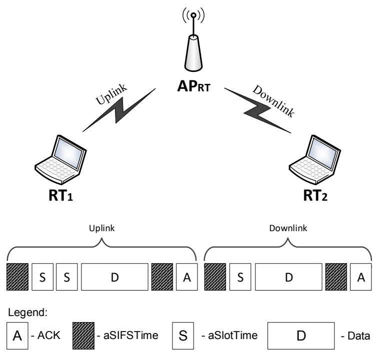


Fig. 4. Transmission flow.

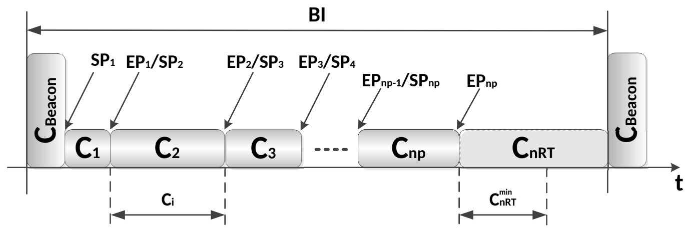


Fig. 5. TDMA rounds of RT-WiFi.

Scheduling list

Addr_STA	TSID	SP	EP
00 : 1b : b1 : 4c : ec : 23	2	0.000150	0.000250
00 : 24 : 54 : ce : c6 : b9	3	0.000250	0.000400
58 : 98 : 35 : 7c : 75 : 3b	2	0.000400	0.000600
00 : 1b : b1 : 4c : ec : 23	1	0.000600	0.000700
08 : 76 : ff : 99 : d0 : 56	3	0.000700	0.000850

Fig. 6. Example of a scheduling list sent into the beacon message.

between an RT station and one or more non-RT stations occurs, all but the RT station will select a random backoff time. For non-RT stations, the backoff time value will be set according to the default parameters for each access category. Conversely, the RT station will try to retransmit the message using the AIFS value of the highest priority access category (voice–VO), both for the uplink ($AIFS_{VO}^{QSTA} = SIFS + 2 \times \mathrm{SlotTime}$) and the downlink traffic streams ($AIFS_{VO}^{QAP} = SIFS + \mathrm{SlotTime}$), as defined in the IEEE 802.11 standard. Therefore, the main difference between non-RT and RT traffic is that the latter is being transmitted with $aCW_{\min} = aCW_{\max} = 0$, meaning that its backoff time is null. Therefore, whenever a collision occurs with an RT message involved, either the RT message is transferred before the other conflicting messages, or none of the messages is transferred at all. The underlying FCR MAC must be complemented by an upper-layer mechanism able to schedule multiple RT stations attempting to simultaneously access the communication medium. The RT-WiFi architecture implements a TDMA-based scheme to serialise the TSs admitted by RT stations.

The proposed TDMA mechanism considers a slot length adjusted to enable multiple retransmissions of RT messages, as the underlying FCR MAC will just prioritise the RT medium access, and, therefore, does not prevent the occurrence of collisions with non-RT messages. As the effective duration to transmit a single RT message (with acknowledgement) will be much smaller than the TDMA slot length, non-RT stations will be able to perform their transmissions within these TDMA intervals, ensuring an adequate fairness level for the non-RT traffic, which is one of the advantages of the proposed TDMA mechanism.

The FCR MAC is also implemented in the AP_{RT} to prioritise the downlink traffic stream, enabling the coexistence with non-RT APs (AP_{NRT}) operating in the same coverage area and frequency band (Fig. 4). Therefore, the retransmission attempts from the AP_{RT} occurs earlier than any other attempt, and after an $AIFS_{VO}^{QAP}$.

It is important to note that interferences from devices operating in an OBSS environment are one of the major limitations of the state-of-the-art approaches presented in Section III, especially those which are contention-free based, e.g. PCF and HCCA. As it will be shown, for the RT-WiFi architecture such type of interferences are regarded as legitimate transmissions that have no significant impact upon the RT transmissions, as long as they follow the MAC access rules defined by the IEEE 802.11 standard.

A.1 MAC Technical Details

The RT-WiFi architecture considers a group of *np* members represented by: $G=\{TS_1,TS_2,\cdots,TS_{np}\}$, where TS_i is the *i*th admitted traffic stream. The *Coordination Layer* organises the RT communication in TDMA rounds defined by a Beacon Interval (BI) (Fig. 5), during which it schedules the accepted traffic streams (TS).

The beginning of each TDMA cycle is defined by the sending of a beacon message from the AP. This message is used to synchronise the station clocks with the AP clock and also to disclose a scheduling list ($\mathrm{Sched_{List}}$). Based on information retrieved from the admission control unit (ACU), the scheduling list has, for each TS_i, the authorisation to transmit in the current cycle, the MAC address, the own ID[3] and the authorised transmission bounds SP_i and EP_i, respectively (Fig. 6). Its content can be modified at each TDMA cycle (BI), ensuring a high flexibility for the RT-WiFi architecture.

A TS_i only can try to access the communication medium during the time interval defined between the bounds SP_i and EP_i (C_i), and send a unique data message. The C_i duration time is computed in order to allow multiple retransmissions (RN) of each TS_i, whether as uplink or downlink flow. However, in most cases, a successful transmission will occur before the end of assigned time for this TS_i. To ensure that RT stations transmit only one message per C_i slot, the respective transmission opportunity (TXOP) is set to 0.

[3] The local ID (in the station) of an admitted TS can be different from ID assigned by ACU. Within this context, at stations level, the identifications are performed by the tuple [MAC address / local ID].

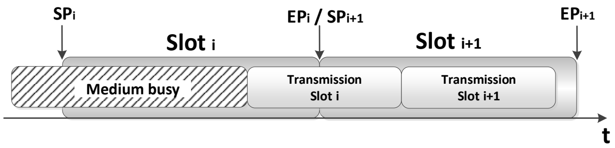


Fig. 7. Partial overlay of TDMA slots.

After receiving a beacon message, initially each station synchronises its local clock with the AP$_{RT}$ clock and then performs a search in the Sched$_{\text{List}}$ (using its MAC address as index), in order to get the SP_i and EP_i values of its TS. Then, the station will schedule interruptions based on received values to signal the begining and ending of each slot. If some station does not receive the beacon message, it will wait one TDMA cycle without performing any transmission. If it receives the beacon message but does not have an assigned slot to the current cycle, it will perform the synchronisation but will not transmit any message.

Importantly, even with the utilisation of the underlying FCR mechanism, there is a probability of multiple collisions between non-RT devices. Thus, the RT stations perform the retransmissions until the assigned slot to TS$_i$ ends or until a successful transmission. In a normal situation, the transmission of any RT message will ends before EP_i, since the C_i duration of TDMA slot allows multiple retransmissions of the RT data message. However, if the current transmission has not ended, it can be finalised during the next TDMA slot (Fig. 7). This situation does not lead to any conflict with message willing to use the next slot, since the communication medium is considered to be busy, blocking the beginning of any new transmission.

Finally, since each RT station can have one or more TS, the ACU assigns slots in an independent way for each TS admitted by the system.

The oversizing of slots helps to avoid deadline misses of RT data messages. However, it can be considered as an overhead, if a high occupation of medium is desired. In these cases, a resizing slots scheme can be used, which is beyond the scope of this paper.

B. Admission Control Mechanisms - ACM

To avoid an RT traffic overload, and consequently the degradation of the communication behaviour, the RT-WiFi architecture implements an admission control mechanism (ACM), composed of two main elements: Scheduler and admission control unit (ACU). This mechanism imposes that stations willing to transmit an RT traffic stream to previously request its admission. The ACM implements joining and leaving mechanisms, and has an Admission Control Unit and a Schedulability test.

B.1 Joining Mechanism

An RT station willing to set a TDMA slot for a traffic stream (TS) firstly requests its association with group G; only RT stations associated with the AP_{RT} have the right to join the group[4].

[4]This procedure can be used to avoid the association of non-authorised stations with the real-time network.

Algorithm 1 Sending ADDTS to AP$_{RT}$.

1: **function** SEND_ADDTSREQUEST(Addr_STA, TSID, P$_k$, L$_k$, II$_k$, CT$_k$)
2: $C^{\text{uplink}}_{\text{attempt}}$ = AIFS$^{QSTA}_{VO}$ + C$_{\text{DATA}}$[L$_k$] + SIFS + C$_{ACK}$
3: $C^{\text{donwlink}}_{\text{attempt}}$ = AIFS$^{QAP}_{VO}$ + C$_{\text{DATA}}$[L$_k$] + SIFS + C$_{ACK}$
4: $SurplusTime_k = (C^{\text{uplink}}_{\text{attempt}} \times RN^{\text{uplink}}_k) + (C^{\text{downlink}}_{\text{attempt}} \times RN^{\text{downlink}}_k)$
5: SENDMSG.ADDTSRequest[Addr_STA, TSID, P$_k$, L$_k$, II$_k$, CT$_k$, SurplusTime$_k$]
6: **while** (!TIMEOUT.ADDTSRequest) **do**
7: **if** (RECEIPT.ADDTSResponse) **then**
8: **if** (ADDTSResponse.STATUS = Accepted) **then**
9: INSERT.*AdmittedList*(TSID, ADDTSResponse.CT)
10: **else**
11: **DELTS(**$TSID$**)**
12: **end if**
13: EXIT()
14: **end if**
15: **end while**
16: **end function**

This request is realised by sending an ADDTS[5] message to the AP_{RT}, with the following parameters: Generation period (P$_k$), nominal MAC protocol data unit (MPDU) size (L$_k$), inactivity interval (II_k), request type (CT_k) and extra allocation time ($SurplusTime_k$). Based on these traffic specifications, the AP_{RT} will verify whether the requested TS requirements can be supported. In this paper, only request type (CT_k) equal to HIGH is considered.

Additionally, the AP_{RT} receives from traffic classification (TCLAS) the MAC address of the RT station (Addr_STA) and the id of TS_k (TSID). The ADDTS request is presented in Algorithm 1.

As it can be observed in algorithm 1 (lines 2 and 3), each RT station determines the length of the TDMA slots for uplink and downlink streams, which are given by:

$$C^{\text{uplink}}_{\text{attempt}} = AIFS^{QSTA}_{VO} + C_{\text{DATA}}[L_k] + SIFS + C_{ACK}$$
$$C^{\text{downlink}}_{\text{attempt}} = AIFS^{QAP}_{VO} + C_{\text{DATA}}[L_k] + SIFS + C_{ACK}.$$

It also defines the $SurplusTime$ (line 4) to encompass an adequate number of retransmission attempts (RN). In the case of a successful RT transmission, this $SurplusTime$ will enable the transmission of non-RT messages. The AP_{RT} receives this message and is responsible for sending an ADDTS response message. When the ADDTS response is received, the station will verify whether the request was accepted or not. If the TS can be admitted, the AP_{RT} will add the station MAC address to a management list, to set subsequently values to the SP_{id} and EP_{id} parameters, performed by the *scheduler mechanism* - line 9. Otherwise, the TS is deleted (line 11).

As the joining procedure is performed only at the beginning of the RT TS transmission, no extra frames needs to be transmitted after the TS admission, avoiding communication overhead between RT stations and the AP_{RT}.

[5]The add traffic stream (ADDTS) and delete traffic stream (DELTS) messages are part of traffic specification (TSPEC)element described in IEEE 802.11 standard.

Algorithm 2 Processing ADDTS by ACU.

1: **function** PROCESS_ADDTSREQUEST(Addr_STA, TSID, P_k, L_k, II_k, CT_k, SurplusTime$_k$)
2: $C^{uplink}_{attempt} \leftarrow AIFS^{QSTA}_{VO} + C_{DATA}[L_k] + SIFS + C_{ACK}$
3: $C^{downlink}_{attempt} \leftarrow AIFS^{QAP}_{VO} + C_{DATA}[L_k] + SIFS + C_{ACK}$
4: $Interf_k \leftarrow C_{DATA}[MSDU^{max}] + SIFS + C_{ACK}$
5: $C^{max}_k \leftarrow (2 \times Interf_k) + SurplusTime_k$
6: **SCHEDTEST**(C^{max}_k, P_k, CT_k)
7: **if** (**SCHEDTEST**.STATUS == SCHEDULABLE) **then**
8: $C^{current}_k \leftarrow C^{max}_k$
9: $CT_k \leftarrow$ **SCHEDTEST**.CT
10: SETINTRPTLOOPINSERTREADYLIST($ReadyListHigh, P_k$)
11: $AdmittedList$.INSERT(Addr_STA, TSID, P_k, II_k, CT_k, $C^{current}_k$, C^{max}_k, $C^{uplink}_{attempt}$, $C^{downlink}_{attempt}$)
12: SENDMSG.ADDTSResponse[Accepted, CT_k]
13: **else**
14: SENDMSG.ADDTSResponse[Denied, NULL]
15: **end if**
16: **end function**

Algorithm 3 Function **SchedTest()**.

1: **function** SCHEDTEST(C^{max}_k, P_k, CT_k)
2: $CheckLow \leftarrow$ FALSE
3: **COMPUTEVALUES**(HIGH)
4: $n^{High} \leftarrow$ **COMPUTEVALUES**.N
5: $Sum^{High} \leftarrow$ **COMPUTEVALUES**.U
6: $n \leftarrow 2 + n^{High}$
7: $Sum \leftarrow (Beacon.\text{SIZE} / BI) + Sum^{High} + (C^{max}_k / P_k)$
8: **if** (**ISHARMONIC**(P_k) **and** ($Sum \leq 1$)) **then**
9: **return** (SCHEDULABLE, HIGH)
10: **else if** (**!ISHARMONIC**(P_k) **and** ($Sum \leq n \times (2^{1/n} - 1)$)) **then**
11: **return** (SCHEDULABLE, HIGH)
12: **else**
13: **return** (NONSCHEDULABLE, NULL)
14: **end if**
15: **end function**

Algorithm 4 Function **COMPUTEVALUES()**.

1: **function** COMPUTEVALUES(Priority)
2: $n \leftarrow 0$
3: $U \leftarrow 0$
4: **for** ($i = 0 \rightarrow AdmittedList.\text{SIZE} - 1$) **do**
5: **if** ($AdmittedList[i]$.CT == $Priority$) **then**
6: $n \leftarrow n + 1$
7: **if** ($Priority$ == HIGH) **then**
8: $U \leftarrow U + (AdmittedList[i].C^{max} / AdmittedList[i].P)$
9: **else**
10: $U \leftarrow U + (AdmittedList[i].C^{current} / AdmittedList[i].P)$
11: **end if**
12: **end if**
13: **end for**
14: **return** (n, U)
15: **end function**

B.2 Admission Control Unit - ACU

Algorithm 2 illustrates the ACU function. This function receives ADDTS messages and evaluates the required duration to transmit a L_K message in the uplink and downlink flows (lines 2–3).

Then, the ACU defines the blocking duration ($Interf_k$) that a station can suffer until starting the transmission attempt, which are given by:

$$Interf_k = C_{\text{DATA}}[MPDU^{\max}] + SIFS + C_{ACK},$$

where $C_{\text{DATA}}[MPDU^{\max}]$ is the time to perform the transmission of a message with the maximum MPDU length.

Afterwards, this function calls the **SCHEDTEST** function that performs the schedulability test (line 6).

B.3 Schedulability Test

The RT-WiFi architecture was designed to allow the use of different scheduling algorithms to ensure the fulfillment of TS_i timing requirements. In the specific case of this work, rate monotonic (RM) is used [56]. However, other scheduling algorithms could be used.

The function that performs the schedulability test is formalised in Algorithm 3. This function is called by the ACU after receiving an ADDTS request. The input parameters used are the maximum slot size (C^{max}_k), the message generation period (P_k) and the request type used to submit TS_k (CT_k[6]). Initially, the ACU executes a function that returns the total number of TS previously admitted and the sum of their utilisation level (lines 3–5). It is important to note that the utilisation level returned by this function for the high priority TS is based on the maximum slot size (C^{max}). After computing this utilisation level, the total number of TS and the total utilisation level that will be taken into account by the schedulability test are defined, including the beacon message and the new TS (line 7). Subsequently, the schedulability test is performed taking into account whether the TS set has a harmonic generation period, or not (lines 8 and 10, respectively). If the result of these tests is positive, the function returns a schedulable state (lines 9 and 11), otherwise it returns an non-schedulable state (line 13).

The function **COMPUTEVALUES** is formalised in algorithm 4, it gets the number and the utilisation level of a TS admitted by a specific priority. Importantly, utilisation level returned by this function for the high priority TS is based on the maximum slot size (C^{max}), whereas for the low priority TS this value is based on current slot size ($C^{current}$). Within this context, two auxiliary variables (lines 2 and 3) are initialised, and then a search in the TS admission list is performed, using as base the priority sent as input parameter (lines 4 and 5). If some entry matches, then the variable n is incremented (line 6) and the variable U is added to the utilisation level of TS found using as base the previously described rule for the different priorities (lines 7–11). Finally, the values of both variables are returned to the previous function (line 14).

B.4 Leaving Mechanism

The stations can be removed from the group G in two different ways. The first is by an explicit request. The second is by the verification of a possible failure in the station. This verification is performed by the AP_{RT}. In the first case, a station willing to request its removal from group G sends a DELTS message to the AP_{RT}. After this, the schedule algorithm removes its requirements from the set of requirements used to define the schedule sequence. The membership control removes its MAC address from the list used by the Beacon message, preventing the transmission of new messages in the subsequent TDMA cycle. After removing the station from the list, the AP_{RT} sends a disassociation message to the station, excluding the station from the BSS

[6] In this paper is considered only $CT_k = HIGH$.

of the RT network.

In the second case, after detecting a failure, a DELTS message is generated by the AP_{RT} and sent to the station to warn about its exclusion. Therefore, the ACU assumes that a TS_i changes to a fail state when the TS_i transmissions stops by a time interval longer than defined by the inactivity interval parameter (II_k) sent by the TS_i (via TSPEC) at the admission moment. Thus, after identifying the TS_i, the ACU can delete it in order to release the assigned resources.

To perform this verification, the ACU inserts in the admission list a variable (IdleTime) that defines the maximum time that a TS_i is able to remain without performing any transmission. Each time that ACU identifies the reception of a data message (with success or not) from the TS_i to the AP_{RT} into its slot, then the $\mathrm{IdleTime}$ variable is reset ($\mathrm{IdleTime} = 0$). Otherwise, its value is incremented based on the message generation period (P_i) defined by TS_i on the admission instant.

V. SIMULATION ANALYSIS

The main target of this section is to assess the behaviour of RT-WiFi versus IEEE 802.11 mechanisms, when supporting RT traffic in an OBSS. The DCF, PCF, EDCA and HCCA IEEE 802.11 mechanisms were selected as benchmark to assess the advantages/disadvantages of the RT-WiFi approach, when compared with the use of standard IEEE 802.11 mechanisms.

It is considered a communication scenario where a RT network is overlapped by a non-RT network (i.e., operating in the same area and same frequency channel), both employing an infrastructured topology. The RT network is composed of stations that transmit RT traffic. The non-RT network is an IEEE 802.11e network whose stations transmit generic non-RT traffic. The simulations were performed using the OPNET tool [57].

A. Evaluated Scenarios

Several simulation scenarios were built to evaluate the impact of non-RT traffic upon RT traffic. The RT network is composed of a variable number of RT stations (clients) that exchange messages with one RT server (SRV_{RT}) through an RT AP (AP_{RT}). Each RT station generates MSDUs with 73 bytes (i.e., 45 bytes of application data payload) with a fixed generation period (P_i). These RT stations implement either the RT-WiFi architecture or the functions defined in the IEEE 802.11 standard.

When RT stations are standard IEEE 802.11 stations, RT traffic is transmitted in the voice AC in the EDCA and HCCA mechanisms, that is, using the highest access category (and priority). For the remaining cases (PCF and DCF), RT traffic is transmitted using the standard queue.

For the sake of simplicity, in this paper we consider periods of 30 and 60 ms, as they are compatible with real industrial scenarios, although periods may vary according to the type of industrial plant [58]. We assume that message deadlines are equal to their periods. It is worth mentioning that RT-WiFi architecture can identically support traffic streams with multiple periods and different deadlines. In this case, it would be only necessary to modify the schedulability test defined in Algorithm 3. Related to the CFP parameter of PCF and HCCA, in both cases it was defined as 50% of P_i, i.e., $P_i/2$. When RT stations are implementing RT-WiFi, RT traffic is transmitted using the methods described in previous sections. As regards the RT-WiFi parameters, it was considered an initial blockage value equivalent to a transmission (with its acknowledgment) of one MSDU with 2304 bytes. As concerns the HCCA parameters, its CFP is the maximum allowed by the IEEE 802.11e.

Each non-RT station generates five types of traffic transmitted in three different AC. The best-effort AC transmits HTTP, FTP and SMTP/POP traffic according to a Poisson distribution. The MSDU size ranges from 350 bytes (e.g. HTTP request) to MSDU maximum size (i.e., 2304 bytes). The voice AC transmits VoIP traffic using a G.711 codec. In this case messages have a constant MSDU size of 160 bytes and are transmitted with a constant period of 20 ms. Finally, the video AC transmits video-conference traffic using a H.264 codec. These results in a bandwidth consumption of 240 Kbits/s per camera stream that is achieved by the transmission of messages with a variable MSDU size.

Since the non-RT traffic is transmitted using the EDCA mechanism, no admission control is used. For the set of non-RT stations, the offered load is classified as low, mid and high corresponding to 10%, 30% and 50% of the maximum theoretical throughput, respectively. Each offered load is composed of 15% of voice traffic, 25% of video traffic and 60% of best-effort traffic. In order to avoid transmission synchronisations, both RT and non-RT stations were randomly started.

For simplicity reasons, the physical layer is based on IEEE 802.11a. All devices operate at orthogonal frequency division multiplexing (OFDM) PHY mode, where control messages are transmitted at a basic rate equal to 6 Mbps, while MSDUs are transmitted at 54 Mbps. An error-prone communication channel is considered, based on the model available in OPNET, where the bit error rate (BER) is dynamically evaluated based on the mean value of signal-to-noise ratio (SNR). For the evaluated scenarios the average BER was set to $\sim 10^{-4}$.

All the simulation results were obtained with a 95% confidence interval, with a half-width relative interval less than 5%. The performance metrics used to analyse RT traffic include: Average communication delay and average number of deadline misses.

B. Average Communication Delay

The average delay represents the end-to-end average communication delay of the successfully received messages at the RT server. It is measured as the time interval between the instant when a message arrives at the station MAC layer to the instant when it is forwarded from the RT server MAC layer to the upper layers.

Figs. 8 and 9 present the average communication delay (and the respective standard deviation) for different numbers of RT stations when RT traffic is transmitted using IEEE 802.11 mechanisms with P_i equal to 30 and 60 ms, respectively. The results for the standard IEEE 802.11 mechanisms show, as expected, that DCF is not adequate to support RT traffic under mid and high load conditions. In both cases (30 and 60 ms), the average delay and standard deviation significantly increase with the increase in the number of RT stations.

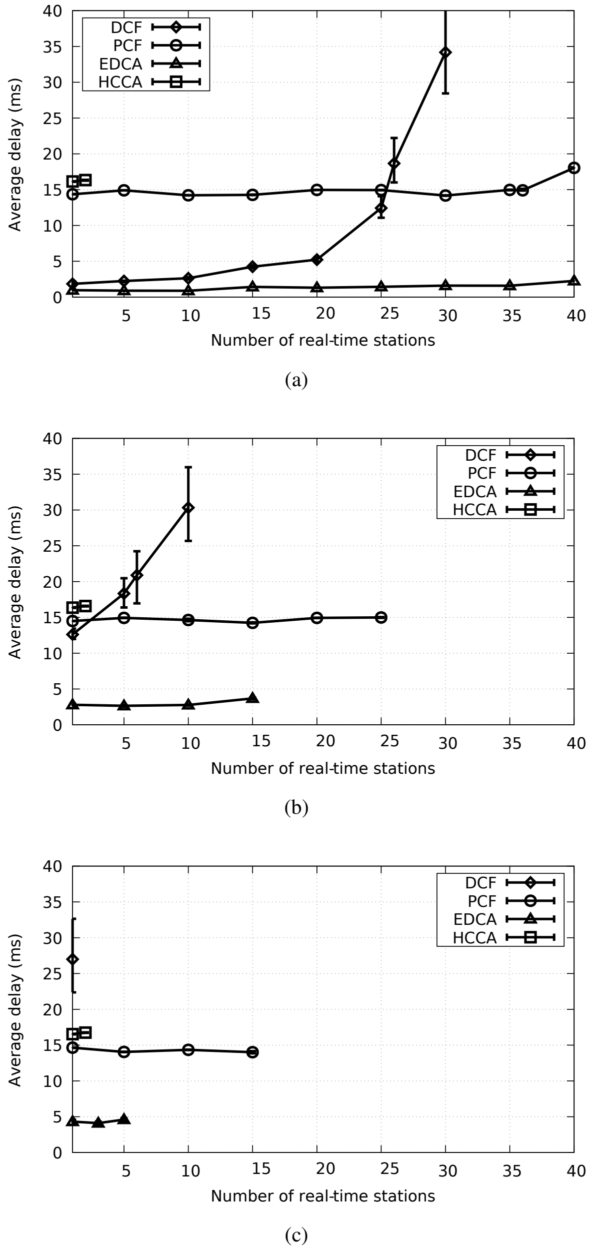


Fig. 8. Average delay when RT traffic is transmitted using IEEE 802.11 mechanisms (P = 30 ms): (a) Network load = low, (b) network load = mid, and (c) network load = high.

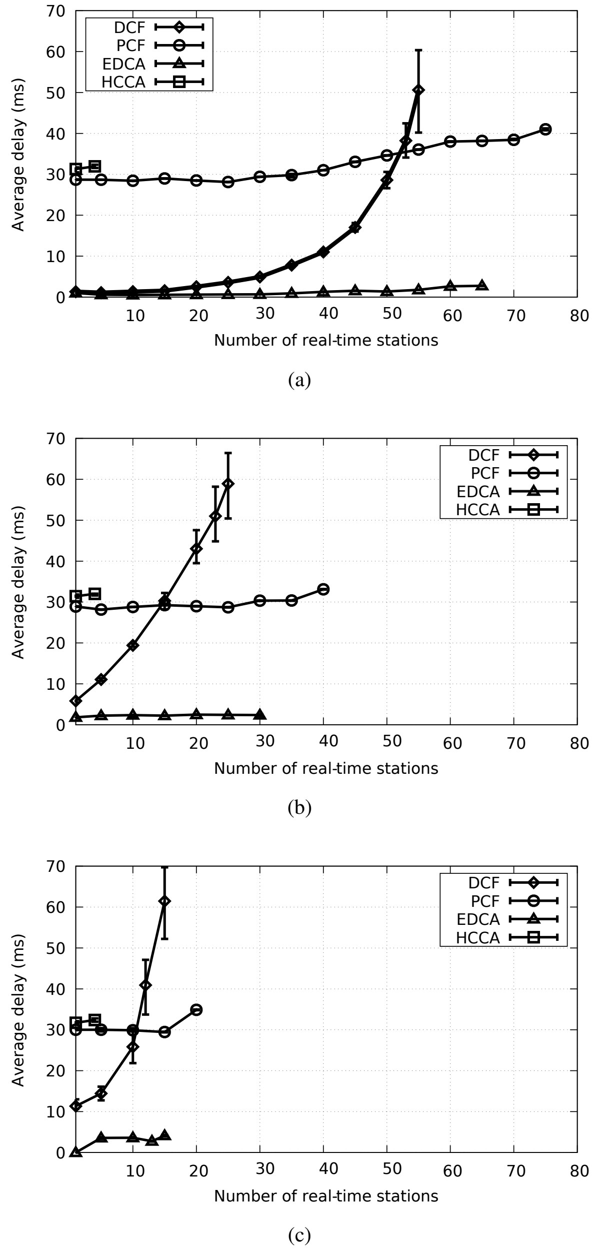


Fig. 9. Average delay when RT traffic is transmitted using IEEE 802.11 mechanisms (P = 60 ms): (a) Network load = low, (b) network load = mid, and (c) network load = high.

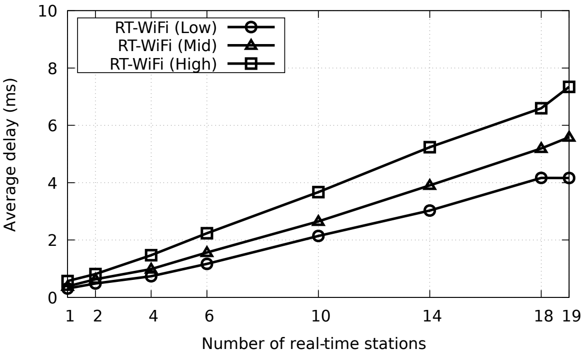
For the case of low network load (Fig. 8(a)), the average delay of EDCA can be considered quite good since it is below the message deadline threshold, even for a reasonable number of RT stations (≈ 30 stations). The trends of PCF and HCCA are a consequence of transmissions made during the CFP, which are periodically created with the transmission of a beacon message. Within this context, both mechanisms show results around 15 ms ($P_i/2$). In the case of PCF, it is possible to verify an increase in the average delay when the number of admitted RT stations reaches its upper bound (Figs. 8(a) and 9(a)).

When the network load is increased to the level defined as mid (Fig. 8(b)) and high (Fig. 8(c)), DCF suffers a considerable increase in its average delay. EDCA, PCF and HCCA follow the same trend of previous results, with a minimal increase in the case of EDCA. The same behaviour can be observed when P_i = 60 ms (Figs. 9(b) and 9(c)).

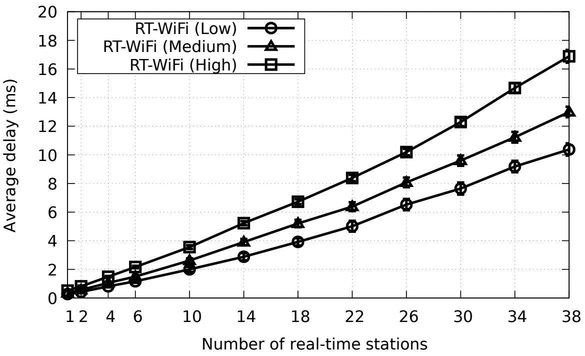
The number of RT stations implementing the RT-WiFi architecture varies between 1 and the maximum number allowed by the network admission control mechanism. The average communication delay for different number of RT stations and different generation periods is presented in Fig. 10. The results were obtained when the network reached a steady-state condition.

From Fig. 10(a), and in what concerns the results of RT-WiFi, three main conclusions can be drawn. First, the average communication delay is significantly smaller than for DCF/PCF/HCCA cases, and well below the message deadline threshold, even for a reasonable number of RT stations.

RT-WiFi presents a quite similar result of EDCA under low



(a)



(b)

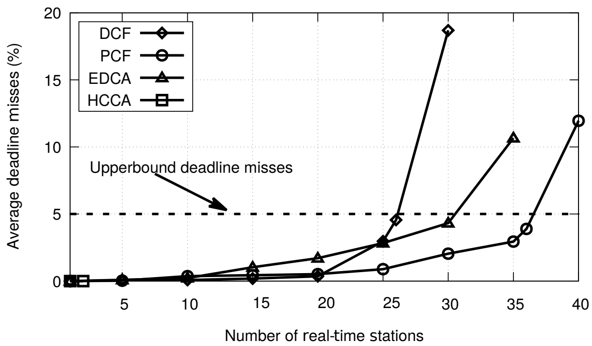
Fig. 10. Average delay when RT traffic is transmitted using RT-WiFi architecture: (a) Generation period of 30 ms and (b) generation period of 60 ms.

network load. However, when the EDCA and RT-WiFi are compared under mid and high network loads, the RT-WiFi architecture maintains the same number of admitted RT stations as in the low network load, with just a slight increase of the average delay. As it will be presented in subsection V.C average number of deadline misses, whenever the EDCA mechanism is used to transmit RT traffic under mid and high network loads, the maximum number of RT stations significantly decrease. It can degrade the communication system (blockage of previously admitted traffic streams) based on the network load.

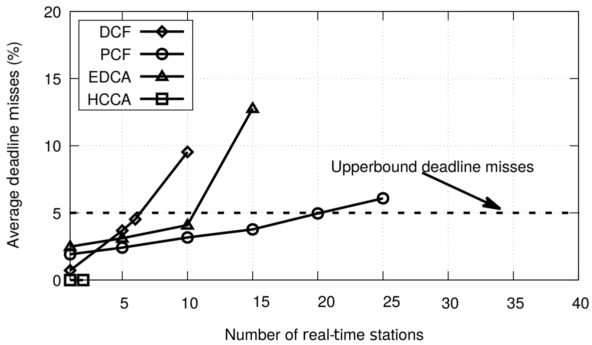
Second, the non-RT traffic has a very small impact on the communication delay. These results both from prioritisation of RT traffic and the dynamic adjustment of the slot length to the transmission conditions. Third, the communication delay increases almost linearly with the number of RT stations, which is a consequence of the TDMA approach. The standard deviation of the communication delay was also computed, but not presented in the figure due to its reduced value (typically $< 5\%$). This in turn implies that the communication jitter is also very small. In Fig. 10(b) the same trends of the previous results can observed.

C. Average Number of Deadline Misses

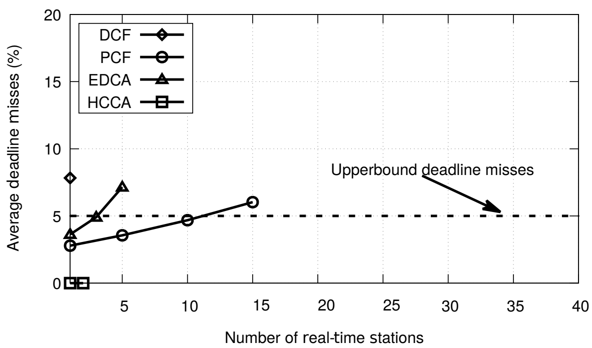
The average number of deadline misses represents the average ratio of RT messages that miss their deadlines because either they have not been delivered (communication errors), or have been delivered late. An upper bound for the admissible ratio of deadline misses has been set to 5%, meaning that above this ratio the network is no longer able to support RT traffic.



(a)



(b)



(c)

Fig. 11. Average deadline misses when RT traffic is transmitted using IEEE 802.11 mechanisms (P = 30 ms): (a) Network load = low, (b) network load = mid, and (c) network load = high.

To evaluate this metric similar communication scenarios were considered. Fig. 11 shows the deadline miss ratio for RT transmission with periodicity of P_i = 30 ms, for IEEE 802.11 standard mechanisms.

When considering the low network load case (Fig. 11(a)), the DCF can support up to 26 RT stations. EDCA and PCF increase this value up to 30 and 36 RT stations, respectively. It is important to note that the deadline miss ratio in the HCCA mechanism is null, but it can support just two RT stations. This is due to the pessimistic assumptions used by its admission control mechanism which computes all ADDTS requests based on the MSDU maximum size. Furthermore, HCCA requires that all its transmissions are performed using the basic transmission rate allowed by the physical layer.

When the network load is increased to the mid level (Fig. 11(b)), the number of supported RT stations is significantly reduced. In the case of DCF, it can only support up to six RT stations (a reduction of $\approx 76\%$ when compared with the previous result). EDCA and PCF can support only up to 10 and 20 RT stations, respectively. This represents a reduction of $\approx 67\%$ and $\approx 45\%$ on the EDCA and PCF, respectively. The supported number of RT stations by HCCA mechanism remains equal to two stations.

For the high network load level (Fig. 11(c)), DCF is no longer able to support any RT stations and EDCA and PCF can support just up to 3 and 10 RT stations, respectively. As expected, HCCA was not affected by the increase in the network load.

The result presented when the RT stations have a P_i = 60 ms (Fig. 12) is quite similar to the previous one. As expected, the number of RT stations supported by each mechanism increases, and the number of the supported RT stations decreases when the network load imposed by non-RT stations increases. At the low network load level (Fig. 12(a)) the DCF mechanism can support up to 52 RT stations and the EDCA and PCF mechanism can support up to 60 and 70 RT stations, respectively. Although not missing any deadlines, the HCCA mechanism is again penalised by its admission control that only allows the admission of four RT stations. Fig. 12(c) also illustrates the impact on the number of supported RT stations when the network load is increased to the level defined as high, supporting up to 10 RT stations in the DCF mechanism, and up to 12 and 15 RT stations in EDCA and PCF, respectively.

Fig. 13 presents the average number of deadline misses for different number of RT stations with different generation periods. The values presented were obtained in steady-state conditions for the RT-WiFi architecture.

Fig. 13(a) illustrates that the average number of deadline misses are below the 5% rule-of-thumb used for control systems. Only the high scenario diverges slightly and presents values higher than 4%. A further investigation of the results showed that the main cause for missed deadlines is related to the loss of the Beacon message. Since the beacon is used for the TDMA synchronisation, a station only transmits if it receives the beacon.

Fig. 13(b) shows that the results are quite similar to the previous ones. Even with 38 RT stations, the RT-WiFi architecture still ensures quite good values in what concerns the average number of deadline misses.

Analysing the presented results, it is possible to observe that RT-WiFi architecture supports a significantly larger number of RT stations when compared to the IEEE 802.11 mechanisms (almost twice), even if considering the worst case situation, i.e., operating under a high network load. Furthermore, RT-WiFi provides a stable operation, keeping almost the same behaviour, independently of network load or number of admitted RT stations. Similar behaviour is achieved only by HCCA, but with a significant limitation in the number of admitted RT stations.

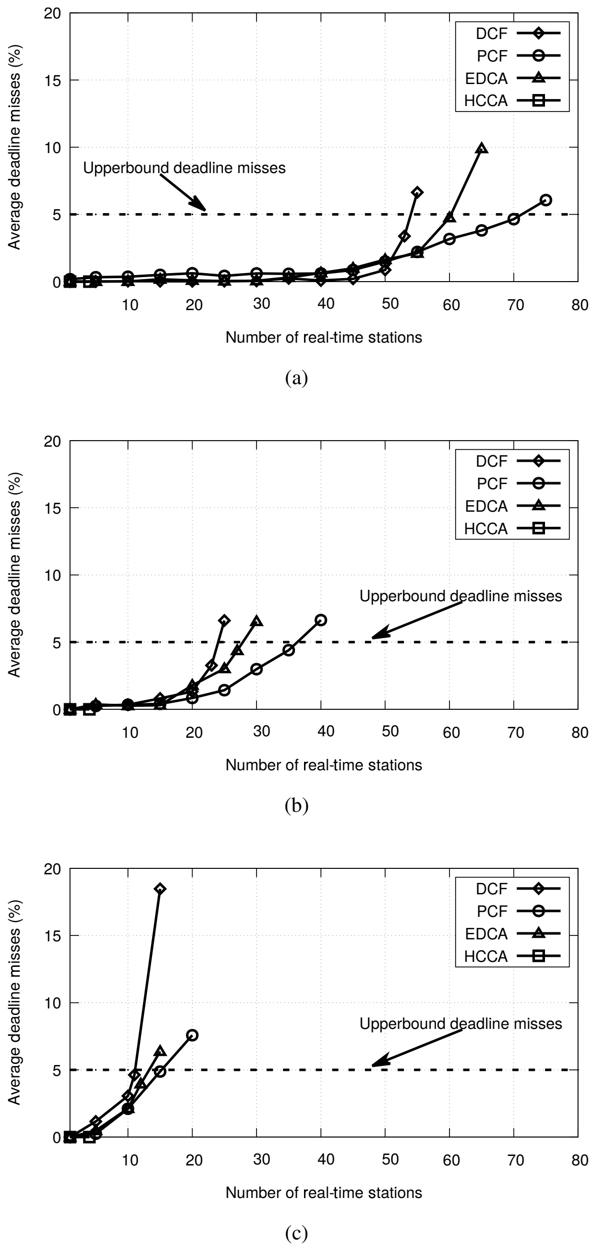
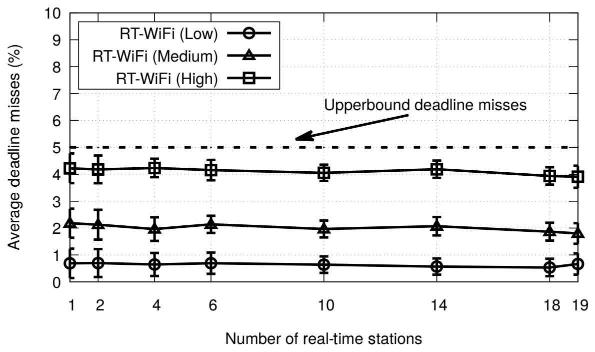


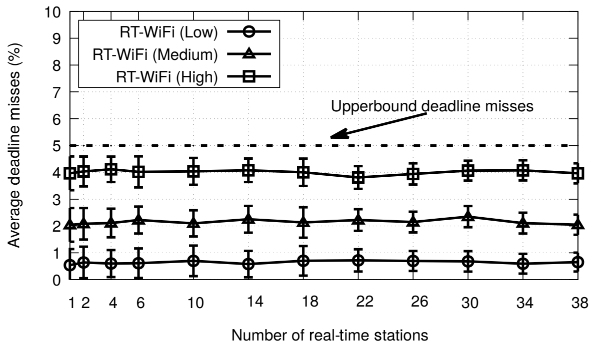
Fig. 12. Average deadline misses when RT traffic is transmitted using IEEE 802.11 mechanisms (P = 60 ms): (a) Network load = low, (b) network load = mid, and (c) network load = high.

D. Impact Upon non-RT Traffic

Although the main goal of RT-WiFi is to support RT traffic, it is important to assess the fairness when non-RT traffic is handled. Fairness is defined, in this case, by the impact of RT traffic (generated by RT stations) over the non-RT traffic (generated by standard IEEE 802.11 stations). This is an important metric to evaluate the coexistence capability of the proposed solution with an already deployed IEEE 802.11 network. It was considered a set of scenarios where the number of RT stations is fixed and the relative aggregate throughput of the non-RT network is measured. For this metric, it was considered as a reference value the aggregate throughput when the number of RT stations is 0,

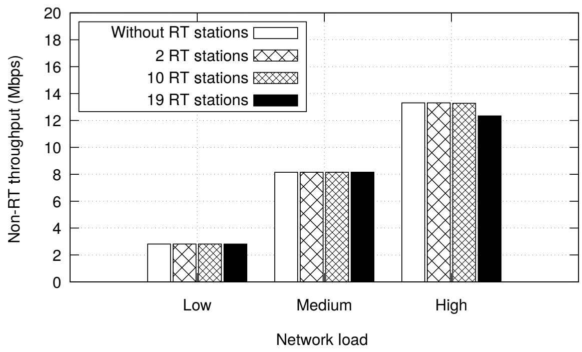


(a)

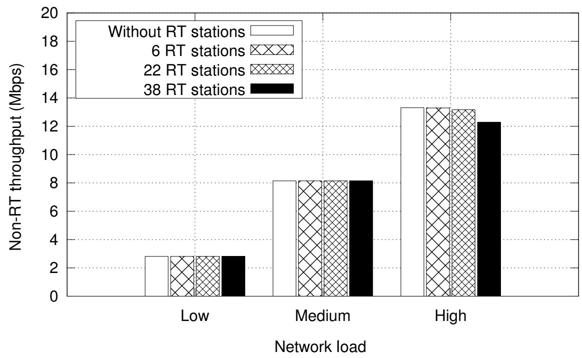


(b)

Fig. 13. Average number of deadline misses when RT traffic is transmitted using RT-WiFi: (a) Generation period of 30 ms and (b) generation period of 60 ms.



(a)



(b)

Fig. 14. Fairness: (a) Generation period of 30 ms and (b) generation period of 60 ms.

i.e., when the RT network is not present (Fig. 14).

Fig. 14 shows the fairness for different numbers of RT stations with different generation periods. In Fig 14(a), when the generation period is 30 ms, the first column shows the non-RT network throughput when the network load is low and without the presence of RT-WiFi network. The following three columns show what happens with the non-RT network throughput when 2, 10, and 19 RT-WiFi stations are overlapped with the non-RT network, respectively. It is possible to verify that no significant modification occurs. The same comparison is performed for mid and high network loads. It is possible to verify only a small modification when the network load is high and the number of RT-WiFi station is the maximum allowed for this specific generation period (19 stations). This same trend can be observed when the generation period is 60 ms (Fig 14(b)). This behaviour is related to the fact that RT-WiFi oversizes the TDMA slot assigned to each traffic stream. Therefore, the remaining time into each slot can be used for the transmission of non-RT traffic, before the beginning of next TDMA slot. In summary, analysing the performance measures of non-RT stations, it can be observed that there is just a small degradation in non-RT throughput when RT traffic streams are inserted into the network.

VI. CONCLUSION

The major motivation of this work was to propose a solution enabling the support of RT communication in wireless IEEE 802.11 environments, where RT devices need to coexist with unconstrained devices in OBSSs. The RT-WiFi architecture targets this problem in infrastructured IEEE communication scenarios.

The RT-WiFi architecture, which is able to handle together both non-RT and RT traffic, combines a FCR MAC that prioritises RT traffic with a TDMA mechanism that serializes the access of RT stations to the communication medium. The RT-WiFi architecture has also the required admission control mechanisms to handle the supported RT traffic flows.

A performance assessment has been done through simulation. The analysis of the results shows that, unlike the DCF, PCF, EDCA and HCCA mechanisms, the RT-WiFi provides: **(i)** An average communication delay that is predictable and almost constant ($C_{SI}/2$); **(ii)** a larger number of admitted station when compared to standard IEEE 802.11 mechanisms.; **(iii)** a stable average deadline miss ratio, even with the increase of the number of RT stations. This shows that the RT-WiFi gathers the conditions to support RT traffic in OBSSs.

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Robson Costa received the Ph.D. degree in Informatics Engineering from the University of Porto, Portugal, in 2013. He is a Professor in Federal Institute of Santa Catarina, Lages, Brazil. His research interests include industrial communication systems and real-time system architectures.

Paulo Portugal received the Ph.D. degree in electrical and computer engineering from the University of Porto (UP), Portugal, in 2005. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, UP, and a Researcher with the Institute for Systems and Computer Engineering of Porto Tech and Science. He has authored or co-authored more than 100 technical papers in the areas of industrial communication systems, RT networks for embedded systems, and dependability modeling and evaluation.

Francisco Vasques received the Ph.D. degree in computer science from the LAAS-CNRS, Toulouse, France, in 1996. Since 2004, he has been an Associate Professor with the Mechanical Engineering Department, University of Porto. He has authored or co-authored more than 150 technical papers in the areas of RT systems and industrial communication systems. His current research interests include RT communication systems, industrial communication, fault-tolerant systems, and RT system architectures.

Jim Lau received the Ph.D. degree in Automation and Systems Engineering from the Federal University of Santa Catarina (UFSC), Brazil, in 2014. He was a Postdoctoral Researcher at the post graduation program in Energy and Sustainability at the Federal University of Santa Catarina, from 2016 to 2017. Since 2018, he has been an adjunct professor and a Researcher with the Department of Computer Engineering, UFSC. His research interests include, web service, fault tolerance in distributed systems, wireless sensor networks.

Ricardo Moraes received the Ph.D. degree in electrical and computer engineering from the University of Porto, Portugal, in 2007. He is an Associate Professor and a Researcher with the Department of Computer Engineering, UFSC. His research interests include distributed systems, real-time communication systems and wireless networks.