A Forcing Collision Resolution Approach able to Prioritize Traffic in CSMA-based Networks

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Abstract

In this paper, a Traffic Separation mechanism (TSm) is proposed for CSMA-based networks. The TSm mechanism is intended to be used as an underlying traffic separation mechanism able to prioritize traffic in CSMA-based networks. It allows the coexistence of standard CSMA (non-modified) stations with TSm (modified) stations in the same network domain. When a station implementing the TSm mechanism has a high-priority message to transfer, it will impose its transfer prior to any other message from standard CSMA stations. This behavior guarantees the highest transmitting probability to the TSm-enabled station in an open communication environment. Therefore, the TSm mechanism can be used as a foundation to build real-time communication systems in CSMA-based networks. The behavior of the TSm mechanism was assessed by simulation in the case of a relevant CSMA-based network (IEEE 802.11). The simulation analysis shows that the TSm mechanism guarantees values for both the throughput and the average access delay that significantly improves the results obtained for standard IEEE 802.11 stations.

Index Terms

Real-time communication, CSMA networks, wireless networks, IEEE 802.11 protocol.

I. INTRODUCTION

The Carrier Sense Multiple Access (CSMA) protocol is a well-known and extensively used Medium Access Control (MAC) protocol. Its inherent simplicity has imposed it as one of the preferred MAC solutions for broadcast networks. The most relevant solutions based on the CSMA protocol are the IEEE 802.3 [1], IEEE 802.11 [2] and IEEE 802.15.4 [3] standards, also known as Ethernet, WiFi and ZigBee protocols, respectively. In addition to the widespread use of CSMA-based protocols in the office environment, there is also a trend for its use in industrial environments [4], where messages must be periodically transferred according to strict deadlines. For instance, not only in voice and video applications, but also in control-related applications [5].

The major challenge concerning the design of real-time (RT) systems upon CSMA-based networks is that the communication channel is a shared resource. As a consequence, when multiple stations start simultaneously a transmission, the probabilistic collision resolution problem arises. Therefore, there is the need to prioritize the high-priority traffic when sharing the same communication infrastructure with multipurpose traffic [6].
Traditionally, the message prioritization in wired CSMA environments has been guaranteed through the tight control of every communicating device. Thus, in order to allow the coexistence of high-priority traffic together with multipurpose one, an usual approach is to severely constrain the behavior of the latter. Unfortunately, when moving from wired to wireless networks, traffic smoothing is no longer adequate. The main reason is that the wireless physical medium is an open communication environment, i.e., any new participant can try to access the communication medium at any instant (according to the MAC rules) and establish its own communication channels. That is, any new participant is able to bypass any CSMA-based admission control mechanism. As a consequence, the system load cannot be predicted at system setup time, nor can be effectively controlled during the system run-time.

It is foreseeable that the existing communication systems will partially move from closed to open communication environments, through the use of a wireless communication infrastructure [5], [7]. Thus a new paradigm for RT communication will need to emerge, as the traditional paradigms are still based upon closed and controlled environments. For the next generation communication environments, allowing the coexistence of both high-priority and multipurpose traffics in the same communication domain is likely to become a requirement. Furthermore, solutions that require the control of every communication device in order to prioritize the high-priority traffic will be impracticable in practice.

The reasoning behind this paper is that a 2-tier architecture may be the most adequate solution to support RT communication in the environments referred above, providing that: in the lower layer (MAC layer) a forcing collision resolution (FCR) mechanism provides a higher priority to the set of RT stations and in the upper layer, a coordination mechanism ensures collision-free access among the set of RT stations (Figure 1). This coordination mechanism can be based on a token passing scheme or a time division multiple access (TDMA) mechanism, for example. It just needs to serialize the medium access of the high-priority stations, as the FCR layer ensures that standard (ST) stations will always loose the contention when contending for the medium access with a RT station.

This contrasts with most part of state-of-the-art communication approaches that rely only upon the use of just a coordination layer. Therefore, they do not allow the coexistence with uncontrolled (external) traffic sources that are out of the sphere-of-control of the RT architecture.

The fundamental assumption of this paper is that the wireless physical medium is an open
Fig. 1. A 2-tier architecture to support real-time communication in wireless networks.

communication environment. As a consequence, communication approaches that do not allow the coexistence of RT and ST stations sharing the same communication medium are no longer adequate. As a consequence, there is the need to define a FCR MAC that enables the separation of the traffics in a shared CSMA environment.

In this paper, a new Traffic Separation mechanism (TSm) is proposed for the MAC level of CSMA-based networks. It enables the implementation of a FCR MAC that is able to prioritize high-priority traffic over multipurpose traffic. The proposed FCR MAC can be easily implemented in CSMA networks using commercial of-the-shelf (COTS) hardware.

The remainder of this paper is organized as follows. Section II describes how the CSMA protocol works, in the case of a collision avoidance (CSMA/CA) approach. Afterwards in Section III it is presented the state-of-the-art on wireless RT communication built upon CSMA-based networks. Section IV highlights the proposed Traffic Separation mechanism (TSm), focusing on the modifications that must be made to IEEE 802.11 standard stations. Then, a simulation analysis is discussed, followed by some conclusions.
II. THE CSMA PROTOCOL

The Carrier Sense Multiple Access (CSMA) protocol defines a probabilistic MAC family of protocols, where stations contending for the access to a shared medium must listen before transmitting. Basically, this family of protocols has the following behavior:

- When a station wants to transmit, it listens to the transmission medium;
- If the medium is idle, the station will start the transmission (either immediately, or after a defined interval, depending on the specific protocol);
- If the medium is busy, i.e. another station is transmitting, the station will defer its transmission to a later time that depends on the specific protocol;
- A collision will occur whenever two (or more) stations sensed the medium idle and decided to simultaneously transmit;

The CSMA medium access methods that are implemented by different communication protocols differ on how the waiting time intervals before transmitting are evaluated, either after sensing the medium idle, or before re-transmitting after a collision. In this paper, the CSMA/CA protocol used in the IEEE 802.11 standard is described. This protocol has been selected to assess the behavior of the TSm mechanism in wireless networks, due to its widely utilization and relevance.

The medium access mechanism of the IEEE 802.11 standard [2] is a CSMA with Collision Avoidance (CSMA/CA), also called Distributed Coordination Function (DCF). More accurately, the IEEE 802.11 MAC sublayer introduces two medium access coordination functions, the mandatory DCF and the optional Point Coordination Function (PCF). DCF\(^1\) is the basic mechanism of the IEEE 802.11, where stations perform a so-called backoff procedure before initiating a transmission. When a station wants to transmit, it senses the medium (carrier sensing) and if the medium is idle during a specific time interval called DIFS (Distributed Interframe Space) it immediately transmits. Otherwise, the station selects a random time called backoff time. The duration of this time interval is a multiple of the Slot Time (ST), which is a system parameter. The number of slots is an integer random number in the range of \([0, CW]\), where \(CW\) (contention windows) is initially assigned as \(aCW_{\min}\). A backoff counter is used to maintain the current

\(^1\)An additional mechanism, RTS/CTS, is defined in the IEEE 802.11 standard to solve the hidden terminal problem and to obtain a better behavior for transmission of long message. For further details, please refer to [2].
value of the backoff time.

In this case, stations keep sensing the medium (listening) for this additional random time, after detecting the medium as idle for a DIFS interval. If the medium gets busy due to interference or other transmissions while a station is down-counting its backoff counter, the station stops down-counting and defers the medium access until the medium becomes idle for a DIFS again. A new independent random value is selected for each new transmission attempt, where the $CW$ value is increased by $[(oldCW + 1) * 2 - 1]$, with an upper bound given by $CW_{max}$. As soon as the backoff counter reaches zero, the station can retry its transmission (Figure 2).

The DCF access method imposes an idle interval between two consecutive frames, which is called the Interframe Space (IFS). Different IFSs are defined in order to impose different priorities to multiple frame types. Four different IFS durations are defined in the IEEE 802.11 standard: SIFS (Short Interframe Space), PIFS (PCF Interframe Space), DIFS (Distributed Interframe Space) and EIFS (Extended Interframe Space). SIFS is the shortest of the Interframe spaces and it is used for ACK frames. Only stations operating under the Point Coordination Function (PCF) will use PIFS. DIFS is used by stations operating under the DCF mechanism to transmit data frames and management frames.

![Interframe spaces in the DCF and EDCA mechanisms.](image)

The IEEE 802.11e standard was published [8] as an amendment to the original standard with the goal of supporting QoS. This amendment incorporates an additional coordination function called Hybrid Coordination Function (HCF) that is only used in QoS network configurations.
The HCF mechanism schedules the access to the channel by allocating transmission opportunities (TXOP) to each of the stations. Each TXOP is defined by a starting time and a maximum duration and may be allocated through one of two access mechanisms specified by the HCF: the Enhanced Distributed Channel Access (EDCA) and the HCF Controlled Channel Access (HCCA) [8].

The EDCA mechanism was designed to provide differentiated transmission services, with four access categories (AC). It enhances the DCF mechanism, as each frame arriving at the MAC layer with a defined priority will be mapped into one of the four AC. These ACs are based on the 8 priority levels of IEEE 802.1D standard, as follows: priorities 1 and 2 for background traffic (BK); priority 0 and 3 for best effort traffic (BE); priorities 4 and 5 for video traffic (VI); and, finally, priorities 6 and 7 are mapped 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: the Arbitration Interframe Space (AIFS), the transmission opportunity time interval (TXOP) and the Contention Window size (CW). For a station operating under EDCA, each frame will wait that the medium remains idle during an \( AIFS[AC] \) interval, instead of a DIFS interval as specified for DCF in IEEE 802.11. The duration of the \( AIFS[AC] \) interval is given by:

\[
AIFS[AC] = AIFSN[AC] \times aSlotTime + aSIFS\text{time} \tag{1}
\]

where the \( AIFSN[AC] \) must be greater than or equal to 2 for all stations, except for the QoS Access Points (QAPs), where it shall be greater than or equal to 1. The default parameters defined for EDCA mechanism are presented in Table I. Figure 2 shows the relationships between the
multiple AIFSs in the EDCA mechanism. It is worth mentioning that the default AIFSN for both voice and video categories is 2. Thus, AIFS[VO] = AIFS[VI] = DIFS.

**TABLE I**

**Default EDCA Parameter Set.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CWmin</th>
<th>CWmax</th>
<th>AIFSN[AC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC_BK</td>
<td>acWmin</td>
<td>acWmax</td>
<td>7</td>
</tr>
<tr>
<td>AC_BE</td>
<td>acWmin</td>
<td>acWmax</td>
<td>3</td>
</tr>
<tr>
<td>AC_VI</td>
<td>(acWmin+1)/2</td>
<td>acWmin</td>
<td>2</td>
</tr>
<tr>
<td>AC_V0</td>
<td>(acWmin+1)/4</td>
<td>(acWmin+1)/2</td>
<td>2</td>
</tr>
</tbody>
</table>

III. **Supporting Real-Time Communication with the CSMA Protocol: Review of Relevant Work**

State-of-the-art approaches to support RT communication in CSMA-based protocols can be classified in three main classes, according to how collisions are dealt with. One common approach is to impose the *collision avoidance*. This is usually achieved through the strict control of all communicating devices. Another common approach is to replace the probabilistic algorithm by a *deterministic collision resolution* algorithm. Finally, the third class is based on *reducing the number of collisions*, through the use of a loosely-coupled distributed algorithm. In this section, we briefly describe the state-of-the-art approaches for the support of RT-communication in IEEE 802.11 standard networks, using this classification.

**A. Avoiding Collisions**

The Point Coordination Function (PCF) is one of the main solutions intended to *avoid collisions* in IEEE 802.11 wireless networks. It has been proposed in the original IEEE 802.11 standard [2] as an optional access mechanism. It implements a centralized polling scheme to support synchronous data transmissions, where the Point Coordinator (PC) performs the role of polling master. Usually, the PC resides in the Access Point (AP).

The HCCA mechanism was proposed in the IEEE 802.11e amendment [8] to improve the PCF scheme. It is based on a round-robin scheme and it is intended to guarantee bounded delay requirements. Like the PCF scheme, the PC also polls *all* the stations in the polling list, even
though some stations may not have messages to transmit. When the PC polls a station that has no packets to transfer, the station will transmit a null frame. As a consequence, the polling overhead is roughly equal to the time interval from sending the polling frame till the end of the ACK frame [9]. A number of improvements have been recently proposed to reduce the HCCA polling overhead [9]–[11].

Solutions based on token passing mechanisms have also been proposed to support RT communication in wireless networks. In [12], Ergen et al. proposed the WTRP (Wireless Token Ring Protocol), which is a MAC protocol that exchanges special tokens and uses multiple timers to maintain the nodes synchronized. The token is rotated around the ring, each station transmits during a specified time and if enough time is left, the station invites nodes outside the ring to join. In [13], 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) frames as tokens, where a node that has the right to send a data frame will send a RTS frame and; a node, which has the right to receive a data frame will send a RTR frame to the sender if the expected RTS frame has not been received. Summing up, a station can only send a DATA frame if it holds a token.

Finally, solutions based on TDMA or Master-Slave mechanisms have also been proposed. In [14], Willig presented the FTDMA (Flexible TDMA) MAC protocol. FTDMA is based on a polling scheme, where a base station polls all registered RT stations in every frame. The main advantage of the FTDMA over traditional TDMA solutions is that unused slots can be used by other stations. In [15], Miorandi et al. proposed a solution based on a Master-Slave architecture on top of IEEE 802.11. In that proposal, cyclic packets are exchanged by means of periodic queries sent by the master to the slaves.

A common characteristic of almost all these solutions is that an enhanced (RT) station is not able to support RT communication in the presence of standard IEEE 802.11 stations, unless these standard stations do not initiate any communication. That is, the majority of the RT communication approaches are not able to support RT communication whenever standard stations try to access the shared communication medium. Relevant exceptions are the improvements included in the HCF (PCF and HCCA) mechanism of the IEEE 802.11e amendment. However, despite PCF being well suited to handle delay-sensitive applications, it is rather complex and almost none WLAN network card ever implemented the PCF scheme [16]. Preliminary studies
have also shown that the HCCA mechanism may not be suitable to guarantee the special requirements of RT applications. Furthermore, it is still not clear whether the HCCA mechanism will be implemented in next generation WLAN network cards, overcoming the unavailability problem of the PCF mechanism. Besides these two approaches, all other mechanisms require the strict control of the communication environment. Therefore, they are not suitable to handle communication environments where a set of non-RT stations can be operating in the same frequency band as the RT stations.

B. Deterministic Collision Resolution

Concerning the deterministic collision resolution, Sobrinho and Krishnakumar [19] adapted the EQuB mechanism (black burst) [20] to ad hoc CSMA wireless networks (IEEE 802.11 DCF). This scheme requires the shutdown of the random retransmission scheme. Real-time stations implementing the EQuB approach contend for the channel access after a medium interframe spacing $t_{med}$, rather than after the long interframe spacing $t_{long}$, used by standard stations. Thus, RT stations have priority over standard stations. When a RT station wants to transmit, it sorts its access rights by jamming the channel with black bursts (BB’s), i.e., energy pulses immediately after an idle period of length $t_{med}$. The length of the BB transmitted by a RT node is an increasing function of the contention delay experienced by the node.

A similar scheme is presented in [21], where voice nodes (RT stations) use energy-burst (EB) (that is similar to BB) periods to prioritize RT packets over data packets. The AP (Access Point) can transmit a VoIP packet after PIFS without backoff or contention. On the other hand, each voice station has its own address (ID), referred as VID (virtual identification). The VID can be assigned during the traffic stream (TS) setup procedure. The VID is expressed as a binary value, which is determined by the voice packet resolution period (VPRP). The station with the highest VID wins the contention.

In [22], Shew et al. proposed a priority MAC protocol based on Sobrinho’s approach, complemented by a binary tree referred as contention tree. Basically, the black-burst (BB) scheme is adopted 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 an unique ID number, which depends on its position in the contention tree.

The deterministic collision resolution techniques are based on forcing the collision resolution
schemes in favor of the RT stations. Although many of these solutions are technically very interesting, they are economically not viable [4], since they require an extensive modification of the WLAN cards, which prevents the use of COTS hardware.

C. Reducing the number of collisions

The EDCA mechanism available in IEEE 802.11e amendment is specifically intended to reduce the number of collisions. A possible solution to support RT communication under EDCA would be to use the highest access category (voice) to transfer RT messages. However, the use of this mechanism suffers from some limitations. Specifically, the communication delays may become unpredictable when considering a communication environment shared with uncontrolled traffic sources. In a previous research work [23], the behavior of the EDCA voice category has been assessed when it is used to transfer small sized packets in an open communication environment. Both the number of packet losses and the average size of the MAC queues forecasted an unacceptable number of deadlines misses for RT message streams, even for intermediate load cases.

Hamidian and Körner [24] presented an interesting solution that provides QoS guarantees to the EDCA mechanism. The proposed solution allows stations with higher priority traffic to reserve time for collision-free access to the medium. Basically, it proposes the transfer of the HCCA admission control and scheduling algorithms from the HCCA controller to the contending stations.

Wang et al. [25] designed a new collision resolution mechanism, referred as gentle DCF or GDCF. The difference between GDCF and DCF is that GDCF takes a more conservative measure by halving the CW (Contention Window) value only if there are \( c \) consecutive successful transmissions. Conversely, DCF reset its CW to the minimum value once there is a successful transmission. The GDCF needs to maintain a continuous successful transmission counter that is reset to zero after each collision. Then, when a collision occurs GDCF works similarly to DCF.

Yang and Vaidya [26] proposed the Busy Tone Priority Scheduling (BTPS) protocol. This scheme makes the following assumptions: (i) each station is capable to monitor the carrier status of the data channel; (ii) each station in idle state is capable to monitor two busy tone channels (BT1 and BT2) and lock onto the signal in the data channel as desired; (iii) it is assumed that the two busy tone signals (BT1 or BT2) sent by a station can be sensed by other stations within
the interference range of the former station. In BTPS, busy tone serves as the indication of backlogged high priority packets.

BTPS works similarly to the IEEE 802.11 DCF, with the difference that high priority and low priority stations behave differently during IFS and backoff stages. The BTPS protocol uses DIFS as the IFS for high priority stations. However, during DIFS and backoff stages, high priority stations with queued packets send an energy pulse every $M$ slots, where $M$ is a constant. Between two consecutive busy tone pulse transmissions, there should be at least one empty Slot Time interval, as the station must have a chance to listen to the data channel. Therefore, $M$ could be any value larger than or equal to 2 and, the IFS of low priority stations should be larger than $M$ slots, in order to enable sensing the busy tone signal.

In [27], it was proposed a distributed algorithm intended to provide fair scheduling in a WLAN, referred as DFS (Distributed Fair Scheduling). The DFS protocol behaves quite similarly to IEEE 802.11 DCF, except in what concerns the backoff interval initially calculated, which is choose proportionally to the finish tag of the packet to be transmitted. The finish tag is calculated similarly to the SCFQ (Self-Clocked Fair Queueing) algorithm [28].

In [29], Lopez-Aguilera et al. evaluated the performance of the IEEE 802.11e EDCA when its working procedure is unsynchronized. The authors proposed the use of AIFS time values whose differences are not multiple of the slot time. As a consequence, it would become possible to avoid collisions between frames from different access categories.

Lo Bello et al. [30] proposed a wireless traffic smoother (WTS) to support soft RT traffic over IEEE 802.11 WLANS. The presented solution is similar to the traffic smoother scheme previously proposed for Ethernet networks [31]. Therefore, the main drawback is that it requires the smoothing strategy to be implemented in all the communicating devices.

Summing up, strategies based on the reduction of the number of collisions increase the network access fairness and reduce the collision occurrence based on some priority criterion. However, these type of solutions cannot be effectively applied in open communication environments, since they are not able to handle uncontrolled traffic sources.

**D. Summary**

Throughout the state-of-the-art analysis, it can be concluded that the *forcing collision resolution approach* is one of the most promising MAC solutions when dealing with the support
of RT communication in open communication environments. To our best knowledge, it is the only technique that allows the coexistence of RT stations with an unknown set of uncontrolled traffic sources that may have an unpredictable timing behavior (non-RT stations). This approach allows focusing the economical/technical investment just in the RT stations, without losing the advantages of using standard IEEE 802.11 stations.

IV. THE TRAFFIC SEPARATION MECHANISM (TSM)

A. Rationale

The target of this paper is to propose a mechanism able to prioritize traffic in CSMA-based communication environments. That is, a RT communication approach able to handle high-priority traffic in communication environments shared with uncontrolled traffic sources. That is, shared with traffic sources that are out of the sphere-of-control of the RT architecture. Basically, three requirements are introduced in our assumptions: (i) the high-priority traffic is being transmitted in the same frequency band as the multipurpose traffic (coexistence of different traffic sources in the same communication environment); (ii) the modifications required to prioritize traffic must be implemented using COTS hardware; (iii) stations generating multipurpose traffic follow the standard CSMA communication rules.

Almost all RT communication approaches for CSMA/CA networks require the modification of all communicating stations. The main reason is that these approaches are built upon the strict control of the communication opportunities of every communication device. That is, they assume a communication environment completely under the control of the RT communication architecture. This assumption is not realistic when addressing wireless communication environments. Whatever the communication scenario, there is always the possibility of an unknown number of uncontrolled traffic sources to start sharing the wireless communication medium.

To address this problem, we propose the use of a novel forcing collision resolution (FCR) MAC mechanism, called TSM. This mechanism is able to prioritize high-priority traffic over multipurpose one, without directly controlling the latter. That is, instead of controlling all the

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2By “inside/outside” sphere-of-control, we mean that whenever a RT entity is in the sphere-of-control of a subsystem, it belongs to a subsystem that has the authority to change all the values of this RT entity. Outside its sphere-of-control, the value of the RT entity can be observed, but cannot be modified. This concept has been used in different areas by a number of authors, e.g. Kopetz [32].
traffic generated by *all* the stations, an approach ruled out in open communication environments, the proposed approach will control only the high-priority traffic sources. More specifically, it prioritizes the high-priority over the other traffics. To our best knowledge, the proposed TSm mechanism and those solutions based on the BB scheme [19] are the only solutions that enable the prioritization of urgent traffic in uncontrolled communication environments. The main disadvantage of the BB scheme against the TSm mechanism is that the BB scheme requires the use of non-COTS hardware, as previously explained.

**B. The TSm mechanism**

In the standard CSMA/CA protocols, whenever there is a collision, the collision resolution algorithm defers the retransmission during a backoff time. Conversely, the proposed TSm mechanism ensures that whenever a collision occurs, either the high-priority messages are transferred before any other message from multipurpose traffic sources, or none of the messages is transferred at all.

The TSm mechanism works as follows: whenever a collision between a message sent by a TSm-enabled station and one or more messages sent by standard (ST) stations occurs, all but the TSm station, will use the standard medium access mechanism (DCF or EDCA) and select a random backoff time. Conversely, the high-priority traffic source implementing the TSm mechanism (hereafter referred as TSm station) transfers its traffic at the highest priority level of the DCF or EDCA modes, i.e., using the minimum Interframe Space (IFS) of both mechanisms \((DIFS = AIFS[VO] = aSIFSTime + 2 \times aSlotTime)\) and setting the Contention Window (CW) to its minimum value: \(aCW_{min} = aCW_{max} = 0\). This means that any TSm station will always try to transmit its frame in the first DCF or EDCA available slot, while all the other ST stations will wait during a time interval evaluated by the local backoff functions.

The behavior of a TSm station is described in Figure 4. In this example, a TSm station competes with an EDCA station, both transmitting packets using the minimum IFS value. That is, all the stations use the IFS value of the voice category (AIFS=2). Nevertheless, it can be seen that when a TSm station has one high-priority message to transmit, its transmission is performed

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3As explained before, in the case of DCF mechanism, the backoff time is only dependent of the PHY characteristics values (\(aCWM\) and \(aCWM\)) or, in the case of EDCA mechanism, defined according to the access category (voice, video, best-effort and background).
immediately after an AIFS, since the backoff counter of the TSm station is always 0. Therefore, and in normal circumstances, the TSm station will always win the medium access before any ST station. The only exception is when there is another (standard) station with its backoff counter at 0 at the same time. A collision will occur in this case and the TSm station will have its transmission deferred. However, even in this scenario, the TSm station will have an improved behavior compared with the standard ones. After a timeout, both stations will invoke its backoff procedure but with major differences. A TSm station always have its backoff counter at 0, while a standard one will update their backoff counter to a value that has a very high probability of being greater than 0. This implies that the TSm station will win the medium access in the next idle time (AIFS) without any extra deferment, while the standard station will necessarily defer its transmission.

This mechanism can be easily implemented upon COTS hardware, due to its simplicity. If the WLAN card enables the access to the $aC_{\min}$ and $aC_{\max}$ parameters, no hardware modification is necessary, and standard WLAN cards can be used. For instance, using the MADWiFi driver for the Atheros 802.11a/b/g chip. This driver allows to adjust the relevant parameters of the EDCA mechanism (e.g. $aC_{\min}$, AIFS, TXOP) and therefore to implement the proposed modifications.

V. SIMULATION STUDY

It is worth noting that, the target of the proposed TSm mechanism is to prioritize traffic in heterogeneous CSMA-based environments, where timing unconstrained stations (ST stations)
and TSm stations are sharing the same communication medium. Moreover, the network load imposed by the set of ST stations can not be controlled.

In order to evaluate the behavior of the proposed TSm mechanism, we decided to assess a representative class of industrial applications that require traffic prioritization. Consider a communication scenario typically found in industrial applications, where real-time (RT) messages streams are usually associated with control applications. In this type of applications, RT messages must be periodically transferred between sensors, controllers and actuators according to strict transfer deadlines. In the context of a TSm communication scenario, high-priority message streams convey control-related messages, where small sized packets are generated in periodic intervals and must be delivered before the end of the message stream period. Otherwise, the message is considered to be delayed and a deadline loss occurs.

A simulation model was built using a Stochastic Petri Net (SPN) tool [33], describing the dynamics of both EDCA and DCF functions of the respectively, IEEE 802.11e and IEEE 802.11a/b/g protocols. All the simulation results have been obtained with 95% confidence interval, with a maximum half-width interval of 5%. The performance metrics include: the packet loss rate, the average packet delay and its average queue size. The packet loss rate represents the percentage of packets that are lost for each traffic stream. The average packet delay is the average time required to transfer a packet, measured from the start of its generation at the application layer to the end of the packet transfer at the receiving station. The average queue size represents the average buffer occupancy.

Finally, it is worth mentioning that the RT communication behavior is usually assessed for worst-case scenarios. However, when dealing with probabilistic medium access networks, the worst-case scenarios address just rarely occurring cases. The analysis of those rarely occurring cases is definitely relevant for safety-critical applications, but it is highly pessimistic when dealing with typical industrial communication environments. It is well known that this type of environments are usually loss tolerant in what concerns the lost of some message deadlines. For instance, the transfer of a video stream may be specified to tolerate a maximum of 10% deadline loss rate, if the lost frames are “adequately” spaced. Another examples of relevant loss tolerant applications are Networked Control Systems scheduled according to the (m,k)-firm model [34], or the support of VoIP applications, where an average packet delay below 150ms and an average jitter below 50ms are acceptable for most typical applications [35]. For a RT
communication system, the average packet delay must be kept smaller than message deadlines, in order to minimize the occurrence of deadline misses. On the other hand, there is also the need to guarantee a reduced number of message losses. Therefore, the use of a simulation setup for the analysis of RT communication in probabilistic medium access networks is well justified, when dealing with loss tolerant applications.

A. Simulation Setup

The simulation setup presented in this paper aims to verify how the TSm station is able to handle high-priority messages. Basically, the TSm mechanism is compared with both DCF (IEEE 802.11a/b/g) and EDCA (IEEE 802.11e) mechanisms, in the presence of external ST stations (operating according to DCF or EDCA modes). In the case of the EDCA mechanism, it is used the highest access category (voice) to transmit the high-priority messages. In this simulation scenario, we consider high priority messages as the messages intended to support the RT periodic data exchanges between sensors, plant controllers and actuators in an industrial environment.

The simulation scenarios were built considering an ad hoc network topology, where one RT station implementing the TSm mechanism (enhanced scenario) resp. the standard mechanism (DCF/EDCA scenario) coexists with a variable number of uncontrolled (external) ST stations ($n=4, 6, 8, 10\ldots 20$). In the enhanced scenario, the RT station transfers high-priority messages (RT traffic), using the TSm parameters (minimum interframe space and contention window equal to zero). In the DCF/EDCA scenario, the RT station transfers high-priority using the default set of parameters defined by the DCF and EDCA mechanisms (Table I). For the latter, it is used the voice (VO) access category. For both scenarios, the RT traffic is modeled according to a normal distribution with $\sigma/\mu \leq 1\%$, 200 packets/s with 64 bytes for data payload, which is equivalent to generate 1 packet every 5\(ms\). On the other hand, the ST stations transmit three types of traffics: voice (VO), video (VI) and background (BK) using the default set of parameters defined by the DCF/EDCA functions. The traffic patterns of ST stations were defined according to [36], where the voice flow is chosen as a 64 Kb/s pulse code modulated (PCM) stream (packet size of 160 bytes). The transmission rate of a video flow is 640 kb/s with a packet size of 1280 bytes. The transmission rate of background traffic is 1024 kb/s (packet size of 1500 bytes). Thus, the external traffic load imposed by the uncontrolled ST stations varies from about 23 to 114 percent.
by increasing the number of ST stations from 4 to 20.

The physical parameters used in the simulations are based on the IEEE 802.11a PHY mode \((aC\text{W}_{\text{min}}=15; aC\text{W}_{\text{max}}=1023)\). Each station operates at OFDM (orthogonal frequency division multiplexing) PHY mode, control frames are transmitted at a basic rate equal to 1 Mbps, while the MSDU (MAC service data units) are transmitted at 36 Mbps. The maximum number of transmission attempts is set to 7. The MAC queue size is set to 50 positions.

B. Simulation Results

The average packet delays are presented in Figures 5(a) and 5(b). These figures show that the proposed TSm mechanism (enhanced scenario) has an average delay much smaller than both the DCF or the EDCA mechanisms. More importantly, it is clear that, whatever the number of external ST stations, the average packet delays are nearly constant. There is even a reduction in the average access delay when the network becomes congested. The main reason for this is that there is a clear increase in the number of lost messages from ST stations, and therefore the RT station is able to access the medium slightly earlier. These results indicate that TSm mechanism leads to a predictable communication delay for high-priority messages. This is a highly relevant result when considering RT communications, as it shows a very small dependence to the external network load that might be imposed by stations out of the sphere-of-control of the RT architecture.

![Figure 5(a)](image1.png)

![Figure 5(b)](image2.png)

Fig. 5. Average packet delay - DCF and EDCA stations vs. enhanced (TSm) station.

Comparing the average packet delay to transfer RT message by both DCF (Figure 5(a))
and EDCA (Figure 5(b)) mechanisms, it is clear that the EDCA presents an improvement to the original DCF proposed in the IEEE 802.11a/b/g standard, when transferring high-priority messages. Figure 5(b) shows that the average packet delay between TSm and EDCA mechanisms are quite similar up to 12 external stations. However, those results have a much higher standard variation. For instance, considering the medium access delay for 10 external stations, there is a considerable difference between the behavior of the EDCA and the TSm mechanisms, as plotted, respectively, in Figures 6(a) and 6(b). It is worth mentioning that the TSm mechanism forecasts a much more predictable communication delay when supporting RT communications.

Fig. 6. Packet delay - EDCA vs. enhanced - for 10 external ST stations.

Another positive aspect of the TSm mechanism can be retrieved from the packet loss rate, that is plotted in Figures 7(a) and 7(b). It is unquestionable the improvement achieved by the TSm mechanism, as the packet loss rate is nearly constant and close to 0. This is a remarkable result, as it indicates that, even in highly loaded network scenarios, the TSm mechanism is able to guarantee the delivery of almost every RT message. Noting that the external traffic load imposed by the uncontrolled ST stations varies from 23% to 114%, by increasing the number of RT stations from 4 to 20.

Finally, an important aspect in RT communication is related to the average queue size (Figures 8(a) and 8(b)). It can be seen that, for the transfer of RT packets, the RT station implementing the TSm mechanism has an average queue size much smaller than in the case of both the DCF
or the EDCA mechanisms. It is also clear that, whatever the network load, the average queue size is nearly constant and smaller than 1. This means that, the pending RT messages are always sustainably transferred before the generation of new RT messages.

From this simulation results, it becomes clear that the TSm mechanism is adequate to implement a FCR MAC in a 2-tier CSMA RT communication architecture, as it is able to prioritize the RT traffic in open communication environments. Moreover, it is able to handle nearly constant
values for both the average access delay and the average throughput, which are highly relevant attributes when supporting RT communication. Another relevant aspect is the negligible loss rate, which is of paramount importance, whatever the type of supported applications.

Summarizing, it can be concluded that the parameters proposed for the TSm mechanism provide the adequate traffic separation for open communication environments. On the other hand, as expected both the DCF and the EDCA standard mechanisms have an unacceptable behavior for RT systems architectures. This misbehavior had already been reported in [23].

VI. CONCLUSION

This paper proposes a forcing collision resolution MAC mechanism (TSm) that allows the coexistence of CSMA standard stations with modified (real-time) stations in the same network domain. The TSm mechanism was designed to be used in CSMA-based networks, where both the number of communicating devices and their traffic patterns are not known by the real-time system designer at setup time. One of the main advantages of this mechanism is related with the easiness of its implementation. In the most recent WLAN cards no hardware modifications are needed, and it is only necessary to perform a simple configuration of the system parameters ($aCW_{\text{min}}$ and $aCW_{\text{max}}$).

The results obtained for IEEE 802.11 wireless networks show that the proposed underlying TSm mechanism guarantees the highest transmitting probability for the TSm station in a wireless environment with multiple EDCA standard stations. More importantly, the results show that, when varying the external (uncontrolled) traffic network load, the average packet delay for the RT traffic is nearly constant. This indicates that the TSm mechanism can provide a predictable behavior for RT traffic.

In conclusion, the TSm mechanism is specially suited for communication environments where there might be communicating devices out of the sphere-of-control of the RT-communication architecture. This is the case of wireless environments.

REFERENCES


