A TDMA-Based Mechanism to Enforce Real-Time Behavior in WiFi Networks

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Abstract

In this paper, a TDMA-based mechanism is proposed for IEEE 802.11 Wireless LANs. This mechanism prioritizes real-time traffic in IEEE 802.11 networks, allowing the coexistence of standard stations with modified (real-time) stations in the same network domain. The worst-case timing analysis of the TDMA-based mechanism shows that the service interval is upper-bounded, even when the communication medium is shared with timing unconstrained stations.

1 Introduction

The demand for high performance wireless networking with real-time (RT) capabilities will increase significantly in the next few years. Concerning the industrial communication environments, there are presently big efforts to move from wired to wireless networks [1]. Voice over IP (VoIP) and Networked Control Systems (NCS) are examples of driving applications in industrial environments. For such type of applications, the support of timely communication services is one of the major requirements. For instance, in NCS applications, RT control data must be periodically transferred between sensors, controllers and actuators according to strict transfer deadlines.

Concerning the timeliness requirements of RT industrial applications, there are a set of soft RT applications that can tolerate some losses of temporal deadlines. For example, a RT control application can tolerate occasional losses of the control law updates, especially if the control law has been modified to account for those lost updates [2].

Traditionally, RT communication behavior in wired CSMA (Carrier Sense Multiple Access) environments has been guaranteed through the tight control of every communicating device. The coexistence of RT controlled stations with timing unconstrained stations has been made possible by constraining the traffic behavior of the latter. For instance, using traffic smoothers [3]. Unfortunately, when moving from wired to wireless networks, this traffic smoothing paradigm is no longer adequate, since it is not possible to impose any traffic smoothing strategy upon stations that are out of the sphere-of-control of the RT architecture. The main reason is that the wireless physical medium is an open communication environment. That is, any new participant can try to access the communication medium at any instant, according to the MAC (Medium Access Control) rules, and establish its own communication channels. As a consequence, the system load cannot be predicted at system setup time, nor can it be effectively controlled during the system run-time. One of the main purposes of this paper is to demonstrate that it is possible to support RT communication services with CSMA-based networks, using a TDMA-based (Time Division Multiple Access) mechanism to manage the medium access.

2 Related Work

In this section, the most relevant proposals to improve the RT traffic support in IEEE 802.11e networks are presented. Although this standard supports ad hoc and infrastructure modes, only the infrastructure-based approaches are presented, as it is the focus of the present work.

In [4] is proposed a multipolling mechanism called contention period multipoll (CP-Multipoll), which incorporates the DCF access scheme into the polling scheme. It uses different backoff values for the multiple message streams in the polling group, where each station executes the backoff procedure after receiving the CP-Multipoll frame. The contending order of these stations is the same as the ascending order of the assigned backoff values. The first station in the polling list initializes its transmission immediately after receiving the CP-Multipoll frame. This action avoids the interference from other stations to perform the backoff procedures in the DCF mode.

In [5], a scheduling algorithm designated as TGe scheduler is proposed. It is compatible with the link adaptation mechanisms implemented in commercial WLANs, as it bounds the amount of time during which each station may control the wireless medium access. This algorithm is based on the mandatory TSPEC (Traffic Specification) parameters, where each station is polled with an independent service interval. Basically, it is used traditional scheduling algorithms from the RT scheduling theory to poll the stations.

In [6], a new scheduling scheme for audio/video trans-
mission using the HCCA access mode is proposed. In this scheduling scheme, the HC (hybrid coordinator) firstly evaluates the TXOP (transmission opportunity) duration in a service interval for each wireless station, on the basis of its mean data rate; it then adds additional TXOPs for each wireless station that had queued audio or video packets at the end of the previous TXOP.

There are a number of interesting proposals based on Master-Slave solutions, e.g. [7, 8]. Additionally, solutions based on token passing mechanisms have also been proposed [9, 10]. However, it is worth noting that, when dealing with open communication environments, the following issues must be carefully considered:

1. The channel contention during the CFP (contention free period) must be protected from the interference of other stations, which are performing the backoff procedures in the DCF or EDCA modes.

2. Repeated collisions may occur if multiple HCs are performing the polling and operating on the same frequency band in the overlapping space.

3. There might exist collisions among polled stations if two polled stations cannot listen to the transmissions of each other in the BSS (hidden station problem).

Analyzing the state-of-the-art approaches, we can observe that neither of the solutions accomplish all these issues. Specially, regarding the third problem, the above described solutions do not consider the open characteristics of the wireless physical medium. I.e. all the described solutions work under the assumption that all stations are able to obey to the NAV rules. However, this is an unrealistic assumption due to the hidden station problem. As a consequence, whenever the channel becomes idle during a period of time larger than DIFS (distributed inter-frame space), which is the smallest interframe space for DCF/EDCA stations, any station can try to send a message, and therefore the NAV protection is overruled.

When analyzing the RT characteristics of both the PCF and HCCA standards, despite both mechanism being well suited to handle delay-sensitive applications, most part of the WLAN network cards never actually implemented the PCF scheme, due to complexity reasons [11]. Concerning the HCCA mechanism, it is still not clear if it will be implemented in next generation WLAN network cards, solving the unavailability problem of the PCF mechanism. Nevertheless, one of the most relevant unsolved problem is that both PCF/HCCA stations may not obey to the NAV rules.

Another unsolved problem concerns the coexistence of RT controlled stations with timing unconstrained stations in the same communication medium. Unfortunately, traditional approaches cannot be enforced in wireless environments, since any station contends for the access to a shared radio channel. Therefore, it is not possible to impose any traffic smoothing strategy upon stations that are out of the sphere-of-control of the RT architecture.

Thus, we entirely agree with Bianchi et al. [12] that in wireless architectures, the service differentiation mechanism must be compulsory introduced as MAC layer extension. Furthermore, we argue that the performance analysis of the upcoming wireless solutions must always consider the impact of external traffic load upon the assessed communication scenarios. Otherwise, the results will become useless.

3 The TDMA-based mechanism

In this section a new TDMA-based communication mechanism is proposed, allowing the coexistence of both RT and non-RT stations in the same communication domain. This solution enables the prioritization of RT traffic by controlling only the subset of RT stations. One of the main purposes of this mechanism is to simplify both traditional medium access mechanisms (PCF and HCCA), enabling the provision of RT guarantees to a well-identified subset of RT stations.

This TDMA-based mechanism is intended to be used in infrastructured networks, using the capability of the AP (Access Point) or of the HC (hybrid coordinator) to send Beacon frames. The basic idea is to use the Beacon frame to synchronize all the RT stations, assigning to each one of them a fixed slot, which is used exclusively by the station. During these slots each RT station contends by the medium access only with non-RT stations. Therefore, there will be just collisions between RT and non-RT stations. However, by managing the values of the AIFS/CW (Arbitration InterFrame Space/Contention Window) parameters assigned to the RT stations the number of such collisions can be drastically reduced. The proposed approach employs the TSin approach [13] to prioritize the RT stations when solving the collision with the non-RT stations.

This proposal considers a RT-group with \( np \) members (RT stations). The membership is represented as \( L = \{STA_1, STA_2, ..., STA_{np}\} \), where \( STA_i \) is used as station identification and \( i \) is used as station index. In the beginning of a SI (Service Interval), the AC or the HC sends a Beacon frame to the stations belonging to the RT-group. Such a Beacon frame contains a MCT (Micro Cicle Time) parameter, which is used to determine the start of each slot. The MCT value is function of the time during which each RT station will be allowed to contend for the medium access with the timing unconstrained non-RT stations.

In order to protect the channel from the interferences of stations performing the backoff procedures in the DCF or EDCA modes, the first station in the RT-group (\( STA_1 \)) will access the channel without any deferment (a PIFS interval after the Beacon frame). In order to avoid repeated collisions among multiple APs or HCs, it is guaranteed that there are no APs or HCs operating in the overlapping frequency space. It is worth noting that the APs or HCs are usually fixed equipments. Therefore, this can be easily provided during network setup time.
The main innovation of the proposed TDMA-based mechanism is related to the way how collision are solved in a TDMA-based context. Whenever a collision between a RT station and a set of non-RT stations occurs (standard stations), all but the RT station will select a random backoff time. In the case of the EDCA mechanism, such backoff time will be set according to the access category (voice, video, best-effort and background). Conversely, the RT station transfers its traffic at the highest priority level of the EDCA mode, i.e., using the same AIFS of the voice category (AIFS[V] = aSIFSTime + 2 × aSlotTime) but, setting the CW to the value \(aCW_{min} = aCW_{max} = 0\). This means that whenever a collision occurs, either the messages from the RT station are transferred before any other message from non-RT stations, or none of the messages is transferred at all.

A RT station (STA1) may contend for the medium access during a MCT interval, starting at the beginning of slot SSi. The slot start for station \(i\) is defined as the time difference (\(\Delta\)) between the start of the Beacon frame and the start of the slot during which station \(i\) may contend for the communication medium access. The setting of these parameters is explained in the next section.

This mechanism can be easily implemented using COTS hardware. If the WLAN card enables the access to the \(aCW_{min}\) and \(aCW_{max}\) parameters, no hardware modification is necessary, and standard WLAN cards can be used. For instance, through 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. \(CW_{min}\), \(AIFS\), \(TXOP\)) and therefore to implement the proposed modifications.

4 Timing Analysis

In this section, the timing analysis of the proposed mechanism demonstrates that the medium access is upper-bounded, even when the communication medium is shared with non-RT stations. This means that the non-RT messages are not able to disturb the timing operation of the RT-group.

Consider an IEEE 802.11e network interconnecting a RT-group with \(np\) stations (RT-stations) and an unknown number of timing unconstrained IEEE 802.11e stations (ST stations). Consider that the RT-stations have addresses ranging from 1 to \(np\). Each RT station accesses the network according to a TDMA-based scheme in previously defined slots. First STA1, then STA2, ..., until STA\(np\), and then again station 1, 2, ..., \(np\). The ST stations implement the traditional backoff procedure according to the default timing values defined in the IEEE 802.11e standard.

Basically, two-collision scenarios are analyzed. Firstly, it is analyzed the maximum delay to transfer a RT message, when the RT station has a data message ready to be transferred (D) (Figure 1). In such a case, it will wait an IFS (InterFrame Space) before starting to transmit it (1st attempt). A station is able to detect a collision only after finishing its transmission plus an \(aSIFSTime\), i.e. if the ACK frame is not received. Afterwards, if the transmission is not correctly acknowledged, the station will wait again during another IFS (IFS: \(aSIFSTime + 2 \times aSlotTime\)) interval and, according to the TDMA-based proposal, it will immediately start to transmit its message (2nd attempt). If a second collision occurs, the station will wait again for the IFS before starting to transmit. The maximum time that a RT station will wait during its slot before starting to transfer a message for the last attempt or eventually discard it, is given by:

\[
T_{col} = (RN - 1) \times (IFS + t_{message})
\]

where \(RN\) is the maximum number of allowed retransmissions and \(t_{message}\) is the duration to transfer a data message (including the ACK frame) from the RT station according to the physical (PHY) characteristics of the channel. For instance, considering 100 bytes for data payload in IEEE 802.11a PHY mode (data rate of 36 Mbps), each attempt takes 0.128ms.

It is clear that this scheme either solves the collisions in a bounded time interval (within \(RN\) retransmission attempts), or it eventually discards the message. Therefore, a relevant focus of research is to evaluate the probability of a message frame being discarded by the IEEE 802.11 stations, whenever the number of collision resolution rounds exceeds the defined number of retransmission attempts. This topic has been addressed in [14], where it has been shown that for a non saturated network, the packet loss rate is smaller than \(10^{-7}\), when considering a collision probability \(p = 0.1\). This satisfies the packet loss requirements of traditional soft real-time applications, such as VoIP or NCS applications.

Therefore, in the following analysis it is only considered the case where no message is discarded by a RT station, due to an excessive number of retransmission attempts. In this case, the worst-case for a transmission attempt occurs when the RT station has enough RT messages to fill up to the maximum TXOP interval defined for the subset of RT stations (\(t_{TXOP_{RT}}\)). This value is a lower bound for the MCT value. Therefore, the MCT value can be set as follows:

\[
MCT = T_{col} + t_{TXOP_{RT}}
\]

On the other hand, when the RT station does not have any RT message ready to be transferred, one of the ST
stations in the wireless domain can successfully start to transfer its own messages. This means that during the MCT assigned to RT stations, any ST station may start to transfer a message, as long as there is no RT traffic. In such a case, the worst-case will be when at instant immediately before the end of the current transmission attempt, a ST station takes the decision of transmit a frame and it acquires the transmission medium and uses all the allowed TXOP time. This occurrence will cause a delay in the beginning of the next transmission attempt. This value will be upper bounded by the TXOP value defined in the standard. Therefore, a Guard time must be defined at the end of each MCT interval, in order to avoid the overlap with the following slot. Considering the SI as the time interval between two consecutive Beacon frames, the upper-bound for the length of the SI cycle is given by (Figure 2):

$$SI = Beacon + PIFS + \sum_{i=1}^{np} (Guard + MCT)$$  \hspace{1cm} (3)$$

This SI value imposes a lower bound for the periodicity of the RT message streams supported by the proposed scheme.

**Figure 2. SI worst-case scenario.**

Finally, the slot start for station $i$ ($SS_i$) can be evaluated as follows:

$$SS_i = Beacon + PIFS + [(i-1) \times (Guard + MCT)]$$  \hspace{1cm} (4)$$

where Beacon is the Beacon frame duration, $i$ is the station index, MCT is the slot duration and Guard is the slot guard duration.

5 Conclusion

This paper proposes a forcing collision resolution MAC mechanism (TDMA-based) that allows the coexistence of CSMA standard stations with modified (real-time) stations in the same network domain. This 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 the easiness of its hardware 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.

**References**


