

A Centralized Scheduling and Retransmission Proposal for Firm Real-time Traffic in IEEE 802.11e

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Abstract. *This work investigates the problem of scheduling network resources in the context of a cooperative mobile multi-robot system that exchanges messages with firm real-time constraints using a wireless network compliant with the IEEE 802.11e amendment. Due to the nature of wireless technology the scheduling algorithm must be able to deal with residual error at the MAC layer to provide a degree of reliability for time bounded messages. Moreover, additional requirements should be satisfied by the scheduling algorithm in order to increase the robustness and adaptability of the system. We propose an integrated scheduling and retransmission mechanism to solve this problem. Simulation experiments are used to evaluate our proposal.*

Resumo. *Este trabalho investiga o problema de escalonamento de recursos de rede no contexto de sistemas móveis cooperativos que trocam mensagens com requisitos de tempo real firmes utilizando uma rede sem fio compatível com o adendo IEEE 802.11e. Dado a comunicação sem fio, a retransmissão de mensagens passa a ser um problema crucial. Para tratar este problema, propõe-se uma nova abordagem que integra retransmissão e escalonamento de mensagens de forma combinada na camada de acesso ao meio, onde o algoritmo de escalonamento é capaz de lidar com os erros de transmissão residuais e aumentar o grau de confiabilidade para as mensagens de tempo real. A solução proposta é capaz de lidar com falhas inesperadas e suportar requisitos adicionais de qualidade de serviço, aumentando a robustez e a adaptabilidade do sistema. A abordagem proposta é avaliada através de simulações em diferentes cenários de carga de tráfego.*

1. Introduction

The IEEE 802.11e [IEEE-802.11e 2005] amendment adds parameterized and prioritized Quality of Service (QoS) mechanisms to the Medium Access Control (MAC) layer of the legacy 802.11. Parameterized QoS is a strict requirement expressed in terms of quantitative values, such as data rate, delay bound, and jitter. Prioritized QoS is expressed in terms of relative delivery priority.

Parameterized QoS supports the use of this technology in firm real-time applications, in which deadline losses may lead to stopping the service being provided. However, despite the efforts of the physical layer to assure reliability in the transmissions through techniques like forward error correction and modulation scaling, the susceptibility of the wireless technology to frame corruption due to signal interference, attenuation, and multipath effect still remains a limiting factor. Therefore, to ensure reliability, the residual

errors must be identified and treated at the MAC layer. Although there are many works in this area, most of them deal with performance issues and soft-real time communication. Moreover, no existing work considered the mentioned problem of transmissions errors.

To tackle this issue, we propose a new mechanism that integrates messages scheduling and retransmission in a unified manner at the MAC layer. In our approach the scheduling algorithm is able to deal with residual transmission errors and then increase the reliability level of the real-time messages. It provides flexibility to deal with unexpected failures and supports additional QoS requirements. Consequently, it allows to increase the robustness and adaptability of the system, so that the application can react to unexpected failures and achieve its goal. The proposed approach is evaluated through simulations for different scenarios of traffic load and compared with the standard approach 802.11e for scheduling and retransmission of real-time messages.

The reminder sections of this paper are organized as follows. Section 2 describes the major features introduced by the IEEE 802.11e that are of interest for this work. Section 3 presents the proposed mechanism, including the detailing of the communication requirements it can provide, the probabilistic analysis to define the degree of reliability for timely messages transmission in the proposed approach, and its operation details. Section 4 shows the evaluation of this approach through simulation. Section 5 presents related works. Finally, conclusions and further work are shown in section 6.

2. Overview of the IEEE 802.11e Technology

The IEEE 802.11e amendment [IEEE-802.11e 2005] adds QoS to the MAC layer of the legacy 802.11. It introduces a Hybrid Coordination Function (HCF) that combines a prioritized contention-based access method called Enhanced Distributed Channel Access (EDCA) and a polling-based access method called HCF Controlled Channel Access (HCCA). EDCA introduces multiple access categories for prioritized traffic. HCCA is designed to provide parameterized scheduling of traffic streams.

One key improvement introduced is the concept of Transmission Opportunities (TXOPs). TXOPs are time intervals that limit the consecutive use of the medium by a node but also allow transmitting multiple frames back to back. To enable parameterized scheduling, TXOPs are allocated according to specific flow requirements called Traffic Specifications (TSPECs). Traffic specifications can be generated by the nodes and then submitted to a central coordinator (Hybrid Coordinator), usually co-located at the AP, by sending a TSPEC request management frame. The coordinator is in charge of the admission control and of the subsequent scheduling of the submitted streams.

Hard/firm real-time applications should use an HCCA-based scheduling, since it has priority over EDCA to access the medium. When it gains control of the medium it starts the Controlled Access Phase (CAP), which is a time period wherein the coordinator controls the channel. During this phase, the coordinator sends data and polling frames to the nodes according to its scheduling algorithm. The data sent to the nodes by the AP is called downlink traffic while the data sent by the nodes in response to a polling frame is called uplink traffic.

HCCA allows eight traffic queues (or classes) per node, which are identified by a Traffic Identifier (TID) with values from 8 up to 15. The polling frames carry information about the length of the transmission opportunity (TXOP) and the TID for which

the polling is intended to, although the requirement to respond to that TID is nonbinding. Thus, each node is responsible to locally schedule its outgoing frames, while the scheduler at the coordinator has to allocate the TXOPs per node¹. The unused portion should be returned to the coordinator through the sending of a so-called null frame or by setting a specific subfield in the response data frame. The nodes can also use the data frame to notify the coordinator the status of their queues. A node may start to retransmit when it detects the absence of an expected reception and if there is enough time in the current TXOP. It is suggested that each node calculates the additional time necessary for retransmission, notifying subsequently this value to the scheduler through the *surplus bandwidth allowance* parameter of the TSPEC request. Notice that, due to the high overhead, HCCA specifications and recommendations tend to prioritize the network performance, as in the case of the nonbinding polling. This may not be suitable for distributed real-time systems in which time constraints are more important than network performance.

The IEEE 802.11e does not define a standard message scheduling mechanism, allowing users to design and hook their own scheduling policy into the legacy system. Nevertheless, it provides the guidelines for the design of a periodic round-robin scheduler that can be used with HCCA. This is known as the reference scheduling mechanism and works as follows. It calculates the schedule for an admitted stream in two steps: (i) it first calculates period of the scheduler (Scheduled Service Interval - SI) and (ii) it calculates the TXOP duration of the admitted streams. These parameters are calculated based on information about transmission rate, packet length, period and/or delay bound of the traffic specifications. The admission control must ensure that the inequality 1 is satisfied.

$$\frac{TXOP_{K+1}}{SI} + \sum_{i=1}^k \frac{TXOP_i}{SI} \leq \frac{T - T_{CP}}{T} \quad (1)$$

Where k is the number of existing streams and $k + 1$ is used as index for the newly arriving stream. T indicates the beacon interval and T_{CP} the time for contention traffic.

3. Proposed Scheduling Mechanism

Given that there are only a few related works tackling the scheduling algorithm used with HCCA and that none of them deals with the retransmission problem, this work proposes a new message scheduling mechanism to be used with firm real-time applications. This mechanism is based on HCCA, therefore it is suitable for systems with differentiated and dynamic communication needs, given that it has the ability to negotiate traffic specifications with parameterized constraints on the fly. It is a centralized algorithm because the decision whether a frame should be scheduled for transmission or retransmission is taken entirely by the scheduler, which is running in the AP. Moreover, it is used in opposition to the standard recovery procedure that enforces a node-oriented retry that can be called a distributed approach. Thus, when a node detects the absence of an expected reception in the centralized approach, instead of retrying it waits for a new opportunity (polling) until the delay of the frame expires and then the frame is dropped. In this section we present the application communication requirements that motivated the development of

¹The TXOP value per polling is limited by country laws and by the protocol itself, which allows a range that goes from 32 to 8160 μs .

this scheduling strategy, the reliability analysis that form the basis of our mechanism, and also the details regarding the mechanism operation.

3.1. Communication Requirements

From the application point of view, the proposed mechanism is designed to satisfy the following requirements, which concern the communication infrastructure:

1. **Reliability:** a high degree of reliability must be provided so that the messages can be successfully transmitted before the expiration of its deadlines.
2. **Predictability:** indicates the existence of a global priority scheme in the communication infrastructure, so that the traffic streams are dispatched in an increasing order of priority, controlling deadlines misses in case of failures.
3. **Adaptability:** it should be flexible enough to adapt to channel varying conditions allocating the communication resources so that the system can achieve its goal. Adaptability implies the need of a global retransmission scheme so that the retransmissions are processed according with the best interest of the entire system.
4. **Performance:** an upper bound for admission control should be provided in order to maximize the network utilization and scalability while maintaining a defined degree of reliability for time bounded messages.

The reliability and performance requirements are satisfied by means of a probabilistic provisioning of retransmissions. Each node is responsible for calculating the time that should be reserved for the retransmission of each individual traffic stream. This additional time is notified to the scheduler in the surplus bandwidth allowance parameter of the traffic specification. Thus, the scheduler must provide a transmission opportunity that contains additional time for individual retransmissions. Additionally, the scheduler should provide a joint additional time that should be reserved for retransmission of the entire set of traffic streams scheduled. This joint additional time is used to establish the limits of the admission control of the scheduler since the sum of all transmission opportunities of each node (which includes the time reserved for retransmissions) can lead to a very small acceptance bound. Also, the high overhead of the polling and acknowledgment frames and the bandwidth limitations of the wireless technology require an efficient admission control in order to improve the network performance.

Predictability is achieved by a priority based scheduler that is used to organize the traffic streams in an increasing order of TID (from 8 to 15). Therefore, lower TIDs have higher priority to access the medium enabling a network scheduling with eight possible local and global message priority levels. Local and global priority refer to importance relationships between messages at the same node or at different nodes, respectively. Thus, under lack of network resources due to unexpected situations, smaller priority messages must be dropped in favor of the highest priority ones. Moreover, predictability can be improved by assigning different degrees of reliability per TID.

Adaptability is supported by the integrated retransmission approach by allowing the implementation of two different retransmission strategies named *immediate* and *enqueued*, as further detailed.

3.2. Reliability Analysis

To calculate the additional amount of time that should be reserved for retransmissions it is assumed that the channel causes errors independently from frame to frame, and that these

errors are uniformly distributed. Usually, the probability of error in a wireless channel is proportional to the size of the frame. However, the 802.11 technology works with different transmission rates. Lower transmission rates use less complex and more redundant methods of encoding the data, so they are less susceptible to corruption. Therefore, different probabilities of errors are attributed for acknowledgment (p_a), data (p_d), and polling (p_p) frames, since they have different lengths and/or are transmitted at different rates. Also, it should be noted that although the polling frame is a data frame it is transmitted at the basic rate in order to synchronize clocks of all stations that are not being polled.

Thus, the probability of a successful uplink or downlink transmission can be determined using equations 2 and 3.

$$p_{up} = (1 - p_p) \cdot (1 - p_d) \cdot (1 - p_a) \quad (2)$$

$$p_{down} = (1 - p_d) \cdot (1 - p_a) \quad (3)$$

Notice that a corrupted positive acknowledgment frame does not represent an unsuccessful reception by the node that is sending the acknowledgment. Nevertheless, when using an individual positive acknowledgment policy, a negative acknowledgment is represented by the absence of an expected acknowledgment or when the frame received is corrupted, preventing that interferences from other stations can be interpreted as a positive acknowledgment. Thus, the node that is expecting the acknowledgment is not able to determine the success or failure of the transmission based only in the medium busy indication. Therefore, the reception of a corrupted acknowledgment still triggers a recovery procedure resulting in duplicate detection at the receiver node and, consequently, an inefficient use of the channel. Moreover, an unacknowledged frame stays in the outgoing queue and may use resources that are not reserved to it compromising the reliability of other transmissions. Thus, to avoid the term referring the probability of the acknowledgment frame in equations 2 and 3 the message retransmissions attempts should exceed the number of retries allowed for that message.

The first step is to calculate the additional number of retries that must be reserved in order to provide a degree of reliability for each traffic stream individually. In an independent and identically distributed error channel, the probability of any given frame being dropped p_{drop} after n_r successive retries, with the probability of the frame not being transmitted successfully denoted by p_e , is given by equation 4.

$$p_{drop} = p_e^{n_r+1} \quad (4)$$

Then, for a required probability of success p_r , the number of retries can be obtained by equation 5

$$n_r = \lceil \frac{\log(1 - p_r)}{\log(p_e)} - 1 \rceil \quad (5)$$

Thus, the number of retries that should be provisioned for an uplink ($n_{r/up}$) or downlink ($n_{r/down}$) traffic stream can be obtained substituting p_e by $(1 - p_{up})$ and $(1 - p_{down})$ respectively. Hence, the surplus bandwidth allowance parameter of the TSPEC

request must be properly set to notify the scheduler that it must provide the additional time for $n_{r/up}$ and/or $n_{r/down}$ retries.

The second step is to calculate the joint additional time that should be used by the admission control mechanism in order to guarantee the same degree of reliability of the individual traffic streams. Notice that the scheduler should not use the sum of the surplus bandwidth allowance parameters of all streams because it can lead to a very small acceptance bound. If there are different degrees of reliability among the scheduled traffic streams, the admission control must consider the highest one.

In the probability theory, the binomial distribution is the discrete probability distribution of the number of successes in a sequence of n independent yes/no experiments, each of which yields success with a probability p . This is also called a Bernoulli trial. Thereby, considering that the frame transmission follows the binomial distribution and considering n as the total number of frame transmissions (including retransmissions), the probability of at least k successful results, denoted by $p_{success}$, can be calculated by the cumulative mass function depicted by equation 6.

$$p_{success} = \sum_{j=k+1}^n \binom{n}{j} \cdot p^j \cdot (1-p)^{n-j} \quad (6)$$

where:

$$\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!} \quad (7)$$

Notice that since n cannot be isolated it must be obtained by an iterative method. Thus, the discrete number of additional retries can be obtained through equation 8.

$$N_r = \lceil n \rceil - k \quad (8)$$

Hence, considering a set of k_{up} and k_{down} traffic streams accepted by the scheduler and a required probability of success p_r , the number of uplink and downlink retries, $N_{r/up}$ and $N_{r/down}$, can be obtained substituting k and p by (k_{up}, p_{up}) and (k_{down}, p_{down}) , respectively, and $p_{success}$ by p_r .

Then, knowing the CAP time (T_{CAP}) allocated for all scheduled streams and the time to transmit a polling frame (T_{poll}), which is the same for all scheduled streams, it is possible to express the additional time for retransmissions as a relative percent of the CAP time, as depicted in equation 9.

$$T_r = \frac{N_{r/data} \cdot \frac{T_{CAP} - k_{up} \cdot T_{poll}}{k_{up} + k_{down}} + N_{r/poll} \cdot T_{poll}}{T_{CAP}} \quad (9)$$

with $N_{r/data} = N_{r/up} + N_{r/down}$ and $N_{r/poll} = N_{r/up}$.

3.3. Details of the Proposed Mechanism

The operation of the proposed approach is composed by three basic steps, which are: (i) admission control; (ii) traffic scheduling; (iii) retransmission control. These steps are detailed below.

3.3.1. Admission Control

To submit a traffic stream to the control of the proposed scheduler the node has to build a traffic specification. This traffic specification contains the application requirements and the additional time that should be reserved for retransmissions. This time is calculated by the MAC level of the node using the equations 2, 3 and 5. It is then used to set the surplus bandwidth allowance parameter of the traffic specification. The resulting traffic specification is submitted to the admission control of the scheduler, which is collocated at the coordinator. Then, the admission control is performed according to the following steps:

1. Calculation of the time required to transmit a packet from that traffic specification following the same specifications of the reference scheduler.
2. Calculation of the joint additional time that should be reserved for retransmissions using equations 6, 8 e 9.
3. Checking for admission using equation 10. This equation is a modified version of the admission control defined by the reference scheduler. It adds the joint additional time for retransmissions calculated by equation 9.

$$(1 + T_r) \cdot \left(\frac{TXOP_{K+1}}{SI} + \sum_{i=1}^k \frac{TXOP_i}{SI} \right) \leq \frac{T - T_{CP}}{T} \quad (10)$$

4. Notification about the acceptance or rejection of the traffic specification to the node.
5. If the traffic specification was accepted, it is scheduled after the last traffic specification with the same TID (in increasing order of TID).

3.3.2. Traffic Scheduling

The designed scheduler is constituted by a modified version of the reference scheduler, with the intention to match the following requirements:

- The traffic specifications should be scheduled in increasing order of TID, to enforce priorities.
- The downlink packets waiting for transmission have higher priority than the uplink packets waiting for a polling with the same of higher TIDs;
- The polling frame contains information about the TID and time to transmit only one data packet.
- The node should return a packet with either the same TID or a null frame.
- In the absence of an expected reception (data or acknowledgment) the scheduler must execute a retransmission strategy and the nodes must wait for a new opportunity (polling), dropping the packet only when its delay bound expires.

3.3.3. Retransmission Control

The packet retransmission is performed by two possible retransmission strategies that are integrated with the scheduler. A retransmission takes place when the scheduler detects the absence of an expected reception, which can occur after a certain interval.

1. **Immediate Retransmission:** aims at improving jitter requirements. In this strategy the scheduler starts the retransmission procedure immediately after the detection of the absence of an expected reception or after the end of the transmission opportunity (in case of reception of a corrupted frame).
2. **Enqueued Retransmission:** aims at improving retransmissions under burst error conditions. In this strategy the pending frame (polling or data) is enqueued to be retransmitted after the scheduler finishes its polling list and there are no more elements in its outgoing (downlink) queue.

4. Evaluation of the Proposed Mechanism

The evaluation was performed by means of two simulation experiments using two different network topologies, both operating under the IEEE 802.11b mode with the default 802.11e MAC and physical parameters. The proposed scenarios were specially designed to provide a comprehensive and comparative analysis of the proposed approach regarding the communication requirements previously exposed. The reference scheduler operating with the standard recommendations for retransmissions is used here as benchmark since there is no other equivalent work in this area to compare with. Also, the proposed retransmission strategies are compared against each other. Therefore, the simulation experiments are performed using the standard (S) approach for scheduling and retransmission and the proposed approach with both retransmissions strategies: immediate (I) and enqueued (E). These simulations are performed using the Network Simulator 2 (NS2) [NS-2 2006] requiring an extension patch to simulate the IEEE 802.11e, which was developed by the authors and is available at [Demarch and Becker 2006].

4.1. Simulation Scenarios

Our application scenario consists of a team of heterogeneous mobile robots working in a coordinated and cooperative manner. Thus, each robot may have different motors, sensors, actuators, and functionalities, thereby introducing differentiated communication needs (traffic specifications) since the task assignment imposes different constraints of timing, load, and importance relationships. The robots exchange messages with real-time constraints, requiring a high reliability from the communication infrastructure. Additionally, there are messages with higher importance, like those containing information about movement control. Missing such information may trigger physical collisions, causing damage to the robots and/or stopping the service. Moreover, the dynamics of the system and the wireless technology require adaptability to allocate the communication resources in the best possible way. There is also a non real-time traffic sharing the communication medium. Consequently, the communication infrastructure must regard performance and reliability at the same time.

Two different network topologies are used to represent such an application scenario. The first topology comprises two nodes (robots) interconnected by one AP. Each node has eight outgoing real-time flows to the other node. Each flow is associated with one TID from 8 to 15. The second topology consists of nine nodes (robots) interconnected by one AP. Each node from 1 to 8 has one incoming and one outgoing flow with the node 9. Each pair of incoming and outgoing flows is associated with a different TID from 8 to 15. Therefore, the scheduler has 16 downlink and 16 uplink streams in both topologies. The node placement for each topology is not relevant because of the robot movement,

attenuation, reflection, and shadowing, are represented by the channel error models. The real-time traffic demanded by the application scenario is represented by packets (MSDU) with 200 bytes length generated periodically at 16 kbit/s. Table 1 summarizes the main parameters of the traffic specifications submitted to the scheduler. The delay bound is derived from de packet length and transmission rate. The minimum physical (PHY) rate is the basic rate of the IEEE 802.11b. The surplus bandwidth corresponds to the amount of time reserved for individual retries and is obtained from table 2.

Table 1. Traffic Specifications

		Parameter	Value
T S P E C	T S I N F O	<i>Traffic Type</i>	periodic
		<i>TSID</i>	8..15
		<i>Direction</i>	uplink / downlink
		<i>Access Policy</i>	HCCA
		<i>Ack Policy</i>	normal
		<i>Nominal MSDU Size</i>	200 bytes
		<i>Mean Data Rate</i>	16 kbps
	<i>Delay Bound</i>	100 ms	
	<i>Minimum PHY Rate</i>	1 Mbps	
	<i>Surplus Bandwidth</i>	5.0 (up) / 4.0 (down)	

4.2. Experiment 1: Topology Exchange Scenario

The first experiment is composed of simulations performed over both network topologies with a uniform error model that uses a random variable to generate uniformly distributed errors with a given probability of 5 %. This error model is compliant with the independent and identically distributed error channel used in the probabilistic analysis. The retransmissions provisioned for the real-time traffic scheduled in both topologies consider a degree of reliability of 99.99 % and a drop rate of 5 %. This is summarized in Table 2.

Table 2. Probabilistic Analysis Summary

Error/Success Probabilities		Scheduled Streams	
$p_a = p_d = p_c$	5 %	k_{up}	16
p_r	99.99 %	k_{down}	16
p_{up}	85.74 %	T_{CAP}	30.526 ms
p_{down}	90.25 %	T_{poll}	492 μs
Individual Retries		Joint Retries	
$n_{r/up}$	4	$N_{r/up}$	13
$n_{r/down}$	3	$N_{r/down}$	10
		$T_r(\%)$	75 %

This scenario aims at comparing the network performance of the proposed approach against the standard approach of 802.11e, also including the jitter response obtained by the retransmission strategies. The performance analysis is evaluated in terms of the drop rate and the additional time necessary to avoid this drop rate, instead of the traditional throughput or goodput analysis. Notice that throughput and goodput should present a proportional behavior. Moreover, the choice to use drop rate and the additional time to avoid this drop rate is more suitable to this work since they express the degree of

reliability of the channel and the admission control limits of the scheduler, which should be used in order to increase this degree of reliability.

Table 3 summarizes the results obtained when each strategy is allowed to retry until the limit imposed by individual TXOPs, but the scheduler does not provide a joint additional time for retransmissions. Note that in the first topology, the standard (S) approach has much better results than both centralized approaches (I/E) in terms of reliability. This is due to the fact that in the standard approach the nodes can reply to a polling using frames of any TID, reducing the polling overhead inherent to the centralized approach. In fact, for this particular experiment, the standard approach allows a polled node to send up to 7 data frames per polling. On the other hand, in the second topology the performance of the standard approach has a severe degradation, presenting worst reliability than both centralized approaches. This is due to the fact that in this case the nodes 1 to 8 have only one outgoing flow each, with one message per SI. Therefore, instead of sharing a transmission opportunity (TXOP) between frames of different TIDs the nodes have to send a null frame to the coordinator to return the unused portion of the TXOP. These results show that the immediate (I) and standard (S) strategies concentrate its losses mainly in the TID 15, while the enqueued (E) strategy distributes its losses, which is not desired. However, the standard approach is not really able to provide a global prioritization scheduling which means that it is not able fulfill the predictability requirement. This is due to the fact that the nonbinding polling of the standard approach can lead to a priority inversion. For instance, in the standard approach a node can respond to a polling for a TID 8 with a packet with TID 15. Therefore, the immediate strategy is the only one that concerns both reliability and predictability requirements.

Table 3. Drop rate (%) without joint additional time

TID	1st Topology			2nd Topology		
	S	I	E	S	I	E
8	0.00	0.00	4.58	0.00	0.00	5.25
9	0.00	0.00	7.25	0.00	0.00	6.79
10	0.00	0.00	8.75	0.00	0.00	7.75
11	0.00	0.00	9.79	0.00	0.00	10.17
12	0.00	0.00	10.92	0.00	0.00	11.29
13	0.00	0.04	11.33	0.46	0.04	13.42
14	0.29	6.12	12.79	20.08	6.12	12.42
15	2.08	73.50	13.38	97.04	73.62	13.75

Figures 1 and 2 show the variation of the maximum joint additional time for both topologies so that there are no losses. Although the standard approach requires less time in the first topology, around 8 %, this value can reach up to 37 % in the second topology, which in practice is the same amount required by the centralized approach in both topologies. These results show that the centralized approach is less affected by the topology or traffic load variations. Moreover, notice that there is a significant difference between the upper bound for admission control obtained through simulations, which stays around 34 % in the worst case as circled in figure 1, and the calculated one of 75 % according to table 2. In fact, for this particular experiment it is possible to disregard the probability of dropping an acknowledgment in equations 2 and 3, which results in an upper bound of 56 %. Moreover, the probabilistic analysis may reach more exact results when the number of

traffic streams increases. Despite that, a simulation approach or an adaptive technique on the fly may be better alternatives to determine the upper bound for admission control improving the network utilization.

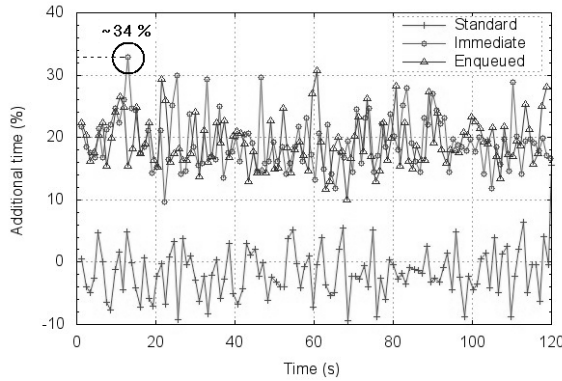


Figure 1. Maximum joint additional time for the 1st topology

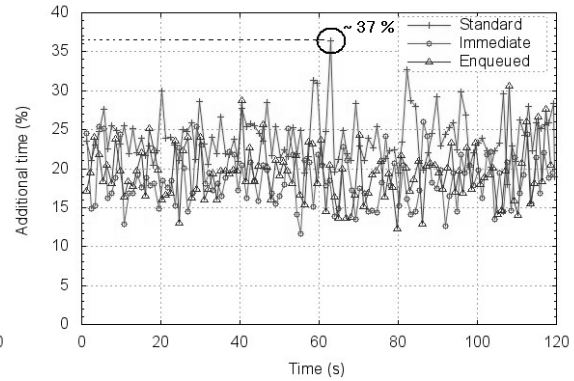


Figure 2. Maximum joint additional time for the 2nd topology

Table 4 shows the average jitter suffered by each TID in both topologies. The immediate strategy has a more linear response than the standard approach, which presents a significant increase in the average jitter of the TID 14 as highlighted in bold face. The enqueued strategy may be considered as the worst strategy to improve jitter, which is expected by design. Table 5 presents the maximum jitter suffered by each TID in both topologies. It can be seen in bold face that the response obtained with the standard approach is highly affected by the topology exchange, and presents worse results in comparison to the immediate strategy. This undesirable behavior is also explained by the nonbinding polling.

Table 4. Average jitter (us)

ID	1st Topology			2nd Topology		
	S	I	E	S	I	E
8	0.98	0.81	7.67	0.71	0.79	7.37
9	1.00	0.99	6.81	1.05	0.94	6.46
10	1.02	1.16	6.38	1.06	1.10	5.88
11	1.03	1.30	5.82	1.12	1.23	5.21
12	1.09	1.43	4.56	1.17	1.34	5.00
13	2.33	1.50	3.90	2.57	1.48	4.34
14	6.70	1.58	3.32	8.72	1.59	3.42
15	1.92	1.69	2.62	2.35	1.72	2.69

Table 5. Maximum jitter (us)

ID	1st Topology			2nd Topology		
	S	I	E	S	I	E
8	4.63	4.41	34.83	4.52	4.11	35.84
9	4.28	4.56	34.15	5.28	4.87	32.68
10	4.53	5.26	28.56	5.28	5.63	27.82
11	4.53	5.62	26.00	12.04	5.63	26.75
12	17.16	6.03	22.65	16.81	6.61	23.50
13	18.68	6.03	18.64	20.26	6.48	19.02
14	21.17	6.14	13.88	22.77	7.12	14.07
15	7.83	6.54	14.08	10.43	7.45	13.36

4.3. Experiment 2: Burst Error Scenario

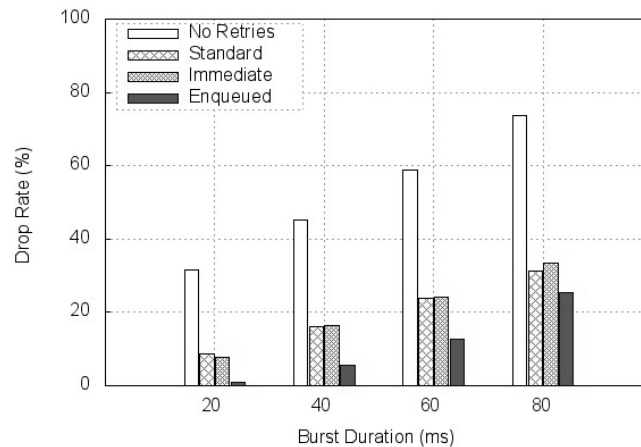
The second experiment comprises a burst error scenario that adds the two-state error model to the node 1 of the second topology. The two-state error model comprises a good and a bad state, wherein each state has associated an average period and a probability of state transition. In the bad state, there is a high probability of error, and in the good state there is a null probability of error. Hence, this error model is set with different burst error

Table 6. Channel Error Model Parameters for Node 1

Two-State Error Model		
Average Periods	Good	$(10 - k).10 \text{ ms}$
	Bad	$k.10 \text{ ms}; k = 2, 4, 6, 8$
Transition Probability	Good to Bad	0.40
	Bad to Good	1.00
Error Probability	Good	0.00
	Bad	0.90

intervals to evaluate the response of the centralized approach against the distributed standard approach operating under different durations of burst errors. Table 6 summarizes the parameters used in the error models.

Figure 3 summarizes the results obtained simulating different burst error durations through variations in the interval of the good and bad states of the two-state error model in node 1. The figure shows the frame drop rate of the node 1 for each retransmission strategy. It also shows the frame drop rate when no retries are allowed. The standard and the immediate strategy have very similar responses while the enqueued strategy has lower drop rates proving to be more suitable to deal with burst error conditions. Nevertheless, when the burst duration increases the relative difference of the enqueued strategy decreases. Also, there are a few losses in other nodes (less than 0,1 % with burst of 80ms) that are not shown. It should be noted that the enqueued strategy has lower drop rates with the same retransmission provisioning per TID. Therefore, as main conclusion, it can be said that the enqueued strategy can provide a higher degree of reliability for scenarios involving bursts of errors.

**Figure 3. Drop rate of node 1 for different durations of bursts of errors**

5. Related Works

There are many works, like [Mangold et al. 2003] and [Ni 2005], presenting the IEEE 802.11e technology and evaluating its performance through simulations usually considering scenarios involving multimedia traffic. In particular, simulations presented in [Ni 2005] show that adaptive techniques may increase the performance of EDCA and HCCA under variable network conditions. Thus, it shows that the reference scheduler

presents good performance for constant bit-rate traffic but it requires adaptive scheduling techniques, like the ones proposed in [Grilo et al. 2003] and [Ansel et al. 2004], to deal with variable bit-rate traffic.

An overview of remaining challenges in QoS provisioning for wireless networks and a survey of techniques that potentially could be used to address these challenges is presented in [Ramos et al. 2005]. Specifically, it focuses on three challenges: handling time-varying network conditions, adapting to varying application profiles, and managing link layer resources. Varying network conditions occur due to propagation loss, multipath effects, interferences and changes in the network load, which can lead to retransmissions and dropped packets at the MAC layer and, consequently, degradation of performance. Varying application profiles refers to the variability of the traffic load and QoS requirements, such as throughput, delay and jitter, of the applications. The works proposed in [Grilo et al. 2003], and [Ramos et al. 2004], address this issue by means of adapting HCCA parameters like TXOP and Service Interval, as well as, changing the scheduling algorithm running at the AP. Network resource management includes HCCA/EDCA coordination and admission control techniques. An extensive survey of admission control can be found in [Gao et al. 2005].

Another works investigate the scheduling algorithm used with HCCA like the one proposed in [Lim et al. 2005]. Also, in [Ciconetti et al. 2005] is proposed a software framework to simulate different scheduling algorithms for HCCA. In [Fallah et al. 2004] is introduced a new scheduling framework that emulates virtual packets at the AP enabling scheduling of uplink and downlink traffic within one scheduling discipline.

6. Conclusions and Future Work

IEEE 801.11e was created to support real-time traffic in wireless networks. Although there are many related works in this area, most of them deal with performance issues and soft-real time communication. No existing work considered the problem of transmissions errors, which are very common in wireless applications.

To solve this problem this paper presented a centralized and integrated message scheduling and retransmission mechanism that supports firm real-time communication requirements in mobile applications. Our approach was evaluated through simulations, providing a quantitative analysis of the proposed approach in respect to the following communication requirements: reliability, predictability, adaptability, and performance. The performed analysis used the reference scheduler and the standard retransmission procedures as benchmark. Also, the two different retransmission strategies proposed are compared with each other. Obtained results confirm that our mechanism is able to satisfy the previously mentioned communication requirements. Moreover, in comparison to the standard approach, our approach does not get affected by variations in the network load or topology. Also, although the standard approach shows better performance when it can benefit from the nonbinding pooling, it is not really able to satisfy the predictability requirement. Finally, results show that the immediate strategy can improve jitter response while the enqueued strategy is ideal to treat stations presenting burst of errors.

For future work it is foreseeing the development of an adaptive mechanism that considers the network fail dynamics on the fly, tailoring the admission control and retransmission strategies to the current network status. Also a new model that abstracts whether a

message is being transmitted or retransmitted using a dynamic priority assignment should be developed. Moreover, the priority assignment to the messages can be based in a variety of parameters like delay bound, jitter, TID, and successive lost of deadlines, which could be applied in a per node basis. Also, the simulations could use different error models and finally a real application scenario could be built and tested.

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