EFFICIENT BANDWIDTH ALLOCATION FOR BASIC BROADCAST AND POINT-TO-POINT SERVICES IN THE ADHOC MAC PROTOCOL [*]

J.R. GÁLLEGO[1], L. CAMPELLI[2], M. CESANA[2], A. CAPONE[2], F. BORGONOVO[2],
A. HERNÁNDEZ-SOLANA[1], M. CANALES[1], A. VALDOVINOS[†]

[1]*Departamento de Ingeniería Electrónica y Comunicaciones, University of Zaragoza,*
María de Luna 1, 50018 Zaragoza, Spain,

[2] *Dipartimento Elettronica e Informazione, Politecnico di Milano, Piazza L. Da Vinci 32,*
20133 Milano, Italy

An effective Medium Access Control for communications in wireless Ad hoc networks should be able to support both broadcast and point-to-point communications paradigms. The ADHOC MAC protocol, recently proposed within the European Commission funded CarTALK2000 project, seems to match these requirements. As a matter of fact, it allows the exchange of connectivity information among wireless terminals which can be usefully exploited to devise both broadcast and point-to-point services. In this paper we evaluate through simulation the efficiency of the protocol in a mixed traffic scenario where broadcast and point-to-point communications coexist. An adaptive bandwidth allocation strategy is proposed to share the resources between both services in a dynamic situation. The capability of the protocol to establish parallel point-to-point data communications and the corresponding improvement in the point-to-point efficiency is also evaluated

1. Introduction

The transmission media in wireless environment has to be shared by definition. Further on, the radio resources are often limited in comparison with the number of users which access them, thus the capacity of any wireless network is highly determined by the capability of the medium access control mechanism to handle the access process and to achieve high resource reuse [1].

ADHOC MAC [2] is a medium access control protocol recently introduced within the European Commission funded CarTalk2000 project [3] for providing connectivity in ad hoc inter-vehicles networks [4]. ADHOC MAC works on a slot synchronous physical layer and implements a completely distributed access technique capable of dynamically establishing a reliable single-hop Basic

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broadcast CHannel (BCH) for each active terminal, i.e., each transmission within a BCH is correctly received by all the terminals within the transmission range of the transmitter. Each BCH carries signalling information that provides a prompt and reliable distribution of layer-two connectivity information to all the terminals. This information provides a valuable basis for the efficient implementation of point-to-point data services, exploiting parallel transmissions, and also supplies a prompt means to manage different QoS requirements for these services, through the use of priorities.

In [5] and [6] we have studied the performance of ADHOC MAC broadcast services in a static scenario and with users' mobility respectively. In this paper we evaluate through simulation the efficiency of the protocol in a mixed traffic scenario where broadcast and point-to-point communications coexist. An adaptive bandwidth allocation strategy is proposed to share the resources between both services in a dynamic situation. The goal of the proposal is to guarantee access requirements for BCH whereas capacity for extra data communications is optimized. The capability of the protocol to establish parallel point-to-point data communications and the corresponding improvement in the point-to-point efficiency is also evaluated. The remaining paper is organized as follows. In Section 2 we briefly summarize the basis of the ADHOC MAC protocol and the proposed bandwidth allocation strategies for basic broadcast and point-to-point services. In Section 3, both the resource sharing strategies and the point-to-point service efficiency are evaluated through simulation. Finally, in Section 4 some conclusions are provided.

2. The ADHOC MAC Protocol

2.1. *Basic Operation Mode for BCH and point-to-point Communications*

ADHOC MAC operates with a time slotted structure, where slots are grouped into virtual frames (VF) of length N, and no frame alignment is needed. In the BCH, each terminal broadcasts information on the status of the channel it perceives. The BCH contains a control field, namely, Frame Information (FI) field, which is an N-elements vector specifying the status of the N slots preceding the transmission of the terminal itself. The slot status can be either BUSY or FREE: it is BUSY if a packet has been correctly received or transmitted by the terminal, otherwise it is FREE. In the case of a BUSY slot the FI also contains the identity of the transmitting terminal.

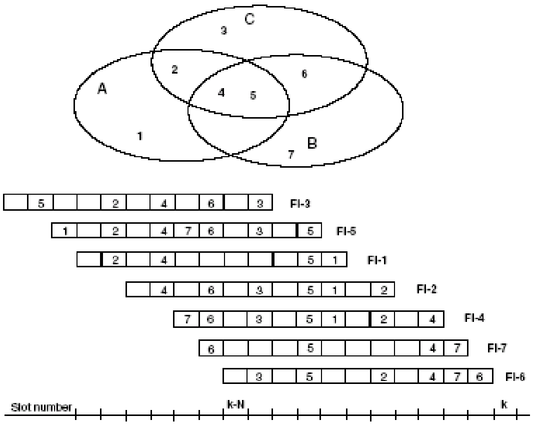


Figure 1. Example of the FI information propagated by the terminals 1-7 in the one-hop clusters A, B, and C represented by ellipses.

Based on received FIs, each terminal marks a slot, say slot k, either as RESERVED, if slot k-*N* is coded as BUSY in one FIs received in the slots from k-*N* to k-1 at least, or as AVAILABLE, otherwise. If a slot is AVAILABLE, it can be used for new access attempts. Upon accessing an AVAILABLE slot, terminal j will recognize after *N* slots (a frame) its transmission either successful, if the slot is coded as "BUSY by terminal j" in all the received FIs, or failed, otherwise. In figure 1, an example of FIs transmitted by a set of terminals is given. The union of all one-hop (OH) clusters with a common subset is denoted as two-hop (TH) cluster. The terminals belonging to the same OH-cluster see the same status (AVAILABLE or RESERVED) for all the slots; terminals belonging to different OH-clusters of the same TH-cluster mark as RESERVED all the slots used in the TH-cluster, whereas terminals belonging to disjoint OH-clusters usually see a different channel status. As a result, slots can be reused in disjoint OH-clusters, but can not be reused in the same TH-cluster and, therefore, the hidden-terminal problem can not occur [4]. The BCH provides a reliable single hop broadcast channel which can be used both for signaling and for data traffic purposes. Upon this basis, point-to-point data communications among terminals can be effectively established by exploiting the distributed signaling provided by the FIs. To this end, each entry of the FI encloses a PointToPoint (PTP) flag, which is handled as follows:

- A terminal sets the PTP flag of a given slot in the FI, if the packet received in the slot is a broadcast one or if it is destined to the terminal itself.

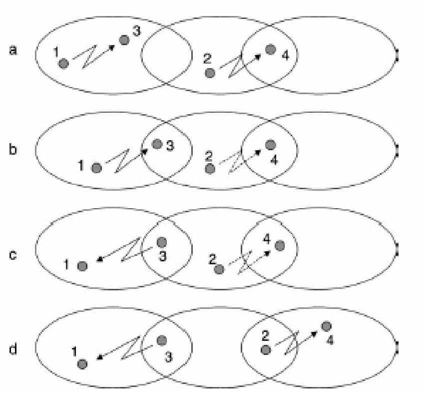


Figure 2. Examples of parallel transmissions. Transmission from terminal 1 is established first. Allowed transmissions by terminal 2 are indicated by solid arrows.

In order to set up a point-to-point communication, all the AVAILABLE slots can be used. Further on, even some RESERVED slots can be used according to the following rule:

- A RESERVED slot can be accessed if:
    1. The PTP flag is signaled off in all the received FIs and
    2. The FI received from the destination terminal signals the slot as FREE.

The conditions above allow point-to-point transmissions to share the same slot when there is no collision at the receivers. This can be seen referring to the four cases shown in figure 2. The cases a and b in the figure consider two transmitting terminals, say 1 and 2, belonging to different not disjoint clusters. Assuming that terminal 1 has already activated a PTP channel with 3, terminal 2 can transmit using the same slot if these two conditions above are satisfied. In case a, terminal 2 can use the same slot as terminal 1 even if it is signalled as RESERVED. In fact, the only PTP flag ON is that in the FI transmitted by terminal 3 and not received by terminal 2 (satisfying condition (1)), and the FI generated by terminal 4 marks the slot as FREE (satisfying condition (2)). In case b the FI, generated by terminal 3 and received by terminal 2, prevents terminal 2 from transmitting (not satisfying condition (1)). In this case parallel transmission would, in fact, interfere at terminal 3. In cases c and d the two transmitting terminals belong to the same cluster. In case d terminal 3 can use a RESERVED slot since both conditions (1) and (2) are satisfied (in fact, this is the exposed-terminal case) whereas in case c condition (2) is not satisfied and a collision would occur at terminal 4. If several access attempts occur concurrently, collisions can still occur. Then, the transmitting terminal has to perform a further check according to the following rule:

- The point-to-point transmission is successful if the slot is coded as BUSY in the FI of the destination terminal; otherwise the transmission is failed.

2.2. *Bandwidth allocation strategies*

Once a terminal has acquired its BCH channel, it can establish additional broadcast data communications if the data payload in the BCH is not long enough. In the same way, different PTP data communications with all its neighbours can be established. In this paper, only extra PTP communications are considered, so in the remaining of the paper these additional communications are referred as PTP. However, the proposed strategy can be generalized since dimensioning is made only according to BCH demands.

In its basic operation mode, every slot in the frame can be used for both PTP and BCH transmissions. In this situation, as the number of PTP communications grows, the number of AVAILABLE slots for new terminals accessing the system decreases, leading to a reduction in the number of terminals that can access the system for a given number of slots. As the acquisition of a basic broadcast channel is mandatory to access the system, an appropriate dimensioning of the network must guarantee certain resources for BCH transmissions. As a metric for the BCH performance, we take into account the outage probability. A terminal is declared in outage if it does not acquire a BCH within a period of a given number of frames after birth. According to this situation, it must be guaranteed a trade-off between ensuring an acceptable outage probability for BCH channels while providing the maximum throughput for PTP data communications. In order to guarantee an outage probability for new terminals accessing the system, we propose a frame subdivision into two subframes, where the performance of BCH is not limited by the amount of PTP traffic in the network: A frame with N slots is divided into N_{BCH} and N_{PTP} slots for BCH and PTP communications.

$$N = N_{BCH} + N_{PTP} \tag{1}$$

For this assumption, it is required a slot and frame time synchronization of each terminal in the network, that can be obtained with the Global Position System (GPS) or other solutions [7], [8]. With this subdivision, the probability of access the system is higher. When a terminal tries to access the system, it looks for an AVAILABLE slot. The existence of an AVAILABLE slot for a new terminal can only be statistically guaranteed: if the neighbours have enough FREE slots, it is probable that there is a common FREE slot for all of them. The frame subdivision brings together the FREE BCH slots making more probable for a terminal to find an AVAILABLE slot.

If a static frame subdivision is considered, N_{BCH} limits the maximum density of terminals supported by the system. A lower density of terminals implies that resources are wasted, since extra PTP communications could be allocated in the free BCH slots. On the other hand, when the density grows over expected, terminals declared in outage could access the system using slots of the PTP subframe. To overcome these limitations, an adaptive subdivision strategy that moves the border between the slots dedicated to each type of traffic within the frame according to the channel dynamics is proposed and evaluated: A set of W possible values for N_{BCH} $\{N_1 < N_2 < \ldots < N_W\}$ is defined. Terminal i chooses the value $N_{BCH,i}$ within this set according to the density of neighbours, ρ_i, it observes. We have considered two possibilities to measure this density:

$$\rho_i = |NB_i| \tag{2}$$

where NB_i is the set of neighbours for the terminal i, and its dimension $|NB_i|$ is equal to the number of BCH channels received by this terminal.

$$\rho_i = \frac{1}{|NB_i| + 1}\left(\sum_{j \in NB_i} |NB_j| + |NB_i|\right) \tag{3}$$

Equation (3) represents the mean number of neighbours in the surroundings of terminal i. This can be obtained through the FI information transmitted by each neighbour of terminal i and its own observed neighbours. According to this density, each terminal updates the $N_{BCH,i}$ value every frame and includes it in the FI transmitted to all its neighbours.

$$N_{BCH,i} = \begin{cases} N_1 & \text{if } \rho_i < th_1 \\ N_2 & \text{if } th_1 \le \rho_i < th_2 \\ \vdots & \\ N_{W-1} & \text{if } th_{W-2} \le \rho_i < th_{W-1} \\ N_W & \text{if } \rho_i \ge th_{W-1} \end{cases} \tag{4}$$

where th_j represents the maximum density of terminals tolerated for a number of slots N_j of the BCH subframe.

In the same way that a terminal i sends this value, $N_{BCH,i}$, it receives the corresponding N_{BCH} values of all its neighbours. Since it must be guaranteed that PTP communications can not be established in any of the BCH subframes of the neighbours, the number of slots where terminal i can establish PTP communications, as a transmitter, is given by

$$N_{PTP-TX,i} = N - \max_{j \in NB_i}\left(N_{BCH,j}\right) \tag{5}$$

whereas the subframe where it can receive PTP communications is limited just by its own $N_{BCH,i}$

$$N_{PTP-RX,i} = N - N_{BCH,i} \tag{6}$$

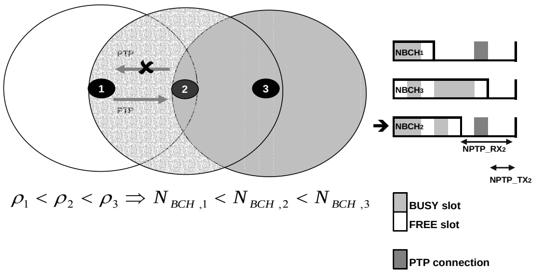


Figure 3. Example of how PTP transmissions can be established according to the subframe division

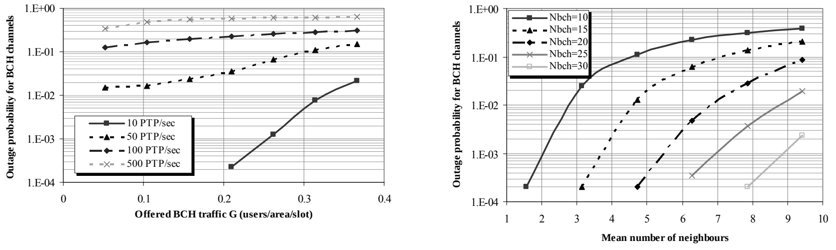
An example of how PTP transmissions can be allocated according to the resource sharing algorithm is given in figure 3. In that situation, terminal 2 cannot establish a PTP communication as a transmitter with terminal 1 in that position, even if the slot is AVAILABLE, because this slot belongs to the BCH subframe of terminal 3. However, terminal 1 can transmit to terminal 2 in the same slot, since this transmission does not affect to terminal 3. This slot belongs to the set of $N_{PTP-RX,2}$, but not to $N_{PTP-TX,2}$.

3. Performance evaluation

In order to evaluate the proposed resource sharing strategies and the performance of the point-to-point services provided by ADHOC MAC, we have built up an event driven simulator which implements all the functionalities of the medium access control protocol. Since we mainly focus on performance evaluation of the medium access control protocol, as first step of analysis, we simplify the physical layer assuming neither fading nor shadowing in the calculation of the received power. The connectivity among terminals is simply determined by their respective distances and no power control procedures are implemented. As consequence, a transmission either broadcast or point-to-point can be erred due to collisions only.

3.1. *Bandwidth allocation evaluation*

The bandwidth allocation strategies are evaluated in a dynamic situation, where terminals are generated within the network according to a Poisson process with average rate Y [new terminals/s]. Each active terminal has a lifetime random variable exponentially distributed with mean L=500 [frames], thus the parameters Y and L define the offered traffic of the basic broadcast service. Terminals are randomly positioned within a square area with edge equal to 1Km. Under these conditions, PTP communications are generated according to a Poisson process with intensity X [PTPconnections/s]. The source of each point-to-point communication is randomly chosen among the users with an active BCH, while the destination is randomly chosen among the source's neighbours. The duration of each point-to-point communication is exponentially distributed with mean D [frames]. The parameters X and D define the point-to-point offered traffic. We define a common framework of simulation by setting the length of a frame F = 100 ms, the number of slots within a frame N = 30, the coverage radius R = 100 m and the point-to-point communications mean duration D = 50 frames. The modification of the simulation parameters only impacts on the absolute values of the performance figures, whereas the comparative results obtained in this paper still hold.

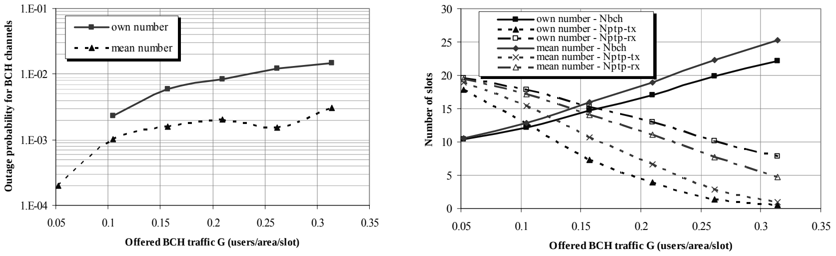


(a) (b)

Figure 4. Outage probability for BCH transmissions versus the BCH offered traffic when varying the intensity of PTP traffic (a) and versus mean number of neighbours with static subdivision (b). Standard Setting of simulation parameters and basic operation.

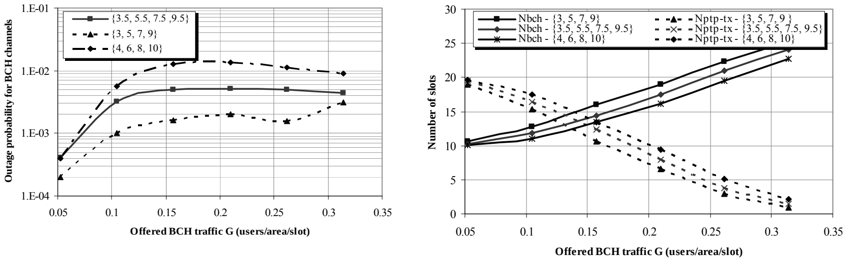
In the basic operation of ADHOC MAC, each slot can be used for both BCH and PTP communications. Under these conditions, figure 4a reports the outage probability for the broadcast channels versus the offered broadcast traffic, defined as the density of BCH channels per slot, when varying the point-to-point traffic intensity. The number of frames a terminal tries to acquire a BCH is set to 10. As it was expected, the outage probability of broadcast traffic increases as the point-to-point traffic grows, since few slots are available for accessing a BCH, and systematic collisions happen.

Capacity in the system can be considered as BCH capacity, referred to the capability of accepting users in the system and PTP capacity, as the extra bandwidth for data communications. Results from figure 4 confirm that a more efficient resource management is necessary to share both capacities. The static frame subdivision in N_{BCH} and N_{PTP} slots tries to guarantee at least the access to the system for new terminals. Figure 4b shows the outage probability for BCH channels with this static subdivision for several values of N_{BCH} (10, 15, 20, 25 and 30). It is represented versus the mean number of neighbours in the network, which is directly related to the offered broadcast traffic. If a specific value, for example 0.01, is considered as an acceptable limit for outage probability, figure 4b shows, that according to the number of terminals in the network, the minimum N_{BCH} that guarantees this requirement changes. Since in a real situation the density of users in the network is not supposed to be known, the use of a dynamic frame subdivision tries to optimize the network dimensioning making the allocation locally, according to the geographical density of terminals.



(a) (b)

Figure 5. Outage probability for BCH transmissions (a) and mean number of slots allocated for BCH and PTP (b) versus the BCH offered traffic with dynamic subdivision using the number and the spatial mean number of neighbours. Standard Setting of simulation parameters.



(a) (b)

Figure 6. Outage probability for BCH transmissions (a) and mean number of slots allocated for BCH and PTP (b) versus the BCH offered traffic with dynamic subdivision (mean number of neighbours) for different sets of thresholds. Standard Setting of simulation parameters.

In order to make this dimensioning, results from figure 4b has been used as a reference to establish the values th_j with $1 \le j < W$, which determine N_{BCH}. The set of N_{BCH} values chosen for this dynamic subdivision is $\{N_1=10, N_2=15, N_3=20, N_4=25, N_5=30\}$ and, according to figure 4b, the chosen set of th is $\{th_1=3, th_2=5, th_3=7, th_4=9\}$. The decisions are taken according to (4). Figure 5 shows the performance of the adaptive algorithm. Using the mean number of neighbours according to (3) clearly outperforms the use of only the own number of neighbours (2). With (3), outage probability is lower and more stable for different densities of users, as it is shown in figure 5a. This is confirmed in figure 5b, where the mean number of slots allocated for BCH is higher with (3). Moreover, the number of slots allocated for PTP transmissions is also higher, i.e., the differences between $N_{PTP\text{-}TX}$ and $N_{PTP\text{-}RX}$ are reduced. The use of the mean number of neighbours allows a terminal to adapt its subframe borders to the variability of the density of neighbours in its surroundings. For example, the loss of a single neighbour, which can be a result of multiple factors (movement, fading, loss of battery, temporal switching off…) has a lower effect over the measured density than if just the own number of neighbours is used, making the frame subdivision more stable. Through the variation of the values of the set of th, it is possible to adjust the balance between BCH and PTP communications, according to the BCH requirements. Figure 6 shows similar results for three different sets of thresholds, {3, 5, 7, 9}, {3.5, 5.5, 7.5, 9.5} and {4, 6, 8, 10}. In order to guarantee an outage probability for BCH around 0.01, the set {4, 6, 8, 10} could be enough, whereas it is the option that provides a higher bandwidth for PTP transmissions.

3.2. *Analysis of the point-to-point efficiency*

Once the outage probability for new accesses is guaranteed by means of the proposed bandwidth allocation strategy, the remaining PTP capacity must be efficiently managed. As a first step, a maximum theoretical value for this capacity has been obtained through simulation. These results are valid as a boundary for the maximum capacity provided by the protocol, but they will not be reachable in a dynamic situation where the BCH requirements limit the actual PTP capacity.

In order to analyze the maximum point-to-point capacity without interacting with the BCH traffic, the simulation has been carried out considering a stationary broadcast situation where all the terminals have an active BCH. For this purpose, a number of terminals that will be active through all the simulation is generated at the beginning of the simulation. This number defines the offered traffic of the basic broadcast service. Upon generation, each terminal tries to acquire a BCH, thus after a certain transient time, all of them have acquired their BCH and a stationary scenario is arranged. On the other hand, simulations in a dynamic situation have been also carried out. For these simulations, the adaptive algorithm with the set of thresholds {4, 6, 8, 10} and the spatial mean number of neighbours have been used, since according to figure 6 they provide the higher available bandwidth for PTP with an acceptable outage for BCH.

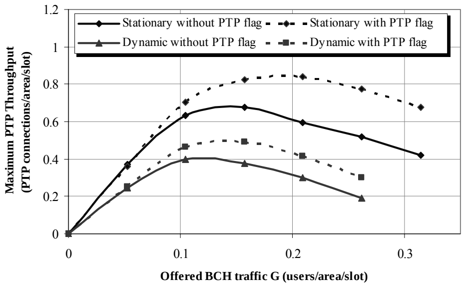


Figure 7. Maximum PTP throughput versus the BCH offered traffic with and without the PTP flag in the FIs. Standard Setting of simulation parameters. Stationary and Dynamic BCH traffic.

Figure 7 reports, for both scenarios, the maximum throughput of point-to-point communications, defined as the maximum density of successful PTP transmissions per slot, versus the broadcast offered traffic, using the standard setting of simulation parameters. For all cases, the amount of PTP offered traffic is high enough to fully occupy the available resources. Two curves are reported for each situation: the dotted one depicts ADHOC MAC working mode with the use of PTP flag in the FIs, while the other one refers to the simplified case where the PTP is not used, i.e., only the AVAILABLE slots can be accessed by point-to-point traffic.

The ADHOC MAC provides higher reuse due to parallel point-to-point communications on the same slot when using the PTP flag, as it solves the exposed terminal problem. As the broadcast offered traffic increases, the use of this flag in the FIs provides an increasing gain with respect to the case where it is not used. As a matter of fact, high broadcast offered traffic means high terminals density, and consequently high probability of exposed terminal situations. Further on, in a stationary scenario, the maximum point-to-point throughput decreases if the broadcast offered traffic keeps increasing above the value 0.2 (terminals/area/slot), since there are less AVAILABLE slots for point-to-point. Below that value the point-to-point throughput increases with the broadcast offered traffic, since the number of point-to-point communications which can be set up is limited by the low number of terminals within the network. In a dynamic situation, since some slots must be kept FREE within the BCH subframe in order to guarantee the access for new terminals, the maximum achievable throughput is lower than in a static scenario, where only the set of BCH channels already acquired by the current terminals is not AVAILABLE for PTP connections.

4. Conclusions

In this paper, resource sharing strategies for basic broadcast channels and point-to-point data communications have been proposed and evaluated through simulation. Basic broadcast traffic and point-to-point communications can efficiently share the total resources with a frame subdivision that allocates separately both services. Moreover, in a dynamic situation, the proposed adaptive strategy, that makes this allocation according to local densities of terminals provides a trade-off between both services guaranteeing the access requirements (outage probability). Regarding point-to-point communications, the performance of the protocol can be improved by means of the slot reuse provided by the parallel transmissions that can be allocated using the PTP flag. Upon these results, the management of point-to-point services with different QoS requirements through the use of priorities will be evaluated in coming works.

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