Reuse Efficiency of Point-To-Point Connections in Ad Hoc Networks

Luca Campelli, Matteo Cesana, Flaminio Borgonovo
Dipartimento Elettronica e Informazione
Politecnico di Milano, Milano, Italy, 20133
Email: {campelli, cesana, borgonov}@elet.polimi.it

***Abstract*—The efficiency of Point-To-Point (PTP) connections in ad hoc networks highly depends on the capability of the Medium Access Control (MAC) layer to reuse the shared wireless resource. One of the most critical impairments to the reuse capability is the *exposed terminal* problem which may prevent feasible PTP communications to run in parallel.**

In this paper we evaluate the impact of the *exposed terminal* on the reuse efficiency of PTP communications in ad hoc random networks. To this end, we propose a scheduling algorithm for PTP connections within the framework of ADHOC MAC, a recently proposed MAC scheme. The simulative results we gather show that the solution of the exposed terminal problem provides a reuse efficiency gain around the 40% in the network scenario we considered.

I. INTRODUCTION

The appearance of ad hoc networks with their distributed applications has faced researchers with severe problems in many areas ranging from access protocols to routing. Particular challenges are encountered in the design of suitable MAC protocols due to problems like *collisions*, *hidden terminals* and *exposed terminals*.

Collisions happen when two or more terminals concurrently attempt to access the channel. If Carrier Sensing (CS) [1] is used in the radio environment, an accessing terminal is prevented from colliding with an ongoing transmission it overhears. However, two accessing terminal may still collide if their access is simultaneous. In this case, the use of *Request To Send* (RTS) and *Clear To Send* (CTS) signals before data transmissions limits possible collisions to the RTS signal only. The IEEE 802.11b standard adopts both types of access in its Distributed Coordination Function (DCF) [2].

The hidden terminal problem [3] arises when terminals not hearing each other transmit to a terminal that is reached by both. In this case, the collision that occurs at the receiver can not be eliminated by the CS mechanism, since the interferer is hidden. In access systems where all terminals communicate with a unique access point, the hidden terminal problem has been almost completely solved by the RTS/CTS mechanism.

The exposed terminal problem [4] happens when a transmitting node is in the range of a possible transmitter, the exposed terminal, but not of its intended receiver (this is the case of terminal 2 in Figure 2.d). If the regular carrier sensing mechanism with the RTS/CTS is used, the exposed terminal will defer from accessing the shared channel, although, in some cases, parallel communications can safely take place.

In access and ad hoc networks all terminals share the same bandwidth, which can be reused at safe distance, giving rise to parallel transmissions. Potentially, the capability of reusing resources may allow to serve an infinite population with a finite bandwidth. The reuse factor measures the efficiency of the bandwidth usage: the shorter is the distance of reuse the higher is the channel efficiency, i.e., the throughput conveyed by the channel within the network.

The efficiency of PTP connections in ad hoc networks highly depends on the capability of the Medium Access Control (MAC) layer to combat the exposed terminal. To this end, several access protocols with different approaches have been proposed in the literature [4][5][6]. Roughly speaking, three groups of protocols can be distinguished: the first one is composed of those solutions relying on inband/outband busy tone signalling to test the feasibility of parallel transmissions [7][8]. The second approach aims at scheduling at the same time feasible transmissions, thus requiring a distributed synchronization method [9]. Finally, in the last class of protocol the choice to access the channel is based on the interference estimation at the intended receiver [10] . The reader is referred to [8] for a comprehensive review of these protocols.

We have recently introduced ADHOC MAC, a TDMA-based access scheme for ad hoc networks able to provide reliable broadcast channels [11]. Furthermore, ADHOC MAC provides an in band signalling channel with local topological information which can be exploited to design effective scheduling mechanism for PTP communications to eliminate the exposed terminal problem.

In this work, we discuss the design of such scheduling algorithm for PTP communications and, within the ADHOC MAC framework, we evaluate the impact of the exposed terminal problem on the PTP reuse efficiency in static random ad hoc networks. The paper is organized as follows. In Section II, we briefly summarize the basics of the ADHOC MAC protocol, whilst Section III describes the scheduling algorithm to set up PTP communications. Sections IV reports the evaluation analysis, whereas Section V introduces a simple geometrical model for the calculation of the asymptotic reuse capability. Concluding remarks are given in Section VI.

II. THE ADHOC MAC PROTOCOL

For the reader's convenience, in the first part of this section we outline the operation of ADHOC MAC; more details on

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the subject can be found in [11].

We consider the terminals as grouped into clusters in such a way that all the terminals of a cluster can receive each others' transmissions. Such a cluster is defined as One-Hop (OH). Terminals can belong to more than one OH-cluster, leading to the case of non disjoint clusters. The union of OH-clusters having a common subset is called a Two-Hop (TH) cluster.

The ADHOC MAC protocol uses Dynamic TDMA on a time slotted channel. Slot assignment is based on a Reliable R-ALOHA mechanism (RR-ALOHA) [12] in which "trial and error" transmission is used to access an available slot, e.g., slot *k* in a frame of N slots. If the transmission is recognized as successful the slot is reserved for that terminal in subsequent frames, and is no longer able to be accessed by other terminals until the channel is released.

The correct operation of R-ALOHA [13] requires a central repeater through which the terminals receive all the transmitted signals and, most important, obtain the same slot status information, e.g., busy, free, or collided. In this way a terminal can avoid collisions among ongoing transmissions and discover possible "on access" collisions. However, ad hoc networks do not have a central repeater, hence the need for RR-ALOHA.

Here, all active terminals transmit in all frames additional information, called the Frame Information (FI), so that all of them can know the status (AVAILABLE or RESERVED) of each slot. The FI can be transmitted either in a subfield of the reserved slot, or in especially devised minislot. In any case a terminal, in order to become active, must acquire such a slot, referred to in the sequel as the Basic CHannel (BCH). This channel can be correctly heard by all the terminals within the same OH-cluster and is used to transmit FI, other signaling information, and also payload information.

In each BCH slot, each terminal transmits a packet containing the FI, that is a vector with N entries which specifies the status of the preceding N slots, as observed by the terminal itself. The slot status can be either BUSY or FREE: if a packet has been correctly received or transmitted by the terminal, the corresponding slot is considered BUSY, otherwise is considered FREE. In the case of a BUSY slot, the FI also contains the identity of the transmitting terminal. Based on received FIs, each terminal marks a slot as RESERVED or AVAILABLE according to:

Rule 1: *the next slot, say slot k is labeled as RESERVED if slot k-N is coded as BUSY in at least one FIs received in the slots from k-N to k-1; otherwise it is labeled as AVAILABLE.*

As in R-ALOHA an AVAILABLE slot can be used for new access attempts. Upon accessing an AVAILABLE slot, terminal *j* will determine, after a frame, the outcome of its transmission according to:

Rule 2: *the transmission is successful if the slot is coded as "BUSY by station j" in all the received FIs; otherwise the transmission has failed.*

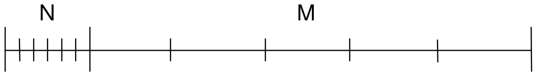

Fig. 1. *Frame structure in ADHOC MAC framework.*

To be successful, Rule 2 requires the transmission to be correctly received by all the terminals belonging to the same OH-cluster of the transmitting terminal. This guarantees that the slot remains AVAILABLE not only if collision has occurred, but also when the terminals decode correctly one of different concurrent access attempts, due to the receiver capture effect. The correctness of the above procedure in setting up a channel has been shown in [11]. As a result:

- any slot signaled as BUSY by any terminal is recognized as RESERVED by all its neighbor.
- all terminals belonging to the same TH-cluster mark the slots RESERVED or AVAILABLE in the same way.

In a dynamic environment where terminals appear, disappear and move clusters configurations change and conflicts can still occur. This issue has been discussed in [14]. In the following we consider a static environment only.

III. POINT-TO-POINT CHANNELS ACQUISITION

RR-ALOHA basic operation provides BCHs that can be used as a signaling channel to reserve further channel resources as needed by terminals. For exemplification purpose we assume a frame as the one shown in Figure 1. The first part of the frame is composed by N slots, or minislots, that are used as BCHs. The second part of the frame is composed of $M \leq N$ slots that are used as PTP channels. The broadcast slots can be effectively used by the terminals to reserve room for PTP transmissions.

The reservations transmitted in BCHs cannot physically collide, since the BCHs are reliable by definition. However, they can logically collide when different reservations compete for the same PTP slot in the case where the concurrent use of the selected slot causes collision at one or more destinations. Ideally, these logical collisions on the reservations can be resolved by a distributed coordination protocol which makes sources and destinations converge to an efficient slot assignment through the exchange of multiple control messages.

The status of the PTP slots is built up with the very same procedure used for BCH slots. Furthermore, a terminal signals in its FI the PTP slots where it is receiving a point to point transmission destined to itself by setting a PTP *flag*. On the basis of the previous information, each terminal can choose to reserve a PTP slot for transmission according to the following:

Rule 3: *A Point-To-Point slot can be further reserved if:*

i) *the slot is AVAILABLE*
ii) *the slot is RESERVED but:*
    a. *the PTP flag signaled in all the received FIs is off and*
    b. *the slot is signaled as FREE in the FI received from the terminal destination of the PTP channel.*

Figure 2 clarifies the previous rule. The cases *a* and *b* in the figure consider two transmitting terminals, say 1 and

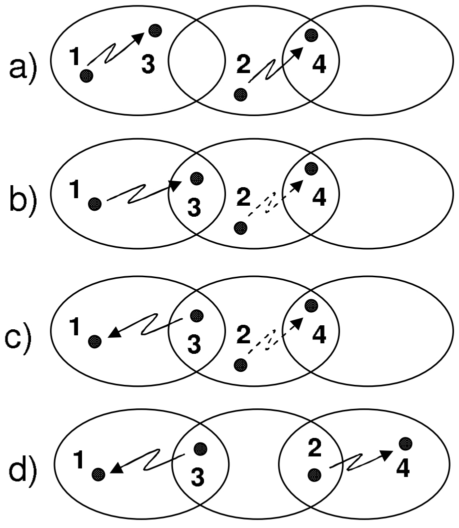

Fig. 2. *Examples of parallel transmissions. Transmission between terminal 1 and 3 is established first. Allowed transmissions by terminal 2 are indicated by solid arrows.*

2, belonging to different not disjoint clusters. Assuming that terminal 1 has already activated a PTP channel with destination 3, terminal 2 can transmit using the same slot if the conditions in Rule 3 are satisfied. In case *a*, terminal 2 can use the same slot as terminal 1 even if it is signaled 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 ii.a), and the FI generated by terminal 4 marks the slot as FREE (satisfying condition ii.b). In case *b* the FI, generated by terminal 3 and received by terminal 2, prevents terminal 2 from transmitting (not satisfying condition ii.a). In this case parallel transmission would, in fact, interfere at terminal 3, thus destroying the already activated PTP channel. In cases *c* and *d* terminal 3 has established a communication towards 1. In *d* terminal 3 can use a RESERVED slot since both conditions ii.a and ii.b are satisfied, while in case *c* condition ii.b is not satisfied and a collision would occur at terminal 4. Note that case *d* represents *the exposed terminal* problem.

Each terminal may reserve a PTP slot by sending a Request To Reserve (RTR) packet on its BCH with the indication of the intended destination. The intended destination acknowledges the reservation by sending a CLear Reservation (CLR) in the following BCH subframe.

Since RTRs are sent out on reliable broadcast channels they cannot collide physically. However, a logical collision is still possible if two or more terminals try to reserve the same PTP slot within the same BCH subframe. This logical collision during the reservation phase can be solved at the intended receiver applying the following:

Rule 4:

i) *if a terminal receives just one RTR then it responds with a CLR*

ii) *if a terminal receives two or more RTR for the same slot it selects which reservation to accept by choosing the one which inserted the smallest random number in its RTR payload, and acknowledges it with a CLR.*

iii) *a terminal can use the requested slot only if it receives a CLR from its destination and does not receive any other CLR from any other terminal it "hears".*

Terminals whose RTR has not been acknowledged may reschedule the access to the PTP resource. Note that point ii) is used to coordinate the choice of two or more destinations belonging to the same OH cluster, whereas point iii) avoid conflicts if the destinations belong to different OH clusters and therefore their choice can not be coordinated. Because of point iii) the selecting procedure can not be optimal. Actually, the entire procedure is suboptimal. In fact, upon a logical collision, it assigns at most one slot per frame, whereas an ideal protocol could optimally assign slots to all contemporary requests.

However, if we refer to cases in which the connection lifetime is long, the reservation traffic is small and logical collisions are very rare, the above procedure becomes optimal. Furthermore, it was the advantage of requiring only the exchange of the two messages RTR and CLR, which takes one frame delay at most. In order to increase the efficiency of the procedure, we also require the PTP flag to be set off before the last slot of a connection is used. In this way the reservation can become active as soon as the last slot of a preceding connection is transmitted and no PTP slot is wasted.

IV. NUMERICAL RESULTS

We consider in our analysis random network topologies with terminals scattered uniformly in a planar network area. Each node is assigned a fixed transmission range r, and the terminal's transmissions are assumed to be correctly received within such range, whilst they do not interfere at any receivers outside this area, according to a disk radius interference model [8][15]. As a consequence transmission errors can occur due to collisions only. The reuse efficiency of the PTP service can be measured as the throughput S_P, defined as the maximum number of PTP communications which can be established in the coverage area normalized with respect to the available point to point bandwidth.

In general, such measure is a function of the offered traffic G and depends on system parameters such as the number of available channels BCHs N, the number of available PTP slots M and the connection lifetime L, due to the impact of access collisions. It also changes with the network topology and the antenna coverage. However, if we refer to users distributed randomly on an infinite surface and measure the throughput and the offered traffic in the antenna's coverage area, the throughput does no longer depend on the size of that area. This happens also with any finite surface when the coverage radius is sufficiently small. To fit with this goal, we have assumed $r = 100m$ and a square area of $1km \times 1km$, and we skip any border effects in the interference determination by folding the simulation area on a torus.

To investigate the above issues we have adopted a semi-dynamic simulation model written in C++ in which, at first,

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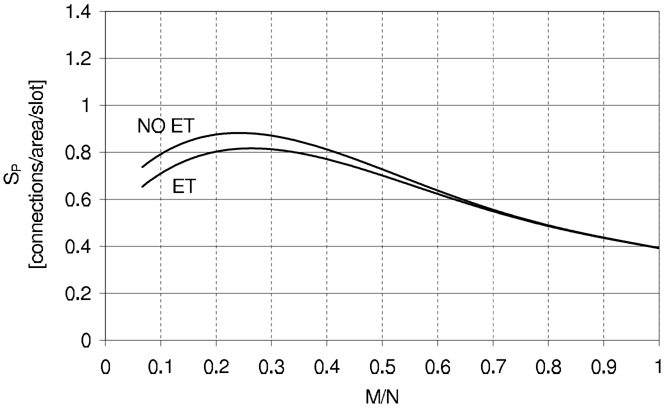

Fig. 3. *The normalized throughput of PTP channels versus the normalized frame size M/N, when $N = 15$.*

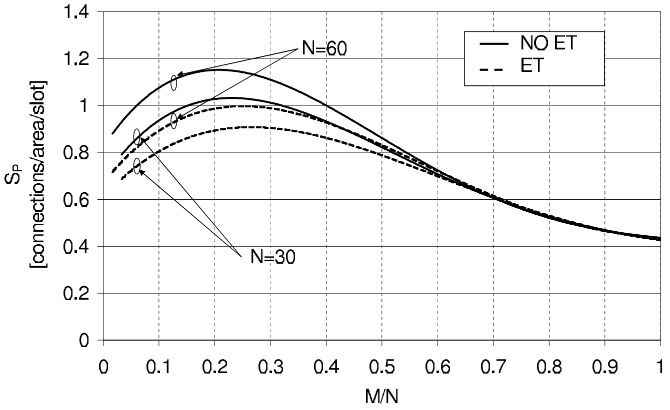

Fig. 4. *The normalized throughput of PTP channels versus the normalized frame size M/N, when $N = 30$ and 60.*

terminals in the network operate to set up the BCHs as seen in section II, one at a time. The procedure is stopped when a loss of 1% is reached to avoid polarizing the choice of terminals within the network, as it would inevitably happen with higher loss percentages. After BCHs have been set up, the same terminals, dynamically generate PTP connections, one per terminal, whose destinations are chosen at random among the active terminals. These connections are queued at the originating terminal until the PTP channel can be set up according to the reservation scheme described in the previous section. The run is stopped when a convergence situation is reached, i.e., when the maximum feasible number of PTP connections is set up. Connections are not set up when there are no more available resources, that is, all the PTP slots are marked as RESERVED by the algorithm. The throughput obtained in this way is averaged over 100 repetitions of the procedure with different samples of active terminals.

Figure 3 reports the maximum value of S_P versus the dimension of the point to point subframe. The two curves labeled *ET* (Exposed Terminal) and *NO ET* (No Exposed Terminal) refer respectively to the cases where the exposed terminal problem is not solved (as in the basic IEEE 802.11b DCF with RTS/CTS), and where the PTP reservation scheme presented in the previous section is adopted, thus getting rid of the exposed terminal problem. PTP connections are set to have an infinite lifetime and, therefore, the set up efficiency is best.

As clear from the figure, the maximum throughput of PTP channels at first increases with the subframe length M, showing that the time multiplexing option is more efficient than assigning the whole bandwidth to only one terminal for the entire connection time. This effect may be surprising since, in access system and disregarding any overhead, the efficiency does not change with the multiplexing degree; in fact, the occupation of the bandwidth resource prevents its use by any other terminal in the net. This is not the case in our environment where reuse is possible. A slot resource can be reused or not depending on the position of the terminal and, the longer is the frame the easier is to find a slot that can be reused. As M increases toward infinity the throughput improves. This effect is due to the statistical gain which is obtained by pooling the available resources, which is best exemplified by the Erlang-B loss formula in a $M/M/m/N$ queuing systems, where N represents the number of available resources (slots). In this case, increasing the traffic and the number of the resources keeping their ratio constant always reduces the blocking probability given by the Erlang-B formula.

The fact that the curves decreases after reaching a maximum value is not due to a decrease in the above effect, but rather to an insufficient load. In fact, as the PTP reuse efficiency is higher than the broadcast one, on the average fewer PTP slots, say $M_o < N$ slots, are needed to accommodate a PTP connection from each of the N terminals (this is the reason why these curves stop before reaching the value $M = N$). Therefore, when more slots are available, the throughput is diluted among all slots as no more traffic can be added (only one PTP connection per terminal is allowed).

Note that the advantage offered by time multiplexing appears to be in contrast with what has been found in [15]; this must be ascribed to the fact that we assume random selection of slots and do not allow intelligent scheduling. Therefore, increasing the PTP slot number up to the optimal value observed facilitates the matching of favorable transmissions.

Figure 4 reports the very same curves of Figure 3 when enlarging the broadcast subframe ($N = 30, 60$). The main result coming from the figure is that a longer BCH subframe provides an higher PTP throughput for any value of the parameter M. This is due to the fact that increasing N means increasing the number of users within the network, and this leads to a consequent increase in the PTP throughput to the same statistical multiplexing effect we have already mentioned. The gain resolving the exposed terminal problem follows this trend, in fact increases from the 10% to the 15% when $N = 30$ and until the 20% for $N = 60$.

V. ASYMPTOTIC GAIN EVALUATION

One might wonder what is the maximum PTP reuse efficiency, i.e., the PTP throughput value obtained with $N \to \infty$. Such asymptotic result is hard to obtain through simulation

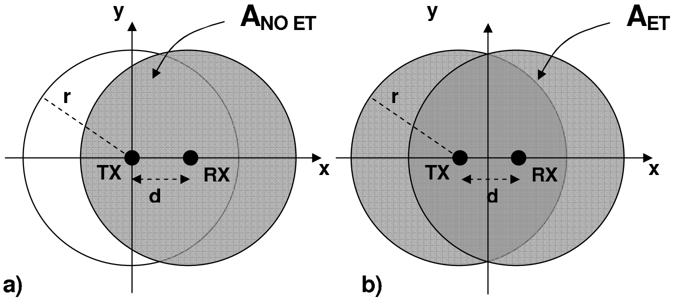

Fig. 5. *Blocked areas for the NO ET (case a) and ET (case b) cases given a PTP couple.*

as it become impractical for values $N > 60$. However, the maximum number of users per coverage area that can use the same slot can be evaluated solving a packing problem, i.e., finding the maximum number of PTP connections, with random source and destination, that can be packed in the plane with no collision at the destination. To this end, in this section we give an estimate of the asymptotic gain obtainable when solving the exposed terminal problem. We use the concept of *blocked area*, A_P, [16] induced by a PTP transmission, defined as a portion of network topology blocked by an ongoing PTP transmission between two ad hoc nodes when implementing the access protocol P. Intuitively, the PTP throughput of a given access protocol will be inversely proportional to the *blocked area* induced by the protocol itself, $S_P \propto \frac{1}{A_P}$.

The gain Γ we are interested in is the ratio between the reuse capability of protocols able to avoid the *Exposed Terminal* problem and protocols which don't. In other words:

$$\Gamma = \frac{S_{NOET}}{S_{ET}} = \frac{A_{ET}}{A_{NO\ ET}} \tag{1}$$

Generally speaking the definition of blocked areas for the different protocols may be hardly manageable since it depends on parameters as the positions of the sources and the destinations, the interference accumulation among ongoing transmissions and the particular propagation conditions.

In order to have a tractable but consistent calculation, we assume that: PTP couples are scattered uniformly in the plane and the signal propagation and interference follow a disk radius model. Under the above assumption, the area which is blocked by a PTP depends on the specific positions of sender and receiver and can be expressed by: $A(d)_P$, being d the random variable giving the distance between the two nodes. The average blocked area A_P can be calculated as:

$$A_P = \int_d A(d)_P f(d) dd \tag{2}$$

where $f(d)$ is the p.d.f. of the distance between the two nodes. If the receiver of the PTP transmission is uniformly drawn in the transmitter's coverage range with radius r, we have:

$$f(d) = \frac{1}{2\pi} \frac{2d}{r^2} \qquad d \in [0, r] \tag{3}$$

Figure 5 shows the blocked areas in the cases where the exposed terminal is/is not solved (labeled as "NO ET" and "ET" respectively in the figure). In the former case, a terminal in the destination's transmission area cannot reuse the same bandwidth because it would corrupt the reception; on the other side another transmitter can be potentially active in the transmitter's range, provided that a feasible receiver can be placed in the system. Thus, assuming that given a transmitter in the system a corresponding receiver can always be found, the blocked area when the exposed terminal is solved is:

$$A_{NO\ ET} = \pi r^2 \tag{4}$$

On the other side, the ET case induces a blocked area which is the union of the coverage areas of the source and the destination and can be defined as:

$$A_{ET} = \int_0^r \left[2\pi r^2 - I(d) \right] \frac{2d}{r^2} dd \tag{5}$$

where $I(d)$ is the intersection is the area of the intersection between the coverage area of sender and receiver, and can be easily calculated to be:

$$I(d) = \pi r^2 - 2r^2 \arcsin\left(\frac{d}{2r}\right) - dr\sqrt{1 - \left(\frac{d}{2r}\right)^2} \quad d \in [0, r] \tag{6}$$

We can now solve the integral in (5) by using the value of $I(d)$ given by (6) obtaining the following value of the average blocked area induced by the exposed terminal.

$$A_{ET} = 1.413\pi r^2 \tag{7}$$

The average gain obtained when adopting a protocol able to get rid off the exposed terminal can be obtained by substituting (7) and (4) in (1), which yields:

$$\Gamma = 1.413 \tag{8}$$

The result shows as the quantity of parallel transmissions prevented in the *exposed terminal* cases is around the 40%, in the environment considered.

To gather a feeling on the quality of such gain estimation, we devised a Monte-Carlo analysis where couples representing source and destination are chosen one at a time at random in a circular area of radius $R > r$ and are accepted if no collisions occur with the other terminals already present. The run is stopped when no more couples are accepted. The figure obtained in this way is averaged over 100 repetitions of the procedure and the result so obtained approaches the maximum PTP reuse as $R \rightarrow \infty$. We adopted a similar procedure to evaluate the maximum reuse in presence of exposed terminals. In this case we add the constraint on the sources, a new couple is not be accepted if the source falls within the coverage area of any source placed in the plane.

The result of this analysis are reported in Figure 6 which gives the maximum reuse factor versus the network dimension.

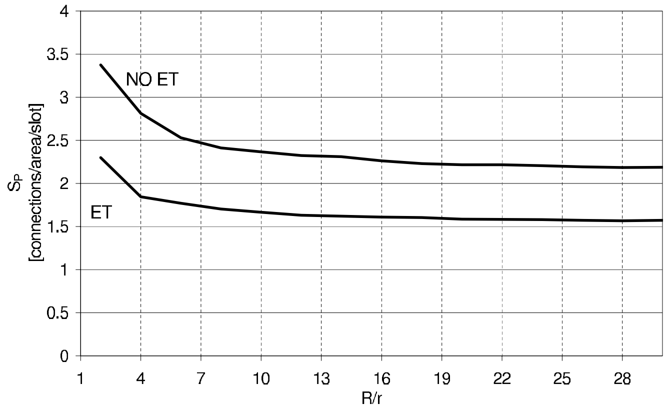

Fig. 6. *The asymptotic throughput when solving/not solving (NO ET/ET) the exposed terminal problem.*

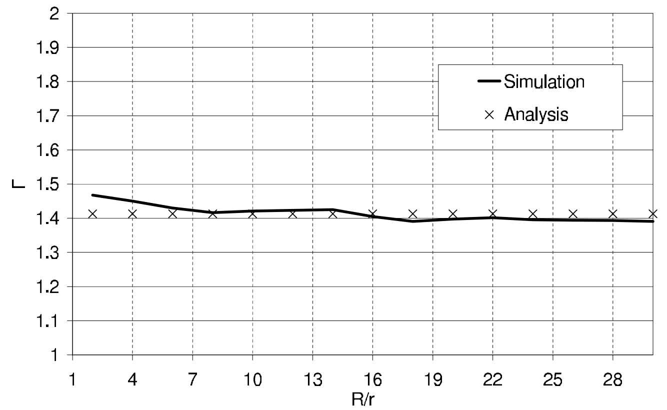

Fig. 7. *Asymptotic gain between the throughput obtained solving the exposed terminal and the throughput affected by the exposed terminal. Comparison between analysis and simulation.*

Figure 7 reports the comparison between the values of the gain Γ obtained through simulation and through analysis. As clear form the figures, the asymptotic gain if solving the exposed terminal is around the 40% with respect to protocols not coping with this issue (e.g., the IEEE 802.11 DCF RTS/CTS) and the gain value predicted by the simple analytical model has a good match with the simulation results.

VI. CONCLUSION

In this paper we have proposed an effective reservation algorithm for the set up of Point-To-Point communications within the framework of the ADHOC MAC, a recently proposed MAC protocols for ad hoc networks. Furthermore, by exploiting the aforementioned algorithm, we have investigated the one-hop channel reuse of general ad hoc networks composed of terminals randomly scattered on the plane.

The main results coming from our analysis are the following:

- the exposed terminal problem causes an asymptotic loss in the reuse efficiency of the PTP services around the 40%;
- considering random distributed scheduling, the reuse efficiency of the PTP service increases when time multiplexing among users is applied and the bandwidth is split among different users rather than assigned completely at a single user at time.

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