

# Why RTS-CTS is not your ideal wireless LAN multiple access protocol

João Luís Sobrinho, Roland de Haan, José Manuel Brázio  
Instituto de Telecomunicações, IST  
Lisboa, Portugal  
Email: {joao.sobrinho, r.dehaan, jose.brazio}@lx.it.pt

**Abstract**—Although Request-To-Send Clear-To-Send (RTS-CTS) has been introduced as a uniform improvement over Carrier Sense Multiple Access (CSMA) in a wireless LAN environment it is not. As it tries to solve the hidden-stations problem of CSMA, it creates new problems derived from the interaction among its control and data packets. In this paper, we systematically identify and classify the sequences of events where CSMA and RTS-CTS depart from an ideal behavior, and we define a reference configuration and an analytical model on the basis of which a comparative study of protocol performance is made. The results show that RTS-CTS falls short of an ideal protocol, in some cases performing even worse than CSMA. This is especially noticeable in situations where the interaction between control packets in RTS-CTS prevents transmissions that under CSMA could occur concurrently and successfully.

## I. INTRODUCTION

In wireless LANs, irrespective of whether operating in ad-hoc or infrastructure mode, the spatial structure of the network may result in partial connectivity, where stations are unaware of activity outside their direct neighborhood. In order to achieve an efficient channel utilization, the choice of a good multiple access protocol becomes essential. An ideal multiple access protocol for wireless LANs should not prevent successful transmissions from taking place nor should it allow collisions.

Currently, the two most common multiple-access protocols used in wireless LANs are Carrier Sensing Multiple Access [1] (CSMA) and Request-To-Send Clear-To-Send [2] (RTS-CTS), both adopted for the IEEE 802.11 standard [3]. It is well-known that CSMA falls short from an ideal protocol, because its operation may both unnecessarily inhibit stations from transmitting in the vicinity of a transmitting station (exposed-station problem) [4] and allow the start of transmissions by a station that will either destroy an ongoing reception by neighboring stations or become destroyed themselves by an already ongoing transmission (hidden-station problem) [5]. Although less widely noticed, the RTS-CTS protocol falls short of an ideal protocol as well, as it inhibits even more potentially successful transmissions than CSMA [6] while still suffering from collisions due to hidden stations [7] — even in the perfect situation of zero propagation delay and negligible control information overhead.

In this paper, we study the departure of CSMA and RTS-CTS from an ideal protocol. For this purpose, we systematically identify and classify the sequences of transmission events where CSMA and RTS-CTS deviate from the ideal behavior, and we define a reference configuration and an analytical model on the basis of which we make a comparative study of protocol

performance. The configuration considered consists of a wireless LAN comprising two interfering cells and subject to several traffic scenarios. The analytical model builds on the work of [8] and [9] and, in contrast to most existing analytical work on RTS-CTS, accurately describes the space and time dependencies between the transmission activity at different stations in the network.

The paper is organized as follows. In Section II, we state the operation of an ideal protocol and closely examine the shortcomings of CSMA and RTS-CTS. Next, in Section III, we describe our modelling approach and the underlying analytical model. In Section IV, we discuss the network capacity for various traffic scenarios under CSMA and RTS-CTS, point out the impact of their weaknesses, and contrast their performance with that of the ideal protocol. We conclude the paper in Section V.

## II. SHORTCOMINGS OF CSMA AND RTS-CTS

An ideal protocol allows a station, that is not currently receiving or transmitting a packet, to transmit if and only if (i) this transmission does not destroy any ongoing transmission, and (ii) the destination of the new packet is able to receive it free from interference from the ongoing transmissions. Such a protocol is ideal in the sense that both it is collision-free and allows any potentially successful transmissions to take place. This protocol is introduced here mainly as a bench-mark; for a possible implementation we refer to [6], [10].

### A. CSMA

Under CSMA a station listens to the channel (carrier sensing) before transmitting. A station defers a transmission if it senses the channel busy, and transmits its packet only when the channel is sensed idle.

CSMA suffers from the exposed-station problem, under which possibly successful transmissions are inhibited. These are the simultaneous transmissions by stations that can hear each other and where each station wants to transmit to a destination out of range of the other transmitters. An example of such a situation is given in Fig. 1a, where the nodes represent stations, the edges indicate hearing relationships between stations, and the arrows imply packet transmissions. The example shows that while a data packet transmission from station  $B$  to  $A$  takes place, a transmission from station  $C$  to  $D$  cannot start, since station  $C$  is exposed to the former transmission. Notice that the ideal protocol does not inhibit this successful transmission.

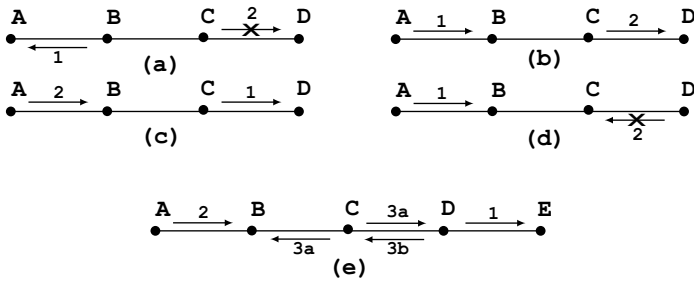


Fig. 1. Shortcomings of CSMA and RTS-CTS (the numbering of the arrows indicates the order of the transmissions).

In addition, CSMA suffers from collisions due to the hidden-station problem. This problem arises when stations that cannot hear each other possess a common neighbor. CSMA allows those stations to transmit simultaneously, which may lead to a collision event at the neighboring station. Fig. 1b shows an example: during the transmission from station  $A$  to  $B$ , station  $C$ , which is hidden from  $A$ , is allowed to initiate a transmission to  $D$ , thereby destroying the packet that is being received at station  $B$ . A similar collision event occurs if the order of these transmissions is reversed as in Fig. 1c: during the transmission from station  $C$  to  $D$ , station  $A$ , which is hidden from  $C$ , may start a new transmission to  $B$  although station  $B$  is not able to receive the packet free from interference.

It becomes clear that CSMA falls short of the ideal protocol since its operation both inhibits potentially successful transmissions and allows packet collisions to take place.

### B. RTS-CTS

The (RTS-CTS) protocol stems from the work of Karn [2]. It has become especially well-known because of its adoption in the IEEE 802.11 standard [3]. Before a data-packet transmission can actually start, the protocol imposes a successful handshake between sender and receiver by means of an exchange of control packets. The sender broadcasts an RTS packet, containing in its control fields both the intended destination of the ensuing data packet and the amount of channel time required for its transmission. If the RTS packet arrives successfully at the intended receiver, the latter broadcasts a CTS packet, containing also the channel time required for the new packet, to inform the sender of the RTS of the acceptance of the transmission and to inhibit neighboring stations from interfering during that period. Of course, a station is only allowed to send an RTS packet if none of its neighbors are transmitting and the station has not heard a CTS covering the time instant when it wants to transmit.

The RTS-CTS protocol also deviates from the ideal protocol, inhibiting potentially successful transmissions and allowing collisions to occur. In addition to the exposed-station problem, arising from the use of carrier sensing, there are other situations where RTS-CTS prevents potentially successful transmissions to take place. Regarding collisions, even though RTS-CTS was designed to solve the hidden-station problem, there are still situations where collisions due to hidden stations occur. Both situations are illustrated below.

1) *The gagged-station problem:* The employment of control packets inhibits successful transmissions that would be allowed not only under the ideal protocol, but also under CSMA [6]; namely, transmissions in a situation where stations that are not interfered by any ongoing transmission and that want to receive a data packet from a neighbor are inhibited from sending a CTS, because they previously heard a CTS sent by a station out of range of their intended transmitter that covers the time of the desired data-packet reception. Fig. 1d clarifies this situation: suppose that during an ongoing transmission from station  $A$  to  $B$ , station  $D$  wants to initiate a transmission to  $C$ . On hearing  $D$ 's RTS packet, station  $C$  is not allowed to reply with a CTS because of the CTS previously heard from  $B$ , although it is not exposed to any ongoing transmission in its vicinity. We refer to this consequence of the inhibitory nature of RTS-CTS as the *gagged-station problem*.

2) *The masked-station problem:* The RTS-CTS protocol solves the hidden-station problem in some, but not all, situations, as under RTS-CTS hidden stations can still interfere with neighboring transmissions and cause data packets to collide. The reason for these collisions is that a CTS sent by a station may not always be heard by all its neighbors, since the latter might already be interfered by an ongoing transmission in their vicinity, thus leading to a hidden-station problem. This problem has only recently been examined in [7], where it is known as the *masked-node problem*.

The masked-station problem only occurs in topologies with five or more stations, an example of which is given in Fig. 1e. Starting from a quiescent situation, suppose that station  $D$  initiates a transmission to  $E$ . A successful RTS-CTS exchange takes place, the transmission starts, and station  $C$  becomes blocked by the RTS. During this data transfer, a new transmission from  $A$  to  $B$  is initiated. The corresponding RTS-CTS exchange is successful and the transmission starts. However, station  $C$  was not able to hear the CTS broadcast by  $B$  because of the ongoing transmission by  $D$ , and in this way  $C$  does not become blocked by the transmission from  $A$  to  $B$ : station  $C$  is now masked. As soon as station  $D$  completes its transmission, station  $C$  becomes unblocked and two types of collision events can take place: (i) station  $C$  initiates a transmission to either station  $B$  or  $D$ , and this destroys the ongoing transmission from  $A$  to  $B$  by an RTS packet, or (ii) station  $D$  sends an RTS packet to start a transmission to  $C$ , whereupon a CTS reply by  $C$  destroys the the ongoing transmission from  $A$  to  $B$ . In the second case not only the data packet at station  $B$  is destroyed, but  $B$  is also unable to hear the CTS packet from station  $C$ , thus becoming itself masked. In this way neighboring stations may become masked and give rise to long sequences of data-packet collisions.

The shortcomings of RTS-CTS presented above make clear that also this protocol is far from ideal as it inhibits transmissions that could have been successful and still does not prevent data packets from colliding.

## III. ANALYTICAL FRAMEWORK

In this section we present the framework for the performance comparison of the various protocols and the underlying analytical model for the link throughput computation.

Assume a network topology is given on which to compare the maximum throughput for different protocols. We study the protocol performance by determining the network capacity under a given *traffic pattern*, i.e., by specifying the proportions between the traffic volumes carried in the network links and then finding the maximum throughput attainable under those restrictions. Further assume the existence of an analytical model which gives the link throughput as function of some vector  $\vec{p}$  of network operation variables. The determination of the network capacity then involves the solution of the non-linear optimization problem:

$$\begin{aligned} \max_{\vec{p}} \quad & S \\ \text{s.t.} \quad & S = \frac{S_1(\vec{p})}{\alpha_1} = \dots = \frac{S_L(\vec{p})}{\alpha_L}, \end{aligned} \quad (1)$$

where  $L$  is the number of links in the network,  $S_i$ ,  $i = 1, \dots, L$ , is the throughput over link  $i$ , and  $(\alpha_1, \dots, \alpha_L) = \vec{\alpha}$  is the traffic pattern.

The analytical model used is based on earlier work on the throughput computation for CSMA in multihop packet-radio networks [8], later generalized in [9] to other multiple-access protocols. We further extend this methodology to enable the throughput computation for the RTS-CTS protocol. Our approach contrasts with most other analytical network models for RTS-CTS in the sense that instantaneous interference dependencies between stations due to ongoing transmissions are taken into account, whereas most other work integrates the consequences of interference in an averaging fashion. Here, we shall not go into all the modelling details, but resort to a concise description containing the most relevant analytical ingredients.

#### A. General model

A network is described by a directed graph with  $N$  nodes, corresponding to stations, interconnected by a set of (directed) links describing the hearing relationships between nodes: if  $n$  and  $l$  are two nodes, link  $(n, l)$  belongs to the graph if node  $l$  can hear node  $n$ . In this situation, node  $n$  is called the *source* and node  $l$  the *sink* of the link.

Links with nonzero packet traffic are called *used* links. Each such link has associated with it an infinite supply of packets to be sent from its source to its sink. Used links alternate between two states: *active* or *inactive*. A link becomes active at the time its source starts a transmission of a data packet (destined to its sink), and inactive at the time a transmission is completed.

Each used link  $i$  has coupled with it a Poisson *scheduling point process* with rate  $\lambda_i > 0$ , at whose event times its source node will apply the rules specified by the access protocol in order to try to initiate a data-packet transmission over link  $i$ ; at each such point in time the node may be *blocked* (i.e., prevented) from transmitting, or it may initiate a data-packet transmission that may itself be successful or unsuccessful (i.e., collided with). The scheduling processes associated with different links are independent. A data-packet transmission over link  $i$  occupies a random amount of channel time with an exponential distribution with mean  $1/\mu_i$ ,  $\mu_i > 0$ , where it is assumed that the durations of different

transmissions are independent<sup>1</sup>. Further assumptions are zero propagation delays and zero turn-around times between receiver and transmitter modes. It is also assumed that control packets have a negligible duration, however their capability to cause collisions is accounted for in the model.

With the above assumptions, a model can be constructed for a discrete-state system evolving through discrete events regulated by exponential clocks, thus giving rise to a continuous-time Markov chain. The system state has to be chosen such that, at any time instant  $t$ , it is possible to determine which links are allowed by the protocol to start a transmission. The information to be kept in the state is thus protocol-dependent. Denote a generic state by  $D$  and let  $A(D)$  and  $U(D)$  be the set of links that are active and the set of links that are not blocked, respectively, when the system state is  $D$ . We then have that, in the interval  $(t, t + \tau)$ , link  $i \in U(D)$  becomes active, and the system enters the corresponding new state, with probability  $\lambda_i \tau + o(\tau)$ , and link  $j \in A(D)$  becomes inactive, and the system enters the corresponding new state, with probability  $\mu_j \tau + o(\tau)$ , independently of its history prior to  $t$ .

1) *State description*: The work in [9] considered protocols where the knowledge about which links are active and which receivers are successfully receiving packets is sufficient to determine whether a given inactive link can start a new transmission. CSMA is a particular case of such protocols: for CSMA, the set  $X(t)$  of the links active at  $t$  is a sufficient state description, and given state  $D$  we have that  $A(D) = D$ , and that  $U(D)$  is the set of inactive links whose source nodes cannot hear any of the source nodes of the links active in state  $D$ .

For the present study, that *link activation model* has been adapted to allow the study of RTS-CTS, for which more complex state information is required: the state information  $D$  now contains (i) the set of *active* links, and (ii) for each *inactive* link, the set of active links whose CTSs the sink of the inactive link under consideration successfully heard. In this way, the set  $U(D)$  of links unblocked when the system is in state  $D$  is given by the subset of the inactive links whose sources or sinks do not possess any currently transmitting neighbor nor have heard a CTS associated with a currently active link. The set  $A(D)$  is simply the set of links that are active in state  $D$ .

2) *State space and equilibrium distribution*: The state space  $\mathcal{S}$  is defined as the set of all states that can be reached starting from an inactive network by means of link activations and deactivations. The state space does not have in general a simple characterization, and has to be algorithmically determined, e.g., by means of a Breadth-First Search [12, Sec. 7.3] applied to the directed graph whose nodes are the states and whose arcs represent the possible state transitions.

The equilibrium probabilities  $Q(D)$  are obtained in the usual way, by balancing for each state  $D \in \mathcal{S}$  the rate of transitions into and out of the state. Since the chain is finite and, by construction, the state space is irreducible, the chain possesses a unique stationary distribution. In general this distribution has to

<sup>1</sup>This model assumes the redrawing of packet lengths when retransmissions are performed; it is somewhat similar to Kleinrock's independence assumption for point-to-point store-and-forward networks [11].

be computed numerically, but a product form solution is available when the chain is reversible (see [9]). Reversibility of the chain is linked to the existence of symmetry properties in link blocking, which is the case with both CSMA and the ideal protocol.

3) *Throughput equations:* Define the throughput  $S_i$  over link  $i$  as the long-term fraction of time that link  $i$  is involved in successful data-packet transmissions. It is shown in [9] that the throughput can be expressed as a function of the transition rates  $\lambda_i$  and the equilibrium probabilities,  $Q(D)$ , of being in state  $D$ , as follows:

$$S_i = \lambda_i \sum_{D \in U_s(i)} Q(D) \bar{T}(D, i), \quad (2)$$

where  $U_s(i)$  is the set of states  $D \in \mathcal{S}$  in which link  $i$  is not blocked from becoming active. The term  $\bar{T}(D, i)$  denotes the expected duration of successful channel usage by a packet sent over link  $i$  given that link  $i$  was activated from state  $D$ , i.e., it is the expectation of a random variable defined as the packet transmission time, if the packet is successful, and as zero, otherwise. In the case where a packet is always successful (e.g., in collision-free protocols) this term is equal to  $1/\mu_i$ . In general, the terms  $\bar{T}(D, i)$  are obtained from an auxiliary Markov chain derived from the original chain, containing a “successful termination” absorbing state and an “unsuccessful termination” absorbing state, by determining the statistics of the time to absorption in the “successful termination” state (see [9]).

The above modelling approach can in principle be applied to any network topology. However, the throughput computation becomes hard for large topologies as the size of the state space grows exponentially in the number of used links.

#### IV. RESULTS

In this section, we present the network model and define the set of traffic patterns used in the ensuing capacity analysis of the protocols.

##### A. Network topology

We analyze the overall throughput performance in the two-cell wireless LAN depicted in Fig. 2. Each cell has an access point: the one on the left comprises also a single mobile station, whereas the one on the right comprises two mobile stations. The mobile station in the left cell can hear—and hence interfere—with one of the mobile stations in the right cell. This topology, on the one hand, models a realistic situation and, on the other hand, strikes a good balance between analytical complexity and the exhibition of the several types of shortcomings of CSMA and RTS-CTS.

The arrows in the figure represent used links. The odd and even numbered links correspond to downlinks (from access point to mobile station) and uplinks (from mobile station to access point), respectively. This numbering of used links is followed throughout the remainder of the paper.

##### B. Traffic pattern and network capacity

The performance measure of interest is the maximum amount of throughput, or capacity, in the network subject to a given traffic

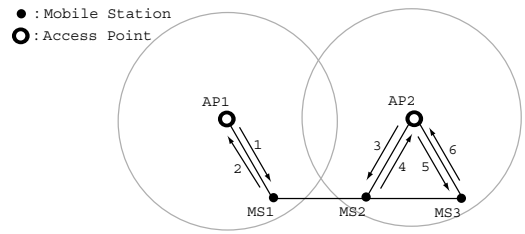


Fig. 2. The two-cell wireless LAN topology.

pattern. We define the system throughput as the average utilization of the two cells as follows:

$$S = \frac{1}{2} (S_1 + S_2 + S_3 + S_4 + S_5 + S_6), \quad (3)$$

where we note that  $S_1 + S_2 \leq 1$  and  $S_3 + S_4 + S_5 + S_6 \leq 1$ . In order to study the protocol behavior under various traffic scenarios, we introduce two parameters for each pair of used links. Define for each link pair  $(2i - 1, 2i)$ ,  $i = 1, 2, 3$ , the fraction of the overall throughput pertaining to that link pair:

$$\gamma_i = \frac{S_{2i-1} + S_{2i}}{S_1 + S_2 + S_3 + S_4 + S_5 + S_6}, \quad i = 1, 2, 3. \quad (4)$$

In addition, let the *downlink ratio* of link pair  $(2i - 1, 2i)$ ,  $i = 1, 2, 3$ , be defined as the fraction of its throughput corresponding to the downlink direction:

$$\delta_i = \frac{S_{2i-1}}{S_{2i-1} + S_{2i}}, \quad i = 1, 2, 3. \quad (5)$$

The traffic pattern  $\vec{\alpha}$  is expressed as a function of  $\gamma_i$  and  $\delta_i$ :

$$\vec{\alpha} = 2 (\delta_1 \gamma_1, (1 - \delta_1) \gamma_1, \delta_2 \gamma_2, (1 - \delta_2) \gamma_2, \delta_3 \gamma_3, (1 - \delta_3) \gamma_3). \quad (6)$$

Capacity results are obtained by solving the Lagrange multiplier formulation (see, e.g., [13, Sec. 10]) of the throughput maximization problem (1) subject to the traffic pattern constraints (6). In the case of collision-free situations with protocols leading to reversible Markov chains, simple expressions are available for the capacity. In the remaining cases, numerical computation has to be resorted to.

##### C. Configuration I: Network capacity in scenarios without masked stations

In this first configuration, links 5 and 6 do not carry traffic ( $\gamma_3 = 0$ ). Exploiting the reversibility of the Markov chain and the absence of collisions it becomes possible to obtain a closed-form expression for the capacity of the ideal protocol as a function of  $\gamma_1$ ,  $\gamma_2$ ,  $\delta_1$  and  $\delta_2$ :

$$S_{max} = \frac{1}{2} \cdot \frac{1}{\max\{\delta_1 \gamma_1, \delta_2 \gamma_2\} + \max\{(1 - \delta_1) \gamma_1, (1 - \delta_2) \gamma_2\}}. \quad (7)$$

In addition, it is readily seen that the RTS-CTS protocol has a capacity equal to 0.5 independently of  $\gamma_1$ ,  $\gamma_2$ ,  $\delta_1$  and  $\delta_2$ . This is because with RTS-CTS only one of the four links 1, 2, 3, and 4, can be active at any given time: the gaged-station problem prevents two simultaneous downlinks; the exposed-station problem

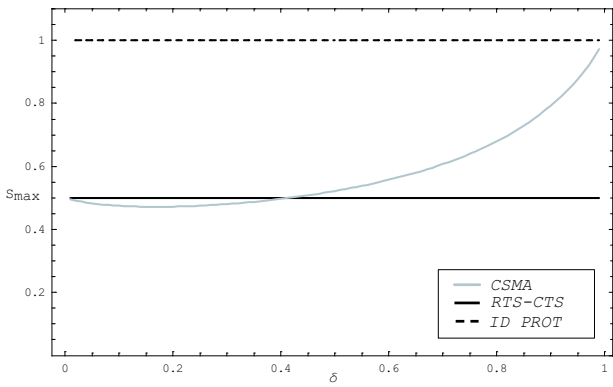


Fig. 3. Network capacity in the case of identical cells ( $\delta_1 = \delta_2; \gamma_1 = \gamma_2 = 0.5$ ).

prevents two uplinks; and the desirable RTS-CTS effect prevents the coexistence of a downlink and an uplink transmission.

In contrast, the presence of collisions in CSMA leads to a complicated expression for its capacity, and only numerical results will be given.

1) *Equal cell downlink ratios*: First we consider a scenario of equal downlink ratios ( $\delta_1 = \delta_2 = \delta$ ) and equal traffic ( $\gamma_1 = \gamma_2 = 0.5$ ) at both used link pairs. The results for the network capacity are presented in Fig. 3 as a function of  $\delta$ .

The ideal protocol attains a capacity of one independently of  $\delta$  since it leads to a mode of operation where at any time either both uplinks or both downlinks are active simultaneously without idle channel time. As previously discussed, the RTS-CTS protocol has a constant capacity of 0.5. As for the CSMA protocol, if there is only uplink traffic ( $\delta = 0$ ) only one of the links can be active at any given time (exposed-station problem) leading to a capacity of 0.5. As the fraction of downlink traffic increases, the capacity initially decreases, though slightly, because of the increasing number of collisions due to hidden stations. But, as the fraction of downlink traffic draws closer to one, an increasing degree of concurrency between downlink transmissions and a decreasing number of collisions is obtained, and the capacity approaches one.

In short, the performance of RTS-CTS and CSMA is similar for low downlink ratios ( $\delta < 0.5$ ), and significantly below that of the ideal protocol, whereas CSMA performs much better than RTS-CTS for high downlink ratios ( $\delta > 0.6$ ), mostly because RTS-CTS suffers from the gagged-station problem.

2) *Unequal cell downlink ratios*: In this scenario we assume the downlink ratio  $\delta_2$  fixed at 0.5. The capacity is plotted as a function of  $\delta_1$  in Fig. 4. The scenario models the effect on the network capacity of having different applications (with their specific traffic requirements) running in neighboring cells.

The capacity of the ideal protocol becomes in this case

$$S_{max} = \frac{1}{1 + |\delta_1 - \delta_2|}. \quad (8)$$

Note that the capacity reaches one only if the downlink ratios match in both cells: if they do not, the restriction of having different throughputs in the downlinks, together with the fact that one downlink and one uplink cannot occur simultaneously, forces

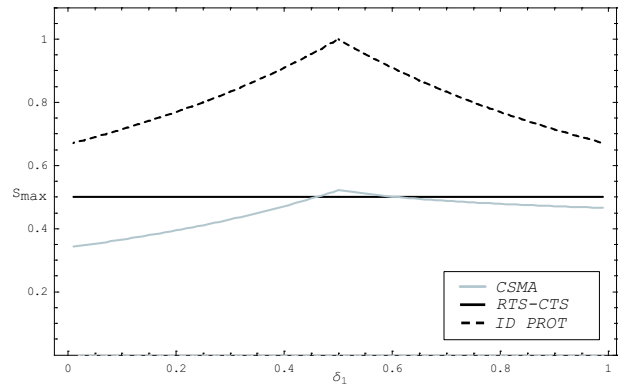


Fig. 4. Network capacity in the case of unequal downlink ratios ( $\delta_2 = 0.5; \gamma_1 = \gamma_2 = 0.5$ ).

the downlink with the lower desired throughput to be inactive in part of the time when the other downlink is active, with a similar argument applying to the uplinks. The capacity of RTS-CTS remains at 0.5 as discussed before, whereas the capacity of CSMA exhibits a behavior similar to that of the ideal protocol but penalized by both exposed- and hidden-station problems.

#### D. Configuration II: Network capacity in scenarios with masked stations

We take now the traffic on links 5 and 6 to be nonzero ( $\gamma_3 > 0$ ). The capacity of RTS-CTS is no longer amenable to a simple expression, and only numerical results are presented.

1) *Only downlink traffic*: The first situation assumes only downlink traffic, that is, only links 1, 3 and 5 are used. Under RTS-CTS, this scenario is prone to both gagged- and masked-station problems, but no exposed-station problems. Figure 5 shows the capacity as function of the traffic split  $\gamma_2/(\gamma_2 + \gamma_3)$  between links 3 and 5 for equal traffic amounts in each cell ( $\gamma_1 = \gamma_2 + \gamma_3 = 0.5$ ). As expected, both the ideal protocol and CSMA have a capacity of one, as these protocols allow simultaneous transmissions over link 1 and over either link 3 or link 5.

The capacity of RTS-CTS is also one when there is only traffic over link 5, since links 1 and 5 are completely decoupled. However, a transmission starting over link 1 while link 5 is active masks station MS2. Therefore, as the fraction of traffic over link 3 starts increasing, the CTSs sent by the masked station MS2 destroy the packets of link 1, justifying the sharp decrease in capacity witnessed in the figure. At the extreme case of no traffic over link 5 ( $\gamma_2/(\gamma_2 + \gamma_3) = 1$ ), the capacity is limited at 0.5 by the gagged-station problem only. The fact that the capacity of RTS-CTS gets below 0.5 for a traffic split  $\gamma_2/(\gamma_2 + \gamma_3)$  between 0.45 and 1 is a clear indication of collisions due to the masked-station problem.

2) *Both downlink and uplink traffic*: Next, we examine a scenario with both downlink and uplink traffic, with the traffic fractions in each link pair given by  $\gamma_1 = 1/2, \gamma_2 = 1/8$  and  $\gamma_3 = 3/8$ , and we study the network capacity as function of the downlink ratio  $\delta_1$  for fixed values of  $\delta_2$ . The capacity of the protocols considered does not depend on  $\delta_3$ , since links 5 and 6 are indistinguishable both from the point of view of their interference

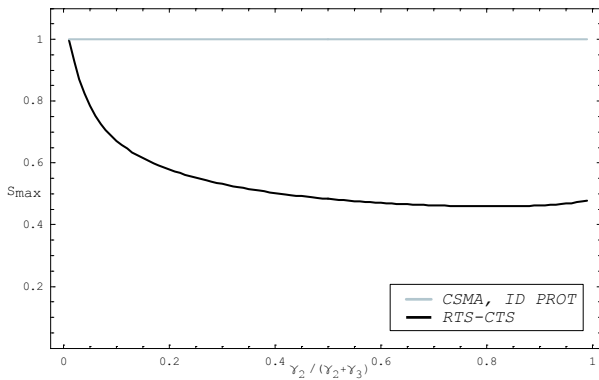


Fig. 5. Network capacity in the case of only downlink traffic ( $\delta_1 = \delta_3 = \delta_5 = 1$ ;  $\gamma_1 = \gamma_2 + \gamma_3 = 0.5$ ).

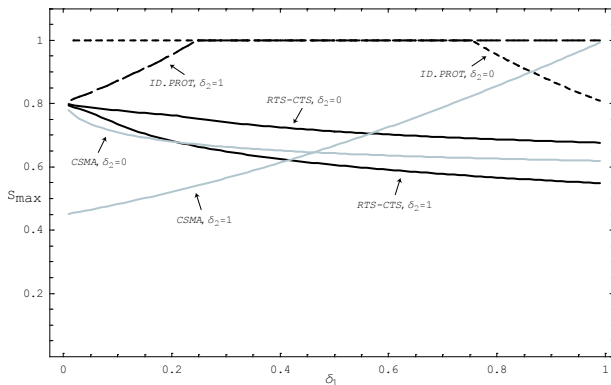


Fig. 6. Network capacity in the case of downlink and uplink traffic ( $\gamma_1 = 1/2$ ,  $\gamma_2 = 1/8$  and  $\gamma_3 = 3/8$ ).

with links 1 and 2, and their blocking and masking of station MS2.

Figure 6 shows, for each of the protocols, capacity curves corresponding to the extreme cases of no downlink and no uplink traffic between AP2 and MS2 ( $\delta_2 = 0$  and  $\delta_2 = 1$ , respectively). Take the case of the ideal protocol with  $\delta_2 = 1$ . Analysis yields the capacity as  $S_{max} = 1/\max\{1, 5/4 - \delta_1\}$ . This equation is easily interpreted: the fractions of time that link 2 and 3 are successfully active are  $S(1 - \delta_1)$  and  $S/4$ , respectively, and since their activation is mutually exclusive, it follows that  $S(1 - \delta_1 + 1/4)$  is less than or equal to one. A symmetry argument shows that the capacity for  $\delta_2 = 0$  is obtained by replacing in the above expression  $\delta_1$  with  $(1 - \delta_1)$ .

Under RTS-CTS and for  $\delta_1 = 0$ , there are no masked stations. Moreover, the capacity is insensitive to the downlink ratio  $\delta_2$ . This is because we just have link 2 transmissions in the left-hand cell and these transmissions cannot occur simultaneously with transmissions on either link 3 (desired control-packet exchange effect) or 4 (exposed-station problem). As the downlink ratio  $\delta_1$  increases we start having masked stations, bringing the capacity down. For  $\delta_2 = 0$  no gagged stations exist; their presence for  $\delta_2 > 0$  accounts for the decrease in capacity witnessed in the figure.

Under CSMA and for  $\delta_2 = 1$  there are no exposed stations.

If  $\delta_1$  is close to zero, there is a strong hidden-stations effect in which the transmissions over link 2 destroy the transmissions over link 3. As traffic over link 1 prevails over traffic over link 2 there is a decrease in the hidden-stations problem and an increase in concurrency over links 1 and 3, with capacity reaching one for  $\delta_1 = 1$ . The capacity curve shows an opposite behavior as a function of  $\delta_1$  for  $\delta_2$  fixed at 0. When  $\delta_1 = 0$ , the capacity is limited by exposed-station effects between links 2 and 4. As we trade traffic over link 2 with traffic over link 1 ( $\delta_1$  increases) we are trading exposed stations with hidden stations, with a nefarious impact on the capacity.

## V. CONCLUSIONS

The RTS-CTS protocol was originally introduced to solve the hidden-stations problem not dealt with by the CSMA protocol. For this purpose, every data packet transmission must be preceded by an exchange of control packets. A close analysis of the RTS-CTS protocol reveals that this exchange not only does it not completely solve the hidden stations problem—there are still remaining collisions due to masked stations—but it introduces a different kind of problem—the gagged stations problem—not present in CSMA.

In this work, we scrutinized the shortcomings of both RTS-CTS and CSMA, and studied their influence on performance against the background of an ideal protocol. The analytical model used accurately represents the time and space dependencies induced by the access protocols. Results were presented for the capacity in an environment of two interfering wireless LAN cells, showing that the protocol limitations identified have a significant influence on their capacity as revealed by a comparison with an ideal protocol. In addition, even neglecting the higher overhead of RTS-CTS over CSMA, the former can perform worse than the latter, mostly in situations where CSMA allows successful concurrency of transmissions that are impaired by the gagged-station problem of RTS-CTS.

## REFERENCES

- [1] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part I - Carrier Sense Multiple-Access modes and their throughput-delay characteristics," *IEEE Trans. Commun.*, vol. 23, no. 12, pp. 1400–1416, 1975.
- [2] P. Karn, "MACA - a new channel access method for packet radio," in *Proc. of the 9th ARRL/CRRL Computer Networking Conference*, London, Ontario, Canada, Sept. 1990, pp. 134–140.
- [3] LAN MAN Standards Committee of the IEEE Computer Society, "Information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements - part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," 1999.
- [4] A. S. Tanenbaum, *Computer Networks*, 4th ed. Upper Saddle River, NJ, United States: Pearson Education International, 2003.
- [5] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part II - the hidden terminal problem in Carrier Sense Multiple-Access and the busy-tone solution," *IEEE Trans. Commun.*, vol. 23, no. 12, pp. 1417–1433, 1975.
- [6] A. Acharya, A. Misra, and S. Bansal, "MACA-P: A MAC for concurrent transmissions in multi-hop wireless networks," in *Proc. IEEE PerCom'03*, Fort Worth, Texas, United States, Mar. 2003, pp. 505–508.
- [7] S. Ray, J. B. Carruthers, and D. Starobinski, "Evaluation of the masked node problem in ad-hoc wireless LANs," *IEEE Trans. on Mobile Computing*, in press.
- [8] R. R. Boorstyn and A. Kershenbaum, "Throughput analysis of multihop packet radio," in *Proc. ICC'80*, Seattle, Washington, United States, 1980, pp. 13.6.1–13.6.6.

- [9] J. M. Brázio and F. A. Tobagi, "Theoretical results in throughput analysis of multihop packet radio networks," in *Proc. ICC'84*, Amsterdam, The Netherlands, 1984, pp. 448–455.
- [10] Z. J. Haas, J. Deng, and S. Tabrizi, "Collision-free medium access control scheme for ad-hoc networks," in *Proc. IEEE MilCom'99*, vol. 1, Atlantic City, NJ, United States, 1999, pp. 276–280.
- [11] L. Kleinrock, *Communication Nets: Stochastic Message Flow and Delay*. New York, United States: McGraw-Hill, 1964.
- [12] A. V. Aho, J. E. Hopcroft, and J. D. Ullman, *Data Structures and Algorithms*, 1st ed. Reading, MA, United States: Addison-Wesley, 1983.
- [13] D. G. Luenberger, *Linear and Nonlinear Programming*, 2nd ed. Reading, MA, United States: Addison-Wesley, 1989.