Carrier-Sense Multiple Access with Transmission Acquisition (CSMA/TA)

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***Abstract*—This paper introduces Carrier-Sense Multiple Access with Transmission Acquisition (CSMA/TA) for wireless local area networks (WLANs) with stations endowed with half-duplex radios using single antennas. In contrast to traditional contention-based channel-access methods, CSMA/TA seeks to increase the likelihood of having the last transmission from a group of colliding transmissions succeed. To accomplish this, a station senses the channel before sending a pilot packet. After finishing the transmission of the pilot, the station is required to wait for a certain amount of time before sensing the channel again. If the channel is sensed to be idle again, the station understands that "it has acquired its right to transmit a data frame" and proceeds with that. The throughput of CSMA/TA is compared with the throughputs of CSMA and CSMA/CD. An important feature of the analysis presented in this paper is the consideration of the impact of the receive-to-transmit and transmit-to-receive turnaround times. It is shown that CSMA/TA performs better than ideal CSMA and CSMA/CD if the propagation delays in the network are larger than the turnaround times, and its performance can still surpass CSMA/CD and CSMA if turnaround times are larger than propagation delays but not too much larger.**

I. Introduction

In the past few decades we have witnessed the explosive deployment of wireless networks worldwide, which has caused a dramatic change in the way people use the Internet and its many services by virtue of mobile devices. In particular, the unprecedented success of wireless local area networks (WLANs) has allowed fast and easy connectivity in a number of environments, and its on-going evolution is now moving towards new realms, such as the Internet of Things (IoT), with long-range connections ($\sim$1000 m) at sub-GHz frequencies, typified by the latest IEEE 802.11ah standard [1]. However, while many technological advances have been incorporated into WLANs over the years, the most significant ones have been done at the physical layer, such as the adoption of advanced modulation and coding schemes, multiple-input multiple-output (MIMO) technologies, and wider channel bandwidths. By contrast, the core of the medium access control (MAC) sub-layer of current WLANs still relies on variations of the traditional carrier-sense multiple access (CSMA) technique first introduced by Kleinrock and Tobagi [2], as it is the case in the DCF used by stations allocated to a restricted access window (RAW) in the IEEE 802.11ah.

One of the key features of CSMA and many of its variants, such as CSMA/CD [3], is that all stations involved in a transmission collision are forced to give up and retry at a later time. Such an approach renders transmission periods during which the channel is wasted with packet collisions without resulting in any successful transmission. In CSMA/CD such wasted periods are shortened due to its full-duplex operation, by which a station monitors the channel while transmitting a frame, followed by its quick abortion if a collision is detected. Nevertheless, to date, CSMA/CD stands as the "holy grail" of contention-based MAC protocols for wireless networks, whose performance a number of works have tried to achieve using different techniques, such as multiple transceivers [4], [5] or the newest *full-duplex* radios based on self-interference cancellation [6], [7] (see Section II for related work).

The contribution of this paper is introducing **CSMA/TA** (Carrier Sense Multiple Access with Transmission Acquisition), which is a variant of CSMA for WLANs based on off-the-shelf *half-duplex* radios, and is such that the last transmission from a group of overlapping transmissions is allowed to succeed. The approach adopted in CSMA/TA leverages the short transmit-to-receive (TX/RX) and receive-to-transmit (RX/TX) turnaround times of modern half-duplex radios, which are about 2μs [8] and are far shorter than the 192μs incurred by other radios [9]. This is significant, because such turnaround times are of the same order of magnitude or even smaller than the propagation delays in many WLAN scenarios, especially those seeking long-range coverage.

Section III describes CSMA/TA. In a nutshell, a node that needs to send a data packet and senses the channel idle, first transmits a pilot packet, stops for a short time period to listen for other pilots, and if the channel is sensed to be idle during that time period it determines that the channel is free and proceeds to transmit the data packet accordingly. We call this process *transmission acquisition*. Section IV presents the throughput analysis of CSMA/TA, which is dictated by the relation between the propagation delay and the radio's TX/RX and RX/TX turnaround times. If the turnaround times are smaller than the propagation delay, then CSMA/TA guarantees that the node that transmitted the last pilot in a group of concurrent pilots *succeeds in acquiring the channel*, while the others back off. But, if the turnaround times are bigger than the propagation delay, the transmission acquisition depends on the *likelihood* of transmission acquisition which, in turn, depends on the relative magnitude of both aforementioned parameters.

Section V compares the throughput attained with CSMA/TA against CSMA and CSMA/CD in different scenarios, considering the impact of the turnaround times of half-duplex radios. As the results show, if the turnaround times are

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much greater than the propagation delay, CSMA/TA performs slightly better than CSMA; however, if they are very close to the propagation delay CSMA/TA becomes more efficient than CSMA/CD. Section VI presents our conclusions.

II. Related Work

A number of contention-based channel access protocols have been proposed since CSMA [2] and CSMA/CD [3] were first introduced [13]. In particular, because collision detection using single-antenna half-duplex radios is not doable, CSMA/CD performance became the benchmark in the design of MAC protocols for wireless networks. Still, few proposals have been reported on how to emulate CSMA/CD using half-duplex radios. Rom [12] proposed a MAC protocol that detects collisions by means of pauses. A station that senses the channel busy defers transmission as in CSMA; a transmitter that senses the channel idle starts transmitting but pauses during transmission and senses the channel. If the channel is sensed idle, the sender completes its transmission; otherwise, the sender continues to transmit for a minimum transmission duration to jam the channel. This approach cannot guarantee that data packets will not collide with other transmissions at the receiver if packets start at the same time or the transmit-to-receive turnaround times are not negligible.

FAMA-PJ [11] emulates CSMA/CD in the context of collision avoidance in WLAN's and prevents data packets from colliding with other transmissions. A transmitter sends an RTS if it detects no carrier in the channel, and listens for a period of time after its RTS to check for jamming signals sent by passive nodes that detected a collision. A passive listener that receives the signal from the one or multiple RTS's sent and is unable to decode an RTS successfully sends a jamming signal for a period of time that is long enough to ensure that active transmitters hear the jamming signals from passive listeners once they can start listening to the channel after sending their RTS's. A remaining limitation of FAMA-PJ is that too many passive nodes end up sending jamming signals.

Other works have tried to emulate CSMA/CD by using more than one transceiver/antenna. For instance, Peng et al. [5] proposed a MAC protocol that requires two separate transceivers to operate on two separate channels for control and data frame transmissions. Pulses over the control channel are used for collision detection, along with a CTS frame to avoid hidden terminals. Also requiring two separate transceivers, CSMA/CN [4] utilizes the standard CSMA to acquire the medium. The intended receiver uses PHY-layer information to detect packet collisions, and notifies the transmitter via a distinct signature sent over the same data channel. The signature is unique to every transmitter, and the transmitter employs a separate, listener antenna to perform signature correlation to identify the notification. If the notification is identified, the transmitter aborts its transmission.

With the advent of single-channel full-duplex (FD) wireless transceivers based on self-interference cancellation (SIC) [10], a number of MAC protocols have been proposed to achieve CSMA/CD-like operation. For instance, FD-WiFi CSMA/CD [6] uses FD to implement carrier sensing while transmitting data. But, due to residual self-interference, the sensing threshold needs to be properly designed to balance the errors due to miss detection and false alarms. FD-CSMA/CD [7] implements a CSMA/CA with collision detection in which the receiver acknowledges the reception of a packet immediately if its header is correct, and keeps sending the ACK as long as no collision is detected. At the same time, the transmitting node keeps sending its packet as long as it keeps receiving the ACK. Thus, if the receiver detects a collision, it stops the ACK, which causes the transmitter to stop its transmission immediately. CSMA/CAD [14] also uses SIC to guarantee collision avoidance under hidden-terminal scenarios, while it implements collision detection during the four-way handshake. It is shown to attain higher throughput than CSMA, DBTMA, and CSMA/CA.

Although the potential of FD radios in the design of future MAC protocols is undeniable, the availability of cheaper half-duplex radios with much faster turnaround times allows the development of simple approaches that can even surpass the performance of CSMA/CD in certain conditions, and CSMA/TA is one alternative.

III. CSMA/TA

A. Motivation and Design Objectives

The operation of CSMA/TA is motivated by the observation that, to date, contention-based medium access control protocols have been designed under the premise that either: (a) all colliding stations should give up on their transmission attempt, no matter the order (and when) each colliding station started its attempt; or (b) stations can attempt to resolve collisions in a sequence of collision rounds. For instance, in CSMA and CSMA/CD, the first station to access the channel is forced to give up due to other stations who, inadvertently, initiated their transmission attempt at a slightly later time, causing frame collisions. Therefore, in such protocols, and the many variants that followed them, all stations are treated equally and are forced to retry at a later time, which leads to a waste of channel usage and, potentially, more channel contention.

But, what if a "winner" station could be named among a group of colliding stations? How would that be possible using only half-duplex radios with a single antenna? With that goal in mind, we designed CSMA/TA to allow the *last transmitting* station in a group of colliding stations to proceed with its data frame transmission, i.e., to implement the idea of the "last standing station always wins."

To accomplish the above, a station running CSMA/TA that has a data frame ready for transmission must first perform carrier sensing to check if the channel is clear. If the channel is clear, the station transmits a *pilot* packet that is common to every station participating in the network. The duration γ of a pilot must be greater than twice the maximum propagation delay τ in the WLAN. Once the transmission of the pilot is over, the sending station must simply *wait* for a period of time *equal to the propagation delay* τ. After waiting for τ seconds, the station executes carrier sensing again. If the channel is sensed to be idle, the station claims to have "acquired its right for transmission," and it immediately proceeds with the transmission of its data frame. Otherwise, if the channel is sensed to be busy, the station must refrain from transmitting its data frame and, consequently, must reschedule its transmission to a future time according to some contention resolution algorithm, such as a back-off algorithm.

To illustrate the basic design idea in CSMA/TA, consider the case of three stations A, B, and C that are exactly within τ seconds from each other, as depicted in Figure 1. Station A senses the channel and finds it to be idle at time instant t_0; therefore, it initiates the transmission of its pilot of duration γ seconds. However, before A's pilot signal reaches stations B and C, i.e., before τ seconds elapse, stations B and C sense the channel at time instants t_B and t_C, respectively, and perceive the channel to be idle as well. Consequently, both stations B and C start transmitting their own pilots at $t_B, t_C \in (t_0, t_0+\tau]$. Once all stations complete the transmission of their pilots, they must all *wait* for τ seconds before sensing the channel again.

In this scenario, both A and B will refrain from transmitting their data frames because they will sense the channel busy after the waiting period of τ seconds. In the case of A, it will detect the presence of the pilots from both B and C, while B will detect the presence of the pilot from C, as indicated in the figure. Therefore, only station C will sense an idle channel after the waiting period of τ seconds, because it is the *last station who transmitted a pilot*. Consequently, C claims that it has *acquired the right to transmit its data frame*, and proceeds to transmit without collisions.

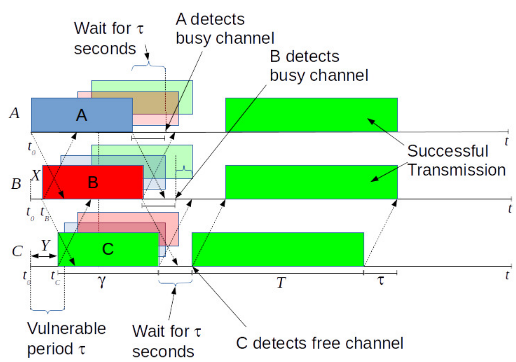

Fig. 1. CSMA/TA example with negligible turnaround latencies

More generally, if n stations initiate their pilot transmissions at *different* time instants in the interval $(t_0, t_0+\tau]$, where t_0 is the time instant where a reference station has first initiated its transmission, and assuming that $t_0 < t_1 < \ldots < t_{n-1} < t_n < t_0 + \tau$, where t_i is the time instant of the i-th pilot transmission then, after waiting for τ seconds after the end of their specific pilot transmission, only the n-th station *acquires the right for transmission*, while all other stations refrain from transmitting their data frames.

Unfortunately, the "wait for τ seconds before transmit" rule may not work if the transmit-to-receive (TX/RX) and the receive-to-transmit (RX/TX) turnaround times of the radios are taken into account. This is especially the case if such latencies are greater than the propagation delay in the WLAN; otherwise, the previous rule is valid. When that is the case, the *vulnerable period* for the occurrence of frame collisions increases, and we need to take that into account. The design of CSMA/TA considers these issues and their impact on the conditions for *transmission acquisition* to occur.

B. Non-negligible RX/TX and TX/RX Turnaround Times

To understand the impact of turnaround times on the operation of CSMA/TA and on the extension of the vulnerability periods surrounding any frame transmission, we go over another simple example. Let us assume that, at time instant t_0, a node A senses the channel, which means that its radio interface is in a state equivalent to a "receive" state. Let us also assume that node A perceives an idle channel at this same time instant, and immediately *starts the procedure* to initiate the transmission of its pilot. Before the pilot is actually transmitted, however, an *RX/TX turnaround time* of duration ε_1 seconds is incurred by the radio interface, followed by the pilot transmission itself, which lasts γ seconds. Once the pilot transmission is over, and following the CSMA/TA design, the station has to switch its radio interface to the *receive state* in order to sense the channel again. This incurs a *TX/RX turnaround time* that lasts ε_2 seconds, which is assumed to be greater than or equal to τ. Because of that, the rule of "wait for τ seconds before sensing the channel again" must be replaced by "wait for the TX/RX turnaround to finish." Then, all that is required is to *immediately sense the channel once the TX/RX turnaround time ε_2 is over*. Notice that, if $\varepsilon_2 < \tau$, we have a scenario that is equivalent to the rule of "wait for τ seconds before sensing the channel again."

Once station A switches to the receive mode, it senses the channel instantaneously. It is assumed that processing delays for carrier sensing or collision detection are negligible. If the channel is sensed to be idle again, the station may start the procedure to transmit a data frame, which will require an *additional RX/TX turnaround time* of duration ε_1, followed by the transmission of the data frame itself, which lasts T seconds. Finally, τ seconds are required for the complete data frame to reach every other node in the network. Figure 2 shows the time intervals incurred in the successful transmission of a data frame when no other station transmits.

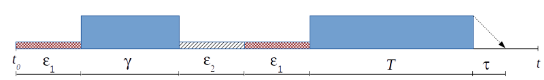

Fig. 2. Time diagram of a successful transmission of a data frame, including all time intervals involved in the process: RX/TX turnaround time ε_1, pilot duration γ, TX/RX turnaround time ε_2, RX/TX turnaround time ε_1, data frame T, and the propagation delay τ for the data frame to be received by all stations in the network completely.

In the previous scenario, a time interval of length $\varepsilon_1 + \tau$ seconds occurs from the instant when station A decides to transmit a pilot to the instant when that pilot first reaches the other nodes in the network (i.e., after a propagation delay). Hence, considering just another station B that has a data frame ready to be sent, and if it senses the channel at any time during the interval $(t_0, t_0 + \varepsilon_1 + \tau]$, station B will perceive an idle channel because A's pilot will not reach station B until the instant $t_0 + \varepsilon_1 + \tau$. Thus, the actual *vulnerability period*, i.e., the time interval during which stations can transmit without noticing other transmissions over the channel, *increases* from τ to $\tau+\varepsilon_1$ seconds. Then, depending on the time instant when station B starts transmitting its pilot, its signal may arrive at A while A is *still switching from transmit to receive mode*, as shown in Figure 3. If this happens, then when A finally switches to the receive mode, *it will perceive an idle channel* similarly to B, in the end of its TX/RX turnaround time. In this case, both nodes will "claim their right to transmit" their data frames, and their frames will collide. Therefore, when the radio's turnaround times are taken into account, collisions may happen with the proposed CSMA/TA rule. Nonetheless, rather than insisting on the idea of having a successful station on *every group* of colliding stations, we will look at the conditions for the *likelihood of having a successful station* within a colliding group.

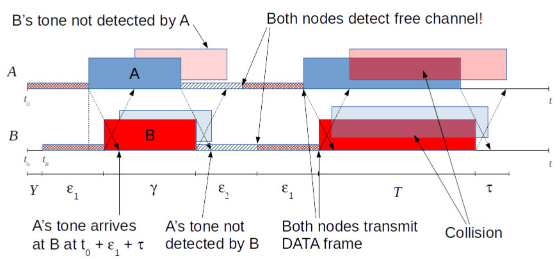

Fig. 3. Example showing transmission acquisition failing: Station A cannot perceive B's frame on the channel because, after finishing its own transmission, there is an extra time interval due to the TX/RX turnaround time before it can actually sense the channel. By the time the TX/RX turnaround time is over, the channel is clear. The same happens to B, and both A and B detect a free channel, which leads to the collision of data frames.

Let us explore the conditions for having station B successfully transmitting a data frame, i.e., to have station A refraining from transmitting its data frame, as in the "ideal" case. Let Y denote the length of the time interval between t_0 and the time instant when node B senses the channel and decides to transmit its pilot, i.e., its RX/TX turnaround time begins, as shown in Figure 4. In order for B to successfully acquire its right for transmission, node A must listen to the end of B's pilot (at least) when A's TX/RX turnaround time is over. This condition is depicted in Figure 4 when station A detects a busy channel.

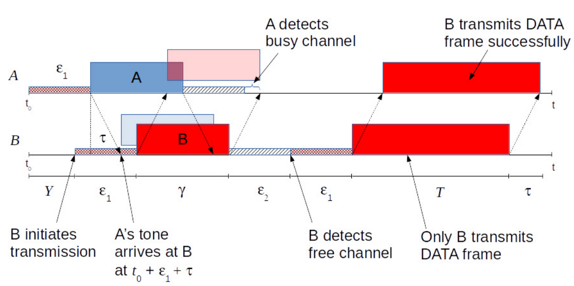

Fig. 4. Example of successful transmission acquisition. The time instant when B switches to transmit mode is such that the end of its pilot is sensed by the end of station A's TX/RX turnaround time.

Based on the above argument, the following inequality relating the relevant time intervals in the process must be always satisfied in order for A to refrain from transmitting its data frame and, consequently, have station B acquiring the channel for its data frame transmission without collision:

$$Y + \varepsilon_1 + \gamma + \tau > \varepsilon_1 + \gamma + \varepsilon_2 \;\Rightarrow\; Y > \varepsilon_2 - \tau, \quad (1)$$

i.e., as long as Y is greater than $\varepsilon_2 - \tau$, station A is able to detect station B's pilot and refrains from transmitting its data frame. At the same time, if $Y > \varepsilon_1 + \tau$, station B detects A's pilot, and defers its transmission. Therefore, the length of the time interval Y that allows station B to acquire the channel successfully is bounded as follows:

$$\varepsilon_2 - \tau < Y \leq \varepsilon_1 + \tau. \quad (2)$$

It follows from (2) that the RX/TX turnaround time ε_1 must be related to the TX/RX turnaround time ε_2 by

$$\varepsilon_1 > \varepsilon_2 - 2\tau, \text{ and } \varepsilon_1 \geq 0. \quad (3)$$

If $\varepsilon_2 = \tau$, i.e., in the ideal case when there is no TX/RX turnaround time and the station has to wait for τ seconds before checking the channel again, the above inequality is satisfied with $\varepsilon_1 = 0$, i.e., when no RX/TX turnaround time is considered. This is exactly the scenario discussed in Section III-A.

Now, let us assume that $n \geq 1$ stations start their transmission procedures after a station A starts its transmission procedure at t_0, i.e., all stations start their transmission procedures in the interval $(t_0, t_0 + \varepsilon_1 + \tau]$, with the beginning of their RX/TX turnaround times at instants denoted by $t_1 < t_2 < \cdots < t_{n-1} < t_n$. Many scenarios are possible in this case. One such scenario is depicted in Figure 5, which shows three nodes A, B, and C starting their pilots at time instants t_0, t_B, and t_C, respectively. Assume that $X = t_B - t_0 > \varepsilon_2 - \tau$, and $Y = t_C - t_B < \varepsilon_2 - \tau$. So, in spite of having B initiating its transmission procedure at an instant that is distant apart from t_0 by more than $\varepsilon_2 - \tau$, station C starts its RX/TX turnaround time at an instant that does not follow the inequality *with respect to the last station that has initiated a transmission*, i.e, station B. As a result, stations B and C will perceive an *idle channel* at the end of their TX/RX turnaround time, and they will incur a collision of their data frames, as shown below.

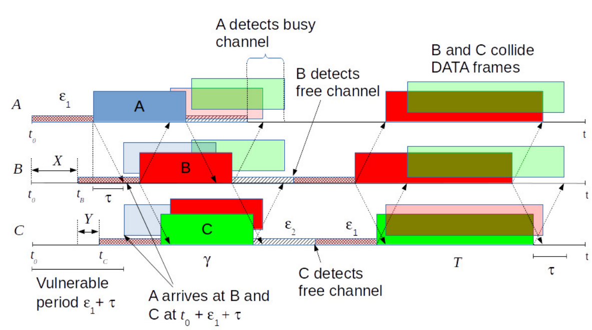

Fig. 5. CSMA/TA example with non-negligible turnaround times

Consider now the case when station C starts its transmission procedure at an instant t_C that is $\varepsilon_2 - \tau$ seconds apart from t_B, i.e., $t_C - t_B > \varepsilon_2 - \tau$. In this case, stations A and B will detect a busy channel, for sure, in the end of their TX/RX turnaround times, and they will defer their data frame transmissions. In this case, station C will *acquire the right for transmission*, and will transmit a data frame without collision, as it is shown in Figure 6.

It is important to notice that it is not enough to have *any* transmission initiation procedures apart from each other by $\varepsilon_2 - \tau$, but only the last and the next-to-the-last initiation procedures. Figure 5 clearly showed this situation, where A

and B are distant apart from each other by more than $\varepsilon_2 - \tau$ seconds, but B and C are not. In that case, B and C detected a free channel and collided.

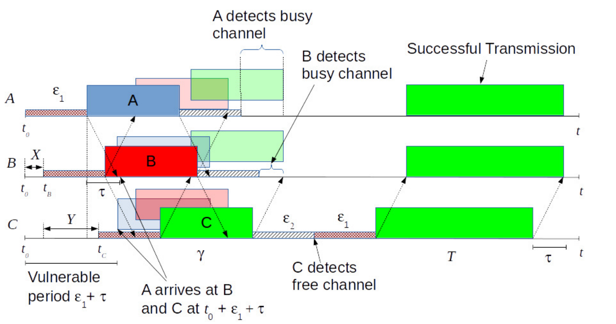

Fig. 6. Example of successful transmission acquisition when three stations compete for the channel. Station C is the last station to start its transmission procedures, and the time instant t_C is distant from the next-to-the-last station B by more than $\varepsilon_2 - \tau$ seconds. As a consequence, it acquires the channel.

Figure 7 shows a time diagram where the arrows indicate the time instants of transmission procedures of n stations within the time interval $(t_0, t_0 + \varepsilon_1 + \tau]$. In this case, the last time instant t_n must be such that $t_n - t_{n-1} > \varepsilon_2 - \tau$. Under such conditions, station n successfully acquires the channel.

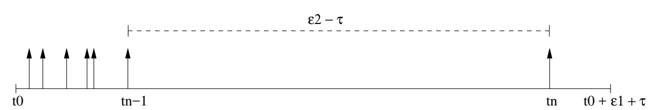

Fig. 7. Time instants of transmission procedures of n stations

IV. Throughput Analysis

We derive the normalized throughput of CSMA/TA for fully-connected networks under ideal channel conditions, and consider the impact of the RX/TX and TX/RX turnaround times. The performance of CSMA/TA is compared with non-persistent CSMA (with and without turnaround times), and CSMA/CD, which does not have turnaround times given that it requires full-duplex radios. We focus on the non-persistent versions of CSMA/TA, CSMA, and CSMA/CD using the traffic model first introduced by Kleinrock and Tobagi [2]. In this analysis, we do not consider the use of priority acknowlegdments (ACKs), because we are only concerned with errors due to multiple access interference.

According to our model, there is a large number of stations that constitute a Poisson source sending data packets to the the channel with an aggregate mean generation rate of g packets per unit time (i.e., new and retransmitted packets). Each node is assumed to have at most one data packet to be sent at any time, which results from the MAC layer having to submit one packet for transmission before accepting the next packet. A node retransmits after a random retransmission delay that, on the average, is much larger than the time needed for a successful transaction between a transmitter and a receiver and such that all transmissions can be assumed to be independent of one another. The channel is assumed to introduce no errors, so multiple access interference (MAI) is the only source of errors. Nodes are assumed to detect carrier perfectly.

We assume that two or more transmissions that overlap in time in the channel must all be retransmitted (i.e., there is no power capture by any transmission), and that any packet propagates to all nodes in exactly τ seconds. The RX/TX and TX/RX turnaround times at each radio interface are ε_1 and ε_2, respectively, and are assumed to be larger than or equal to the propagation delay τ, which agrees with the parameters assumed in IEEE 802.11 DCF. The transmission time of a data packet is T. For the case of CSMA/CD, the time of a jamming bit sequence is J, which is larger than the error-checking field of a packet (e.g., 48 bits). We assume that processing delays are negligible, which includes the time to detect carrier or do collision detection. The protocols are assumed to operate in steady state, with no possibility of collapse, and hence the average channel utilization of the channel is given by [2]

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}}, \tag{4}$$

where $\overline{B}$ is the expected duration of a busy period, defined to be a period of time during which the channel is being utilized; $\overline{I}$ is the expected duration of an idle period, defined as the time interval between two consecutive busy periods; and $\overline{U}$ is the time during a busy period that the channel is used for transmitting user data successfully.

A. Non-Persistent CSMA/TA

Theorem: The throughput of non-persistent CSMA/TA is

$$S = \frac{T e^{-g(\varepsilon_2 - \tau)}}{\frac{1}{g} + 3\varepsilon_1 + 2\tau + \gamma + \varepsilon_2 + T - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1 + \tau)}\right]^2 + K}, \tag{5}$$

where $K = -(\varepsilon_1 + \tau) e^{-g(\varepsilon_1 + \varepsilon_2)}$.

Proof: Based on the discussion in Section III-B, event E, which denotes successful transmission acquisition, can be described by the union of two mutually exclusive events as follows:

$$E = \{\{\text{no transmissions} \in [t_0, t_0 + \varepsilon_1 + \tau]\} \cup \{\{\text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau]\} \cap \{t_n - t_{n-1} > \varepsilon_2 - \tau\}\}\}, \tag{6}$$

where the event $t_n - t_{n-1} > \varepsilon_2 - \tau$ requires that the interval between the last and next-to-the-last transmission attempt must be greater than $\varepsilon_2 - \tau$. Hence, the probability P_{suc} of *successful transmission acquisition* is given by

$$P_{suc} = P\{E\} = P\{\text{no transmissions} \in [t_0, t_0 + \varepsilon_1 + \tau]\} + P\{\{\text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau]\} \cap \{t_n - t_{n-1} > \varepsilon_2 - \tau\}\}, \tag{7}$$

where, due to our Poisson assumptions,

$$P\{\text{no transmissions} \in [t_0, t_0 + \varepsilon_1 + \tau]\} = e^{-g(\varepsilon_1 + \tau)}. \tag{8}$$

The second probability in (7) can be written as

$$P\{\text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau] \cap t_n - t_{n-1} > \varepsilon_2 - \tau\} = = P\{t_n - t_{n-1} > \varepsilon_2 - \tau \mid \text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau]\} \times \times P\{\text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau]\}, \tag{9}$$

where

$$P\{\text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau]\} = 1 - e^{-g(\varepsilon_1 + \tau)}. \tag{10}$$

To simplify notation, let $A = \{\text{some trans.} \in [t_0, t_0 + \varepsilon_1 + \tau]\}$. Then, for the conditional probability in (9) we use total probability to get

$$\begin{aligned} &P\{t_n - t_{n-1} > \varepsilon_2 - \tau \,|A\} = \\ &= \sum_{n=1}^{\infty} P\{t_n - t_{n-1} > \varepsilon_2 - \tau, N = n|A\} \\ &= \sum_{n=1}^{\infty} P\{t_n - t_{n-1} > \varepsilon_2 - \tau|N = n, A\} P\{N = n|A\}, \quad (11) \end{aligned}$$

where N is the number of transmission attempts initiated in $(t_0, t_0 + \varepsilon_1 + \tau]$. Using Bayes' rule,

$$\begin{aligned} P\{N = n|A\} &= \frac{P\{N = n, A\}}{P\{A\}} = \frac{P\{A|N = n\}P\{N = n\}}{P\{A\}} \\ &= \frac{P\{A|N = n\}[g(\varepsilon_1 + \tau)]^n e^{-g(\varepsilon_1+\tau)}}{[1 - e^{-g(\varepsilon_1+\tau)}]n!}, \quad (12) \end{aligned}$$

which leads to

$$P\{N = n|A\} = \begin{cases} 0, & \text{if } N = 0 \\ \frac{[g(\varepsilon_1+\tau)]^n e^{-g(\varepsilon_1+\tau)}}{[1-e^{-g(\varepsilon_1+\tau)}]n!}, & \text{if } N > 0, \end{cases} \quad (13)$$

because $P\{A|N = n\} = 1$ if $N > 0$. From (11), we need to compute $P\{t_n - t_{n-1} > \varepsilon_2 - \tau|N = n, A\}$. For a Poisson process, the conditional probability density function of the first n count times, $T_1, T_2, \ldots, T_n$, given $\{N_{\Delta T} = n\}$, i.e., given that $N = n$ time instants have occurred in a given time interval ΔT, is given by [15]

$$f(t_1, t_2, \ldots, t_n|N = n) = \frac{n!}{(\Delta T)^n}, \quad (14)$$

if $0 < t_1 < \cdots < t_n < \Delta T$, and 0 elsewhere, where ΔT is the length of the time interval of interest, i.e., in our case, $\Delta T = \varepsilon_1 + \tau$. Using this fact, and since $0 < t_1 < t_2 < \cdots < t_{n-1} < t_n$, it can be shown that

$$\begin{aligned} &P\{t_n - t_{n-1} > \varepsilon_2 - \tau|N = n, A\} = \\ &= \int_{\varepsilon_2-\tau}^{\varepsilon_1-\tau} \int_0^{t_n-\varepsilon_2+\tau} \int_0^{t_{n-1}} \cdots \int_0^{t_2} \frac{n!}{(\Delta T)^n} dt_1 \ldots dt_{t_{n-1}} dt_{t_n} \\ &= \left[\frac{\varepsilon_1 - \varepsilon_2 + 2\tau}{\varepsilon_1 + \tau}\right]^n. \quad (15) \end{aligned}$$

Substituting (15), (13), (11), (10), and (8) into (7), we have

$$\begin{aligned} P_{suc} &= e^{-g(\varepsilon_1+\tau)} + [1 - e^{-g(\varepsilon_1+\tau)}] \sum_{n=1}^{\infty} \frac{[(\varepsilon_1 - \varepsilon_2) + 2\tau]^n}{(\varepsilon_1 + \tau)^n} \times \\ &\times \frac{[g^n(\varepsilon_1 + \tau)^n]e^{-g(\varepsilon_1+\tau)}}{[1 - e^{-g(\varepsilon_1+\tau)}]n!} \\ &= e^{-g(\varepsilon_1+\tau)} + e^{-g(\varepsilon_2-\tau)} \sum_{n=1}^{\infty} \frac{[g(\varepsilon_1-\varepsilon_2+2\tau)]^n}{n!} e^{-g(\varepsilon_1-\varepsilon_2+2\tau)} \\ &= e^{-g(\varepsilon_1+\tau)} + e^{-g(\varepsilon_2-\tau)} [1 - P\{N = 0 \text{ in } (\varepsilon_1 - \varepsilon_2 + 2\tau)\}] \\ &= \underbrace{e^{-g(\varepsilon_1+\tau)}}_{\text{no transmission in } [t_0, t_0 + \varepsilon_1 + \tau]} + \underbrace{e^{-g(\varepsilon_2-\tau)}}_{\text{no transmission within } (\varepsilon_2 - \tau) \text{ s}} \\ &\times \underbrace{[1 - e^{-g(\varepsilon_1-\varepsilon_2+2\tau)}]}_{\text{some transmission in the interval of length } (\varepsilon_1 + \tau) - (\varepsilon_2 - \tau)} \quad (16) \end{aligned}$$

Finally,

$$\begin{aligned} P_{suc} &= e^{-g(\varepsilon_1+\tau)} + e^{-g(\varepsilon_2-\tau)} \left[1 - e^{-g(\varepsilon_1-\varepsilon_2+2\tau)}\right] \\ &= e^{-g(\varepsilon_2-\tau)}, \quad (17) \end{aligned}$$

which reduces to the fact that a successful transmission acquisition happens if the *last station* to transmit in $(t_0, t_0 + \varepsilon_1 + \tau]$ starts its transmission procedures within an interval that is at least $\varepsilon_2 - \tau$ seconds away from the next-to-the-last station in the same interval. Note that, if $\varepsilon_2 = \tau$, then $P_{suc} = 1$, regardless of the value of the propagation delay τ and the RX/TX turnaround time ε_1. Later, we will show that CSMA/TA has an *effective vulnerable period* that is $\varepsilon_1 - \varepsilon_2 + 2\tau$ seconds *smaller than Nonpersistent CSMA*, if we take into account the RX/TX turnaround time in CSMA as well. Given the P_{suc}, we can now proceed with the evaluation of $\overline{U}$, $\overline{B}$, and $\overline{I}$.

1) Average Busy Period: For the average busy period $\overline{B} = E[B]$, two events can happen: either a successful data frame transmission happens or a collision occurs. Therefore,

$$E[B] = E[B|\text{success}]P\{\text{success}\} + E[B|\text{fail}]P\{\text{fail}\}. \quad (18)$$

In the case of success, we need to consider the cases where either no one transmits in $[t_0, t_0 + \varepsilon_1 + \tau]$ (i.e., $N = 0$), or one or more stations transmit in $[t_0, t_0 + \varepsilon_1 + \tau]$ (i.e., $N > 0$), which leads to

$$\begin{aligned} E[B|\text{success}] &= E[B|\text{success}, N = 0]P\{N = 0\}+ \\ &+ E[B|\text{success}, N > 0]P\{N > 0\}. \quad (19) \end{aligned}$$

For the first conditional probability, we have

$$\begin{aligned} E[B|\text{success}, N = 0] &= \varepsilon_1 + \gamma + \varepsilon_2 + \varepsilon_1 + T + \tau \\ &= 2\varepsilon_1 + \gamma + \varepsilon_2 + T + \tau, \quad (20) \end{aligned}$$

while for the case $N > 0$ we have

$$\begin{aligned} &E[B|\text{success}, N > 0] = \\ &= E[Y + \varepsilon_1 + \gamma + \varepsilon_2 + \varepsilon_1 + T + \tau|\text{success}, N > 0] \\ &= E[Y|\text{success}, N > 0] + 2\varepsilon_1 + \gamma + \varepsilon_2 + T + \tau. \quad (21) \end{aligned}$$

To compute $E[Y|\text{success}, N > 0]$ we need to first notice that, given there is a success, the last node to transmit in the interval $[t_0, t_0 + \varepsilon_1 + \tau]$ must have actually transmitted within the interval $[t_0 + \varepsilon_2 - \tau, t_0 + \varepsilon_1]$, because its transmission procedures must start at least $\varepsilon_2 - \tau$ seconds away from the next-to-the-last node in the interval. Therefore, for the last transmitting node, $\varepsilon_2 - \tau \leq Y \leq \varepsilon_1 + \tau$.

Let $Z = Y - (\varepsilon_2 - \tau)$. Then, $0 \leq Z \leq \varepsilon_1 - \varepsilon_2 + 2\tau$, and we can compute $F_Z(z) = P[Z \leq z]$ by making

$$\begin{aligned} P[Z \leq z] &= P\{\text{no transmission in } [\varepsilon_1 - \varepsilon_2 + 2\tau - z]\} \\ &= e^{-g(\varepsilon_1-\varepsilon_2+2\tau-z)}. \quad (22) \end{aligned}$$

Given that $Z \geq 0$, we can compute $E[Z]$ as follows

$$\begin{aligned} E[Z] &= \int_0^{\infty} [1 - F_Z(z)]dz \\ &= \int_0^{\varepsilon_1-\varepsilon_+2\tau} 1 - e^{-g(\varepsilon_1-\varepsilon_2+2\tau-z)} dz \\ &= \varepsilon_1 - \varepsilon_2 + 2\tau - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1-\varepsilon_2+2\tau)}\right]. \quad (23) \end{aligned}$$

Finally, because $Y = Z + (\varepsilon_2 - \tau)$,

$$E[Y|\text{success}, N > 0] = E[Z] + \varepsilon_2 - \tau$$
$$= \varepsilon_1 + \tau - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1 - \varepsilon_2 + 2\tau)}\right]. \quad (24)$$

Given $E[Y|\text{success}, N > 0]$ we can substitute its value in (21) to compute $E[B|\text{success}, N > 0]$, i.e.,

$$E[B|\text{success}, N > 0] =$$
$$= 3\varepsilon_1 + 2\tau + \gamma + \varepsilon_2 + T - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1 - \varepsilon_2 + 2\tau)}\right]. \quad (25)$$

Hence,

$$\begin{aligned} E[B|\text{success}] &= (2\varepsilon_1 + \gamma + \varepsilon_2 + T + \tau)e^{-g(\varepsilon_1+\tau)} + \\ &+ \left[1 - e^{-g(\varepsilon_1+\tau)}\right]\{3\varepsilon_1 + 2\tau + \gamma + \varepsilon_2 + T - \\ &- \frac{1}{g}\left[1 - e^{-g(\varepsilon_1 - \varepsilon_2 + 2\tau)}\right]\Big\} \\ &= \underbrace{(2\varepsilon_1 + \gamma + \varepsilon_2 + T + \tau)}_{\text{length with no transmission}} + \\ &+ \underbrace{\left\{\varepsilon_1 + \tau - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1 - \varepsilon_2 + 2\tau)}\right]\right\} \times}_{\text{additional length due to some transmission in } [t_0, t_0 + \varepsilon_1 + \tau]} \\ &\times \left[1 - e^{-g(\varepsilon_1+\tau)}\right] \end{aligned} \quad (26)$$

To compute $E[B|\text{fail}]$ we notice that, in this case, the last transmission can happen anywhere in $(t_0, t_0 + \varepsilon_1 + \tau]$, which leads to

$$\begin{aligned} E[B|\text{fail}] &= E[Y + \varepsilon_1 + \gamma + \varepsilon_2 + \varepsilon_1 + T + \tau|\text{fail}] \\ &= E[Y|\text{fail}] + 2\varepsilon_1 + \gamma + \varepsilon_2 + T + \tau. \end{aligned} \quad (27)$$

The computation of $E[Y|\text{fail}]$ can be obtained by first noticing that, in this case, $0 < Y < \varepsilon_1 + \tau$. Therefore, because arrivals are Poisson distributed,

$$\begin{aligned} F_Y(y) &= P\{Y \leq y\} = P\{\text{no transmission in } \varepsilon_1 + \tau - y\} \\ &= e^{-g(\varepsilon_1 + \tau - y)}. \end{aligned} \quad (28)$$

Since Y is a non-negative random variable, we have

$$\begin{aligned} E[Y] &= \int_0^\infty [1 - F_Y(y)]dy = \int_0^{\varepsilon_1+\tau} 1 - e^{-g(\varepsilon_1+\tau-y)}dy \\ &= \varepsilon_1 + \tau - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1+\tau)}\right] \end{aligned} \quad (29)$$

Therefore,

$$E[B|\text{fail}] = 3\varepsilon_1 + 2\tau + \gamma + \varepsilon_2 + T - \frac{1}{g}\left[1 - e^{-g(\varepsilon_1+\tau)}\right]. \quad (30)$$

Finally, the average busy time $E[B]$ is given by

$$\begin{aligned} \overline{B} &= 3\varepsilon_1 + 2\tau + \gamma + \varepsilon_2 + T - (\varepsilon_1 + \tau)e^{-g(\varepsilon_1+\varepsilon_2)} - \\ &- \frac{1}{g}\left[1 - e^{-g(\varepsilon_1+\tau)}\right]^2. \end{aligned} \quad (31)$$

2) Average Idle Period ($\overline{I}$): The average length of an idle period I is simply the average inter-arrival time of packets, which are preceded by pilot transmissions, and this equals $1/g$ because inter-arrival times are exponentially distributed with parameter g.

3) Average Successful Busy Period: The average time period used to transmit useful data $\overline{U}$ is simply the useful portion of a successful busy period, which occurs with probability $P_{suc} = e^{-g(\varepsilon_2 - \tau)}$.

Substituting the values of $\overline{U}$, $\overline{B}$, and $\overline{I}$ into (4) we obtain (5). □

Usually, it is more convenient to work with normalized values in the computation of the average throughput. Hence, if we normalize all time intervals with respect to the data frame transmission time T, i.e., if we make $a = \tau/T$, $b = \varepsilon_1/T$, $c = \varepsilon_2/T$, $d = \gamma/T$, and $G = gT$, then (5) becomes

$$S = \frac{Ge^{-G(c-a)}}{1 + (1 + 2a + 3b + c + d)G - \left[1 - e^{-(a+b)G}\right]^2 + K}, \quad (32)$$

where $K = -(a+b)Ge^{-(b+c)G}$. One special case of interest is the "ideal case," i.e., when $\varepsilon_1 = 0$ and $\varepsilon_2 = \tau$, i.e., $b = 0$ and $c = a$, which refers to the case when there are no turnaround times, and the rule "wait for τ" is employed. In this case,

$$S = \frac{G}{1 + (1 + 3a + d)G - [1 - e^{-aG}]^2 - aGe^{-aG}}. \quad (33)$$

B. Non-Persistent CSMA

The throughput for non-persistent CSMA is well-known [2]. If the RX/TX turnaround time is considered, however, the vulnerable period of CSMA increases to $\varepsilon_1 + \tau$. Therefore, if the ACKs are assumed to be received instantaneously through an ideal secondary channel, the normalized throughput becomes

$$S = \frac{Ge^{-(a+b)G}}{1 + [2(a+b) + 1]G - [1 - e^{-(a+b)G}]^2 - K}, \quad (34)$$

where $K = (a + b)Ge^{-(a+b)G}$ and $b = \varepsilon_1/T$. Note that, if we consider the RX/TX turnaround time, the successful probability of CSMA considers an interval $\varepsilon_1 + \tau$ (or $a + b$) that is 2τ seconds bigger than the interval of CSMA/TA, which is $\varepsilon_2 - \tau$ (or $b - a$) in the case when $\varepsilon_1 = \varepsilon_2$. In other words, the successful probability of CSMA decays faster than CSMA/TA for non-negligible turnaround times.

C. Non-Persistent CSMA/CD

The throughput of non-persistent CSMA/CD under the previous assumption of instantaneous ACKs can be easily derived (see [16] without considering priority ACKs). There are no turnaround times in CSMA/CD because the stations can sense the channel while transmitting. Hence, if J denotes the jamming signal time duration, and $h = J/T$, then the normalized throughput is given by

$$S = \frac{Ge^{-aG}}{2 + (2a + h)G + Ge^{-aG}(1 - a - h - 1/G)}. \quad (35)$$

V. Numerical Results

We compare the performance of CSMA/TA with CSMA and CSMA/CD by considering different scenarios in terms of the data rate R, the transmission range r, and the packet size L. We assume that the TX/RX and RX/TX turnaround times are equal ($\varepsilon_1 = \varepsilon_2 = \varepsilon$) and fixed at 2μs. The CSMA/TA pilot signal is set to three times the propagation delay τ in every case, while the jamming signal of CSMA/CD has the same time duration J as its counterpart in Ethernet, i.e., 48-bit time, which favors CSMA/CD when propagation delays are longer.

The scenarios depict cases when the propagation delay is smaller than the turnaround times. Therefore, the modifier "ideal" in the graphs correspond to turnaround times that are smaller than the propagation delay, which we take into account by assuming a turnaround time of 0 for ideal CSMA/TA and CSMA. Such results (shown in dashed lines) are included to understand the impact of turnaround times on CSMA and CSMA/TA. We remind the reader that, if the propagation delay is *greater* than the turnaround times, CSMA/TA operates according to the *ideal* case, while CSMA still suffers the impact of the turnaround times. Hence, in long-haul coverage scenarios with propagation delays larger than or equal to 2μs, CSMA/TA would perform just as the "ideal CSMA/TA."

Figure 8 shows the results when $L = 1500$ bytes, $R = 1$ Mb/s and $r = 100$ m. In this case, the turnaround time $\varepsilon = 6\tau$. It is clear that *ideal* CSMA/TA achieves the best throughput, which increases monotonically to a value very close to 1.0 as the offered load G increases without bound (i.e., by taking the limit $G \to \infty$ in (33)). This behavior is in stark contrast to CSMA/CD and ideal CSMA, whose throughput values collapse as G increases, due to higher chances of frame collisions. If we consider the turnaround times, CSMA/TA performs slightly better than CSMA (solid lines), while CSMA/CD surpasses both of them. It is interesting to observe that, with turnaround times, the range of G values over which CSMA has non-zero throughput is almost an order of magnitude smaller than in the ideal case.

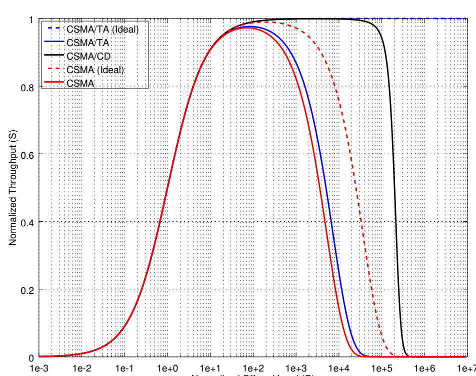

Fig. 8. S vs. G for $L = 1500$ bytes, $R = 1$ Mb/s, and $r = 100$ m.

Figure 9 shows the results when $L = 1500$ bytes, $R = 1$ Mb/s, and a turnaround time that is just 1% above the propagation delay, i.e., $\varepsilon = 1.01\tau$, which gives us $r = 594.06$ m. We can observe the great advantage of non-ideal CSMA/TA, whose throughput values not only match, but also surpass CSMA/CD at high loads. The results indicate that CSMA/TA can, in practice, accommodate a large number of devices that collectively generate a high traffic load (e.g., IoT scenarios). In this scenario, the likelihood of having a transmission acquisition within a group of colliding stations is high, as opposed to CSMA and CSMA/CD, who always force the whole group of colliding stations to retransmit in a future time.

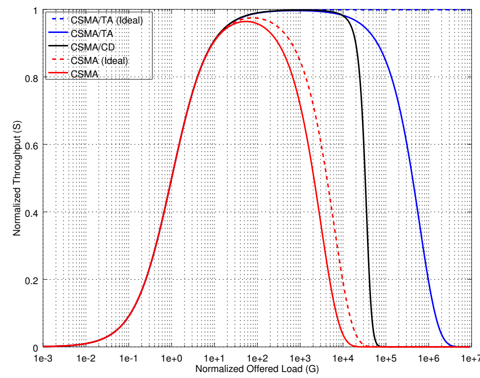

Fig. 9. S vs. G for $L = 1500$ bytes, $R = 1$ Mb/s, and $r = 594.06$ m.

Figure 10 shows the results for a data rate of 300 Mb/s with $L = 1500$ bytes, and an 100-m range. The performance of any protocol based on carrier sensing degrades as the ratio $a = \tau/T$ increases. Hence, the impact of the turnaround time is significant on both CSMA and CSMA/TA, and they achieve a maximum normalized throughput of about 0.6 and allow a much smaller range of traffic-load values, compared to the results of Figure 8. Here, the range of viable traffic-load values decreases by more than two orders of magnitude. We also notice that CSMA/TA performs slightly better than CSMA at high loads.

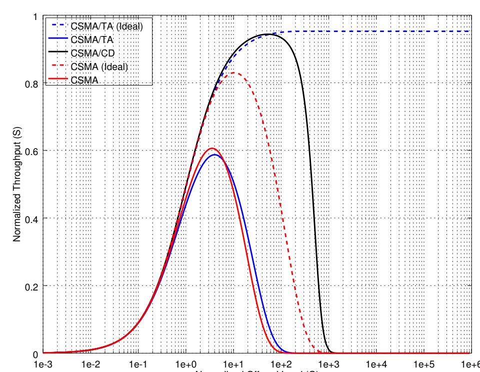

Fig. 10. S vs. G for $L = 1500$ bytes, $R = 300$ Mb/s, and $r = 100$ m.

Figure 11 shows the results for a data rate of 300 Mb/s, $L = 1500$ bytes, and a transmission range $r = 594.06$ m, i.e., $\varepsilon = 1.01\tau$. In this case, the maximum throughput of CSMA/TA is 0.68, which is 32% higher than the maximum throughput of CSMA, but just 8% smaller than CSMA/CD. At higher data rates, the overhead due to the pilot signal of CSMA/TA becomes more significant. In spite of that, CSMA/TA maintains throughput values above 0.6 for a wider range of traffic loads compared to CSMA/CD.

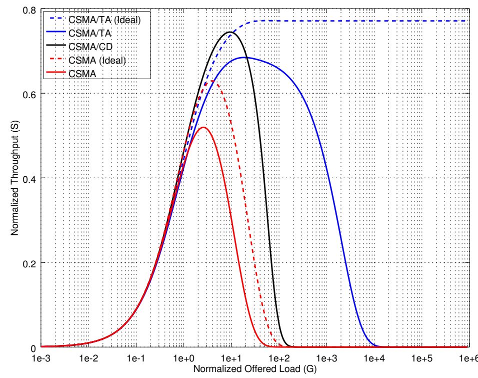

Fig. 11. S vs. G for $L = 1500$ bytes, $R = 300$ Mb/s, and $r = 594.06$ m.

Figure 12 shows the results for $r = 100$ m ($\varepsilon = 6\tau$) and Figure 13 shows the results for $r = 594.06$ m ($\varepsilon = 1.01\tau$) when $L = 100$ bytes and $R = 1$ Mb/s. These results can be related to Figures 8 and 9, respectively, since they have the same general behavior, except for the fact that the range of traffic-load values over which the throughput is non-zero is smaller by more than an order of magnitude across all protocols, and there is a slight decrease in the maximum throughput values due to the small packet size. The cases for $L = 100$ bytes and $R = 300$ Mb/s are not shown due to lack of space, but all protocols have the same general behavior shown in Figures 10 and 11, and perform poorly due to the high τ/T ratio.

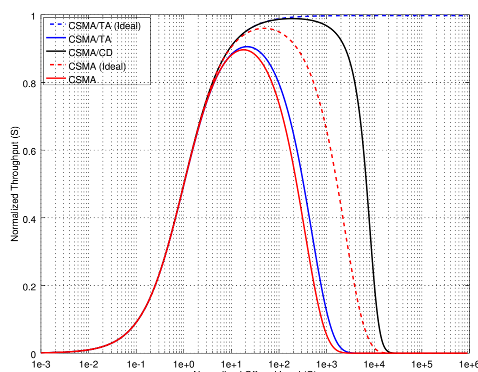

Fig. 12. S vs. G for $L = 100$ bytes, $R = 1$ Mb/s, and $r = 100$ m.

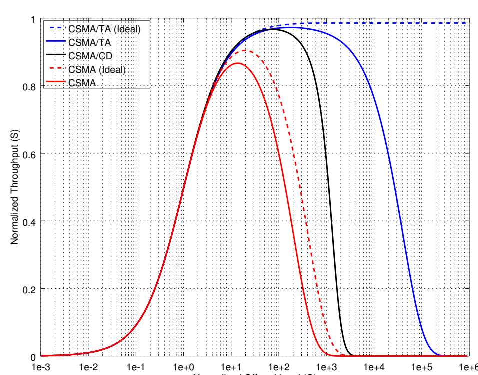

Fig. 13. S vs. G for $L = 100$ bytes, $R = 1$ Mb/s, and $r = 594.06$ m.

VI. Conclusions

We introduced Carrier-Sense Multiple Access with Transmission Acquisition (CSMA/TA) as an extension of CSMA for stations using half-duplex radios with a single antenna. CSMA/TA seeks to increase the likelihood of having a successful transmitting station among a group of colliding stations. It was shown that CSMA/TA can perform better than CSMA and CSMA/CD (which would require using full-duplex radios in WLANs) if the radio's turnaround times are close to the propagation delay. This is a very promising result, because the chipsets available in the market today and in the near future are such that turnaround times are being reduced dramatically. Given that half-duplex radios with much faster turnaround times are much cheaper than full-duplex radios, this makes CSMA/TA an attractive approach for future WLANs compared to traditional CSMA. Our future work addresses the embedding of CSMA/TA as part of the IEEE 802.11 standard for WLANs.

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