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Author
Garcia-Luna-Aceves, J.J.

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Design and Analysis of CSMA/CAD

J.J. Garcia-Luna-Aceves
Computer Engineering Department
UC Santa Cruz, Santa Cruz, CA 95064
jj@soe.ucsc.edu

Abstract—Carrier-Sense Multiple Access with Collision Avoidance and Detection (CSMA/CAD) is introduced and analyzed. The new protocol operates in a single channel and consists of taking advantage of self-interference cancellation to enable collision detection (CD) in the context of collision-avoidance (CA) handshakes in multi-hop wireless networks. It is shown that CSMA/CAD eliminates the collisions of data packets in the presence of hidden terminals. The throughput of CSMA/CAD is analyzed and compared with the throughput of CSMA, CSMA/CA, and dual busy-tone multiple access (DBTMA). The analysis results show that CSMA/CAD provides better performance than the other channel-access schemes aimed at combating hidden terminals, and that the throughput degradation due to hidden terminals in CSMA/CAD is limited compared to CSMA.

I. INTRODUCTION

Wireless networks have become an integral component of the Internet, and single-hop and multi-hop wireless networks have become pervasive. Carrier-sense multiple access (CSMA) [15] is arguably the most widely used method for the sharing of radio channels in wireless local-area networks or ad-hoc networks in which wireless nodes establish a network without the need for centralized control or preexisting infrastructure. CSMA provides far better throughput than ALOHA [1] when all nodes sharing a common channel can hear one another. However, the performance of CSMA quickly degrades in the presence of hidden terminals [20] and as a result many approaches have been proposed and implemented to address the performance problems of CSMA in ad-hoc networks.
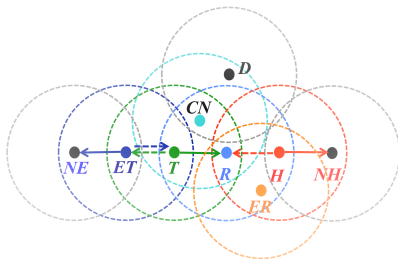

Fig. 1. Hidden and exposed terminals in CSMA with ACKs

Figure 1 illustrates some of the hidden- and exposed-terminal problems in CSMA with ACKs, which are more complex than the problems found when no ACKs are used. In the example, node T transmits to node R and its transmission is also received by node ET and CN. Node H transmits to node NH and its transmission is also received by node R. Even if node T listens to the channel before transmitting,

it cannot detect any carrier produced by the transmission of node H, which is a *hidden terminal* from the standpoint of node T. As a result, the transmissions from T and H collide at node R. On the other hand, node ET is forced to back off if it senses carrier in the channel before transmission as a result of the transmission from node T, even though its transmission to node NE would not be affected. Node ET is an *exposed terminal* from the standpoint of node T. Using acknowledgments (ACK) from receivers to transmitters makes these problems even worse. For example, for T to receive the ACK from R without interference, node ET must back off for the duration of the exchange between T and R, and ACKs from node ER may interfere the reception of data packets at node R.

Section II provides a review of prior work aimed at reducing or eliminating the negative effects of hidden terminals on contention-based channel access. This work has assumed that nodes are endowed with half-duplex radios, and has focused on the use of busy tones (e.g., [20], [12]) and collision-avoidance (CA) handshakes between transmitters and receivers over a single channel (e.g., [5], [14], [8], [10]). Recently, however, the feasibility of self-interference cancellation (SIC) techniques at the physical layer [13] has opened up the possibility of using collision detection in ad-hoc networks. However, as our review of prior work reveals [19], few proposals exist on how to take advantage of SIC at the medium-access control (MAC) layer.

The main contribution of this paper is the introduction, verification, and analysis of **CSMA/CAD** (*Carrier-Sense Multiple Access with Collisions Avoidance and Detection*).

Section III describes CSMA/CAD, which combines collision-avoidance (CA) handshakes aimed at eliminating hidden-terminal problems with collision detection (CD) enabled by SIC and aimed at reducing the negative effects of signaling packets colliding at receivers due to inevitable propagation delays.

In contrast to prior proposals focusing on enabling full-duplex exchange of data packets between neighboring nodes, CSMA/CAD simply focuses on making the collision-avoidance handshake much more effective. However, it constitutes a building block for more sophisticated channel-access disciplines enabling full-duplex data exchange between neighboring nodes.

Section IV shows that CSMA/CAD eliminates the collision of data packets with other transmissions even in the presence of hidden terminals.

Sections V to VII analyze the throughput of CSMA/CAD

and compare it against the throughput of previous proposals based on collision avoidance and busy tones. The results show that CSMA/CAD is more efficient than prior solutions, because it reduces the signaling overhead and latencies incurred by nodes in avoiding data-packet collisions compared to collision-avoidance approaches or busy-tone methods.

Section VIII presents our conclusions and proposes future research areas.

II. Related Work

Tobagi and Kleinrock introduced CSMA [15] and were the first to address the hidden-terminal problem present in CSMA [20]. In the presence of hidden terminals, the performance of CSMA degrades to the same performance attained with ALOHA because a transmitter is unable to sense the transmissions from hidden sources.

The Busy-Tone Multiple Access (BTMA) approach proposed by Tobagi and Kleinrock [20] eliminates multiple-access interference around a central receiver. The available channel is partitioned into a data channel and the busy-tone channel. The central receiver, which has radio connectivity with all other nodes in the system, transmits a busy tone over the busy-tone channel as soon as it detects carrier in the data channel resulting from transmissions from any subset of transmitters. This reduces the vulnerability period of a data packet to a time interval proportional to the channel propagation delay and the time needed by the transmitters to detect the busy tone from the central receiver.

Several busy-tone protocols have been proposed, such as RI-BTMA (Receiver-Initiated Busy Tone Multiple Access) [23] and DTBMA (Dual Busy Tone Multiple Access) [12]. In RI-BTMA, the channel is divided into a data channel and a control channel. When the receiver detects the preamble of the transmission by the sender, it transmits its busy tone in the control channel. DBTMA adopts a similar approach but uses two busy tones. The available bandwidth is partitioned into a data channel and two control channels for the transmission of busy tones from transmitters and receivers. A transmitter aborts its transmission if it detects a receiver busy tone or a transmitter busy tone, and the receiver busy tone helps eliminate hidden-terminal interference.

A number of approaches have been proposed based on handshakes between transmitter and receiver using small signaling packets. The basic approach is called *collision avoidance* and has been proposed for wired and wireless networks [5], [14]. Karn proposed Multiple Access with Collision Avoidance (MACA) [14], which consists of a transmitter sending a request-to-send (RTS) packet to an intended receiver and the receiver sending a clear-to-send (CTS) packet if the RTS is successful. MACA does not use carrier sensing and does not perform well in the presence of hidden terminals, even tough the protocol was designed in part to solve that problem. Many variants have been proposed and analyzed since the introduction of these early works on collision avoidance. In some schemes the transmitter initiates the handshake [7], [8], [9] and in others the receiver does [10]. The IEEE 802.11 distributed coordination function (DCF) combines carrier sensing with the RTS-CTS handshake followed by a data packet and an ACK in successful cases.

CSMA with collision detection (CSMA/CD) was introduced as part of the original Ethernet design [16]. With CSMA/CD, a transmitter listens for carrier before transmitting just as in CSMA. If no carrier is found and the transmitter starts a new transmission, it also listens during its own transmission and terminates the transmission upon detecting a collision with other signals in the channel. After a transmitter detects a collision, it sends a jamming signal to inform the rest of the network of the event.

Given that only half-duplex radios have been available in the past, CSMA/CD has not been applied to wireless networks. However, a few proposals have been advanced to emulate CSMA/CD using half-duplex radios. Rom [17] proposed a channel-access protocol similar to non-persistent CSMA 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 (called the collision detection interval or CDI). Unfortunately, this protocol cannot guarantee that data packets will not collide with other transmissions at the receiver [17], and the main reasons of this is the non-negligible transmit-to-receive turn-around times and the possibility that two or more sources transmit roughly at the same time.

FAMA-PJ [6] was proposed to ensure that emulating CSMA/CD prevents data packets from colliding with other transmissions in wireless LANs. It consists of a transmitter sending an RTS if it detects no carrier in the channel, and listening for a period of time after its RTS to check for jamming signals sent by nodes that detected a collision. A node with no packet to send that detects a collision of RTS's based on the characteristics of the waveform it receives sends a jamming signal for a period of time that is long enough to ensure that active transmitters hear the jamming signal once they start listening to the channel after their RTS's are sent. The main limitation of FAMA-PJ and prior CSMA/CD emulation approaches is that making the transmitter pause to detect collisions does not solve the hidden-terminal problem, because collisions happen at the receivers and may be due from transmissions hidden to some sources. Furthermore, FAMA-PJ may result in too many passive nodes sending jamming signals after detecting the collision of RTS packets.

The development of self-interference cancellation (SIC) techniques at the physical layer (e.g., see [3], [13]) opens up the possibility of using communicating radios that can detect interference by comparing their output with the signal they receive, or even operating in full-duplex (FD) mode while accessing a common channel.

A few approaches have already been proposed that take advantage of SIC at the MAC layer, and focus on attaining FD

operation for data exchange. Some proposals aim at exploiting FD operation to allow nodes to transmit concurrently as primary or secondary transmitters and receivers and allow relaying nodes to receive transmissions while forwarding their own [11], [18], [19]. Other proposals [2], [24] focus on the interplay between the up-link and down-link with an access point of a wireless LAN or base stations in 5G wireless networks. The fact that SIC enables a node to implement collision detection has not been fully exploited, and the interplay between collision-avoidance and collision-detection techniques in ad-hoc networks has not been addressed in the past.

III. CSMA/CAD

A silent receiver does not benefit from full-duplex communication when it receives multiple concurrent transmissions. However, self-interference cancelation (SIC) can be used to make collision avoidance more efficient. Using SIC while sending an RTS and CTS enables a node to detect the presence of interference within one maximum propagation delay from the start of the interfering signals, and this is the fastest-possible feedback that can be given to the sender of an RTS or a CTS. Furthermore, this feedback is provided without incurring any transmit-to-receive turnaround latency or the need for secondary channels. Hence, collision detection can improve the performance of collision avoidance substantially.

Rather than attempting to enable FD operation for the bidirectional dissemination of data packets, CSMA/CAD eliminates the collision of data packets at their intended receivers while minimizing the latencies incurred in securing collision-free handshakes between transmitters and receivers.

We describe the operation of CSMA/CAD for the case in which transmitters do not persist attempting to access the channel after detecting carrier or collisions. In a nutshell, a node uses carrier sensing before sending an RTS, and uses collision detection while transmitting an RTS or a CTS. If either carrier is detected before an RTS is sent or a collision is detected while an RTS or CTS is being sent, the node backs off, and aborts its ongoing transmission. The successful reception of a CTS from the receiver prompts the transmitter to send a data packet and to wait for the ACK from the receiver. A successful RTS-CTS handshake ensures that a data packet and its associated acknowledgment (ACK) are received without multiple-access interference (MAI).

Figure 2 illustrates the state machine of non-persistent CSMA/CAD assuming that at most one packet is passed to the MAC layer for transmission at any given time.

A node that is just initialized waits for a period of time equivalent to a DIFS (DCF inter frame space) as defined in IEEE 802.11. After that time, the node transitions to the PASSIVE state and waits for a local packet or carrier. This waiting period ensures that a node entering an ad-hoc network learns about ongoing packet transmissions if they exist. If a node is in PASSIVE state, there is no carrier in the channel, and the node receives a packet to send, then it starts transmitting an RTS to the intended receiver and transitions

to the RTS state. Alternatively, if the node detects carrier, it transitions to the REMOTE state.
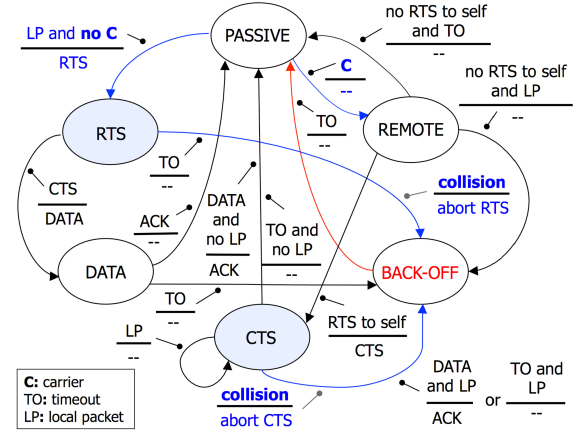

Fig. 2. Non-persistent CSMA/CAD

If a node detects a collision while sending an RTS, it aborts the RTS and injects a short jamming bit sequence before transitioning to the BACK-OFF state. Once a node sends an RTS without collisions, it waits for a CTS from the receiver for an RTS-timeout time. If no CTS is received, the node assumes that a collision occurred and transitions to the BACK-OFF state to transmit its RTS at a future time. If a CTS is received correctly, the node transmits a data packet and transitions to the DATA state to wait for an ACK from the receiver. The node transitions to the BACK-OFF state if no ACK is received within an ACK timeout that is long enough to allow the node to receive and decode an ACK.

If a node is in the REMOTE state and decodes an RTS from a transmitter intended for itself (shown as "RTS to self" in Fig. 2), it starts sending its CTS to the transmitter and transitions to the CTS state.

If a node detects a collision while transmitting its CTS, it aborts the transmission, injects a short jamming bit sequence, and transitions to the BACK-OFF state. If the node is able to transmit its entire CTS, then it waits for a data packet and remembers whether or not it has a local packet to send. If a data packet is received from the transmitter, the node sends an ACK accordingly. The node transitions to the PASSIVE state if there is no local packet to send, or to the BACK-OFF state if it has a local packet to send. Similarly, the node transitions to PASSIVE or BACK-OFF state depending on whether it has a packet to send if a CTS timeout elapses with no data packet being received from the transmitter. The length of a CTS timeout is long enough for the node to be able to start decoding a valid data packet.

If the node is in REMOTE state and does not receive an RTS intended for itself (denoted by "no RTS to self" in Fig. 2) after a timeout interval, the node transitions to the PASSIVE state if it has no local packet to send, or to the BACK-OFF state if it has a local packet to send. The timeout interval in the REMOTE state is long enough to allow a complete handshake between another receiver and a transmitter to take place without interference from the node itself.

Once a node transitions to the BACK-OFF state, it computes a random back-off time, and transitions to the PASSIVE state after that time has elapsed. An exponential back-off discipline can be used to account for unsuccessful retransmission attempts for the same data packet and limit congestion. However, it is not shown for simplicity.

IV. CORRECTNESS OF CSMA/CAD

Theorem 1 below shows that, under a number of assumptions, CSMA/CAD ensures that all data packets and ACKs are delivered to their intended receivers without colliding with other transmissions around those receivers. The assumptions used are the following: (a) There are at least two nodes in the network, and a node knows the addresses of its neighboring nodes through some means external to the protocol; (b) all nodes execute the CSMA/CAD protocol correctly; (c) the propagation delay t_p between any two neighboring nodes is $0 < t_p \leq \tau$; (d) a node requires a transmit-to-receive and receive-to-transmit turn-around time of at most ω seconds; (e) the transmission time of an RTS and a CTS packet is γ, the transmission time of a data packet is δ, and the transmission time for an ACK is α; and (f) the time needed for a node with an ongoing transmission to detect a collision and transmit a jamming bit pattern is $\eta < \gamma$.

Theorem 1: CSMA/CAD ensures that no data packets or their ACKs collide with any other transmissions.

Proof: For a data packet from transmitter T to be sent to receiver R, a successful RTS-CTS handshake must first take place between T and R, i.e., R must receive the RTS from T free of collisions and T must receive the CTS from R free of collisions. Accordingly, the rest of the proof must show that, if an RTS-CTS handshake succeeds, any neighbor of T or R must back off long enough to allow the data and ACK sent between T and R to be received free of MAI.

For a successful RTS-CTS handshake to occur between T and R, T must be in PASSIVE state when it has a packet to send, and it must transmit its RTS without detecting a collision. Let t_0 be the time when node T sends its RTS to node R. Any neighbor n_T of T receives the entire RTS from T at time $t_T = t_0 + \gamma + t_p$, where $0 < t_p \leq \tau$.

Because T sends its entire RTS without detecting collisions, n_T must either transition to the REMOTE or the BACK-OFF state. If $n_T \neq R$ then it must defer for a back-off time T_{BT} of at least $\gamma + \delta + \alpha + 3\omega + 4\tau$ seconds if it is in the REMOTE state, or defer for a much longer time if in the BACK-OFF state. Accordingly, n_T cannot attempt to transmit any packet until time $t_{NT} \geq t_T + \gamma + \delta + \alpha + 3\omega + 4\tau$. Therefore, given that $t_0 + \gamma < t_T$, it must be true that

$$t_{NT} > t_0 + 2\gamma + \delta + \alpha + 3\omega + 4\tau \qquad (1)$$

A neighbor n_R of R other than T receives the entire CTS from R at time t_R, where $t_0 + 2\gamma < t_R \leq t_0 + 2(\gamma + \tau) + \omega$, because a propagation delay is $0 < t_p \leq \tau$ and R incurs at most ω seconds of turnaround time processing an RTS.

Because R sends its CTS without detecting collisions, neighbor n_R must transition to the REMOTE or the BACK-OFF state. Accordingly, n_R must defer for at least a back-off time T_{BR} in the REMOTE state after receiving the CTS from R, where $T_{BR} \geq \delta + \alpha + 3\omega + 4\tau$, or defer for a much longer time in the BACK-OFF state. Hence, n_R cannot attempt to transmit any packet until time $t_{NR} \geq t_R + T_{BR}$. Therefore, given that $t_0 + 2\gamma < t_R$, it follows that

$$t_{NR} > t_0 + 2\gamma + \delta + \alpha + 3\omega + 4\tau \qquad (2)$$

Node R receives the entire data packet from T at time

$$t_{RD} \leq t_0 + 2\gamma + \delta + 2\omega + 3\tau \qquad (3)$$

From Eqs. (2) and (3), it must be the case that $t_{RD} < t_{NR}$ and node n_R cannot interfere with the reception of the data packet from T. On the other hand, node T must receive the entire ACK from R at time

$$t_{TA} \leq t_0 + 2\gamma + \delta + \alpha + 3\omega + 4\tau \qquad (4)$$

From Eqs. (1) and (4), it must be true that $t_{TA} < t_{NT}$ and node n_T cannot interfere with the reception of the ACK from R. It follows from this argument that no MAI exists for the reception of a data packet and its ACK; therefore, the theorem is true. $\square$

V. THROUGHPUT IN FULLY-CONNECTED NETWORKS

We assume the same traffic model first introduced by Kleinrock and Tobagi [15] to analyze CSMA/CAD, CSMA/CA, DBTMA, and CSMA with ACKs. According to the model, there is a large (essentially infinite) number of nodes that constitute a Poisson source sending RTS's or data packets to the the channel with an aggregate rate of λ packets per unit time. We assume the use of priority acknowledgments (ACK) in all protocols, because they are needed in practice to account for transmission errors not due to multiple-access interference. For brevity, we only address the non-persistent versions of the protocols.

The throughput attained by a channel-access protocol is a function of the physical and medium-access control (MAC) layers. However, for the channel-access protocols we consider, the physical-layer overhead is roughly the same for each packet transmission in all the protocols. For simplicity, we assume that the transmission time of any control or data packet includes the overhead induced by the physical layer. A fixed receive-to-transmit and transmit-to-receive turnaround time of ω seconds is assumed, and the same assumptions stated in Section IV for packet sizes apply.

Nodes have at most one data packet to sent at any time, which results from the MAC layer having to submit one packet for transmission before accepting the next packet. For the case of CSMA/CAD, it is assumed that the time needed for a node to detect a collision with its own transmission and send a jamming bit sequence lasts η seconds. In our model $\eta \ll \gamma$, because η is simply the time needed to identify the presence of a non-zero signal after SIC is applied to the received signal,

plus the transmission of a short bit sequence that has to be larger than the error-checking field of a packet (e.g., 48 bits).

When a node has to retransmit a packet it does so 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 of RTS's or data packets can be assumed to be independent of one another.

The channel is assumed to introduce no errors, and nodes are assumed to detect carrier and, depending on the protocol, collisions or busy tones perfectly. To further simplify the problem, 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 protocols are assumed to operate in steady state, with no possibility of collapse, and hence the average utilization of the channel is given by [15]

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}}. \tag{5}$$

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. This model is only an approximation of the real case, in which a small number of nodes may access the same channel, and transmissions and retransmissions are correlated because of the relationships between them. However, our analysis provides a good baseline for the comparison of the various channel-access protocols and the relative benefits of the joint use of collision avoidance and detection compared to other techniques.
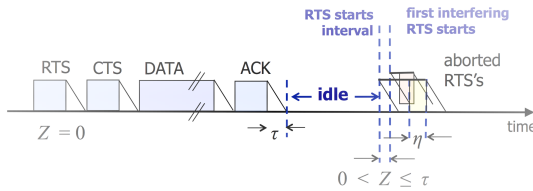
A. CSMA/CAD

Fig. 3. Transmission periods in CSMA/CAD

Figure 3 shows the transmission periods that may occur in a fully-connected ad-hoc network for the non-persistent CSMA/CAD protocol. As the figure illustrates, the utilization of the channel consists of idle periods, successful busy periods during which data packets are sent as part of successful collision-avoidance handshakes, and collision intervals resulting from the collision of two or more RTS's sent within one propagation delay of one another. No turnaround delays are incurred because a node listens while it transmits.

Theorem 2: The throughput of CSMA/CAD with a non-persistent transmission strategy is

$$S_{CAD} = \frac{\delta}{\delta + 2\gamma + \alpha + 2\tau - \eta - \frac{1}{\lambda} + e^{\lambda\tau}(\frac{2}{\lambda} + \eta + 2\tau)} \tag{6}$$

Proof: A transmitter in CSMA/CAD uses carrier sensing before transmitting an RTS and collision detection while transmitting the RTS. Accordingly, the probability that an RTS is sent without multiple access interference (MAI) and a successful transmission period occurs equals the probability that no arrivals of other RTS's take place within τ seconds from the start of the RTS. This probability is $P_S = e^{-\lambda\tau}$, and the probability that a collision interval occurs is simply $1 - P_S = 1 - e^{-\lambda\tau}$.

If an RTS does not collide with any other transmission, a CTS, a data packet, and an ACK follow. This occurs with probability P_S and takes $2\gamma + \delta + \alpha + 4\tau$ seconds.

If an RTS collides with other RTS's, then all the nodes that sent RTS's detect the collision, abort their RTS transmissions, and send jamming bit sequences. By assumption, the time needed to detect a collision and the transmission of the jamming bit sequence takes η seconds.

Any node sending an RTS that interferes with the first RTS of a collision interval starts receiving the carrier from the first RTS in τ seconds after the first RTS starts, takes η seconds to detect the collision and transmit a jamming pattern, and its own transmission propagates in τ seconds to all nodes. Therefore, the time incurred by any interfering RTS is $\eta + 2\tau$ from the start of the collision interval.

On the other hand, the node that starts a collision interval with its RTS detects a collision τ seconds after the first interfering RTS starts. Accordingly, the length of a collision interval is given by $Z + \tau + \eta + \tau$, where Z is a random variable that varies from 0 to τ and represents the time between the arrival of the RTS that starts the collision interval and the arrival of the *first* RTS that creates a collision.

Given that arrivals of RTS's are Poisson distributed, it is not possible to have two or more arrivals of RTS's into the channel exactly at the same time; therefore, $Z = 0$ occurs when an RTS is successful. Accordingly, the length of an average busy period equals

$$\overline{B} = \overline{Z} + (1 - e^{-\lambda\tau})(\eta + 2\tau) + e^{-\lambda\tau}(2\gamma + \delta + \alpha + 4\tau) \tag{7}$$
$$= \overline{Z} + \eta + 2\tau + e^{-\lambda\tau}(\delta + 2\gamma + \alpha + 2\tau - \eta)$$

For Z to last more than z seconds, it must be the case that no arrival occurs in the first z seconds of a collision interval, that is, $P(Z > z) = P\{\text{no arrivals in } [0, z]\} = e^{-\lambda z}$. Therefore, the cumulative distribution function of Z is

$$F_Z(z) = P(Z \le z) = 1 - P(Z > z) = 1 - e^{-\lambda z} \tag{8}$$

Z assumes non-negative values, and hence its mean can be computed using $F_Z(z)$ in Eq. (8) as follows:

$$\overline{Z} = \int_0^\infty (1 - F_Z(t))dt = \int_0^\tau e^{-\lambda t}dt = \frac{1}{\lambda}\left(1 - e^{-\lambda\tau}\right) \tag{9}$$

Substituting $\overline{Z}$ in Eq. (7) we have

$$\overline{B} = e^{-\lambda\tau}\left(\delta + 2\gamma + \alpha + 2\tau - \eta - \frac{1}{\lambda}\right) + \eta + 2\tau + \frac{1}{\lambda} \tag{10}$$

The average length of an idle period $\overline{I}$ in CSMA/CAD is just the average inter-arrival time of RTS's, which equals $1/\lambda$,

because inter-arrival times are exponentially distributed with parameter λ. The average time period used to transmit useful data $\overline{U}$ is simply the useful portion of a successful busy period, i.e., $\delta P_S = \delta e^{-\lambda\tau}$. Substituting the values of $\overline{U}$, $\overline{B}$, and $\overline{I}$ into Eq. (5) we obtain Eq. (6). $\square$

B. CSMA/CA

Fig. 4. Transmission periods in CSMA/CA

We obtain the throughput of non-persistent CSMA/CA to evaluate the benefit of embedding collision detection in the collision-avoidance handshake. Figure 4 illustrates the transmission periods for non-persistent CSMA/CA assuming priority ACKs. Complete RTS's are transmitted during a collision interval, and the length of a CTS must last at least the duration of an RTS plus a round-trip time and transmit-to-receive turnaround time required for the radios to avoid the possibility of collisions of data packets with other transmissions [8]. As a result, collision intervals are longer in CSMA/CA than in CSMA/CAD.

The following theorem provides the throughput of non-persistent CSMA/CA. We assume that the minimum length of a CTS is equal to $\gamma' = \gamma + 2\tau + \omega$, where ω is the turn-around time. Our result differs slightly from prior results [7], [8] because of the use of ACKs and a simplification of the protocol we use as CSMA/CA compared to FAMA protocols.

Theorem 3: The throughput of non-persistent CSMA/CA is

$$S_{CA} = \frac{\delta}{\delta + \gamma + \alpha + 4\omega + 5\tau + \frac{1}{\lambda} + e^{\lambda(\omega+\tau)}(\gamma + 2\tau + \omega)} \quad (11)$$

Proof: A node using CSMA/CA must sense the channel before sending an RTS, and then it incurs a turnaround time ω during which the node is unable to listen to the channel. Therefore, the vulnerability period of an RTS is $\omega + \tau$, and the probability that an RTS succeeds and a successful transmission period occurs equals $P_S = e^{-\lambda(\omega+\tau)}$. It also follows that a collision interval occurs with probability $1 - P_S = 1 - e^{-\lambda(\omega+\tau)}$.

If an RTS is sent without MAI, then a CTS, a data packet and an ACK follow. This takes $\gamma + \gamma' + \delta + \alpha + 3\omega + 4\tau = 2\gamma + \delta + \alpha + 4\omega + 6\tau$ seconds and occurs with probability P_S.

If an RTS collides with other RTS's, then no receiver is able to decode any RTS. As Fig. 4 illustrates, the length of a collision interval is given by $Y + \gamma + \tau$, where Y is a random variable that varies from 0 to $\omega + \tau$ and represents the time between the arrival of the first RTS and the last RTS in a collision interval.

$Y = 0$ occurs when an RTS is successful, which follows from the assumption that packet arrivals are Poisson distributed. Therefore, the length of an average busy period equals

$$\overline{B} = \overline{Y} + (1 - e^{-\lambda(\omega+\tau)})(\gamma+\tau) + e^{-\lambda(\omega+\tau)}(2\gamma+\delta+\alpha+4\omega+6\tau) \quad (12)$$

If the time period between the start of the the first and the last RTS in a collision interval equals y seconds, then there are no more arrivals of RTS's in the remaining time of the vulnerability period of the first RTS of the collision interval, i.e., $\omega + \tau - y$ seconds. Accordingly, $P(Y \le y) = F_Y(y) = e^{-\lambda(\omega+\tau-y)}$. Therefore, the average value of Y equals

$$\overline{Y} = \int_0^\infty (1 - F_Y(t))dt = \int_0^{\omega+\tau} \left(1 - e^{-\lambda(\omega+\tau-t)}\right) dt$$

$$= \omega + \tau - \frac{1 - e^{-\lambda(\omega+\tau)}}{\lambda} \quad (13)$$

Substituting Eq. (13) in Eq. (12) we have

$$\overline{B} = e^{-\lambda(\omega+\tau)}\left(\delta+\gamma+\alpha+4\omega+5\tau+\frac{1}{\lambda}\right)+\gamma+\omega+2\tau-\frac{1}{\lambda} \quad (14)$$

The average time period used to transmit useful data $\overline{U}$ is just $\delta P_S = \delta e^{-\lambda(\omega+\tau)}$. As in CSMA/CAD, the average length of an idle period $\overline{I}$ is $1/\lambda$. Substituting the values of $\overline{U}$, $\overline{B}$, and $\overline{I}$ into Eq. (5) we obtain Eq. (11). $\square$
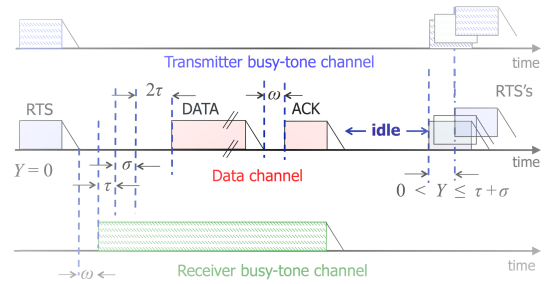
C. DBTMA

Fig. 5. Transmission periods in DBTMA

We compute the throughput of DBTMA to account for non-trivial turnaround times and the use of ACKs, and to correct modeling inconsistencies in the results by Haas and Deng [12]. Fig. 5 illustrates the transmission periods in DBTMA.

We assume that the data channel is assigned a percentage of the total bandwidth equal to $0 < \beta < 1$, with each busy-tone channel having an equal portion of the remaining bandwidth. The time needed for a node to detect the presence of a busy tone from a transmitter or a receiver is σ seconds. We assume that busy tones are detected perfectly, and that the probability of false busy-tone detection is 0. For simplicity we assume that receive-to-transmit latencies are the same for the data and control channels. As with the other MAC protocols we consider, a receiver sends an ACK after the successful reception of a data packet. Following the design of DBTMA in [12], a transmitter waits a round-trip time after detecting the busy tone from its receiver before sending a data packet (see Fig. 5).

The analytical result for the throughput of DBTMA reported in [12] assumes that colliding RTS's arrive to the channel uniformly distributed in the duration of a collision interval. However, this cannot be true with the arrival of RTS's being Poisson distributed in order to compute success probabilities

and the average length of idle periods. Furthermore, receive-to-transmit turnaround times in the receiver busy-tome channel must be taken into account. The following theorem provides the throughput of DBTMA assuming that the total available bandwidth is the same as in the other channel-access protocols.

Theorem 4: The throughput of non-persistent DBTMA over a data channel using only β (with $0 < \beta < 1$) of the total available bandwidth is

$$S_{DBT} = \frac{\delta}{\delta + \alpha + \beta^{-1}\left(2\omega + \sigma + 5\tau + \frac{1}{\lambda}\right) + He^{\lambda(\tau+\sigma)}} \tag{15}$$

where $H = \gamma + \beta^{-1}[\sigma + 2\tau]$

Proof: A node decides that the channel is busy in DBTMA if it detects a busy tone in one of the control channels. Because a busy tone is a narrow-band signal, a non-negligible tone-detection delay σ is incurred *after* the signal propagates in τ seconds to the node receiving the signal. Hence, the vulnerability period of an RTS is $\tau + \sigma$ seconds, because a transmitter sends a transmit busy tone at the same time that it transmits an RTS in the data channel. Given that RTS arrivals are Poisson distributed with parameter λ, the probability with which an RTS is sent without MAI and a successful transmission period occurs is $P_S = e^{-(\tau+\sigma)}$. Correspondingly, the probability that a collision interval occurs is $1 - P_S = 1 - e^{-\lambda(\tau+\sigma)}$.

If an RTS does not collide with other transmissions, the receiver starts transmitting its receive busy tone after a turnaround time, and its busy tone takes τ seconds to propagate and σ seconds to be detected by the transmitter. After that, the transmitter waits 2τ seconds and starts sending its data packet and the receiver transmits its ACK accordingly. Therefore, the time incurred in a successful handshake using busy tones is $\delta + \gamma + \alpha + 2\omega + \sigma + 6\tau$ seconds.

If an RTS collides with other RTS's, then all the transmit busy tones and RTS's involved in the collision are transmitted in their entirety, but no receiver is able to decode any of them given that we assume no capture effect for busy tones.

As Fig. 5 illustrates, the length of a collision interval in DBTMA is $Y + \gamma + \tau$, where Y is a random variable that varies from 0 to τ and represents the time between the arrival of the first and the last RTS in the collision interval, similar to the case of CSMA/CA.

$Y = 0$ necessarily implies that an RTS is successful, because arrivals of RTS's are Poisson distributed. Hence, the length of an average busy period equals

$$\overline{B} = \overline{Y} + (1 - e^{-\lambda(\tau+\sigma)})(\gamma + \tau) \tag{16}$$

$$+ e^{-\lambda(\tau+\sigma)}(\delta + \gamma + \alpha + 2\omega + \sigma + 6\tau)$$

$$= \overline{Y} + \gamma + \tau + e^{-\lambda(\tau+\sigma)}(\delta + \alpha + 2\omega + \sigma + 5\tau)$$

Given that the vulnerability period of the first RTS in a collision interval is $\tau + \sigma$, $F_Y(y) = P(Y \leq y)$ equals the probability that no RTS arrivals occur in the remaining $\tau+\sigma-y$

seconds of the vulnerability period of the first RTS of the collision interval. Therefore,

$$F_Y(y) = P\{\text{no arrivals in } \tau + \sigma - y\} = e^{-\lambda(\tau+\sigma-y)} \tag{17}$$

Because Y assumes non-negative values, we have that

$$\overline{Y} = \int_0^{\tau+\sigma} \left(1 - e^{-\lambda(\tau+\sigma-t)}\right) dt = \tau + \sigma - \frac{1 - e^{-\lambda(\tau+\sigma)}}{\lambda} \tag{18}$$

Substituting Eq. (18) in Eq. (16) we obtain

$$\overline{B} = \tau + \sigma - \frac{1 - e^{-\lambda(\tau+\sigma)}}{\lambda} \tag{19}$$

$$+ \gamma + \tau + e^{-\lambda(\tau+\sigma)}(\delta + \alpha + 2\omega + \sigma + 5\tau)$$

$$= e^{-\lambda(\tau+\sigma)} \left(\delta + \alpha + 2\omega + \sigma + 5\tau + \frac{1}{\lambda}\right)$$

$$+ \gamma + \sigma + 2\tau - \frac{1}{\lambda}$$

The average length of an idle period $\overline{I}$ is $1/\lambda$, because RTS arrivals are Poisson distributed with parameter λ. On the other hand, the average time period used to transmit useful data $\overline{U}$ is $\delta P_S = \delta e^{-\lambda(\tau+\sigma)}$.

The data-channel capacity in DBTMA is reduced by the amount of bandwidth needed for the two busy-tone channels. To account for this, the transmission time for data packets and signaling packets must be normalized to the length of a data packet enjoying the entire channel bandwidth. Accordingly, substituting the values of $\overline{U}$, $\overline{B}$, and $\overline{I}$ into Eq. (5) and multiplying each packet length by β we obtain Eq. (15). □
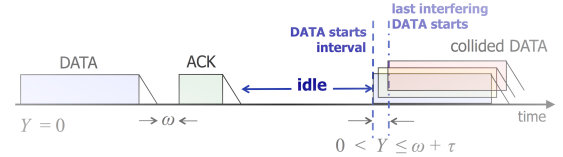
D. CSMA with Priority ACKs

Fig. 6. Transmission periods in CSMA

The original throughput results for non-persistent CSMA by Kleinrock and Tobagi [15] assume an ideal secondary channel over which ACKs are sent in 0 time. We consider the throughput of non-persistent CSMA with priority ACKs to provide a level-playing field for the comparison of all the MAC protocols. Figure 6 illustrates the transmission periods in non-persistent CSMA with priority ACKs, and the following theorem specifies its throughput.

Theorem 5: The throughput of non-persistent CSMA with priority ACKs is

$$S_{CS} = \frac{\delta}{\alpha + \omega + \tau + \frac{1}{\lambda} + e^{\lambda(\omega+\tau)}(\delta + \omega + 2\tau)} \tag{20}$$

Proof: The proof is presented in [21] using different terminology and assuming zero turnaround times. In our model, the vulnerability period of a data packet is $\omega + \tau$ rather than just τ, and the proof for this case is similar to the proof of Theorem 3. □
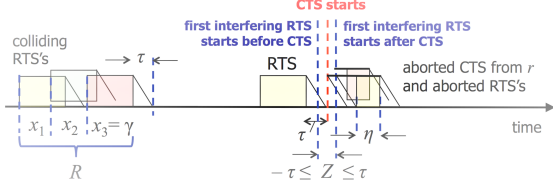
VI. Impact of Hidden Terminals

Fig. 7. Effect of hidden terminals in CSMA/CAD

We analyze the impact of hidden terminals on the performance of CSMA/CAD. To simplify our modeling problem, we assume a star network in which all traffic is sent to a central receiver r and all nodes other than r are hidden from one another, which constitutes a worst-case performance scenario for CSMA/CAD, because it renders carrier sensing and collision detection useless for the transmission of RTS's. However, together with the results of the previous section, it provides sufficient insight on the efficacy of CSMA/CAD. Other than the fact that all sources are hidden from one another, the assumptions made in Section V apply to this case. Figure 7 illustrates the collision intervals that may occur in non-persistent CSMA/CAD with the assumptions we make.

Theorem 6: The throughput of CSMA/CAD with a non-persistent transmission strategy at a central receiver r with a large population of sources hidden from each other is

$$S_{CAD} \approx \frac{\delta}{H + e^{\lambda\tau}\left[\, e^{\lambda\gamma}\left(\tau + \frac{1}{\lambda}(e^{\lambda\gamma} - 1)\right) + J \,\right]} \quad (21)$$

with $J = \frac{1}{\lambda} + \gamma + \eta + 2\tau$ and $H = \delta + \gamma + \alpha + \tau - \eta$

Proof: A node aborts its RTS or CTS if it detects a collision. By assumption, transmitters are hidden from one another, and hence an RTS is vulnerable for its entire length and arrives successfully at receiver r with probability $P_{SR} = e^{-\lambda\gamma}$. On the other hand, receiver r sends its CTS successfully with probability $P_{SC} = e^{-\lambda\tau}$, because it can detect any RTS that collides with its CTS in one propagation delay.

With Poisson arrivals, having no arrivals in a given time interval is independent of having no arrivals in another non-overlapping time interval. Hence, given that RTS arrivals are Poisson distributed and a data packet is sent only if an RTS and the corresponding CTS are sent successfully, we have $\overline{U} = \delta P_{SR} P_{SC} = \delta e^{-\lambda(\gamma+\tau)}$.

On the other hand, the value of $\overline{I}$ is the same as in Theorem 2, i.e., $\overline{I} = 1/\lambda$.

A busy period is an RTS collision interval (RCI) if the first RTS suffers MAI with probability $1 - P_{SR}$. An RCI lasts $\tau + R$ seconds, where R is a random variable whose value depends on the number of RTS's involved in the collision interval and the inter-arrival times of those RTS's.

For an RCI to have k RTS's, some RTS's must arrive during the transmission time of each of the first $k-1$ RTS's and no RTS arrives during the transmission time of the last RTS in the RCI. With the simplifying assumption that there is an infinite number of transmitters around receiver r, this corresponds to

the geometric random variable in which the probability of successfully ending the RCI is the probability that no RTS arrives during the γ seconds, or $e^{-\lambda\gamma}$. Therefore, the average number of RTS's in an RCI is $e^{\lambda\gamma}$.

The inter-arrival times between consecutive RTS's in an RCI are exponentially distributed and each can be at most γ seconds. Therefore, the average $\overline{X}$ of such times is

$$\overline{X} = \int_0^\infty (1 - F_X(t))dt = \int_0^\gamma e^{-\lambda t}dt = \frac{1}{\lambda}\left(1 - e^{-\lambda\gamma}\right) \quad (22)$$

It thus follows that the average value of R is given by

$$\overline{R} = e^{\lambda\gamma}\overline{X} = \frac{e^{\lambda\gamma}}{\lambda}\left(1 - e^{-\lambda\gamma}\right) = \frac{e^{\lambda\gamma} - 1}{\lambda} \quad (23)$$

If an RTS arrives at its receiver r with no MAI (with probability P_{SR}) and the CTS succeeds (with probability P_{SC}), the length of the busy period is $\overline{T} = \delta + 2\gamma + \alpha + 4\tau$.

If a CTS from r fails (with probability $1 - P_{SC}$), it must collide with RTS's sent within the period of time starting with the reception of the RTS at r and ending τ seconds from the start of the CTS, after which all neighbors of r detect the carrier of the CTS from r.

Any neighbor of r creating MAI for the CTS must abort its transmission after detecting collision with the CTS, and node r must abort its transmission after detecting a collision with the *first* interfering RTS. The average length of a CTS collision interval is then $\overline{C} = \gamma + \tau + \overline{Z} + \eta + \tau$, where Z is a random variable that varies from $-\tau$ to τ and represents the time between the arrival of the CTS from receiver r and the arrival of the first RTS causing MAI to the CTS.

The longest CTS collision interval occurs when $Z = \tau$ and for simplicity we approximate $\overline{C} \approx C_{max} = \gamma + \eta + 3\tau$. This is safe to use because it results in a lower bound for the throughput. We can then express $\overline{B}$ as follows:

$$\overline{B} \approx e^{-\lambda\gamma}\left(\overline{T}e^{-\lambda\tau} + C_{max}(1 - e^{-\lambda\tau})\right) + (1 - e^{-\lambda\gamma})(\overline{R} + \tau) \quad (24)$$

Substituting the values of $\overline{T}$, C_{max}, and $\overline{R}$ into Eq. (24), and then substituting the values of $\overline{U}$, $\overline{B}$, and $\overline{I}$ into Eq. (5) we obtain Eq. (21). $\square$

VII. Performance Comparison

A. Modeling Assumptions

We assume a channel data rate of 1 Mbps even though higher data rates are common today; this is done just for simplicity. We assume MAC-level lengths of signaling packets similar to those used in IEEE 802.11 DCF. For simplicity, however, we assume that an RTS and an ACK is 40 bytes.

We assume that the time needed to detect collisions and send a jamming signal (η) in CSMA/CAD is roughly twice the duration of a jamming signal in CSMA/CD, or 84-bit time. A CTS in CSMA/CAD has the same length of an RTS. On the other hand, to ensure floor acquisition using CTS's in the version of CSMA/CA we use for comparison, the length of a CTS equals the length of an RTS plus a round-trip time and a transmit-to-receive turnaround time ω. We assume that ω is 20μs, similar to the recommendations for IEEE 802.11 DCF.

We assume that the busy-tone detection time σ in DBTMA is 100 μs, which corresponds to a probability of correct busy-tone detection close to 1 according to the model presented in [20]. We use $\beta = .9$ to assume that DBTMA dedicates most of the available bandwidth to the data channel.

We normalize the results to the length of a data packet by making $G = \lambda \times \delta$ and $a = \tau/\delta$; and by using the normalized value of each other variable, which equals its ratio with δ (e.g., the normalized RTS length is γ/δ).

B. Results for Fully-Connected Scenarios

We compare the throughput of CSMA/CAD with the throughput (S) versus the offered load (G) attained by CSMA/CA, DBTMA, and CSMA based on Eqs. (6), (11), (15), and (20). We present results for a local-area scenario and a geographically-dispersed scenario.

The local-area scenario highlights the performance of the protocols when latencies are very short and signaling overhead is small relative to the time needed to transmit data packets. Physical distances are around 500 meters, and the duration of a data packet is 1500 bytes, which is an average-length IP packet and takes 0.012s to transmit at 1 Mbps. We use a normalized propagation delay of $a = 1 \times 10^{-4}$. The geographically-dispersed scenario was considered to highlight the impact of increasing latencies and signaling overhead in the various protocols. For this scenario we assume that a data packet is only 400 bytes and that distances are around 1000 meters. We thus assume a normalized propagation delay of $a = 1 \times 10^{-3}$. Figures 8 and 9 show the results for these scenarios.

CSMA attains a larger throughout than the other approaches at light loads because the other protocols use additional signaling to eliminate MAI due to hidden terminals. However, the maximum-throughput values for the other protocols approach or surpass that of CSMA as the propagation delay and length of signaling packets tend to zero. CSMA/CAD, CSMA/CA, and DBTMA are more stable at higher loads because they reduce the length of collision intervals compared to CSMA.

Compared to CSMA/CA and CSMA/CAD, DBTMA suffers from the latencies incurred in detecting busy tones and the reduced bandwidth available for the transmission of data packets. CSMA/CAD attains higher throughput than CSMA/CA and DBTMA at higher loads because of the reduced overhead associated with using SIC to detect collisions compared to using a long CTS as an in-band busy tone, or requiring a separate control channel to transmit busy tones. Overall, CSMA/CAD provides the highest throughput of the channel-access schemes capable of eliminating MAI due to hidden terminals. This is because CSMA/CAD provides the fastest feedback to transmitters when MAI occurs, which results in the shortest collision intervals.

C. Results for Scenarios with Hidden Terminals

We compare CSMA/CA with the ideal non-persistent CSMA protocol assuming the same parameter values for the geographically-dispersed scenario. We do not consider CSMA/CA and DBTMA because they would require modifications to eliminate hidden-terminal MAI when ACKs are used, which is needed in a MAC protocol. We use Eq. (21)
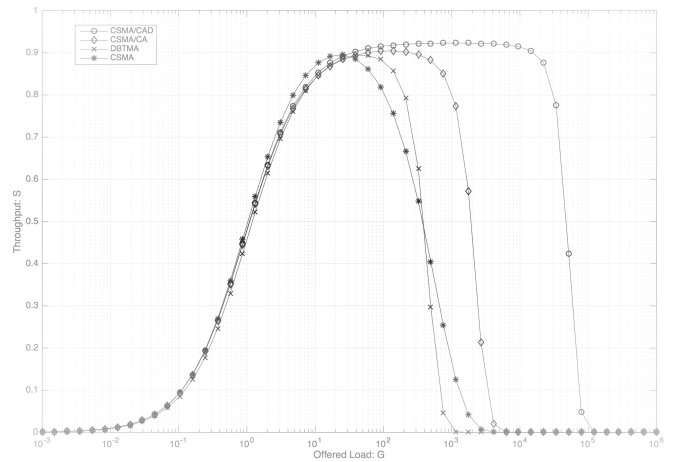

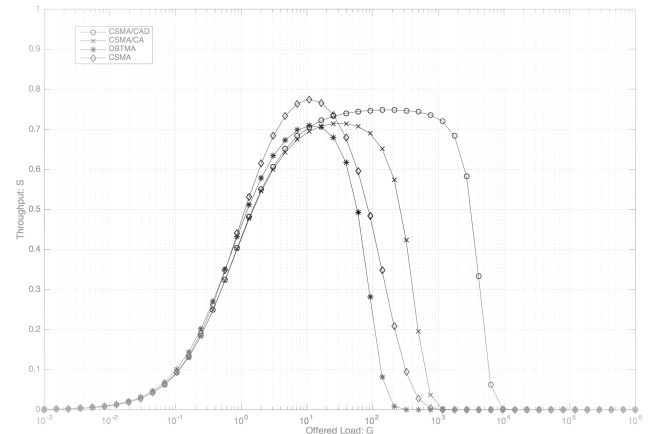Fig. 8. S vs. G with short distances and large data packets

Fig. 9. S vs. G with long distances and medium-size data packets

for CSMA/CAD and correspondingly assume that transmitters in CSMA cannot hear each other. Fig. 10 shows the results. With hidden terminals, the throughout of ideal non-persistent CSMA is the same as pure ALOHA [20] and is an upper bound on the performance of CSMA with ACKs.

The results in Fig. 10 clearly show that CSMA/CAD provides a marked improvement over CSMA even if ACKs in CSMA are assumed to be delivered without MAI and in 0 time. The reduction in CSMA/CAD throughput with hidden terminals compared to the fully-connected scenarios is due primarily to RTS's being vulnerable for their entire transmission time, rather than just a propagation delay.

VIII. Conclusions

We introduced CSMA/CAD (Carrier-Sense Multiple Access with Collision Avoidance and Detection) and showed that no data packets or ACKs sent into the channel can collide with other transmissions. We compared the throughput attained with CSMA/CAD with the throughput of CSMA/CA, DBTMA, and CSMA with priority ACKs for the case in which nodes use a non-persistent transmission strategy. Our results show that
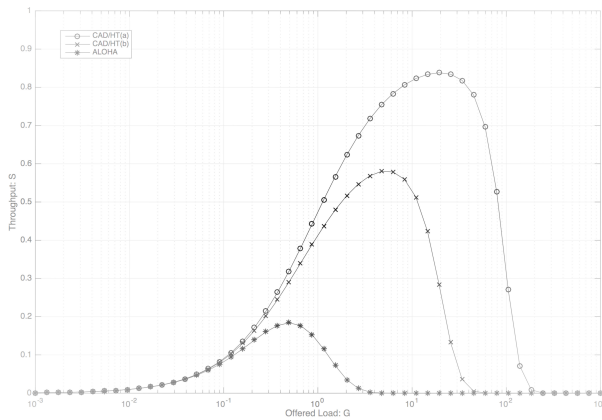
Fig. 10. S vs. G with hidden terminals: (a) large packets, (b) medium-size packets

using collision detection as an integral part of the collision-avoidance handshake among nodes of ad-hoc networks has clear advantages over the other techniques.

Our future work focuses on: (a) the impact of persistence in the transmission of signaling packets, (b) the use of back-off strategies to address congestion, (c) full-duplex data exchanges between neighbors that successfully complete a collision-avoidance handshake, and (d) the analysis of CSMA/CAD in multi-hop networks using approximate models [4], [22].

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