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Carrier-Tone Multiple Access with Collision Avoidance and Detection

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Abstract—A new approach for collision avoidance and collision detection in ad-hoc networks of nodes with half-duplex radios is introduced. Rather than using a single busy tone indicating that a receiver is busy, three types of carrier tones sent by receivers or passive listeners indicate that an intended receiver is busy receiving or acknowledging a data packet, or a passive listener has detected a collision. All carrier tones are sent over a single control channel, and the data channel is used only for data and request-to-send (RTS) packets. The Carrier-Tone Multiple Access with Collision Avoidance and Detection (CTMA/CAD) is described and its performance is compared with the performance of DBTMA in a hidden-terminal scenario. The results of the analysis show that CTMA/CAD is a more efficient channel-access method for networks with hidden terminals.

I. INTRODUCTION

Carrier-sense multiple access (CSMA) [9] is arguably the most widely used technique for the sharing of common radio channels in ad-hoc networks today. It is well known that while carrier sensing renders far better throughput than simply transmitting data packets without any coordination among nodes, which is the case of the ALOHA protocol [1], the performance of a CSMA degrades substantially in the presence of hidden terminals [11]. The main problem introduced by hidden terminals is that two or more transmitters around a receiver are unable to hear the transmission from one another, which renders carrier sensing useless.

As Section II summarizes, many approaches have been developed over the years to limit or eliminate multiple-access interference (MAI) due to hidden terminals, which can be classified into collision-avoidance schemes (e.g., [2], [8]) and busy-tone schemes [5], [6], [11].

The focus of this paper is on the use of multiple carrier tones to make collision avoidance (CA) more efficient and enable collision detection (CD) with half-duplex radios. Our approach is inspired by Tobagi and Kleinrock's seminal busy-tone solution to combat hidden terminals [11], prior results on collision avoidance and collision detection in wireless networks [2], [3], as well as the use of more than one busy tone in a single control channel first proposed in [5].

Section III describes *Carrier-Tone Multiple Access with Collision Avoidance and Detection (CTMA/CAD)*.

CTMA/CAD uses three types of carrier tones as an integral part of collision-avoidance (CA) handshakes between senders and receivers to eliminate the negative effects of hidden terminals and limit the length of collision intervals. The channel

is partitioned into a data channel and a small control channel, and a half-duplex transceiver is used to access each channel. To transmit a data packet, a node that detects no carrier in the data channel sends a short request-to-send (RTS) packet over the data channel. If the RTS is received correctly, the receiver starts transmitting a receiver tone (RT) over the control channel that lasts until the receiver obtains the data packet from the sender. Once the sender detects an RT in the control channel, it transmits its data packet after a short delay. In turn, the receiver responds to the data packet with a short acknowledgment tone (AT) over the control channel. In addition, a listening node that detects the collision of RTS's in the data channel transmits a collision tone (CT) in the control channel, which forces all nodes transmitting RTS's to abort their transmissions.

Sections IV and V analyze the throughput of CTMA/CAD and compare it against the throughput of Dual Busy Tone Multiple Access (DBTMA) [6]. The results of the analysis show that CTMA/CAD is much more efficient than the prior approaches designed for half-duplex transceivers. Section VI presents our conclusions.

II. RELATED WORK

The channel-access protocols that have been developed to date to address the negative effect of multiple-access interference (MAI) caused by hidden terminals in CSMA [11] can be classified in two types: protocols based on collision-avoidance (CA) handshakes and protocols based on busy tones sent over secondary channels.

One of the first channel-access protocols based on CA handshakes was Multiple Access with Collision Avoidance (MACA) [8], 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 its performance degrades in the presence of hidden terminals. Many subsequent variants of channel-access protocols based on CA handshakes have been proposed and analyzed since the introduction of MACA and have integrated carrier sensing together with CA handshakes. In some schemes the transmitter initiates the handshake [2] and in others the receiver does (e.g., [4], [10]). The IEEE 802.11 distributed coordination function (DCF) is arguably the most popular example of combining carrier sensing with the RTS-CTS handshake followed by a data packet and an ACK in successful cases.

The only known CA handshake that has been shown to succeed in avoiding MAI from hidden terminals requires a CTS from a receiver to be much longer than the length of an RTS in order to serve as a busy tone in those cases in which multiple signaling packets are transmitted concurrently [2]. The limitation with this approach is that it works correctly only if either fixed-length data packets are transmitted or very long back-off periods are applied, which renders lower throughput.

The Busy-Tone Multiple Access (BTMA) [11] 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 has radio connectivity with all other nodes in the system and 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. A few channel-access protocols based on one or more busy tones have been proposed [6], [12].

In RI-BTMA RI-BTMA (Receiver-Initiated Busy Tone Multiple Access) [12], the channel is divided into a data channel and a control channel and both channels are assumed to be time slotted, with each time slot lasting the length of a preamble. When the receiver detects the preamble of the transmission by the sender, it transmits its busy tone in the control channel. The obvious limitation of this approach is the need to use a time-slotted channel.

DBTMA (Dual Busy Tone Multiple Access) [6] does not require time slotting and uses two busy tones, each sent on a separate control channel. Before sending a data packet, a transmitter sends an RTS over the data channel and transmits a transmitter busy tone while sending the RTS. A transmitter aborts its transmission if it detects a receiver busy tone or a transmitter busy tone. A receiver starts transmitting a busy tone after receiving an RTS for itself. A receiver busy tone serves as a CTS and lasts as long as needed to protect the reception of a data packet by the receiver. The transmitter sends its data packet after detecting a receiver busy tone. The limitations of DBTMA are that it does not consider the use of ACKs, and requires two busy-tone channels and hence two busy-tone radios operating concurrently.

III. CTMA/CAD

We recently introduced a variant of CTMA [5] in which a receiver sends a busy tone after receiving an RTS packet and an acknowledgment tone after receiving a data packet. The advantage of this approach over previous busy-tone schemes is that it does not require time slotting or multiple busy-tone channels.

CSMA/CAD extends the use of carrier tones for collision avoidance with the use of carrier tones transmitted in the control channel when nodes listening to the data channel detect the occurrence of RTS collisions. The objectives in the design of CSMA/CAD are to: (a) Eliminate the collision of data packets in the presence of hidden terminals by informing transmitters about interference at the receivers; (b) inform senders when their packets are received successfully; and (c) reduce the overhead incurred in CA handshakes as much as

possible. The available bandwidth is partitioned into a data channel and a much smaller control channel.

CTMA/CAD combines the use of three carrier tones transmitted over a single control channel with physical-layer mechanisms used to implement carrier sensing [7]. We assume that carrier sensing is based on preamble detection and energy detection. Energy detection consists of comparing the signal strength readings obtained from the radio front end (the Received Signal Strength Indicator or RSSI reading) and a carrier-sense threshold used as the noise floor corresponding to the channel being idle. A node determines that the channel is busy when the instantaneous RSSI reading is larger than its carrier-sense threshold. In addition, each packet begins with preamble sequence, such that there is a high likelihood that a transmission is taking place if the radio decodes a preamble.

Fig. 1 illustrates the use of carrier tones during a successful collision-avoidance (CA) handshake. In the example shown in the figure, σ is the time needed to detect a carrier tone and τ is the propagation delay, d is a delay introduced by the sender of a data packet to prevent collisions with RTS transmissions, δ is the length of a data packet, and γ is the length of an RTS.

Fig. 1. Use of carrier tones for collision avoidance in CTMA/CAD

A receiver transmits a *receiver tone* (RT) to protect the reception of a data packet, and transmits its RT as soon as it receives an RTS. A sender transmits its data packet after a short delay of d seconds following its detection of the RT from the receiver. In turn, the receiver stops transmitting its RT after it receives the data packet correctly and transmits a short *acknowledgment tone* (AT) after a short delay of σ seconds. CTMA/CAD takes full advantage of physical-layer carrier sensing. The time it takes to detect carrier in the data channel at the physical layer (ξ) is smaller than γ , because carrier is detected using the preambles of RTS's. Hence, a node that detects carrier in the data channel sets its control-channel transceiver to the transmit mode before an entire RTS is received. As a result, a receiver does not incur any turnaround latency in sending an RT.

Figure 2 illustrates the use of carrier tones for collision detection for the case of a fully-connected network. A collision tone (CT), is used to emulate CSMA/CD using half-duplex transceivers. The full-duplex operation of transceivers needed for CSMA/CD is replaced by the transmission of CT's in the control channel by passive listeners.

Based on the carrier-sensing methods used at the physical layer, a node listening to the data channel assumes that a collision is taking place when its RSSI reading indicates the presence of transmissions and the node is not able to decode a valid preamble. The time needed to detect carrier and the occurrence of a collision (ξ) is necessarily shorter than the

length of an entire RTS packet, because it is done as part of the processing of the packet headers required at the physical layer to map frames onto the transmission medium (e.g., the Physical Layer Convergence Procedure or PLCP in IEEE 802.11). A node listening to the data channel that detects the presence of an invalid packet transmission in the data channel transmits a CT in the control channel that lasts at most a maximum propagation delay plus the time needed for a node to detect a tone (i.e., $\tau + \sigma$). On the other hand, a node that receives a CT in the control channel while transmitting an RTS in the data channel aborts its transmission immediately and transitions to the BACK-OFF state.

Fig. 2. Use of carrier tones for collision detection in CTMA/CAD

Figure 3 illustrates the state machine of non-persistent CTMA/CAD, in which a transmitter backs off immediately after detecting carrier or a tone. It is assumed that a single 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 that is long enough to ensure that a node entering an ad-hoc network learns about ongoing packet transmissions if they exist. After that time, the node transitions to the PASSIVE state. Once a node is in PASSIVE state, it listens to the control channel for the presence of any transmission tone.

Fig. 3. Non-persistent CTMA/CAD

A node in the BACK-OFF state computes a random back-off time and transitions to the passive state after that time has elapsed. The back-off time is longer than the time needed for an RTS-RT-data-AT exchange to take place assuming the maximum allowed data packet. A back-off discipline can be used to account for unsuccessful retransmission attempts for the same data packet and limit congestion.

A node in the PASSIVE state with no local packet to send transitions to the WAIT state if it either decodes an RTS for

another node or detects a tone other than an AT. Alternatively, a node in the PASSIVE transitions to the BACK-OFF state if it receives a local packet to send and decodes an RTS for another node or detects a tone other than an AT.

A node in the WAIT state that detects the collision of RTS's transmits a CT as described above (see Fig. 2) and transitions to the BACK-OFF state if it has a local packet to send or to the PASSIVE state if it does not have a local packet to send. If a node in the WAIT state does not detect a collision of RTS's and a timeout (TO) expires or it detects an AT, then the node transitions to the BACK-OFF state if it has a local packet to send, or to the PASSIVE state otherwise. The TO in the WAIT state is long enough for an RTS-RT-data-AT exchange to take place assuming the maximum allowed data-packet length.

If a node in the PASSIVE state receives a local packet to send and detects no carrier in the data channel and no tone in the control channel, then it starts sending an RTS to the intended receiver and transitions to the SEND state.

A node in the SEND state aborts its RTS transmission and transitions to the BACK-OFF state if it detects any carrier tone in the control channel. A node that completes its RTS transmission also transitions to the BACK-OFF state if it either detects no RT after a TO or detects a carrier tone other than an RT. On the other hand, the node transitions to the DATA state if it detects an RT in the control channel after completing its RTS transmission.

Once in the DATA state, a node waits for d seconds before sending its data packet in the data channel to the receiver. The purpose of the delay in sending the data packet is to avoid the possibility of MAI from RTS's sent by neighboring nodes. For this purpose, $d \geq 2\tau$, i.e., d is at least one maximum round-trip time. The node transitions to the PASSIVE state if it receives an AT over the control channel, or to the BACK-OFF state if it does not receive an AT within a TO that is long enough to allow the AT to be decoded.

If a node in the PASSIVE state decodes an RTS for itself with no carrier tone present in the control channel (shown simply as "RTS to self" in Fig. 3), it starts transmitting an RT in the control channel and transitions to the RECEIVE state.

A node in the RECEIVE state remembers whether or not it has a local packet to send. The node stops transmitting its RT and transmits a short AT if it receives the expected data packet. The node then 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. Similarly, the node stops transmitting its RT and transitions to the PASSIVE or BACK-OFF state depending on whether it has a packet to send if a RECEIVE TO elapses with no data packet received from the transmitter. The length of the TO in the RECEIVE state is long enough for the node to start decoding a valid data packet.

IV. THROUGHPUT ANALYSIS

We analyze the non-persistent version of CTMA/CAD using the traffic model first introduced by Kleinrock and Tobagi [9]. There is a large number of stations that constitute a Poisson source sending RTS's to the the channel with an aggregate

rate of λ packets per unit time. Each node is assumed to have at most one data packet to send at any time, and 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 of RTS's or data packets 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 or busy tones perfectly, and the probability of false busy-tone detection is 0. The time required to detect any type of tone or the presence of overlapping tones is σ . The transmit-to-receive and receive-to-transmit turn-around times in the data channel and a control channel is ω . The transmission time of a data packet is δ and the transmission time of an RTS packet is γ .

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 channel utilization of the channel is given by [9]

$$S = \frac{\bar{U}}{\bar{B} + \bar{I}}. \quad (1)$$

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

Due to space limitations, we consider only 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 the worst-case performance scenario for channel-access schemes based on carrier sensing or tone detection. However, it provides valuable insight on the efficacy of protocols under hidden terminals.

A. CTMA/CAD

Figure 4 illustrates the collision intervals that may occur in non-persistent CTMA/CAD in our star-network scenario. What is most striking in this example is that the length of an RCI resulting from the concurrent transmission of multiple RTS's is bounded and defined by the length of the time interval between the arrival of the RTS that starts the RCI and the arrival of the first RTS that causes interference. By contrast, a collision interval in CSMA under the same scenario would consist of an unbounded train of overlapping packet transmissions, because sources cannot sense the carrier from other transmissions.

The bounded length of RCI's in the presence of hidden terminals is made possible in CTMA/CAD by the feedback provided by any passive listeners to sources hidden from one another while they are transmitting their RTS's. A passive listener is any node that is not engaged in sending an RTS

and transmits a CT as soon as it detects that the transmission taking place in the data channel does not correspond to a valid RTS. In our case, there is no need for any node other than r to monitor the occurrence of RTS collisions. The central receiver r becomes the designated passive listener for all RTS transmissions, because traffic is being sent to it.

Fig. 4. RTS collision interval with hidden terminals in CTMA/CAD

Theorem 3: The throughput of CTMA/CAD with a non-persistent transmission strategy at a central receiver r with a large population of sources hidden from each other is

$$S_{CTMA/CAD} = \frac{\delta}{\delta + H + e^{\lambda\gamma}\zeta^{-1}(\frac{2}{\lambda} + \sigma + \xi + 3\tau)} \quad (2)$$

where $H = \gamma + \zeta^{-1}(d + a + \tau - \xi - \frac{1}{\lambda})$.

Proof: The average length of an idle period $\bar{I}$ in CTMA/CAD is simply the average inter-arrival time of RTS's into the channel, which equals $1/\lambda$ because inter-arrival times are exponentially distributed with parameter λ .

A busy period is either an RTS collision interval (RCI) as illustrated in Fig. 4 or a successful RTS-RT-DATA-AT handshake, as illustrated in Fig. 1. Given the assumption that all the sources transmitting to the central receiver r are hidden from one another, r receives an RTS without MAI if no other RTS is sent during its transmission. Therefore, a successful handshake of T seconds occurs with probability $P_S = e^{-\lambda\gamma}$.

An RCI occurs if the first RTS of the interval suffers MAI, which occurs with probability $1 - P_S$. In this case, receiver r detects that the signal it starts receiving τ seconds after the start of the RCI does not correspond to a valid packet once it starts receiving the pilot signal from the first interfering RTS. Hence, receiver r transmits a CT at time $Z + \tau + \xi$, where Z is a random variable representing the time interval between the arrival of the RTS that starts the RCI and the arrival of the first interfering RTS. Z takes values in the interval $[0, \gamma]$ because sources are hidden from one another and hence the vulnerability period of the first RTS of an RCI is the entire length of the RTS. Each node transmitting an RTS detects the CT from r at time $Z + \xi + \sigma + 2\tau$ and must abort its RTS transmission. As illustrated in Fig. 4, given that a CT lasts $\tau + \sigma$ seconds, the length of an RCI is given by $C = Z + \xi + \sigma + 3\tau$.

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 (CDF) of Z is

$$F_Z(z) = P(Z \leq z) = 1 - P(Z > z) = 1 - e^{-\lambda z} \quad (3)$$

Z assumes non-negative values, and hence its mean can be computed using $F_Z(z)$ in Eq. (3) as follows:

$$\bar{Z} = \int_0^\infty (1 - F_Z(t))dt = \int_0^\gamma e^{-\lambda t} dt = \frac{1}{\lambda} (1 - e^{-\lambda\gamma})$$

Because a node is able to determine if a transmission in the data channel is valid before an entire RTS is received, the receiver can set its transceiver for the control channel in the transmit mode well before it receives the entire RTS in the data channel. Therefore, it does not incur a turnaround delay after the RTS before transmitting its RT. The sender starts transmitting its data packet after it receives and detects the RT from the receiver, plus the added delay of d seconds imposed to avoid collisions. In addition to propagation delays for packets and carrier tones, the duration T of a successful transmission period in CTMA/CA includes Z , because RTS arrivals are Poisson and hence the case of $Z = 0$ only occurs when the first interfering RTS is the same as the first RTS of a busy period. Therefore,

$$T = Z + \gamma + \sigma + d + \delta + a + 4\tau. \quad (4)$$

The average length of a busy period ($\bar{B}$) is given by

$$\begin{aligned} \bar{B} &= \bar{Z} + (1 - e^{-\lambda\gamma})(\xi + \sigma + 3\tau) + e^{-\lambda\gamma}(T) \\ &= \bar{Z} + \xi + \sigma + 3\tau + e^{-\lambda\gamma}(\gamma + d + \delta + a + \tau - \xi) \end{aligned} \quad (5)$$

Substituting $\bar{Z}$ in Eq. (5) we have

$$\bar{B} = e^{-\lambda\gamma} \left(\gamma + d + \delta + a + \tau - \xi - \frac{1}{\lambda} \right) + \sigma + \xi + 3\tau + \frac{1}{\lambda}$$

We account for the reduced data-channel capacity resulting from the use of a control channel using ζ of the available bandwidth by normalizing packet transmission times relative to the length of a data packet using the entire available bandwidth. We obtain Eq. (2) by substituting the values of $\bar{U}$, $\bar{B}$, and $\bar{I}$ into Eq. (1), and multiplying the length of packet sent over the data channel by ζ . $\square$

B. DBTMA

Fig. 5 illustrates the transmission periods that can occur in DBTMA in the hidden-terminal scenario we consider. These periods are successful transmission periods during which data packets are sent to r as part of successful CA handshakes, or RCI's resulting from the collision of two or more RTSs sent to receiver r . We assume that a receiver transmits receiver busy tone until it is done with the transmission of its ACK. A receiver incurs a turnaround delay in transmitting its receiver tone because nodes must listen to the two control channels for the presence of busy tones. In addition, a receiver also incurs a turnaround delay in sending its ACK after processing a data packet from a sender. A sender transmits its data packet after a delay equal to a maximum round-trip delay according to the description of DBTMA in [6].

The vulnerability period of an RTS is its entire duration, because a source decides to transmit its RTS if it does not detect a sender busy tone or a receiver busy tone, and sources cannot hear the busy tones from each other in the scenario we consider. This is because the feedback provided to sources hidden from one another can only come from intended receivers in the form of receiver busy tones after the receivers decode valid RTS's. In the star-network scenario we consider,

r is able to inform hidden sources of the fact that a valid RTS was received, but not about the occurrence of RTS collisions. As a result, in contrast to the case of CTMA/CAD, an RCI is an unbounded sequence of RTS inter-arrival times and an RTS length followed by a propagation delay, as illustrated in Fig. 5.

Fig. 5. Transmission periods in non-persistent DBTMA with hidden terminals

Theorem 4: The throughput of non-persistent DBTMA at a central receiver r with a very large population of sources hidden from each other and with only β (with $0 < \beta < 1$) of the total available bandwidth being used for the data channel is

$$S_{DBTMA} = \frac{\delta}{\delta + B + \beta^{-1}e^{\lambda\gamma} \left(\tau + \frac{1}{\lambda}(e^{\lambda\gamma}) \right)} \quad (6)$$

where $B = \alpha + \beta^{-1}(2\omega + \sigma + 5\tau)$

Proof: As illustrated in Fig. 5, a busy period in DBTMA consists of one or multiple RTS transmissions, and a successful transmission period between a source and receiver r corresponds to a busy period with a single RTS. An RTS is successful probability $P_S = e^{-\lambda\gamma}$, because an RTS is vulnerable for its entire duration. By the same token, a busy period with more than one RTS transmission is an RCI and occurs with probability $1 - P_S$.

For a busy period to have k RTS transmissions, there must be an RTS arriving during the transmission time of each of the first $k - 1$ RTS's and no RTS arriving during the transmission time of the last RTS in the busy period. Accordingly, with our simplifying assumption of an essentially infinite number of sources, the number of RTS's in a busy period (N_R) is random variable that is geometrically distributed with the probability of successfully ending the busy period being the probability that no RTS arrives during the γ seconds of the RTS transmission, or $e^{-\lambda\gamma}$. Hence, the average number of RTS's in a busy period is $\bar{N}_R = e^{\lambda\gamma}$.

The inter-arrival times between consecutive RTS's in a busy period are exponentially distributed and each can be at most γ seconds. Therefore, the average of such times is

$$\bar{X} = \int_0^\infty (1 - F_X(t))dt = \int_0^\gamma e^{-\lambda t}dt = \frac{1}{\lambda} (1 - e^{-\lambda\gamma}) \quad (7)$$

The length T of a successful transmission periods equals

$$T = \delta + \gamma + \alpha + 2\omega + \sigma + 6\tau \quad (8)$$

A busy period has a single RTS only or the case of a successful transmission period that lasts $T - (\gamma + \tau)$ seconds

beyond the RTS itself and its propagation, and this occurs with probability P_S . Accordingly, from Eqs. (7) and (8), the length of an average busy period is

$$\bar{B} = \frac{1}{\lambda}(e^{\lambda\gamma} - 1) + \tau + e^{-\lambda\gamma}(\delta + \alpha + 2\omega + \sigma + 5\tau) \quad (9)$$

The proportion of time that the channel is used for data during a successful handshake is $\bar{U} = \delta P_S = \delta e^{-\lambda\gamma}$. On the other hand, $\bar{I} = 1/\lambda$ because RTS arrivals are Poisson distributed. Substituting the values of $\bar{U}$, $\bar{I}$, and $\bar{B}$ into Eq. (1) and multiplying each packet length by β to normalize it with respect to a data packet using the entire bandwidth, we obtain Eq. (6). $\square$

V. PERFORMANCE COMPARISON

We assume that the data rate is 1 Mbps for the entire available bandwidth, and that an RTS and an ACK lasts 352 bits including the MAC and the physical-layer headers. We also assume that ω is $10\mu s$, which agrees with the characteristics of half-duplex transceivers available today. We assume that DBTMA and the CTMA protocols use the majority of the available bandwidth for the data channel. More specifically, we assume that DBTMA uses 90% of the bandwidth for the data channel and the CTMA protocols use 95% of the bandwidth for the data channel. Accordingly, we set $\zeta = .95$ for CTMA/CA and CTMA/CAD, and $\beta = .9$ for DBTMA. The busy-tone detection time σ in CTMA and DBTMA is set to $50\mu s$. We make the conservative assumption that ξ equals 100 bit times in the data channel, which corresponds to a large portion of the PLCP preamble in IEEE 802.11.

These assumptions provide a fair baseline for comparing the performance of CTMA/CAD with DBTMA.

Fig. 6. S vs. G with hidden terminals

Fig. 6 shows the throughput of CTMA/CAD and DBTMA based on Eqs. (2) and Eq. (6), as well as the throughput of ALOHA. Physical distances are around 500 meters, and the duration of a data packet is 1500 bytes including the physical and MAC-layer headers, which corresponds to an average-length IP packet and takes 0.012s to transmit at 1 Mbps. We use a normalized propagation delay of 1×10^{-4} .

The results clearly show that CTMA/CAD provides a marked improvement over DBTMA, which results from the transmission of CT's by passive listeners when they perceive the occurrence of RTS collisions. Interestingly, CSMA/CA would exhibit similar throughput than DBTMA because collision intervals also consist of unbounded trains of colliding RTS's. The throughput of CSMA with hidden terminals would be worse than the throughput of ALOHA. The price paid for the efficiency of CTMA/CAD is the possibility of many passive listeners sending CT's when RTS collisions occur.

VI. CONCLUSIONS AND FUTURE WORK

We introduced CTMA/CAD and described how it uses three types of carrier tones to avoid collisions of data packets with other transmissions, inform transmitters of successful packet receptions, and alert nodes about RTS collisions. We compared the throughput attained with CTMA/CAD with the throughput of DBTMA for a worst-case scenario of hidden terminals in which no source can hear other sources when transmitting to a central receiver. Our results show that CTMA/CAD renders better results compared to DBTMA, which requires two busy-tone radios and two busy-tone channels. Our future work focuses on analyzing the performance of CTMA in more complex models of networks with hidden terminals, and the design of distributed algorithms that reduce the number of nodes that act as designated listeners sending collision tones when RTS collisions occur.

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