Busy-Tone Multiple Access with Collision Avoidance and Detection for Ad-Hoc Networks

J.J. Garcia-Luna-Aceves
Computer Science and Engineering Department, University of California, Santa Cruz, CA 95064
PARC, Palo Alto, CA 94304
jj@soe.ucsc.edu

***Abstract*—Busy-Tone Multiple Access with Collision Avoidance and Detection (BTMA/CAD) is introduced. BTMA/CAD integrates collision avoidance and collision detection mechanisms in ad-hoc networks of nodes with half-duplex radios by means of a single busy tone transmitted over an orthogonal narrowband channel. The throughput of BTMA/CAD is compared with that of Carrier-Sense Multiple Access (CSMA) and CSMA with Collision Avoidance (CSMA/CA) using an analytical model. It is shown that BTMA/CAD is more efficient than CSMA and CSMA/CA in ad-hoc 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, as it is an integral part of the IEEE 802.11 protocol standard. It is well known that the performance of a CSMA degrades in the presence of hidden terminals [10], because two or more transmitters around a receiver are unable to hear the transmission from one another, which renders carrier sensing useless.

Many approaches have been developed over the years to limit or eliminate the negative effects of multiple-access interference (MAI) due to hidden terminals in networks of nodes endowed with half-duplex radios, and some of these are based on the transmission of busy tones over secondary channels aimed at alerting potential sources that the data channel is busy. The first among these schemes was Busy-Tone Multiple Access (BTMA) [10]. Surprisingly, very few proposals based on busy tones have been reported since the introduction of BTMA. Some require time-slotted channels (e.g, [12]) while others (e.g., DBTMA [8]) need multiple control channels and hence multiple busy-tone radios per node. More recently, CTMA (Carrier-Tone Multiple Access) [5], [6] was introduced that requires no time slotting and in which a single control channel is used to transmit different types of busy tones. The limitation of the CTMA approach is that using multiple types of busy tones introduces complexity that, as we prove with the design of BTMA/CAD, is unnecessary.

This paper introduces **BTMA/CAD** (Busy-Tone Multiple Access with Collision Avoidance and Detection). The novelty in the design of BTMA/CAD compared to prior proposals based on secondary busy-tone radios is twofold. First, it uses a single type of busy tone sent over a narrowband busy-tone channel that is orthogonal to the data channel to ensure that both variable-length data packets and acknowledgments (ACK) are received without multiple access interference (MAI). This makes BTAM/CAD as simple to implement than the original BTMA proposal, which is cheaper than using two busy-tone radios as required in DBTMA and avoids the need for clock synchronization assumed in RI-BTMA. Second, it emulates collision detection (CD) using only a half-duplex transceiver for data and a half-duplex transceiver for busy tones. Consequently, its implementation is much simpler and cheaper than using full-duplex transceivers required in some prior schemes [4].

Section II describes BTMA/CAD. Its design is inspired by Tobagi and Kleinrock's seminal busy-tone solution to combat hidden terminals [10], prior results on collision avoidance and collision detection in wireless networks [4], and prior protocols based on the use of multiple busy tones [8], [5]. BTMA/CAD uses a data channel and an orthogonal narrowband busy-tone channel, and relies on a half-duplex transceiver 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 busy tone (BT) over the busy-tone channel. Once the sender detects a BT in the busy-tone channel, it transmits its data packet after a short delay. In turn, the receiver responds to the data packet by continuing its BT for a period of time that is long enough to inform the sender that the BT conveys an acknowledgment (ACK) for its data packet. In addition, BTMA/CAD takes advantage of BT's to emulate collision detection using only half-duplex transceivers. A listening node that detects the collision of RTS's in the data channel transmits a BT in the busy-tone channel, which forces those nodes transmitting RTS's that hear the BT to abort their transmissions.

Sections III and IV analyze and compare the throughput of BTMA/CAD, CSMA with ACK's and CSMA/CA. We use an analytical model to provide insight on the worst-case hidden-terminal scenario for BTMA/CAD. Our analysis favors CSMA and CSMA/CA over BTMA/CAD because it uses a hidden-terminal scenario that prevents collisions of ACK's with data packets at the intended receivers for the case of CSMA and CSMA/CA and hence provides an upper-bound on their performance. Nevertheless, the results of the analysis show that BTMA/CAD is far more efficient than CSMA or CSMA/CA. Section V presents our conclusions.

II. BTMA/CAD

The objectives in the design of BTMA/CAD are to: (a) Allow the use of half-duplex transceivers; (b) eliminate multiple access interference on data packets; (c) reliably inform senders when their packets are received successfully; and (d) emulate collision detection (CD) to limit the impact of RTS collisions.

BTMA/CAD uses a data channel and an orthogonal narrow-band busy-tone channel. Data and RTS packets are sent over the data channel, and bust tones are sent over the busy-tone channel. How a node interprets a busy tone is driven by the state of the node when it receives the busy tone.

We assume that carrier sensing in the data channel is based on preamble detection and energy detection, given that both techniques are well established today. 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.

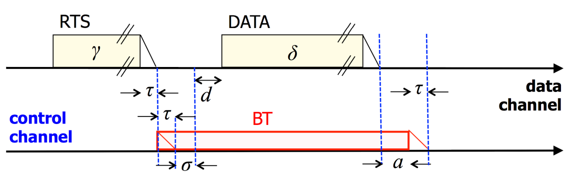

Fig. 1. Using a busy tone for collision avoidance

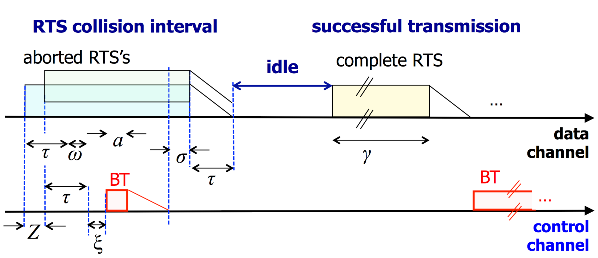

Fig. 2. Using a busy tone for collision detection

Figure 1 illustrates how BTMA/CAD uses a busy tone for CA. In the example shown in the figure, σ is the time needed to detect a carrier tone and τ is the propagation delay in both channels, 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.

The time needed by a node to detect the presence of carrier in the data channel is much smaller than the time needed to transmit the preamble of an RTS for any specific physical layer. Furthermore, a node that is transmitting an RTS sets its busy-tone radio in receive mode, while a node that is listening to the data channel sets its busy-tone radio in transmit mode. This means that the receiver of an RTS can send a busy tone without incurring any turnaround latency.

Once the sender of an RTS detects a busy tone, it transmits its data packet after a short delay of d seconds. In turn, after receiving a data packet correctly, the receiver continues transmitting its busy tone for an additional short period lasting a seconds. After the sender completes the transmission of its data packet, it interprets the presence of a busy tone for a period of time longer than a seconds (which is due to propagation delays) as an ACK from the receiver.

Figure 2 illustrates the use of a busy tone to emulate collision detection in BTMA/CAD taking advantage of carrier detection in the data channel. A passive 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 much shorter than the length of the entire RTS, because it is done as part of the processing of the packet header required at the physical layer to map frames onto the transmission medium (e.g., the Physical Layer Convergence Procedure (PLCP) in IEEE 802.11). As the figure shows, a node listening to the data channel that detects the presence of an invalid packet transmission in the data channel transmits a busy tone for a seconds in the busy-tone channel. On the other hand, a node that receives a busy tone while transmitting an RTS in the data channel aborts its transmission immediately and transitions to the BACK-OFF state.

Figure 3 illustrates the state machine of non-persistent BTMA/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.

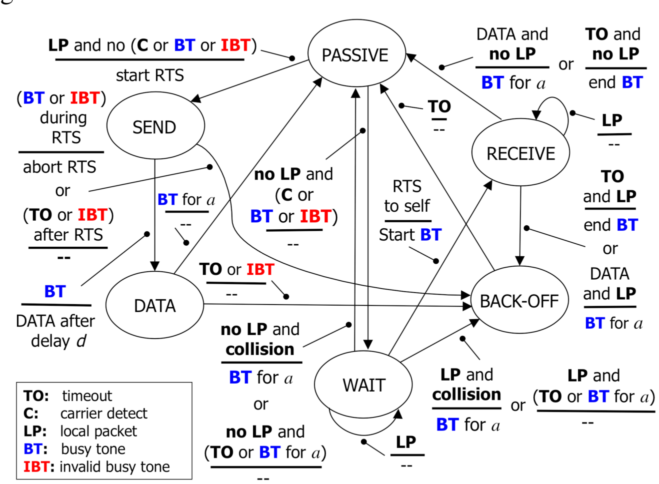

Fig. 3. Non-persistent BTMA/CAD

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 busy-tone channel for the presence of any transmission tone.

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 node in the PASSIVE state with no local packet to send transitions to the WAIT state if it carrier, a busy tone, or noise in the busy-tone channel (invalid busy tone). A node in the WAIT state that detects the collision of RTS's transmits a busy tone for a seconds 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.

If a node in the WAIT state does not detect a collision of RTS's and a timeout (TO) expires or it detects a busy tone for a seconds, 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 a CA handshake to take place assuming the maximum lengths of data packets, propagation delays, and turnaround times.

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

A node in the SEND state aborts its RTS transmission and transitions to the BACK-OFF state if it detects any busy tone. A node that completes its RTS transmission 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 a busy tone 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 a busy tone for more than a seconds, or to the BACK-OFF state if it does not.

If a node in the WAIT state decodes an RTS for itself and no busy tone is present in the busy-tone channel (shown simply as "RTS to self" in Fig. 3), it starts transmitting a busy tone 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 keeps transmitting its busy tone for a seconds after 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 busy tone and transitions to the PASSIVE or BACK-OFF state depending on whether it has a packet to send if a timeout elapses with no data packet received from the transmitter. The length of the timeout in the RECEIVE state is long enough for the node to start decoding a valid data packet.

III. Throughput Analysis

We analyze BTMA/CAD and CSMA/CA 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 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. 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 busy-tone 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]

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

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 an average busy period that the channel is used for transmitting user data successfully.

We analyze the throughput of BTMA/CAD and CSMA/CA in a star network configuration in which all traffic is sent to a central receiver r and all nodes other than r are hidden from one another. This scenario provides valuable insight on the efficacy of the two protocols under hidden terminals, because it renders carrier sensing useless for both protocols. In general, ACK's can collide with data packets in CSMA/CA; however, our scenario favors CSMA/CA over BTMA/CAD in that no such collisions can occur given that receiver r is the only node that can send ACK's to data packets sent to it.

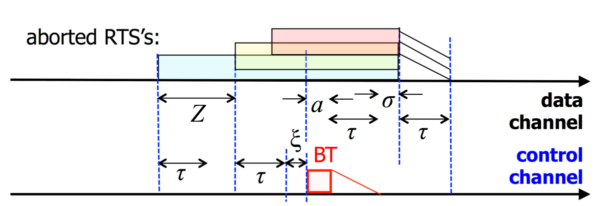

Fig. 4. Example collision interval in BTMA/CAD with hidden sources

1) BTMA/CAD: Fig. 4 illustrates a collision interval (CI) in our star-network scenario with non-persistent BTMA/CAD. We observe that the length of a CI 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 CI and the arrival of the first RTS that causes interference. By contrast, a collision interval in CSMA/CA under the same scenario consists of an unbounded train of overlapping RTS transmissions, because sources cannot sense the carrier from other RTS's.

The bounded length of CI's in the presence of hidden terminals is made possible in BTMA/CAD by the feedback provided over the busy-tone channel by passive listeners to sources hidden from one another while they are transmitting their RTS's. In our scenario, the central receiver r serves as the passive listener for all RTS transmissions, because all traffic is being sent to it.

Theorem 1: The throughput of BTMA/CAD with a non-persistent transmission strategy at a central receiver r with a large population of sources hidden from each other is

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

where $H = \delta + \gamma + \zeta^{-1}\left(d + 2\tau - \xi - \frac{1}{\lambda}\right)$.

Proof: Given that RTS arrivals are Poisson distributed with parameter λ, the average inter-arrival time of RTS's is $1/\lambda$ and hence the average length of an idle period is $\overline{I} = 1/\lambda$. A busy period is either an RTS collision interval (CI) as illustrated in Fig. 4 or a successful CA handshake, as illustrated in Fig. 1.

As Fig. 1 illustrates, if an RTS is sent without MAI, then the receiver starts transmitting a busy tone, the sender transmits its data packet, and the receiver continues transmitting its busy tone for a seconds after it receives the entire data packet. A node that is not sending an RTS or has sent an RTS has its busy-tone radio in transmit mode; therefore, it does not incur a turnaround delay to transmits its busy tone after receiving an RTS for itself. The sender starts transmitting its data packet after it receives and detects the busy tone from the receiver, plus the added delay of d seconds imposed to avoid collisions. By assumption, packets and busy tones propagate in τ seconds. Accordingly, the duration of a successful transmission period in BTMA/CAD equals

$$T = \gamma + \sigma + d + \delta + a + 4\tau. \qquad (3)$$

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 $P_S = e^{-\lambda\gamma}$.

A CI 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 CI does not correspond to a valid packet once it starts receiving the pilot signal from the first interfering RTS. Hence, receiver r transmits a busy tone at time $Z + \tau + \xi$, where Z is a random variable representing the time interval between the arrival of the RTS that starts the CI 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 in a CI is its entire length. Each node transmitting an RTS detects the busy tone from r at time $Z + \xi + \sigma + 2\tau$ and must abort its RTS transmission immediately (see Fig. 4). Given that the busy tone from r lasts a seconds, the length of a CI is given by

$$C = Z + \xi + a + \sigma + 2\tau \qquad (4)$$

The case of $Z = 0$ occurs when the transmission period is successful, because RTS arrivals are Poisson distributed. Accordingly, the average length of a busy period ($\overline{B}$) is

$$\overline{B} = \overline{Z} + (1 - e^{-\lambda\gamma})(\xi + a + \sigma + 2\tau) + e^{-\lambda\gamma}(T) \qquad (5)$$

For Z to last more than z seconds, no arrival can occur in the first z seconds of a collision interval, that is,

$$P(Z > z) = P\{\text{no arrivals in } [0, z]\} = e^{-\lambda z}.$$

Given that Z assumes non-negative values, its mean can be computed as follows:

$$\overline{Z} = \int_0^\gamma P(Z > z)dt = \int_0^\gamma e^{-\lambda t}dt = \frac{1}{\lambda}\left(1 - e^{-\lambda\gamma}\right)$$

Substituting $\overline{Z}$ and Eq. (3) in Eq. (5) we have

$$\overline{B} = e^{-\lambda\gamma}\left(\delta + \gamma + d + 2\tau - \xi - \frac{1}{\lambda}\right) + \frac{1}{\lambda} + a + \sigma + \xi + 2\tau$$

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

2) Non-Persistent CSMA/CA: We make two simplifying assumptions for CSMA/CA in the star configuration. We assume that $\omega > \tau$, which is consistent with the distances assumed for IEEE 802.11 and the physical-layer parameters of half-duplex transceivers available today. We also assume that the lengths of RTS's, CTS's and ACK's are the same. In IEEE 802.11, the actual length of a CTS or an ACK is slightly shorter than the length of an RTS, but only by a few bit times, which does not impact the analysis.

As Fig. 5 shows, the types of transmission periods that may occur in CSMA/CA with the assumptions we have made are: successful CA handshakes, RTS collision intervals, and idle transmission periods. The following theorem provides the throughput of CSMA/CA.

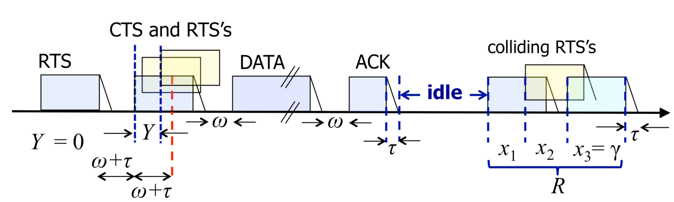

Fig. 5. Example transmission periods in CSMA/CA with hidden sources

Theorem 2: The throughput of non-persistent CSMA/CA at a central receiver r with a very large population of sources hidden from each other is

$$S_{CSMA/CA} = \frac{\delta}{\delta + 3(\gamma+\omega+\tau) + \frac{1}{\lambda} + e^{\lambda\gamma}\left(\tau + \frac{1}{\lambda}(e^{\lambda\gamma}-1)\right)} \quad (6)$$

Proof: A busy period is either an RTS collision interval or a successful CA handshake as illustrated in Fig. 5.

Receiver r receives an RTS without MAI if no other RTS is sent during its transmission because all sources are hidden from one another. Therefore, a successful handshake of T seconds occurs with probability $P_S = e^{-\lambda\gamma}$.

If r obtains an RTS without MAI from a given neighbor, it can transmit a CTS to that neighbor and receive its data packet without MAI even when other neighbors transmit RTS's to r concurrently. This is because the additional RTS's sent to r must be transmitted within $\tau+\omega$ of the start of the CTS from r, after which all neighbors of r must detect carrier from the CTS. Given that $\omega > \tau$ by assumption, receiver r is unable to detect the overlapping RTS transmissions. On the other hand, the neighbors of r are hidden from each other and the neighbor that sent the first RTS is able to decode the CTS from r successfully. As a result, if an RTS is sent without MAI with probability P_S, the length of time Y between the CTS send by r and the last RTS sent to r concurrently (see Fig. 5) has no impact on the success of the CA handshake or the duration of the busy period. Accordingly, we have $T = \delta + 3\gamma + 3\omega + 4\tau$.

An RTS collision interval (RCI) consists of a sequence of complete RTS transmissions and all the neighbors of receiver r may participate in the RCI. This results from the fact that the vulnerability period of an RTS is its entire transmission time. An RCI takes place if the first RTS of the interval suffers MAI with probability $1-P_S$. Each 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 the RTS's.

For an RCI to have k RTS's, 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 RCI. Given our simplifying assumption of an essentially infinite number of sources 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 of the RTS transmission, or $e^{-\lambda\gamma}$. Hence, 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 of such times is

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

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

$$\overline{R} = e^{\lambda\gamma}\overline{X} = \frac{e^{\lambda\gamma}}{\lambda}\left(1-e^{-\lambda\gamma}\right) = \frac{e^{\lambda\gamma}-1}{\lambda} \quad (8)$$

The average length of a busy period is simply

$$\overline{B} = Te^{-\lambda\gamma} + (\overline{R}+\tau)(1-e^{-\lambda\gamma}) \quad (9)$$

Substituting T and Eq. (8) in Eq. (9) we have

$$\overline{B} = e^{-\lambda\gamma}\left(\delta + 3(\gamma+\omega+\tau) + \frac{1}{\lambda}\right) + \tau + \frac{e^{\lambda\gamma}-2}{\lambda}$$

The proportion of time that the channel is used for data during a successful handshake is $\overline{U} = \delta P_S = \delta e^{-\lambda\gamma}$, and the length of an average idle period is the same as the average inter arrival time of RTS's $\overline{I} = 1/\lambda$. Substituting the values of $\overline{U}$, $\overline{I}$, and $\overline{B}$ into Eq. (1) we obtain Eq. (6). ■

3) Non-Persistent CSMA with ACK's: The types of transmission periods that may occur in CSMA with the assumptions of a central receiver and sources hidden from one another are successful transmissions, collision intervals, and idle transmission periods. However, packet transmissions from hidden sources may be sent to the central receiver while the receiver transmits its ACK for a prior data packet received correctly as well as after the ACK is sent. The following theorem states the throughput of CSMA with ACK's under the assumptions we have made.

Theorem 3: The throughput of non-persistent CSMA with ACKs at a central receiver r with a very large population of sources hidden from each other is

$$S_{CSMA} = \frac{\delta}{\delta + 2\tau + \frac{1}{\lambda} + Ue^{\lambda\delta} + Ve^{-\lambda\omega} + (\omega+\gamma)e^{-\lambda(\omega+\tau)}} \quad (10)$$

where

$$U = \tau + \frac{e^{\lambda\delta} - e^{-\lambda(\omega+\tau)}}{\lambda} \quad \text{and} \quad V = \frac{e^{-\lambda(\omega+\tau)}-1}{\lambda}$$

Proof: The proof is presented in [7]. ■

IV. Performance Comparison

We assume that the channel data rate is 1 Mbps for the entire available bandwidth, and that the length of an RTS, CTS, or an ACK is 360 bits including the MAC and PLCP headers. The length of a data packet is set to 1500 bytes, which together with the PLCP header corresponds to 12,200 bits. We set ω equal to 2μs, which is consistent with the characteristics of modern half-duplex transceivers available today.

We assume that BTMA/CAD uses the majority of the available bandwidth for the data channel. More specifically, we assume that BTMA/CAD uses 95% of the bandwidth for the data channel and set $\zeta = .95$. The busy-tone detection time σ is set to 50 μs, which results in a probability of correct busy-tone detection close to 1 [10]. Furthermore, $a = \sigma$, given that nodes simply need to detect a busy tone to discern an ACK or a collision from it.

The time needed to detect carrier and a collision in BTMA/CAD (ξ) equals 144 bit times, which corresponds to the transmission time of the PLCP preamble for direct sequence spread spectrum (DSSS) in IEEE 802.11. Furthermore, we assume that the carrier-detection time is negligible, which favors CSMA and CSMA/CA.

We normalize the results to δ and use a normalized propagation delay of 1×10^{-4}, which corresponds to a few hundred meters of distance between neighboring nodes. Using these parameters, we compare the throughput (S) versus the offered load (G) of channel-access protocols.

Fig. 6 shows the throughput of BTMA/CAD, CSMA/CA, CSMA with ACKs and ideal ALOHA with hidden terminals based on Eqs. (2), Eq. (6), and Eq. (10). We also include the well-known throughput of ideal ALOHA with no ACKs as a reference point.

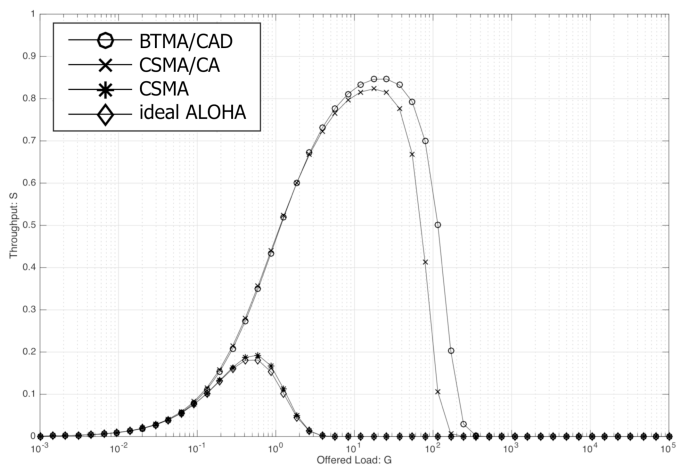

Fig. 6. S vs. G with hidden terminals

The results clearly show that BTMA/CAD provides higher throughput than CSMA/CA at higher loads in the presence of hidden terminals. This is a consequence of the transmission of a busy tone by a passive listener when it perceives the occurrence of RTS collisions, which limits the length of collision intervals and emulates collision detection even with hidden terminals being present.

It is important to note that our hidden-terminal scenario prevents MAI on the reception of ACKs from the central receiver at any one source. This biases the results in favor of CSMA/CA and CSMA compared with BTMA/CAD, because CSMA/CAD is able to eliminate MAI on data packets and ACKs independently of the network connectivity at senders and receivers. As predicted by Theorem 1, the performance degradation due to hidden terminals experienced by CSMA/CA and CSMA would be much more severe if multiple receivers were at play. However, even in this hidden-terminal scenario that favors CSMA/CA over BTMA/CAD, it is clear that the use of busy tones for CA and CD constitutes more efficient approach that attempting four-way CA handshakes over a single channel.

The results for CSMA with ACKs and CSMA/CA also illustrate the advantage of using CA compared to simply using carrier sensing in the presence of hidden terminals. The throughput of CSMA with ACKs degrades to almost that of ideal ALOHA with no ACKs. This performance degradation results from the fact that the vulnerability period of data packet is its entire transmission time, and this results in successful and unsuccessful busy periods to consist of trains of colliding data packets. The presence of priority ACKs that may force some hidden sources to back off and that cannot collide at their intended receivers in the star-network configuration we assume is what gives CSMA with ACKs a very small edge over ideal ALOHA.

V. Conclusions

We introduced BTMA/CAD and compared it with CSMA/CA and CSMA with ACKs in a scenario of hidden terminals in which no source can hear other sources when transmitting to a central receiver. Our results show that BTMA/CAD renders far better throughput compared to CSMA and CSMA/CA and that it is a viable approach to emulate collision detection even in the presence of hidden terminals.

The high efficiency of BTMA/CAD opens up interesting avenues for future research in channel access protocols for ad hoc networks. New research directions include: (a) Limiting the number of nodes that must transmit busy tones when RTS collisions occur, (b) using busy tones to improve the performance of channel-access protocols designed for multiple data channels or transmission scheduling [1], [3], (c) exploring directional transmissions over the data and busy-tone channels, (d) introducing the use of a secondary radio operating in an orthogonal narrowband channel in the context of ad-hoc networks using IEEE 802.11, and (e) comparing the throughput and energy consumption of BTMA/CAD against CSMA and CSMA/CA [2].

Acknowledgments

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