

Channel-Hopping Multiple Access

Asimakis Tzamaloukas and J.J. Garcia-Luna-Aceves
Computer Engineering Department
Baskin School of Engineering
University of California, Santa Cruz, California 95064
{jamal, jj}@cse.ucsc.edu

Abstract— The medium-access control (MAC) protocols for wireless networks proposed or implemented to date based on collision-avoidance handshakes between sender and receiver either require carrier sensing or the assignment of unique codes to nodes to ensure that intended receivers hear data packets without interference from hidden sources. We present and analyze a protocol that we call channel-hopping multiple access (CHMA) for multi-channel, ad-hoc networks which does not require carrier sensing or the assignment of unique codes to nodes to ensure collision-free reception of data at the intended receivers in the presence of hidden terminals. We compare CHMA against MACA-CT and show considerable improvement in the performance achieved. The correct avoidance of collisions in CHMA protocols is verified, and their throughput and delay characteristics is studied analytically. CHMA protocols are applicable to ad-hoc networks based on commercial off-the-shelf spread spectrum radios operating in unlicensed frequency bands.

I. INTRODUCTION

Medium-access control (MAC) protocols based on collision avoidance have received considerable attention over the past few years, because they are simple to use in wireless LANs and ad-hoc networks. The traditional collision-avoidance protocols, a node that needs to transmit data to a receiver first sends a request-to-send (RTS) packet to the receiver, who responds with a clear-to-send (CTS) if it receives the RTS correctly. A sender transmits a data packet only after receiving a CTS successfully. Several variations of this scheme have been developed since SRMA (split-channel reservation multiple access) was first proposed by Kleinrock and Tobagi [10], including IEEE 802.11 [1] and FAMA [3]. More recently, receiver-initiated collision-avoidance protocols have also been proposed for single-channel networks, in which the receiver initiates the collision-avoidance handshake [5], [9].

The need for collision-avoidance MAC protocols for single-channel networks to sense the channel as an integral part of the collision-avoidance handshake limits their applicability. Most commercial radios do not provide true carrier sensing, and direct sequence spread-spectrum (DSSS) radios may capture none or one of multiple overlapping transmissions depending on the proximity and transmission power of the sources. Even if frequency-hopping spread-spectrum (FHSS) radios are used, carrier sensing adds to the complexity of the radio, which has already to provide coarse time synchronization at the dwell-time level.

In the past, several MAC protocols have been proposed and analyzed that take advantage of spreading codes for multiple access. Sousa and Silvester [8] presented and analyzed various spreading-code protocols that are sender-, receiver- or sender-receiver based, i.e., in which codes are assigned to senders, receivers, or combinations. Gerakoulis et. al. [6] used carrier sensing to propose a receiver-based, asynchronous transmissions protocol. Several other proposals have been made to implement correct collision-avoidance in multi-hop networks without requiring nodes to use carrier sensing; these proposals rely on multiple codes assigned to senders, receivers or a combination of the two, to eliminate the need for carrier sensing (e.g., [2], [4], [7]). The limitation of protocols based on code assignments is that

senders and receivers have to find each others' codes before communicating with one another. Most of the commercial DSSS radios today use only 11 chips per bit therefore CDMA is not an option. On the other hand, according to the FCC regulations up to 15 FHSS radios can be co-located with minimum interference problems. In ad-hoc networks built with commercial radios operating in ISM bands, code assignments do not guarantee that receivers can capture one of multiple simultaneous transmissions.

Section II describes a new protocol that that operates over any spread spectrum modulation and does not require code assignments or carrier sensing. We call this new protocol CHMA (channel hopping multiple access). According to CHMA, all nodes in a network are required to follow a common channel-hopping sequence. A channel can be defined to be a frequency hop, a spreading code, or a combination of both. At any given time, all nodes that are not sending or receiving data listen on the common channel hop. To send data, nodes engage in a sender-initiated dialogue over the channel hop in which they are at the time they require to send data; those nodes that succeed in a collision-avoidance handshake remain in the same channel hop for the duration of their data transfer, while the rest of the nodes continue to follow the common channel hopping sequence. Section III proves that, in the absence of fading, CHMA protocol provides correct floor acquisition in a multi-hop network. Section IV analyzes the throughput in unslotted, multi-hop networks with CHMA. We compare CHMA with the MACA-CT protocol [7], which uses MACA collision-avoidance handshakes over a common channel and a transmitter-oriented data channel assigned to avoid collisions of data packets; we chose MACA-CT for our comparison, because it is essentially the same concept as that used in CHMA and is a good representative of collision-avoidance solutions that eliminate the need for carrier sensing at the expense of requiring unique channel assignments. Section V calculates the system delay in multi-hop networks for CHMA as well as MACA-CT. Section VI presents our conclusions.

II. CHANNEL-HOPPING PROTOCOLS

A. Basic Concepts in Channel Hopping

Hidden-terminal interference can be eliminated by the assignment of channels or codes to senders or receivers in a way that no two senders or receivers share the same code if they are within a two hop neighborhood. With commercial frequency-hopping radios operating in ISM bands, radios have to synchronize in time so that all radios hop to different frequency hops at approximately the same time.

CHMA exploits the fact that the nodes of a frequency-hopping network must agree on when to hop to eliminate hidden-terminal interference. A common frequency-hopping sequence is assumed by all the nodes (i.e., a common channel), so that nodes listen on the same frequency hop pattern at the same time, unless instructed otherwise. Nodes then carry out a sender-initiated collision-avoidance handshake to determine which sender-receiver pair should remain in the same hop in order to exchange data, while all other nodes that are not engaged in data exchange continue hopping on the common hopping sequence.

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Because the collision-avoidance handshake ensures that the receiver of a successful handshake cannot receive packets that suffer from hidden-terminal interference, and because all nodes not able to exchange data must hop to the next frequency hop, CHMA eliminates the need for carrier sensing and code assignment by simply allowing the sender and receiver of the handshake to remain on the same frequency hop in which they succeeded in their handshake.

The dwell time for a frequency hop in CHMA need be only as long as it takes for a handshake to take place; as it will be clear, this time need only be long enough to transmit a pair of MAC addresses, a CRC and framing. On the other hand, according to FCC regulations, a frequency-hop radio can remain in the same hop for up to 400msec, which at a data rate of 1 Mbps is ample time to transmit entire data packets. Hence, CHMA can be implemented by either allowing a sender-receiver pair communicate for up to 400msec, or by using a few orthogonal frequency-hopping sequences (e.g., 10, which is smaller than the number of simultaneous orthogonal frequency hops around a receiver in the 2.4 GHz band).

B. CHMA

The basic operation of CHMA is shown in Fig. 1. All the nodes follow a common channel-hopping sequence and each hop lasts the amount of time needed for nodes to receive a collision-avoidance control packet from a neighbor. A node that has a local data packet to send to any of its neighbors sends a ready-to-send (RTS) control packet over the current channel hop specifying the address of the intended receiver and its own address. All the nodes hop to the next channel hop, and if the RTS is received successfully by the intended receiver, it sends a clear-to-send (CTS) to the source node over the same common channel hop. At that time, the two given nodes will proceed to exchange data over the same channel hop whereas all the other nodes hop immediately to the next channel hop. In practice, the dwell time of a channel hop needs to be only long enough to allow an RTS to be received by a destination node. When the transmission of data is completed, then sender and receiver re-synchronize to the current common channel hop. If either multiple RTSs are sent during the same channel hop, or the destination node does not receive the RTS (because it is already engaged in another handshake), no CTS is sent to the source node. Consequently, the source node does not hear anything a round-trip time after sending its RTS and must rejoin the rest of the network at the current channel hop.

In Fig. 1, all the nodes start at time $t1$ from hop $h1$. At time $t1$ the system is at hop $h2$ and so on. At time $t1$ node x sends an RTS to node y . At time $t2$ all the nodes hop to frequency $h2$. Node y immediately responds with a CTS which is received by node x before the beginning of $t3$ time slot. Upon reception of a collision free CTS, node x will remain at the same frequency along with y to transmit its data. While x and y , stay in $h2$ until x has finished sending its data, all the other nodes continue to $h3$. At time $t3$, node a sends an RTS to node b but node b is busy transmitting data to another node (notice that we only consider uni-directional radios). Therefore, node b does not receive the RTS and at time $t4$ there is silence. In this case node a has to back off and therefore continues to hop with the other nodes to hop $h4$. At time $t4$ node c sends an RTS to node k and d sends an RTS to node l within τ seconds. Since nodes c, d, k, l are in the same neighborhood a collision occurs. Both nodes c and d have to back off and try to send an RTS at a later time.

C. MACA-CT

The key difference between CHMA and MACA-CT is that, in MACA-CT, the control packet handshake occurs in the common channel and then only the data are sent in a private per-node channel

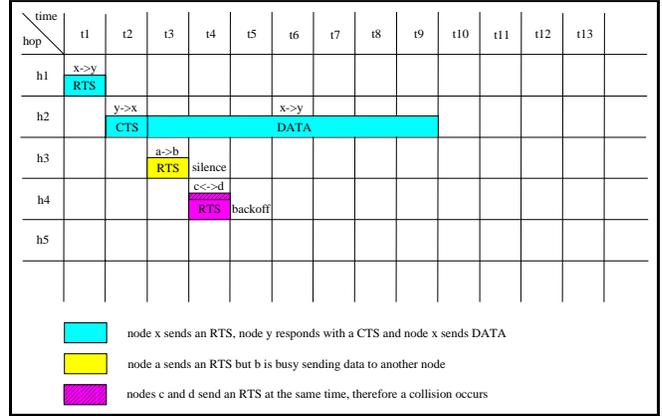


Fig. 1. CHMA illustrated

(Fig. 2). Since the CTS is now sent in the common channel there is a possibility that a hidden node will transmit an RTS at the same time with the CTS, therefore resulting in a collision. It is obvious that the vulnerability period in this case is double the one in CHMA.

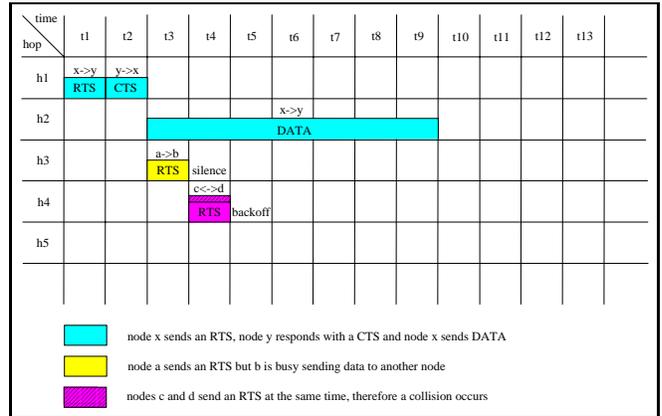


Fig. 2. MACA-CT illustrated

III. CORRECT COLLISION AVOIDANCE

In [7] it is shown that MACA-CT provides correct floor acquisition in the presence of hidden terminals. Theorem 1 below shows that CHMA also guarantees that there are no collisions between data packets and any other transmissions. The following assumptions are made to demonstrate correct collision avoidance [3]:

- A0) A node transmits an RTS that does not collide with any other transmissions with a non-zero probability.
- A1) The maximum end-to-end propagation time in the channel is $\tau < \infty$.
- A2) The transmission time of an RTS and a CTS is γ , the transmission time of a data packet is δ , and the hardware transmit-to-receive transition time is zero; furthermore, $2\tau < \gamma \leq \delta < \infty$. The dwell time in each hop is equal to the time needed to transmit an RTS (or CTS) plus the maximum end-to-end propagation time.
- A3) There is no capture or fading in the channel. Moreover, any overlap of packet transmissions at a particular receiver, causes that receiver to not understand any of the packets (worst case scenario).

The approach used to show that a collision-avoidance protocol works correctly, i.e., that it prevents data packets from colliding with any type of packets, consists of showing that, once a data packet is sent by a node, the intended receiver obtains the packet without interference. Assuming zero processing and turn-around delays is done for convenience; however, the same type of proofs, with adjusted parameters, apply for non-zero hardware delays.

Theorem 1: CHMA provides correct collision avoidance in the presence of hidden terminals when the maximum number of nodes within any 2-hop distance in the network is less than the orthogonal channels available.

Proof: Consider a polling node A and a polled node X and assume that A sends an RTS at time t_0 . We denote with h the dwell time in a particular hop. If X does not receive the RTS correctly due to interference from any neighbor hidden from A , it does not transit to the particular base frequency in which A is waiting for data and consequently no data are sent. Else, X receives A 's RTS at time $t_1 = t_0 + h$ and transmits to the particular base frequency specified in the RTS from A . At time $t'_1 > t_0 + h$, node X sends a CTS to A enabling A to send its data packet. Both nodes A and X hop in the same hopping pattern that never collides with any other hopping pattern since we have made the assumption that all nodes exchange data in their unique preassigned hopping frequency channel and that there are enough channels for all the nodes in the network. \square

IV. APPROXIMATE THROUGHPUT ANALYSIS

The objective of our analysis is to calculate the throughput achieved with CHMA, and to compare them against other sender-initiated protocols, namely, C-T [8] and MACA-CT [7]. The choice of protocols was made because we wanted to show how CHMA performs against popular CDMA protocols, presented extensively in the bibliography to date. Since in [7] it is proven that MACA-CT performs better than C-T [8] we will focus on comparing CHMA with MACA-CT.

Our analysis shows some very interesting results. By transmitting the CTS in a private channel we reduce the vulnerability period and consequently the probability of collisions. CHMA sustained throughput is much higher than MACA-CT. In addition, the system delay is decreased considerably even under heavy load traffic with CHMA.

A. Assumptions

We analyze the throughput of CHMA using the model first introduced by Sousa and Silvester [8] for CDMA protocols. We will calculate the throughput and delay CHMA with a discrete-time Markov chain. The following assumptions are made:

1. There are N nodes in a multi-hop, wireless network.
2. A single unslotted channel is used for all packets, and the channel introduces no errors (capture or fading).
3. At any given time slot, at most 1 RTSs can be successfully transmitted.
4. The data packet length distribution is geometrically distributed with parameter q ; therefore, the probability of a data packet with length l is, $P[L = l] = (1 - q)q^{l-1}$ and the average packet length, measured in mini-packets per slot is, $\bar{L} = \frac{1}{1-q}$.
5. The size for an RTS and CTS packets plus a maximum end-to-end propagation is equal to h , where h is the dwell time in a particular hop; the size for a data packet is always a multiple of h .

B. CHMA

Even though CHMA is designed to operate over an unslotted channel, we can think of CHMA operating over a slotted channel where

each slot corresponds to the duration of a frequency hop. In order to make a fair comparison with MACA-CT we will use in both protocols the same average packet length, L . However, since in MACA-CT a slot is equal to the size of an RTS plus a CTS plus the corresponding propagation time needed, the duration of a slot size, h , for CHMA is equal to half the size of the slots used in MACA-CT. Consequently, the average packet length for MACA-CT will be equal to $\frac{1}{2(1-q)}$.

At any given slot a node can be (a) idle, (b) transmitting an RTS or a CTS control signal, and (c) sending a series of consecutive (in time) slots with segments of the data packet. The possible scenarios that can occur in CHMA are:

- node x sends an RTS to node y and y replies with a CTS to x . In this case x sends its data to y
- node x sends an RTS at the same time that node y sends an RTS, therefore a collision occurs
- node x sends an RTS but node y is already tuned in a different hopping pattern, therefore node x does not hear anything in the next hop

At any given time the system state can be described by the number of communicating pairs of nodes. Because all the nodes that transmit an RTS that is not received at time slot $t - 1$ are available at slot t , the system state at any given time slot t is independent from the number of nodes that send an unanswered RTS. We need to calculate the transition probabilities of this Markov chain under the assumptions presented above. A transition in the Markov chain from one state to another occurs when: (a) at least one member from the set of nodes exchanging data packets, finish transmitting data, and (b) the nodes that participate in the handshake either succeed or fail sending an RTS. To calculate the transition probability from the current state we need to know the number of nodes that will finish sending data and the number of nodes that succeed or fail sending an RTS.

We will use $B(n, p, k)$ in the following to represent a geometric distribution; that is:

$$B(n, p, k) = \binom{n}{k} p^k (1-p)^{n-k} \quad (1)$$

Since we have made the assumption of geometrically distributed data packet lengths with parameter q , at any given time slot the probability that i pairs of nodes will become idle is equal to

$$Pr \left(\begin{array}{c} i \text{ pairs} \\ \text{become idle} \end{array} \right) = \binom{m}{i} (1-q)^i q^{(m-i)} = B(m, 1-q, i) \quad (2)$$

Let $P_{k,l}$ be the transition probability in the Markov chain from state k in slot $t - 1$, to state l in slot t . We condition on the number i of communicating pairs of nodes finish sending or receiving data packets at the beginning of slot t . At time slot $t - 1$ the system is at state l and therefore the number of nodes that are available to receive or transmit is equal to $N - 2(l - i)$. If the transition to state l is made, then let x' be the number of nodes which transmit an RTS at the beginning of time slot t . Furthermore, $l' = l - (k - i)$ pairs of nodes will become busy exchanging data packets and $n' = x' - l'$ nodes will transmit an RTS packet that will not be received. Because only 1 RTS can be successful at a given time slot, a transition from state k to state l is possible only if $m' = 1$ or $m' = 0$.

Let Φ be the event that a transition from k to l occurs, ΦI the event that exactly one transmission occurs and it is addressed to an idle node, and ΦB the event that exactly one transmission occurs and it is addressed to a busy terminal. Then, the transition probabilities can be calculated as follows

$$p_{k,l} = \sum_{i=0}^k \binom{i \text{ pairs}}{\text{idle}} \cdot [P[\Phi \cap \Phi I] + P[\Phi \cap \Phi B] + P[\Phi \cap (0 \text{ or } > 1 \text{ trans.})]]$$

$$\begin{aligned}
&= \sum_{i=0}^k B(k, 1-q, i) \cdot [\delta(m' - 1)\delta(n')B(N', p, 1) \left(\frac{N' - 1}{N - 1}\right) \\
&\quad + \delta(m')\delta(n' - 1)B(N', p, 1) \left(\frac{N - N'}{N - 1}\right) \\
&\quad + \delta(m')(1 - \delta(n' - 1))B(N', p, n')] \quad (3)
\end{aligned}$$

where $B(n, p, k)$ is given from Eq. 1, $\delta(0) = 1$, and $\delta(x) = 0$ if $x \neq 0$. Given the transition probability formula we can solve the steady-state probabilities to calculate the average throughput. If PS_l is the steady state probability for state l , then the average throughput S is equal to the number of data packets transmitted at the same frequency hop; that is

$$S = \sum_{l=0}^{\lfloor \frac{N}{2} \rfloor} l \cdot PS_l \quad \square \quad (4)$$

Fig. 3 shows the throughput achieved versus the probability of transmission p for various numbers of nodes in the network. Since the slot duration in CHMA is half the one in MACA-CT the probability of transmission at a given slot is $\frac{p}{2}$. Because the vulnerability period in CHMA is half the time spend in MACA-CT the maximum throughput is always higher for CHMA. Due to the small vulnerability period with CHMA, even for high probability of transmission, i.e. $p > 0.5$, the sustained throughput is high. Since no data will be ever send with CHMA to a busy terminal, nodes in CHMA are immediately available to try again, something that is not the case in C-T [8]. Therefore, at any given time slot the number of nodes available to transmit an RTS is maximized whereas at the same time the contention period is minimized providing a highly efficient combination.

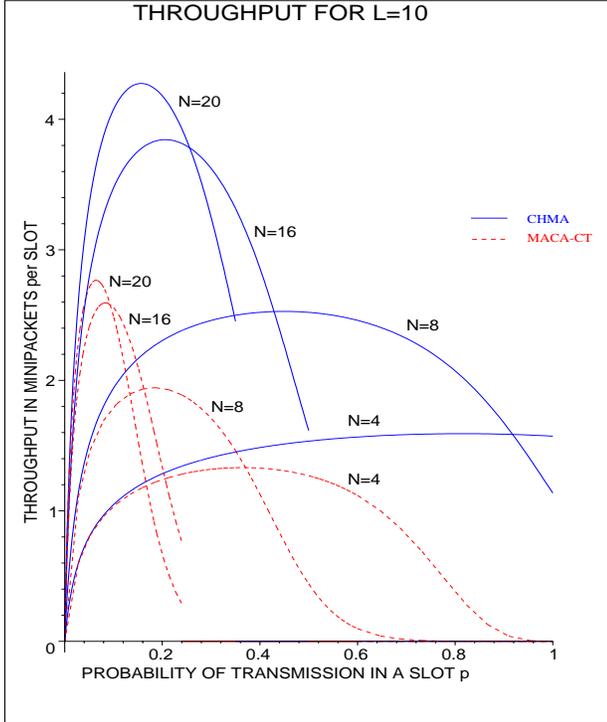


Fig. 3. Throughput versus transmission probability for MACA-CT and CHMA for a fixed average packet length $\bar{L} = 10$

Likewise, Fig. 4 shows the throughput against the probability of transmission p for a fixed number of nodes ($N = 12$) with the average length packet L being the parameter. As it is obvious, CHMA

again has a higher throughput than MACA-CT regardless of the size of the data packet. The general conclusion that can be drawn in this case is that with a longer average packet length higher throughput can be achieved. However, in a realistic environment, by increasing the length of the transmitted packet we also increase the probability that errors will occur. Furthermore, when the number of co-located nodes is high the interference from adjacent frequency channels is more likely to introduce errors in the transmission of data packets.

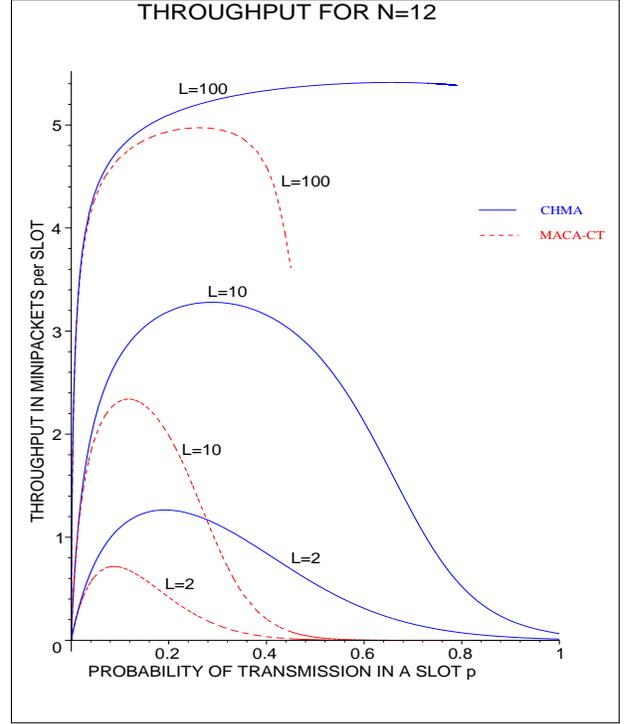


Fig. 4. Throughput versus transmission probability for MACA-CT and CHMA for a fixed number of nodes $N = 12$

V. DELAY ANALYSIS

To calculate the average delay we need to define the retransmission policy. We assume that the arrival process is Bernoulli with probability p for every node. Since we have a queue of maximum size equal to one packet, if a packet is waiting in the queue then there will not be any further new packet arrivals, and the waiting packet will be retransmitted in the next slot with probability p . If a node has a packet waiting to be send, but a packet from some other user is received, then the waiting packet is discarded and when the handshake is completed the given node becomes idle and generates a new packet with probability p .

We use Little's theorem to calculate the average delay. We define the system delay D as the time that it takes for a new arriving packet that is waiting in the queue to be transmitted and successfully received by the intended receiver. If \bar{m} is the average number of pairs of nodes that simultaneously exchange data packets, and \bar{B} is the average number of blocked users, then at any given time the average number of packets in the system will be equal to $\bar{m} + \bar{B}$. That is,

$$\bar{m} = \sum_{m=0}^{\lfloor \frac{N}{2} \rfloor} m P_m \quad (5)$$

$$\bar{B} = \sum_{m=0}^{\lfloor \frac{N}{2} \rfloor} p(N-2m) \left(1 - \frac{N-m-1}{N-1}\right) P_m \quad (6)$$

The average delay normalized to a packet length is derived by applying Little's theorem as follows

$$\bar{D} = \frac{\bar{m} + \bar{B}}{S} \quad (7)$$

In Fig. 5 we can see the numerical results obtain for the normalized delay performance of CHMA and MACA-CT. For light load ($p < 0.2$) we notice that both protocols have the same system delay. However, the system delay with CHMA remains almost the same until $p > 0.6$ whereas with MACA-CT it increases exponentially when $p > 0.4$. This is to be expected since when the load is high in the network the collisions between the control packets increase the delay. In this case, it is crucial to minimize the length of the handshakes that are susceptible to collisions. Indeed, with CHMA only RTSs can collide and therefore the vulnerability period is half the one in MACA-CT. Notice that, in general by increasing the packet length we reduce the normalized delay noticeably.

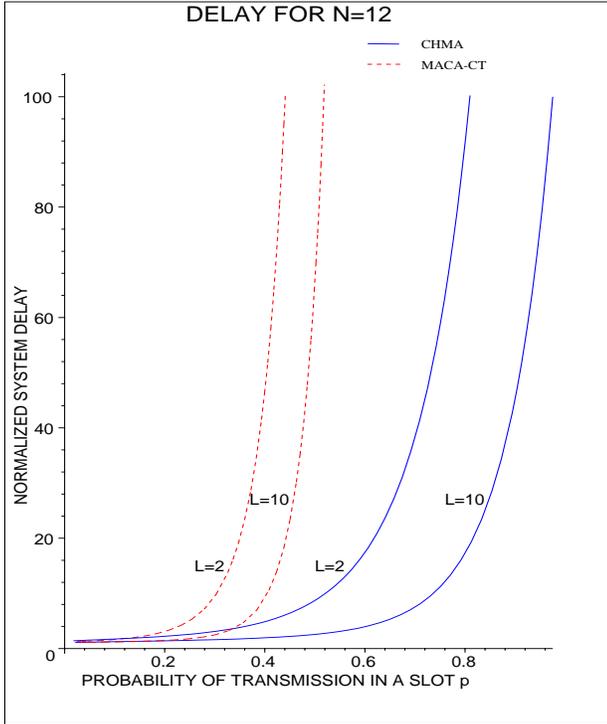


Fig. 5. Normalized system delay versus transmission probability for MACA-CT and CHMA for a fixed number of nodes $N = 12$

The actual system delay should include the transmission time for the data packet. Therefore, $D = \bar{D}/(1-q)$. In Fig. 6 the actual system delay that includes the packet transmission time is shown. In this figure, contrary to what happened with the normalized system delay, we notice that by increasing the packet length we do not achieve smaller delays. However, this is to be expected since the transmission time is the dominating delay in this case.

VI. CONCLUSIONS

Our focus in this work is to present a collision-avoidance channel access protocol that guarantees correct floor acquisition without

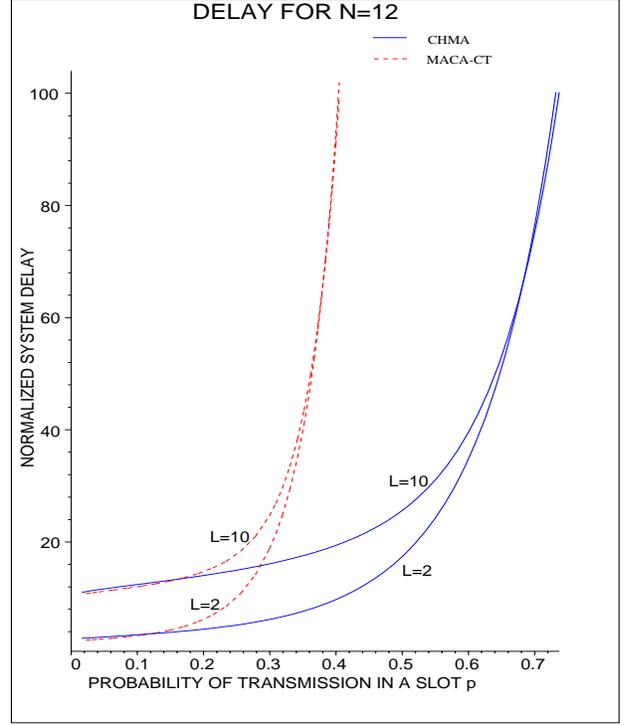


Fig. 6. Actual system delay versus transmission probability for MACA-CT and CHMA for a fixed number of nodes $N = 12$

using carrier sensing or code assignment. With CHMA, we propose a very simple channel access protocol that can be used in any wireless radio with minimal effort. We compared the throughput achieved with CHMA against MACA-CT [7], which is a recent example of collision-avoidance protocols that do not require carrier sensing but need code assignment to operate correctly. For this comparison, we used the same analysis method introduced by Sousa and Silvester for code-hopping protocols [8] and showed that CHMA achieves higher throughput than MACA-CT, without the need for carrier sensing or any code assignments. We also presented a novel analytical method to calculate the corresponding delays of the two protocols. Our results showed that the average system delay is much less with CHMA under any given load in the network.

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