

A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks

Asimakis Tzamaloukas and J.J. Garcia-Luna-Aceves

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 new collision-avoidance MAC protocol that we call receiver-initiated channel-hopping with dual polling (RICH-DP). RICH-DP is the first MAC protocol based on a receiver-initiated collision-avoidance handshake that does not require carrier sensing or the assignment of unique codes to nodes in order to ensure collision-free reception of data at the intended receivers in the presence of hidden terminals. The throughput and delay characteristics of RICH-DP is studied analytically, and extensive simulations are presented to verify the analysis and to present a more accurate prediction of how RICH-DP would operate in realistic scenarios. RICH-DP is applicable to ad-hoc networks based on commercial off-the-shelf frequency hopping radios operating in unlicensed frequency bands.

Keywords—Medium Access Control, multiple access, collision avoidance, wireless networks, ad-hoc networks, multichannel radio, frequency hopping spread spectrum, performance analysis

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. In 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 [17], including MACA [14], MACAW [2], IEEE 802.11 [1], and FAMA [4]. Fullmer and Garcia-Luna-Aceves [4] showed that, in order to avoid data packets from colliding with any other packets at the intended receivers in networks with a single channel, the senders had to sense the channel before sending their RTSs. More recently, receiver-initiated collision-avoidance protocols have also been proposed for single-channel networks, in which the receiver initiates the collision-avoidance handshake [7], [16]; these receiver-initiated collision-avoidance protocols also require carrier sensing to ensure correct collision avoidance.

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. Some commercial radios do not provide true carrier sensing, and direct sequence spread-spectrum (DSSS) radios may capture none or one of multiple overlapping transmissions in a non-deterministic manner, 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 must already provide coarse time synchronization at the dwell-time level. On the other hand, using one or more busy tones to indicate when a receiver is busy [10] requires, in essence, a second transceiver, which is not economically attractive.

In the past, several MAC protocols have been proposed and analyzed to take advantage of spreading codes for multiple access. Sousa and Silvester [15] 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. [8] used carrier sensing to propose a receiver-based, asynchronous transmissions protocol. Jiang and Hsiao [12] proposed a receiver-based handshake protocol for CDMA (code division multiple access) networks that improved the efficiency of the network by reducing the amount of unsuccessful transmissions and unwanted interference. Several other proposals have been made to implement correct collision-avoidance in multihop wireless networks without requiring nodes to use carrier sensing; these proposals rely on multiple codes assigned to senders or to receivers to eliminate the need for carrier sensing (e.g., [3], [5], [13]).

The key limitation of protocols based on code assignments is that senders and receivers have to find each others' codes before communicating with one another. Future DSSS are expected to use 15 chips per bit, allowing two different systems to operate over the same DS frequency channels as they were defined in IEEE 802.11 [1]. On the other hand, up to 26 FHSS radios can be co-located. According to the FCC regulations, up to 15 FHSS radios can be co-located with minimum interference problems. For wireless LANs (compatible with IEEE 802.11b) the number of co-located users is fixed and in most cases the network is customized towards higher data rates. In this case, DSSS is preferred at a slightly higher cost. However 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, and the number of users in a given area might be changing rapidly. Slow frequency hopping (with one or more packets sent per hop) is the viable way to achieve multiple orthogonal channels. Therefore, for ad-hoc networks it becomes imperative to develop MAC protocols that can take advantage of the characteristics of FHSS radios operating in ISM bands to ensure that transmissions are free of collisions due to hidden-terminal interference.

Section II describes the operation of a new receiver-initiated collision-avoidance protocol which we call RICH-DP, that does not require code assignments or carrier sensing. RICH-DP requires all nodes in a network to follow a common channel-

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hopping sequence. This requirement can be easily met in practice. A channel can be defined to be a frequency hop, a spreading code, or a combination of both. However, with commercial radios operating in ISM bands, a channel should be viewed as a frequency hop or a hopping sequence. 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 receiver-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, and the rest of the nodes continue to follow the common channel hopping sequence. With RICH-DP the polling and polled nodes can transmit data after a successful handshake.

Section III analyzes the throughput of RICH-DP for the case in which a single data packet is sent with every successful collision-avoidance handshake. We compare RICH-DP with MACA-CT protocol [13], 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 the best representative of collision-avoidance solutions that eliminates the need for carrier sensing at the expense of requiring unique channel (code) assignments. Section IV calculates the system delay for RICH-DP. Section V presents the suite of simulation experiments used to understand the performance of RICH-DP in realistic scenarios. Section VI presents our conclusions.

II. RECEIVER-INITIATED CHANNEL-HOPPING WITH DUAL POLLING

A. Basic Concepts in Channel Hopping

RICH-DP is based on three basic observations. First, as it has been shown [7], reversing the collision-avoidance handshake (i.e., making the receiver in charge of avoiding collisions), improves the throughput of the network. Second, 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 two hops away from one another. Third, 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.

A key benefit of the dual-use polling in RICH-DP is that both polling and polled nodes can exchange data in a round of collision avoidance. To eliminate hidden-terminal interference, RICH-DP exploits the fact that the nodes of a frequency-hopping network must agree on when to hop. A common frequency-hopping sequence is assumed by all the nodes (i.e., a common channel), so that nodes listen on the same channel at the same time, unless instructed otherwise. Nodes then carry out a receiver-initiated collision-avoidance handshake to determine which sender-receiver pair should remain in the present hop in order to exchange data, while all other nodes that are not engaged in data exchange continue hopping on the common hopping sequence. Because the collision-avoidance handshake ensures that the receiver of a successful handshake cannot re-

ceive packets that suffer from hidden-terminal interference, and because all nodes not able to exchange data must hop to the next frequency hop, RICH-DP 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 RICH-DP 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 and packet trains. Hence, RICH-DP can be implemented by allowing a sender-receiver pair to communicate in the same frequency hop for a period of time that must be the smaller of 400msec and the time elapsed before the same frequency hop is used again in the common hopping sequence. Alternatively, a few orthogonal frequency-hopping sequences can be defined (e.g., 10, which is smaller than the number of simultaneous orthogonal frequency hops around a receiver in the 2.4 GHz band) for each frequency hop of the common hopping sequence.

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 attempts to poll its neighbors at a rate that is a function of the data rate with which it receives data to be sent, as well as the rate with which the node hears its neighbors send control and data packets. A node ready to poll any of its neighbors sends a ready-to-receive (RTR) control packet over the current channel hop specifying the address of the intended sender and the polling node's address. If the RTR is received successfully by the polled node, that node starts sending data to the polling node immediately and over the same channel hop, while all other nodes hop to the next channel hop. In practice, the dwell time of a channel hop needs to be only long enough to allow an RTR to be received by a polled node. When the transmission of data from the polled node is completed, the polling node can start transmitting its own local data packet to the polling node over the same channel hop. After all the appropriate data transmissions are completed, sender and receiver re-synchronize to the common channel hop. If either multiple RTRs are sent during the same channel hop, or the polled node has no data to send to the polling node, the polling node does not receive any data for a time duration equal to a round-trip after sending its RTR and must rejoin the rest of the network at the current channel hop. To permit the polling node to determine quickly that no data packet is to be expected, the polled node can transmit a short preamble packet in front of the data packet. However, to simplify our description, in the rest of this paper we simply assume that a node is able to detect that no data packet is arriving.

B. RICH-DP

Fig. 1 illustrates the operation of RICH-DP for the case in which sender-receiver pairs exchange data over a single frequency hop. In the figure, all the nodes start at time t_1 from hop h_1 . At time t_2 the system is at hop h_2 , and so on. Node x sends an RTR to node y and node y responds with data over the

same channel at time $t1$. Notice that, there is a probability of $\frac{1}{N-1}$ that node y has data for x , where N is the number of nodes in the network. Node y receives an ACK from node x at time $t9$ and at time $t10$ node x is now enabled to transmit its own data packet to the polled node y . While x and y stay in $h1$ until y has finished sending its data, all the other nodes hop to $h2$. Another node z sends an RTR to node w at time $t2$, but now it is the case that w does not have a data packet for z ; therefore, w sends a CTS, enabling z to send any data to w . Node z starts sending its data to w at time $t4$. Again, nodes z and w stay in $h2$ until z finishes sending its data, while the other nodes hop to $h3$. Node a sends an RTR to node b at time $t3$, but node b is busy transmitting data to another node (uni-directional radios). Therefore, node b does not receive the RTR and there is silence at time $t4$. In this case, node a continues to hop with the other nodes to hop $h4$. At time $t4$ nodes c and d send an RTR and therefore a collision occurs. Both nodes have to back off and try to send an RTR at a later time. Notice that a successfully received data packet is always followed by an acknowledgment (ACK) from the destination node to the source node.

After a node is properly initialized, it transitions to the PASSIVE state. In all the states, before transmitting anything to the channel, a node must listen to the channel for a period of time equal to a dwell time (time spent in one frequency hop). If node x is in PASSIVE state and obtains an outgoing packet to send to neighbor y , it transitions to the RTR state. In the RTR state, the node sends an RTR packet with the destination address of the node that is the target destination, in this case y . After sending its RTR, node x waits for a response in the same frequency hop.

If node y receives the RTR correctly and has data for x , node y transitions to the XMIT state, where it transmits a data packet to x in the same frequency hop; otherwise, if node y cannot decode the RTR correctly, it perceives noise or silence, depending on the radio being used in that hop and continues to hop with the rest of the nodes in the common hopping sequence. After sending its RTR, node x waits until the beginning of the next hop. At this time, if a preamble is not detected node x transitions to a new frequency channel according to the common hopping sequence; otherwise, x remains in the same frequency channel until (a) either a data packet arrives with the duration of it being part of its header, or (b) a Clear To Sent (CTS) packet arrives allowing x to send a data packet at the same unique frequency channel.

When multiple RTRs are transmitted within a one-way propagation delay, a collision takes place and the nodes involved have to transition to the BACKOFF state and try again at a later time chosen at random. Node x determines that its RTR was not received correctly by z after a time period equal to one hop. If that is the case, node x will synchronize with the other nodes at a frequency hop that can be determined easily, because node x is aware of the common hopping sequence.

To reduce the probability that the same nodes compete repeatedly for the same receiver at the time of the next RTR, the RTR specifies a back-off-period unit for contention. The nodes that must enter the BACKOFF state compute a random time that is a multiple of the back-off-period unit advertised in the RTR. The simplest case consists of computing a random number of back-off-period units using a uniformly distributed random variable from 1 to d , where d is the maximum number of neighbors for

a receiver. The simplest back-off-period unit is the time it takes to send a small data packet successfully.

III. APPROXIMATE THROUGHPUT ANALYSIS

The objective of our analysis is to calculate the throughput achieved with RICH-DP and compare our results against sender-initiated CDMA protocols, i.e., MACA-CT [13]. The choice of MACA-CT was made because we want to show how RICH-DP performs against the best performing CDMA protocol reported to date for ad hoc networks in which receivers can detect at most one transmissions at a time. Our analysis shows a number of interesting results. By making collision-avoidance a joint effort by sender and receiver, a much better performance is obtained than what can be achieved with MACA-CT; this should be expected, because the vulnerability period with RICH-DP is half the one with MACA-CT, and dual-use polling doubles the opportunity for collision-free data to be sent.

A. Assumptions

We analyze the throughput of RICH-DP using the model first introduced by Sousa and Silvester [15] for CDMA protocols. We calculate the throughput and average delay for RICH-DP with a discrete-time Markov chain. The following assumptions are made:

1. There are N nodes in the fully-connected network.
2. A single unslotted channel is used for all packets, and the channel introduces no errors (no capture or fading).
3. At any given time slot, at most one RTR can be successfully transmitted.
4. Since there is an upper limit in the number of transmissions that can co-exist at the same time in an ISM radio band when using FHSS, we can have up to m pairs of nodes that exchange data at the same time.
5. 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, $\bar{L} = \frac{1}{1-q}$.
6. The size for an RTR and a CTS 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 .

A polled node has a packet addressed to the polling node with probability $\frac{1}{N-1}$ (i.e. uniform distribution). Furthermore, we assume that each node sends its RTR according to a Poisson distribution with a mean rate of $\frac{\lambda}{N-1}$, and that (when applicable) the polling node chooses the recipient of the RTR with equal probability.

B. RICH-DP

To make a fair comparison with MACA-CT, we use the same average packet length, \bar{L} , for both protocols. 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 RICH-DP 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 RTR or a CTS control signal, and (c) sending a series of

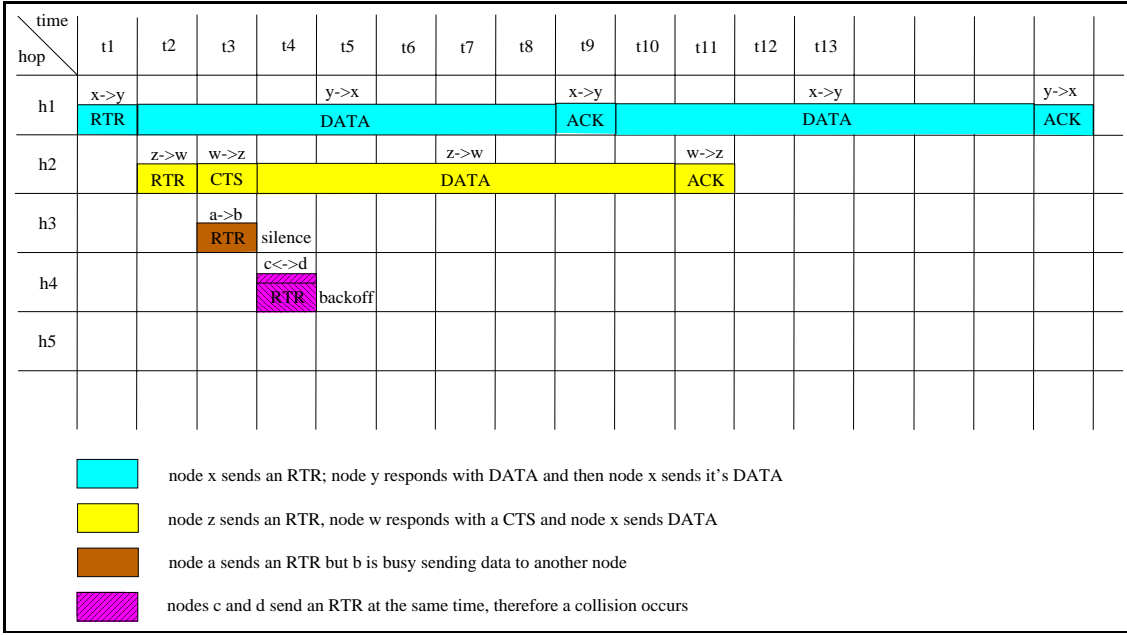


Fig. 1. RICH-DP illustrated

consecutive (in time) slots with segments of the data packet. The possible scenarios that can occur in RICH-DP are the following:

- Node x sends an RTR to node y and y sends its data packet to x with probability $\frac{1}{N-1}$.
- Node x sends an RTR to node y but y does not have any data for x , therefore y sends a CTS to x and x sends its data to y .
- Node x sends an RTR at the same time that node y sends an RTR, therefore a collision occurs.
- Node x sends an RTR 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 (Fig. 2). Notice that, because all the nodes that transmit an RTR that is not received during 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 transmit an unanswered RTR. 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 finishes transmitting data, and (b) the nodes that participate in the handshake either succeed or fail transmitting an RTR. To calculate the transition probability from the current state, we need to know the number of nodes that finish transmitting data and the number of nodes that succeed or fail transmitting an RTR.

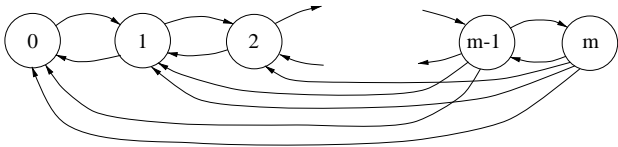


Fig. 2. Markov Chain defining the average number of communicating pairs

We will use $B(n, p, k)$ in the following to represent a geomet-

ric distribution, that is:

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

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

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

$$\begin{aligned}
 p_{k,l} = & \sum_{i=0}^k \binom{i \text{ pairs}}{\text{idle}} \cdot \{P[\Phi \cap \Phi I] + P[\Phi \cap \Phi B] + \\
 & P[\Phi \cap (0 \text{ or } > 1 \text{ transmission})]\} = \\
 & \sum_{i=0}^k \binom{i \text{ pairs}}{\text{idle}} \cdot \left\{ \delta(m' - 1) \delta(n') B(N', p, 1) \left(\frac{N' - 1}{N - 1} \right) \right. \\
 & \left. + \delta(l') \delta(n' - 1) B(N', p, 1) \left(\frac{N - N'}{N - 1} \right) \right\}
 \end{aligned}$$

$$+ \delta(l')(1 - \delta(n' - 1))B(N', p, n') \} \quad (2)$$

where $\delta(0) = 1$ and $\delta(x) = 0$ if $x \neq 0$.

The number i of pairs of nodes that become idle at any given time slot t , is dependent of the number of nodes that are exchanging only one data packet, as well as the number of nodes that are exchanging two data packets. Because all the nodes are independent sources of packets with identical geometrically distributed packet lengths, the length of the data transmitted is equal to a negative binomial distribution when two nodes exchange data packets during the same busy period. The probability that a data packet has length l is equal to $P[L = l] = (1 - q)q^{l-1}$. If two data packets are to be sent, then the average length will be $\bar{L} = \frac{2}{1-q}$. We denote with q' the parameter of the binomial distribution when two packets are transmitted.

To calculate the probability that i pairs of nodes become idle in a given time slot t , we assume that, out of those i pairs that become idle, x are idle after exchanging only one data packet and the remaining $i - x$ pairs are idle after exchanging two data packets. Figure 3 shows the sets of nodes at the beginning of every time slot. Notice that set A contains pairs of nodes that exchange only one data packet, and pairs of nodes that exchange two data packets.

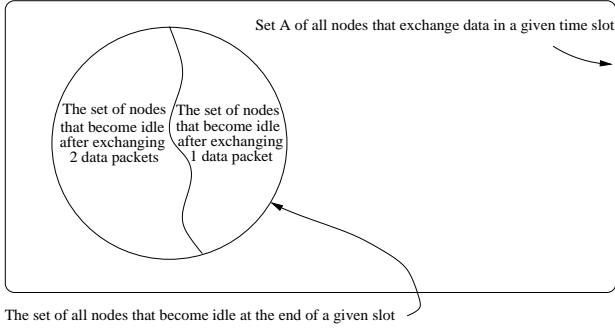


Fig. 3. The various sets of nodes when RICH-DP is deployed

Because the events are mutually exclusive, we can make use of the multinomial probability law. If B_1, B_2, B_3 are the three partitions of the sample space, then let q be the probability that a pair of nodes becomes idle after exchanging one data packet, and q' be the probability that a pair of nodes becomes idle after exchanging two data packets. Then,

$$Pr \left(\begin{array}{c} i \text{ pairs} \\ \text{become idle} \end{array} \right) = \frac{k!}{x!(i-x)!(k-i)!} \left(\frac{x}{i}q \right)^x \left(\frac{i-x}{i}q' \right)^{i-x} \left(1 - \frac{xq + (i-x)q'}{i} \right)^{k-i} \quad (3)$$

Substituting Eq. 3 into Eq. 2 we have

$$p_{k,t} = \sum_{x=0, k-l \neq \{0, -1\}}^{x=k-l+1} \left\{ \frac{k!}{x!(k-l+1-x)!(l-1)!} \left(\frac{x}{k-l+1}q \right)^x \left(\frac{k-l+1-x}{k-l+1}q' \right)^{k-l+1-x} \left(1 - \frac{xq + (k-l+1-x)q'}{k-l+1} \right)^{l-1} B(N', p, 1) \frac{N'-1}{N-1} \right\} + \sum_{x=0, k-l \neq \{0, -1\}}^{x=k-l} \left\{ \frac{k!}{x!(k-l-x)!(l)!} \left(\frac{x}{k-l}q \right)^x \left(\frac{k-l-x}{k-l+1}q' \right)^{k-l-x} \right\}$$

$$\left(1 - \frac{xq + (k-l-x)q'}{k-l} \right)^l B(N', p, 1) \frac{N'-N'}{N-1} \} + \sum_{x=0, k-l \neq \{0, -1\}}^{x=k-l} \left\{ \frac{k!}{x!(k-l-x)!(l)!} \left(\frac{x}{k-l}q \right)^x \left(\frac{k-l-x}{k-l+1}q' \right)^{k-l-x} \left(1 - \frac{xq + (k-l-x)q'}{k-l} \right)^l (1 - B(N', p, 1)) \right\} \quad (4)$$

To calculate the average throughput we need to know the steady-state probabilities that correspond to each one of the states of the Markov chain (Fig. 2). Given the transition probabilities (Eq. 4), we can solve a linear system of equations with as many unknowns as the number of states in the Markov chain to calculate the steady-state probabilities. 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

$$S = \sum_{l=0}^{\frac{N}{2}} l \cdot PS_l \quad (5)$$

Figure 4 shows the throughput achieved by RICH-DP and MACA-CT versus the probability of transmission p for various numbers of nodes in the network. Because the slot duration in RICH-DP is half the one in MACA-CT, the probability of transmission at a given slot is $\frac{p}{2}$. The maximum throughput of RICH-DP is always higher than MACA-CT because the duration for the exchange of the control signals is half the size of the one used in MACA-CT and consequently the vulnerability period in RICH-DP is half the time spent in MACA-CT. Since no data will be ever sent with RICH-DP to a busy terminal, nodes in RICH-DP are immediately available to try again, something that is not the case in C-T [15]. Therefore, at any given time slot, the number of nodes available to transmit an RTR in RICH-DP is maximized while the contention period is minimized!

Figure 5 shows the throughput against the probability of transmission p for a fixed number of nodes ($N = 12$) with the average packet length L being the parameter. As it is obvious, RICH-DP 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, higher throughput can be achieved with a longer average packet length. However, notice that we have made the assumption of a perfect channel. 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. It has been shown [9] that there is no improvement in the throughput achieved by increasing the length of the data packet after a certain threshold in a non-perfect channel for other spread spectrum protocols. The same should be expected for RICH-DP.

IV. DELAY ANALYSIS

To calculate the average delay for RICH-DP we need to first define a retransmission policy. We assume that the arrival process is Bernoulli with probability p for every node. Because we have a queue of maximum size equal to one packet, if a packet

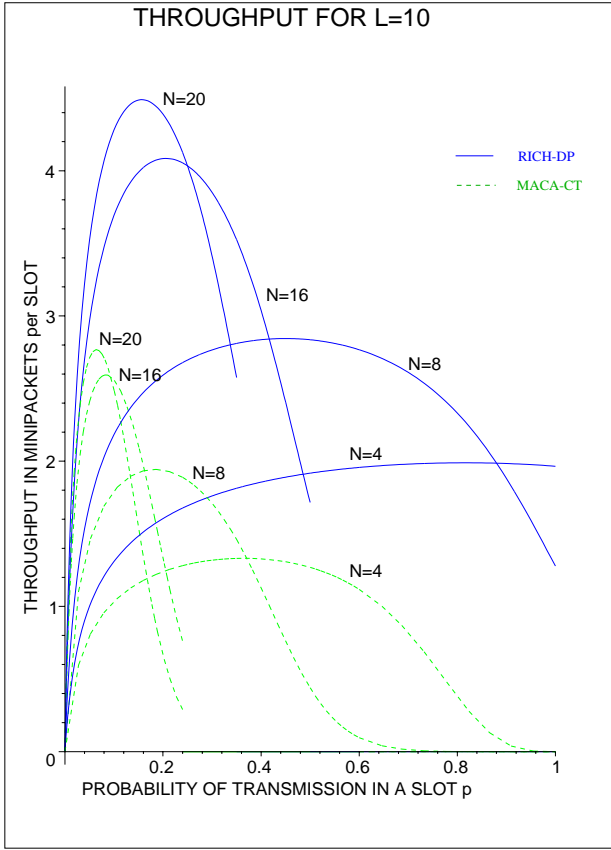


Fig. 4. Throughput versus transmission probability for MACA-CT and RICH-DP for a fixed average packet length $\bar{L} = 10$

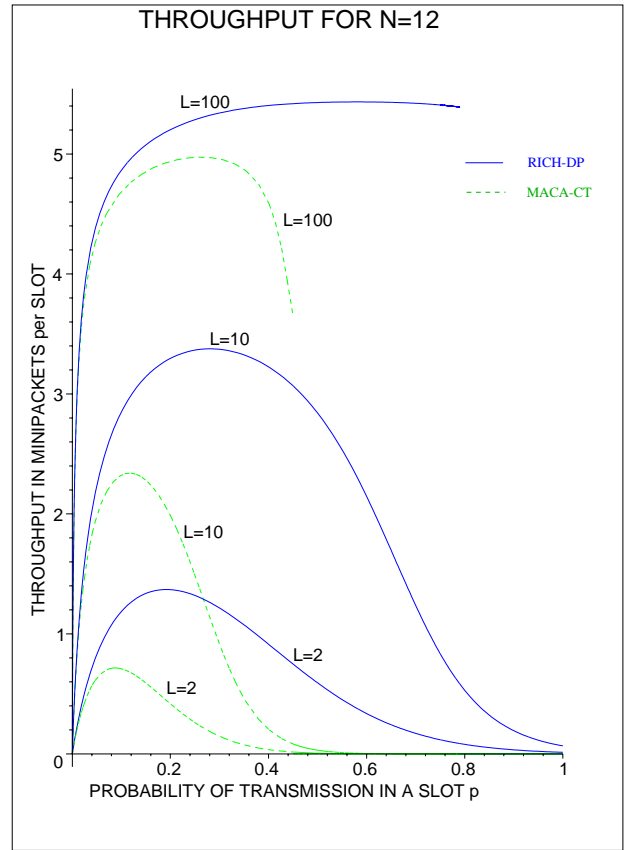


Fig. 5. Throughput versus transmission probability for MACA-CT and RICH-DP for a fixed number of nodes $N = 12$

is waiting in the queue then there are no further new packet arrivals, and the waiting packet is retransmitted in the next slot with probability p . If a node has a packet waiting to be sent, 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 . All the assumptions that were presented in section III are valid in the following derivation as well.

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 (due to collision of RTSs or RTSs that are not received), then at any given time the average number of packets in the system will be equal to $\bar{m} + \bar{B}$. We can calculate \bar{m} and \bar{B} as follows

$$\bar{m} = \sum_{m=0}^{\lfloor \frac{N}{2} \rfloor} m P_m \quad (6)$$

$$\bar{B} = \sum_{m=0}^{\lfloor \frac{N}{2} \rfloor} p(N-2m) \left(1 - \frac{N-m-1}{N-1}\right) P_m \quad (7)$$

The average delay normalized to a packet length is derived by

applying Little's theorem as follows

$$\bar{D} = \frac{\bar{m} + \bar{B}}{S} \quad (8)$$

Since the mean transmission time for a packet is equal to $\frac{1}{1-q}$ the actual system delay should include the transmission time for the data packet. That is

$$D = \frac{\bar{D}}{(1-q)} \quad (9)$$

In Figure 6 we can see the numerical results obtained for the normalized delay performance of MACA-CT and RICH-DP. It is clear that RICH-DP offers the smallest delay at any load. The system delay with RICH-DP remains almost the same up to $p > 0.6$ whereas with MACA-CT the delay increases exponentially when $p > 0.3$. This is to be expected, because collisions between control packets increase as the offered load increases, and minimizing the length of the collision-avoidance handshakes that are susceptible to collisions becomes crucial. Indeed, with RICH-DP, only RTRs can collide and therefore the vulnerability period is half the vulnerability period in MACA-CT. From the same figure it is obvious that the normalized delay can be reduced noticeably by increasing the packet length.

In Figure 7 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.

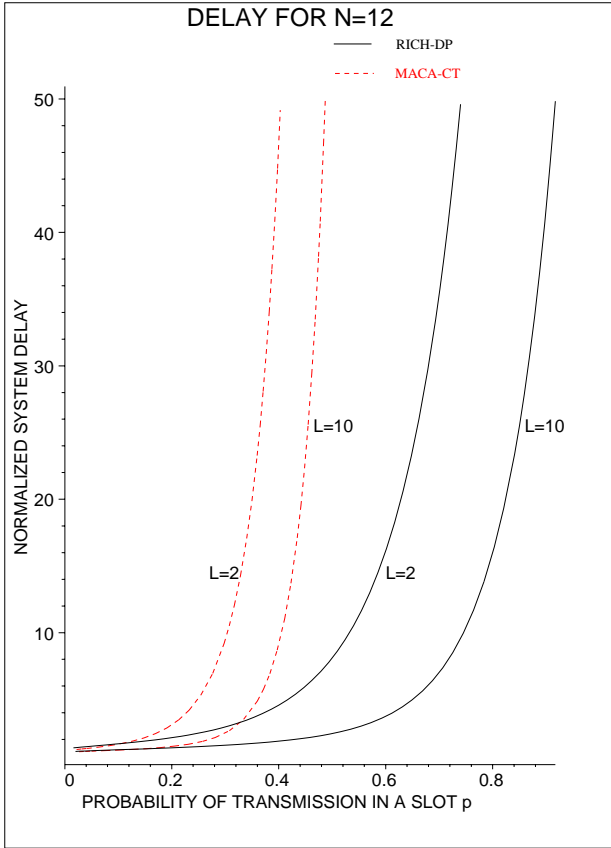


Fig. 6. Normalized system delay versus transmission probability for MACA-CT and RICH-DP for a fixed number of nodes $N = 12$

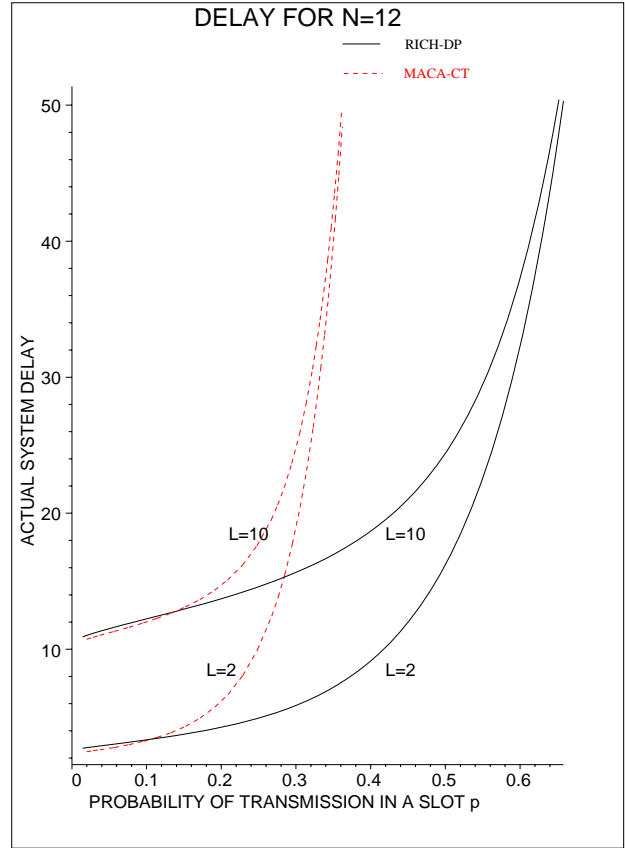


Fig. 7. Actual system delay versus transmission probability for MACA-CT and RICH-DP for a fixed number of nodes $N = 12$

This is to be expected since the transmission time is the dominating delay in this case.

V. SIMULATION RESULTS

We validated our analytical results by performing a number of simulation experiments. Our goal was to investigate the performance of RICH-DP under different network topologies and to show how the results compare against the analytical results presented previously. We used the OPNET simulation tool to implement MACA-CT and RICH-DP.

For the simulation experiments, we used a multiple-channel capable radio that approximates a commercially available frequency hopping radio operating over the 2.4GHz ISM band. By using the external model access (EMA) capability of the OPNET simulation tool, we produced a radio model with 79 frequency channels of bandwidth 1MHz and maximum data rate of 1Mbps. Because all the commercially available radios are half duplex, the simulated radio can only receive or transmit data at the same time. The simulation model for the physical layer was derived from the standard, high-fidelity, 13-pipeline stages model that is embedded in the simulation tool [11]. To be compatible with the analysis, we chose not to include any modifications in the physical layer that would simulate delay or power capture phenomena.

Nodes are assumed to be approximately one mile away from each other, giving a maximum propagation delay of 5 microseconds. We included an overhead of 24 microseconds to account

for receive-to-transmit turn-around time, the necessary framing (preamble) bits, and guard-bands. Because the size of an RTR is equal to 96 bits, we chose our slots to be equal to 120 microseconds. When two control packets collide they back-off for an amount of time that is exponentially distributed up to the size of a data packet. Clearly, there are many different back-off strategies that can be applied to help improve the performance of RICH-DP or MACA-CT for that matter, but this is not the focus of this paper. If a node fails to initiate a handshake after seven retransmissions, the data packet is dropped from the head of the queue.

Figure 8 shows the various topologies used in the experiments. Figure 8(a) shows a fully-connected network in which all the traffic produced from nodes $N1$ to $N16$ is directed to the base station, *Base*. Figure 8(b) shows two groups of eight nodes that can hear each other node in the same group but are hidden from all the nodes in the other group. Again, traffic is generated from all the nodes in each group with destination the central base station *Base*. In Figure 8(c) a multihop network of sixteen nodes in a four dimensional hypercube configuration is depicted. The lines between the nodes show the connectivity in the network. A node is generating traffic that four other nodes will receive at any given time whereas there are always at least three other nodes that are hidden. These topologies were chosen for two reasons: to compare with similar topologies used in prior work on collision avoidance [4], and to test the performance of the protocols under widely different conditions.

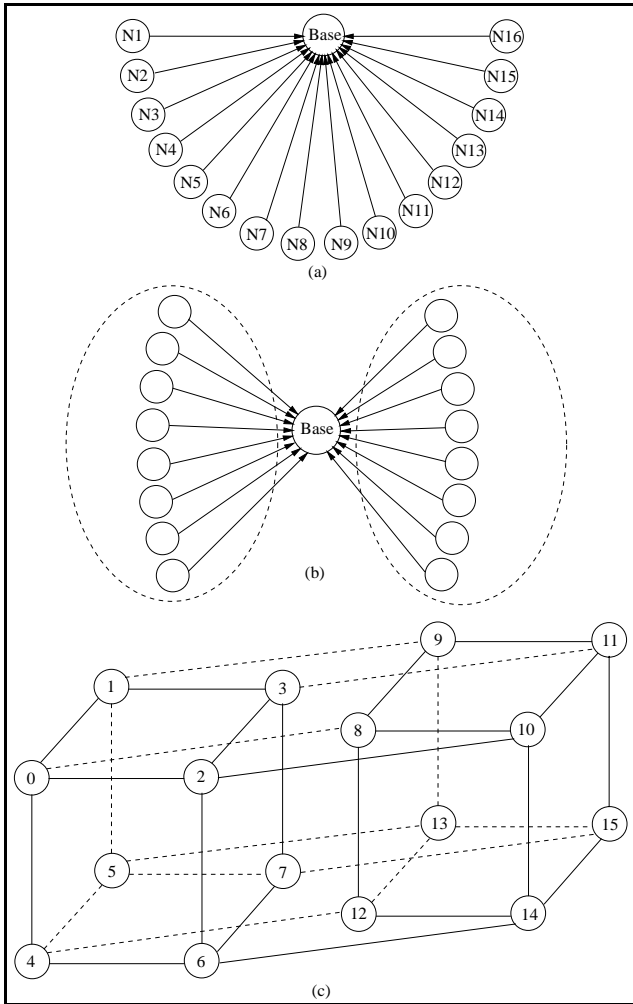


Fig. 8. Various network topologies used in the simulations

Data packets are generated according to a Poisson distribution and the data packet size is assumed to be constant equal to 150 bytes, which equals to approximately 10 slots (i.e. $L = 10$) of 120 bits each. According to our analytical model for the same number of nodes in the network the number of packets transmitted per slot remains the same. To demonstrate that the performance of RICH-DP does not depend on the selected network topology, we collected simulation results for all three topologies shown in Figure 8. Figure 9 shows the throughput measured for MACA-CT and RICH-DP versus the results found with analytical methods and described in section III. It is clear that the effective throughput is fairly independent of the exact network topology; Our simulation results are within a 10% difference from the results obtained from the analysis for all three configurations. This difference is expected, because the simulated radio model includes extra overhead bits for a more accurate representation of the physical effects that take place when a packet is sent or received (i.e. framing bits, padding bits). The two factors that contribute to performance that is network-topology independent are that any node in any of the networks has more available channels than neighbors competing for them, and RICH-DP provides correct collision avoidance in the presence of hidden terminals [19] [18].

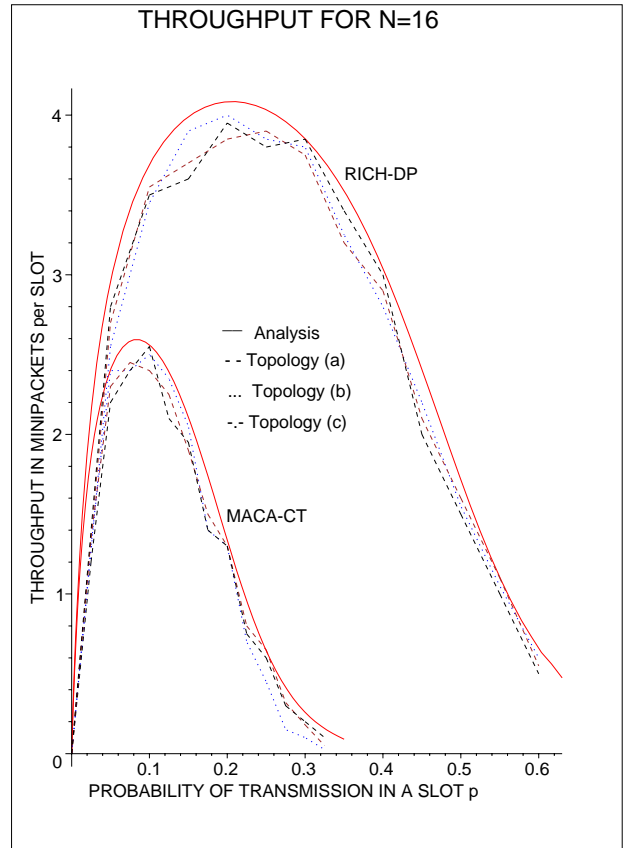


Fig. 9. Aggregate throughput for RICH-DP versus MACA-CT for the topologies of Fig. 8; the number of nodes is $N = 16$ and the average packet length is $L = 10$ or approximately 150 bytes

In addition, using all three network topologies, a number of statistics were recorded to help understand the various effects that take place when a commercially available frequency hopping radio operates. For example, when the nodes in the network produce packets in a data rate higher than the available channel bandwidth, the size of the packets waiting in the queue to be serviced grows rapidly. As can be seen in Figures 10 to 12 for the network topology in Figure 8(a), when the data rate is low, all the packets are received by the base station and the end-to-end medium access delay remains almost constant (Fig. 10). However, when the data rate is higher than what the radio can deliver, packets are lost (after exceeding the available amount of retransmissions) and the delay increases rapidly (Fig. 11). A collision resolution mechanism could be applied in the future to guarantee delay bounds for such applications as voice. There are many examples of such a mechanism in the literature (e.g., [6]).

VI. CONCLUSIONS

We have presented RICH-DP, a collision-avoidance protocol that provides correct floor acquisition without the need for carrier sensing or the assignment of unique codes to network nodes, both of which are difficult to accomplish in ad-hoc networks based on commercial radios operating in ISM bands. We compared the throughput for RICH-DP against MACA-CT, which is a recent example of collision-avoidance protocols that do not

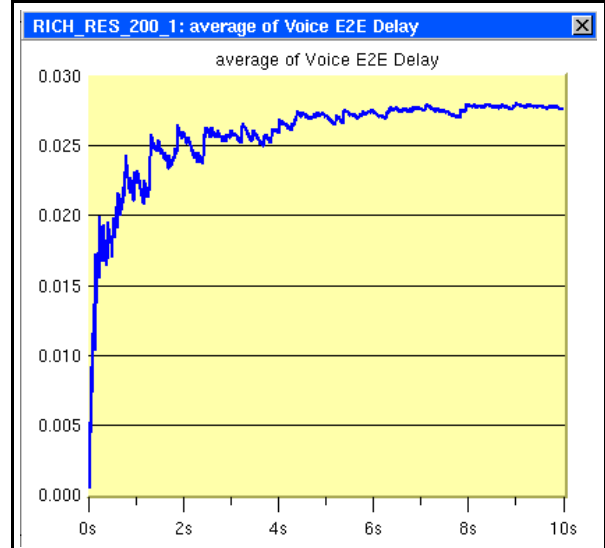
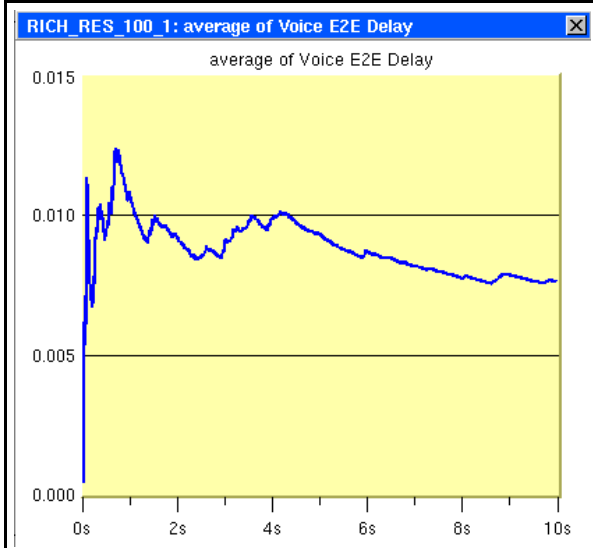
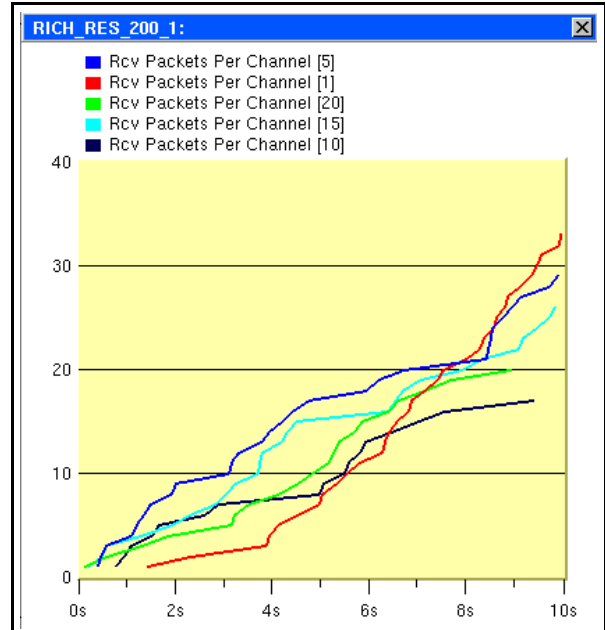
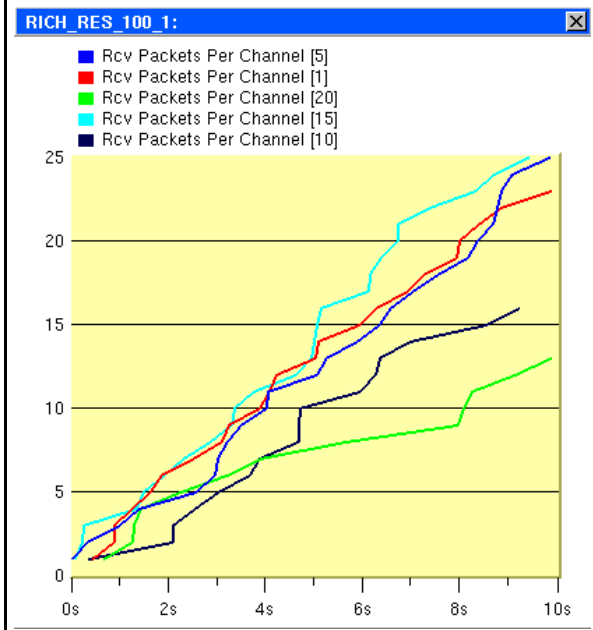
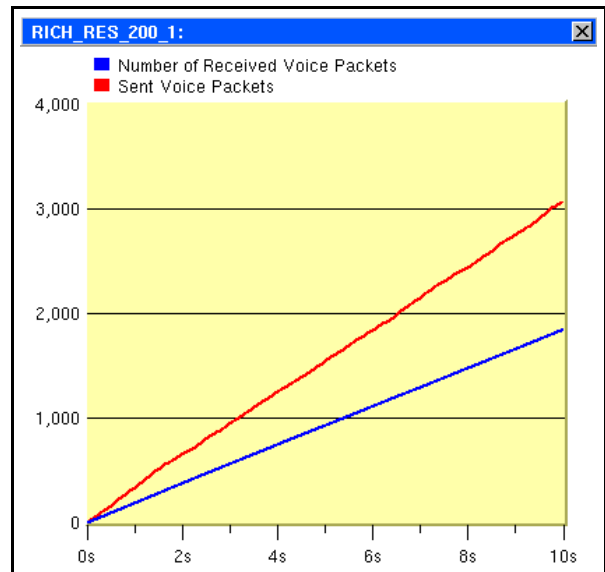
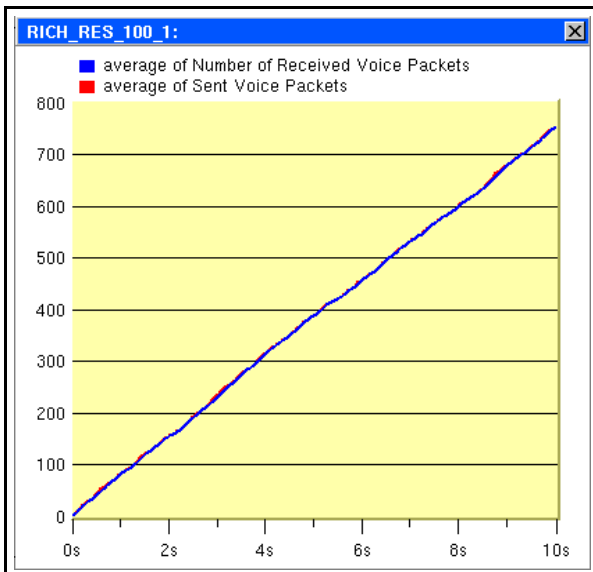


Fig. 10. Packets send with an aggregate node data rate less than the available channel bandwidth

Fig. 11. Packets send with an aggregate node data rate higher than the available channel bandwidth

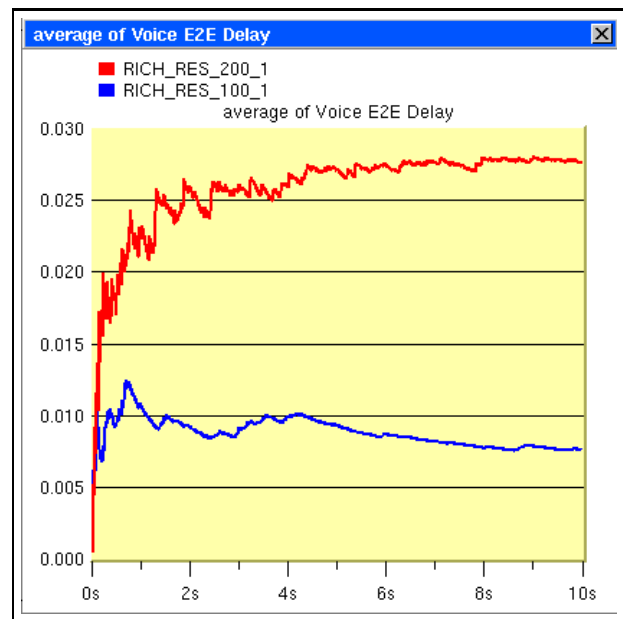
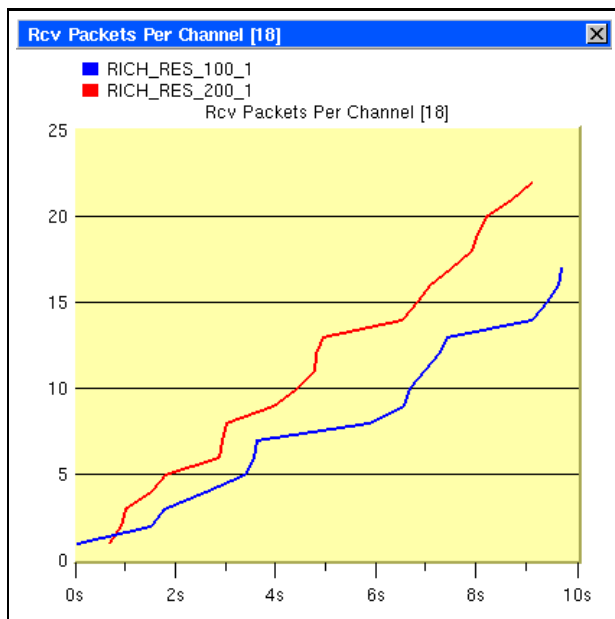


Fig. 12. Difference between an aggregate arrival rate that is less and more than the available channel bandwidth

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 [15] and showed that RICH-DP achieves higher throughput than MACA-CT, without the need for any code assignments. Various simulation scenarios were developed to verify the analysis.

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