A Channel-Hopping Protocol for Ad-Hoc Networks

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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 correct avoidance of collisions under hidden terminals is verified. 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 [11], including IEEE 802.11 [1]. Fullmer and Garcia-Luna-Aceves [2] 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 [3], [10]; 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 [5] 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 [9] 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. [4] used carrier sensing to propose a receiver-based, asynchronous transmissions protocol. Jiang and Hsiao [7] 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., [8]).

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. Most of the commercial DSSS radios today use only 11 chips per bit; therefore, CDMA is not an option. 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 called RICH-DP, which does not require code assignments or carrier sensing. RICH-DP requires all nodes in a network to follow a common channel-hopping sequence. This requirement can be easily met in practise. 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-

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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 proves that, in the absence of fading, RICH-DP solves the hidden-terminal problem, i.e., it eliminates collisions of data packets, without the need for carrier sensing or code assignments. As such, RICH-DP is the first approach reported to date that accomplish correct collision avoidance without carrier sensing or code assignment. Section IV presents the suite of simulation experiments used to understand the performance of RICH-DP in realistic scenarios. We compare RICH-DP with MACA-CT protocol [8], 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 eliminate the need for carrier sensing at the expense of requiring unique channel (code) assignments. Section V summarizes 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 [3], 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 receive 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 current 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. 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 $t1$ from hop $h1$. At time $t2$ the system is at hop $h2$ and so on. At time $t1$ node x sends an RTR to node y and node y responds with data over the same channel. At time $t9$ node y receives an ACK from node x 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. At time $t4$ node z starts sending its data to w. Again, nodes z and w stay in $h2$ until z finishes sending its data, while the other nodes hop to $h3$. At time $t3$, node a sends an RTR to node b but node b is busy transmitting data to another node (uni-directional radios). Therefore, node b does not receive the RTR and at time $t4$ there is silence. In this case, node a continues to hop with the other nodes to hop $h4$. Nodes c and d send an RTR at time $t4$ 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 acknowledgement (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

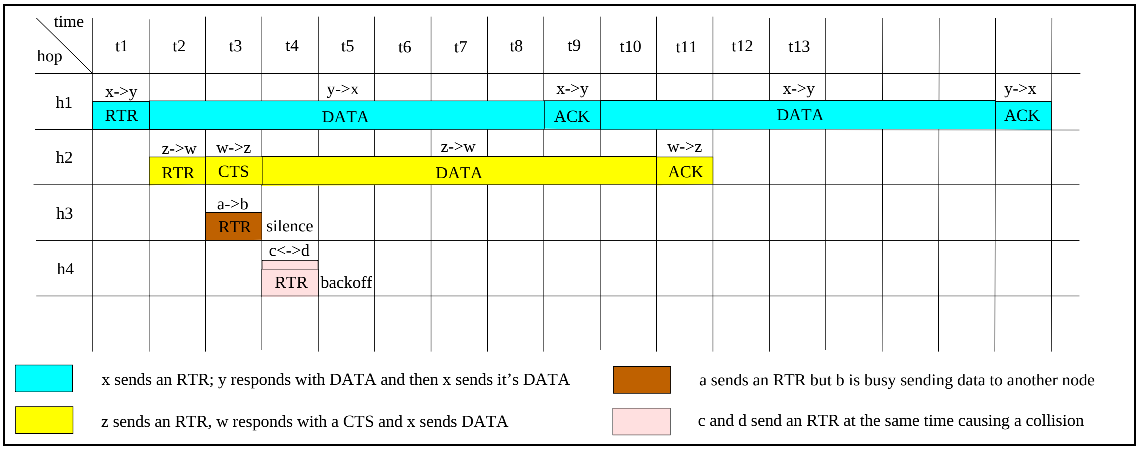

Fig. 1. RICH-DP illustrated

the RTR state. In the RTR state, the node sends an RTR packet to the intended receiver.

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 hop according to the common hopping sequence; otherwise, x remains in the same hop 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 sent a data packet at the same unique frequency hop.

Although the 400msec allowed per dwell time by the FCC is a long time to transmit data in ISM bands, it may be desirable to allow nodes sending data to hop over multiple frequency hops, because staying at the same frequency hop for a long period of time does not take advantage of many inherent advantages that come with frequency hopping. For example, frequency hopping can continue to work efficiently even in the presence of narrow-band jamming and is resilient against fading and erasures. To this effect a receiving frequency-hopping sequence must be defined that is guaranteed to be free of interference from other data transmissions for at least a few dwell times, which could be up to the time when the same frequency hop occurs in the common hopping sequence used for handshakes. The key difference here is that in the CTS sent back to the source from the destination, the base frequency of the destination (which is part of the CTS) is used by the sender to discover the unique hopping pattern to be used to exchange data. Notice that sending data in this way requires packet trains consisting of packets with lengths equal to the size that can be accommodated in a single hop.

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. After sending its RTR, node x waits for a response in the new frequency base. Node x determines that its RTR was not received correctly by z after a time period equal to one hop duration. If that is the case, node x will synchronize with the other nodes at a frequency hop that can be determined easily since node x is aware of the base frequency hop where the whole system is hopping, from the initialization that took place at the beginning of the *hop cycle*.

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. CORRECT COLLISION AVOIDANCE IN RICH-DP

Theorem 1 below shows that RICH-DP ensures that there are no collisions between data packets and any other transmissions under the following assumptions [2]:

A0) A node transmits an RTR that does not collide with any other transmissions with a non-zero probability.

A1) The maximum end-to-end propagation time is τ, the transmission time of an RTR 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, $2\tau < \gamma \leq \delta < \infty$.

A2) The dwell time in each hop is equal to the time needed to transmit an RTR (or CTS) plus the maximum end-to-end propagation time.

A3) There is no capture or fading in the channel. Any overlap of packet transmissions at a particular receiver, causes that receiver to not understand any of the packets.

A4) Any frequency hopping pattern depends solely in the base frequency hop used and the probability that two or more distinct hopping sequences will collide is zero. In the following, for simplicity we assume that data packets are exchanged over a single frequency hop, rather than over a hopping sequence.

The approach used to show that a collision-avoidance protocol 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 from any other source. The intuition why this is possible is shown in Fig. 2, which illustrates that pairs of nodes can exchange data over a given hop h_i while the other nodes move on with the common hopping sequence or are exchanging data over a different hop.

With the commercially available spread spectrum radios today, periods of deep fading (*erasures*) disrupt any type of collision avoidance dialogue, i.e., data packets may experience collisions in the presence of fading. However, with frequency hopping radios, the higher the rate with which a radio hops from one frequency to another the less the probability that an erasure will affect a collision-avoidance exchange. Because the dwell time used in RICH-DP needs to include only two MAC addresses, a CRC, and framing bits, the effect of erasures should be small. 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: RICH-DP provides correct collision avoidance in the presence of hidden terminals when the time spent exchanging data is shorter than the time elapsed before the same frequency hop is reused in the common hopping sequence.

Proof: Consider a polling node A and a polled node X and assume that A sends an RTR at time t_0. After sending its RTR, node A remains in frequency hop H for a period of time that is long enough to detect a CTS or the presence or absence of a data packet. We denote by h the dwell time in a particular hop. If X does not receive the RTR correctly due to interference from any neighbor hidden from A, it does not send any data. Else, X receives A's RTR at time $t_1 = t_0 + h$ and remains in the same frequency hop H where the RTR was received. At time $t_1' > t_0 + h$, if node X has a local data packet for A, then it starts sending its data to A; otherwise, X sends a CTS to A enabling A to send its data packet. Both nodes A and X remain in frequency hop H, that never collides with the common hopping sequence since we made the assumption that the time spent exchanging data is shorter than the time elapsed before the same frequency hop is reused in the common hopping sequence (Fig. 2). ☐

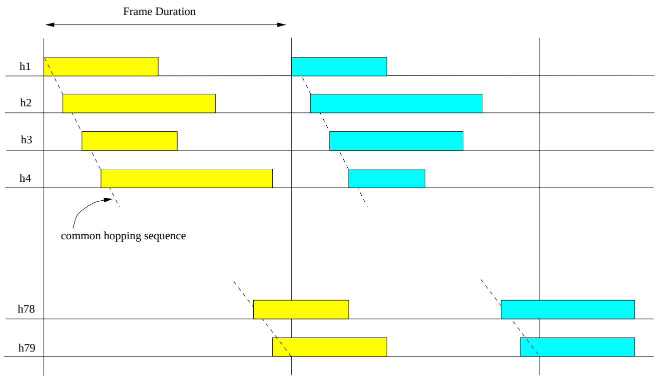

Fig. 2. RICH-DP provides correct floor acquisition since there are no conflicts between the common frequency hopping sequence and ongoing DATA packet transmitions

IV. SIMULATION RESULTS

We performed a number of simulation experiments. Our goal was to investigate the performance of RICH-DP under different network topologies. We implemented in the OPNET simulation tool MACA-CT and RICH-DP. 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 [6]. 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.

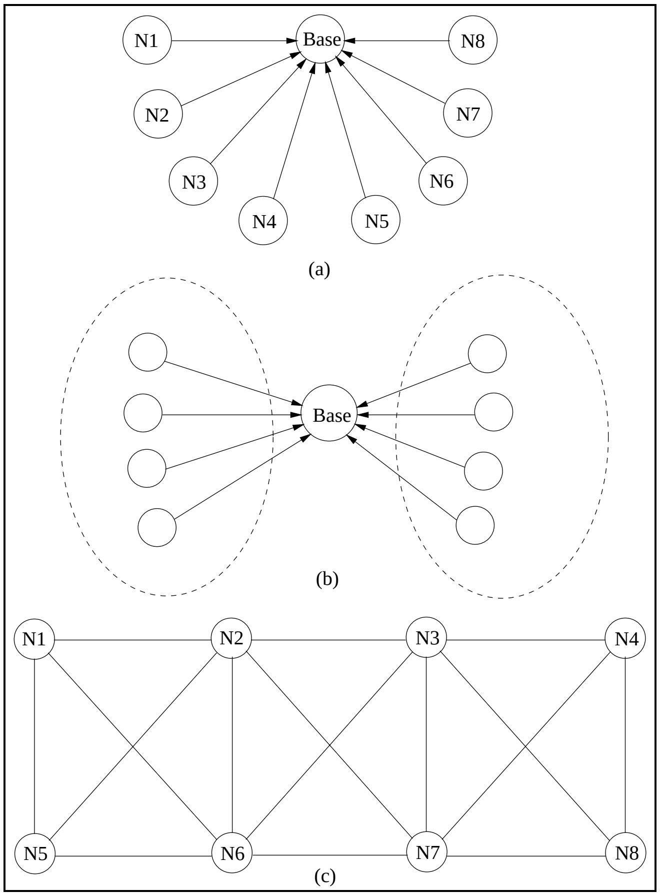

Fig. 3. Various network topologies used in the simulations

Figure 3 shows the various topologies used in the experiments. Figure 3(a) shows a fully-connected network in which all the traffic produced from nodes $N1$ to $N8$ is directed to the base station, $Base$. Figure 3(b) shows two groups of four nodes that can hear every 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 being the central base station $Base$. In Figure 3(c) a multihop network is depicted. The lines between the nodes show the connectivity in the network. A node is generating traffic that three other nodes will receive at any given time whereas there are always at least two other nodes that are hidden. These topologies were chosen given that they have been used in prior work on collision avoidance [2] for single channel medium access protocols.

Data packets are generated according to a Poisson distribution and the data packet size is assumed to be 500 bytes, which equals approximately 34 slots (i.e. $L = 34$) of 120 bits each. Figure 4 shows the throughput measured for MACA-CT and RICH-DP for all three topologies shown in Figure 3. It is clear that the effective throughput is fairly independent of the exact network topology since for all three configurations our simulation results are within a 10% difference from each other. In addition, the results for MACA-CT are very close to the results obtained with analysis in [8]. The difference between the analytical results in [8] and our simulation, 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, is that any node in any of the networks has more available channels than neighbors competing for them, and both MACA-CT and RICH-DP provide correct collision avoidance in the presence of hidden terminals.

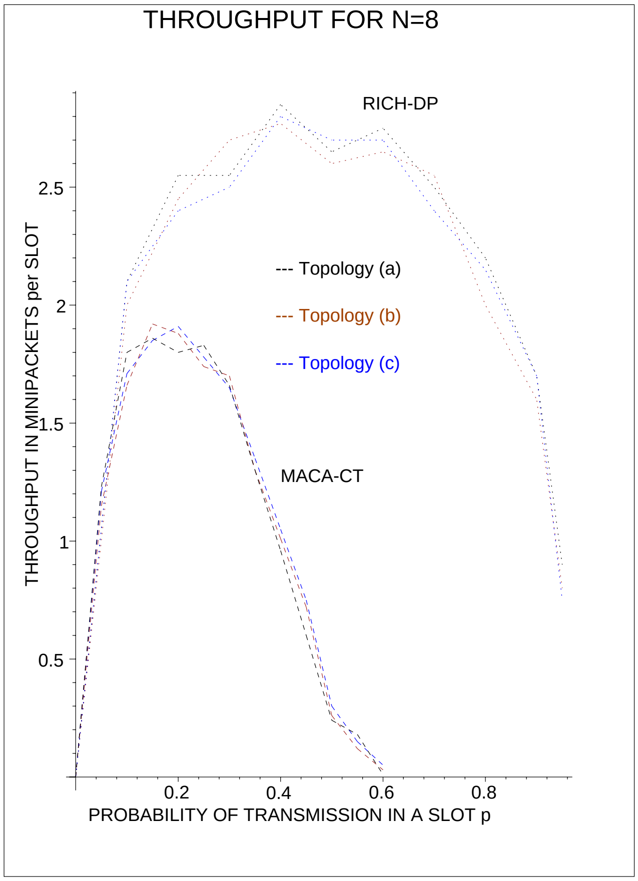

Fig. 4. Aggregate throughput for RICH-DP for the topologies of Fig. 3; the number of nodes is N = 8 and the average packet length is L = 10

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 5 to 7 for the network topology in Figure 3(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. 5). However, when the data rate is higher than what the radio can achieve, packets are lost (after exceeding the available amount of retransmissions) and the delay increases rapidly (Fig. 6).

V. CONCLUSIONS

We have presented RICH-DP, a collision-avoidance protocol that correctly eliminates hidden-terminal interference 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 proved that RICH-DP eliminates hidden-terminal interference and compared its throughput against MACA-CT, which is a recent example of collision-avoidance protocols that do not require carrier sensing but need code assignment to operate correctly. The simulation results show that RICH-DP achieves higher throughput than MACA-CT, without the need for any code assignments.

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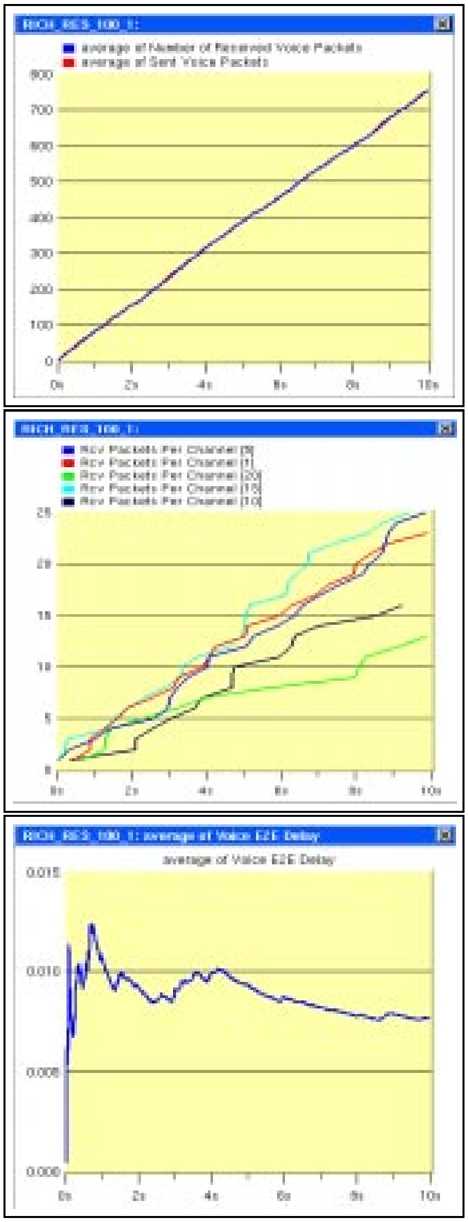

Fig. 5. Packets send with an aggregate node data rate less than the available channel bandwidth

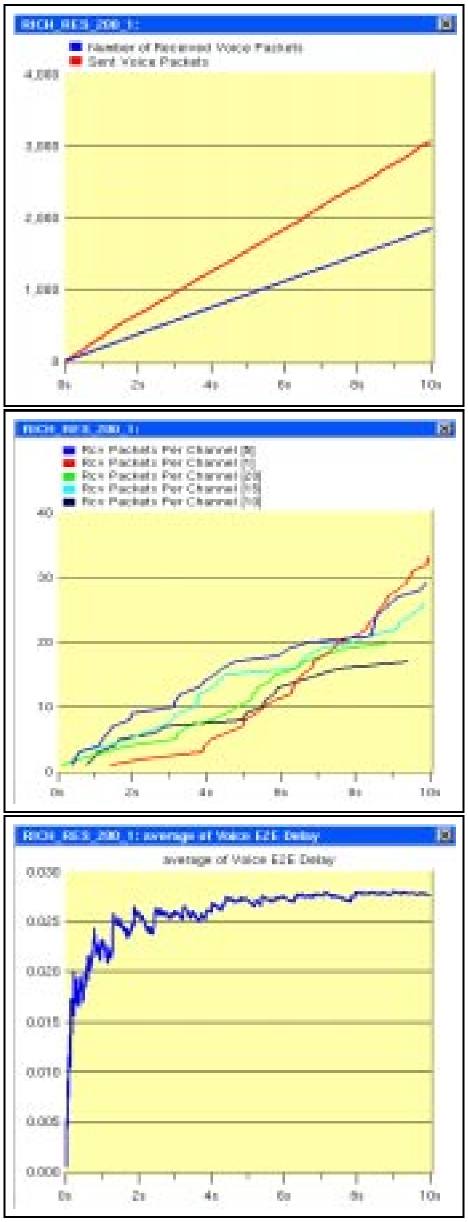

Fig. 6. Packets send with an aggregate node data rate higher than the available channel bandwidth

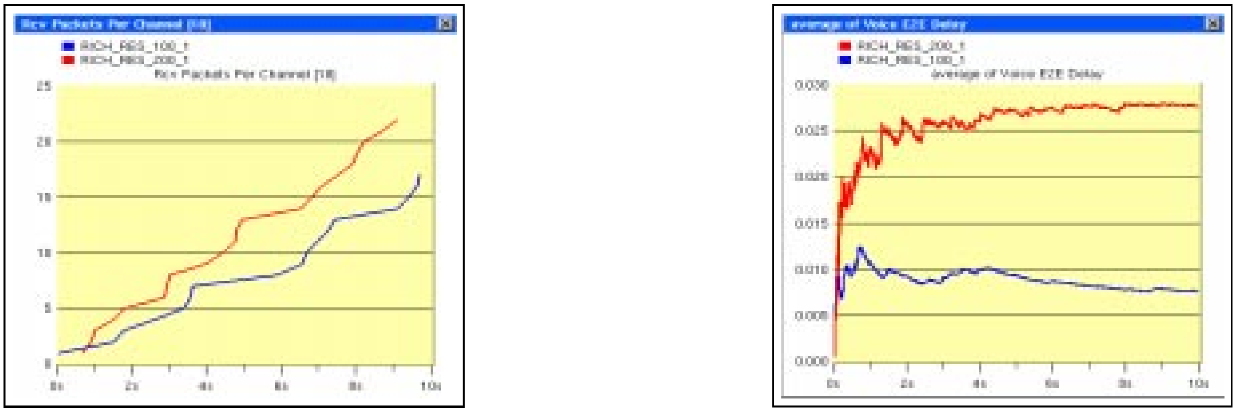

Fig. 7. Difference between an aggregate arrival rate that is less and more than the available channel bandwidth