Simulcast Packet Transmission in Ad Hoc Networks

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Abstract

In previous work, unequal error protection techniques have been applied to improve the throughput of a wireless communication system in which a transmission is received by several radios with different capabilities. For instance, these capabilities may correspond to differences in path loss, fading, or interference. By taking advantage of the broadcast nature of the channel, additional messages for the more-capable receivers can be included on transmissions to the less-capable receivers at very little cost (in terms of required energy at the transmitter or error probabilities at the receivers). This technique has been termed simulcasting or multicast signaling. In this paper, we consider the use of these techniques in an ad hoc network. We evaluate the performance for different medium-access control parameters. The results indicate that simulcasting can improve the throughput in ad hoc wireless networks.

Keywords: simulcasting, multicast signaling, ad hoc networks, unequal-error protection, nonuniform modulation

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I. Introduction

In most ad hoc wireless networks, a radio’s ability to communicate with its neighbors often varies considerably because of differences in channel conditions, such as propagation loss and interference levels. In unicast transmissions, in which a single transmitter communicates to a single receiver, the transmitter can compensate for these variations in capability by using adaptive signaling if the channel conditions are accurately known. However, the shared channel is not necessarily used effectively because a signal that is intended for one radio may also be received by other radios in the system that have much better link conditions than the original destination receiver. We refer to such radios as more-capable radios. In this scenario, additional messages could be included for the more-capable radios at little expense to the original destination of the unicast transmission. Similarly, broadcast transmissions, which are intended for all of a radio’s neighbors, are often ineffective in their use of the shared communication medium because the transmissions must be designed to allow reception by the least capable of a radio’s neighbors. Thus, for any broadcast transmission there are often many more-capable receivers that could successfully receive additional messages that are simultaneously transmitted with the broadcast message. Broadcast transmissions are often required for network maintenance in ad hoc networks. The concepts behind the simultaneous transmissions schemes were originally explored in the context of broadcast channels by Cover and Bergmans [1], [2].

We have previously shown that modulation and coding schemes can be modified to allow the inclusion of additional messages for more-capable receivers at very little cost to the performance at the less-capable receiver [3], [4], [5]. In our previous work, we used the term multicast signaling to refer to such techniques. However, in ad-hoc networks, the term multicasting refers to a process that is primarily associated with the network layer in which a single message is delivered to multiple destinations. In this paper, we refer to our techniques as simulcasting to distinguish them from multicasting and to convey their ability to simultaneously transmit multiple messages to different receivers. We have previously shown that nonuniform phase-shifty-key constellations provide a simple and effective way to convey multiple messages from a single transmitter to two receivers of different capabilities [3], [4], [5].

In this paper, we investigate the performance of simulcast transmissions in a mobile ad hoc network. We consider a system that uses slotted ALOHA [6], [7], [8], [9], [10] for channel access. The routing algorithm used is a minimum-hop routing algorithm that is modified to incorporate
the simulcast capability. The packet selection mechanism is also modified to provide efficient use of the simulcast capability. We present simulation results for different channel models and mobility. We also investigate the effects of varying the medium access control (MAC) parameters based on the link environment of a radio. In addition, we consider MAC schemes that can improve the utilization of the simulcasting capability by giving priority to those radios that have neighbors capable of receiving additional messages. The results indicate that simulcast transmission can improve the throughput in distributed wireless networks.

II. NETWORK MODEL

Before developing the application of simulcasting in ad hoc networks, we first provide an overview of the network model used in this research. The network model used for this study was chosen to be as fundamentally simple as possible, while still providing insight into the effects of using simulcasting. The system is a slotted transmission system, where we assume that all radios are perfectly synchronized. The packet arrival process is modeled by a Bernoulli random process. We assume that the radios have large packet buffers. Multiple access is provided by slotted-ALOHA [8].

Our physical-layer models are also selected to avoid obscuring the effects of simulcasting among other physical-layer phenomena. We begin by specifying some maximum transmission range at which a basic message can be received with a target error probability. Radios are considered to be neighbors if they are within that maximum transmission range. A packet collision occurs whenever a radio transmits a packet during a time slot when there is also a transmission by any of the neighbors of the packet’s designated recipient. We assume that signals from radios that are not neighbors can neither be received nor cause a packet collision by interfering with transmissions from a radio’s neighbors. Furthermore, we assume that all collisions result in packet errors and that there is immediate and perfect feedback on packets that collided or were otherwise received in error. Retransmissions occur after a back-off period that is chosen according to a geometric random variable, as discussed in Section IV.

A. Simulcast Transmission

Consider first the application of simulcasting to improve throughput from a transmitter to a group of receivers with differing capabilities. The easiest way to visualize this is in terms of propagation distance, which generally results in lower average received energy at the more-distant receivers.
This is illustrated in Figure 1 for the case of two receivers. Suppose that the power spectral density of the noise is the same at the two receivers and the only difference in received power is due to the difference in propagation distances. Then receiver 2 will be more-capable than receiver 1 in the sense that the higher signal-to-noise ratio at receiver 2 will allow it to successfully recover a message transmitted with a higher code rate or higher-order modulation than can be successfully recovered at receiver 1. Thus, in the terminology of [3], [4], [5], receiver 1 is a less-capable receiver, and receiver 2 is a more-capable receiver. By using unequal error protection modulation or coding, each time that the transmitter sends a message to receiver 1, it can include extra messages that can be recovered by receiver 2 because of its higher signal-to-noise ratio. In this case, the message intended for receiver 1 is called a basic message, and the messages intended for receiver 2 are called additional messages. We refer to these as the class of the message.

Simulcast transmission can be achieved in many ways but depends on the ability to achieve a different level of error protection for the basic message than for the additional messages. One simple way that this unequal error protection can be achieved is through nonuniform modulation [3], [4]. For instance, one of the simplest examples is the nonuniform quadriphase-shift key (QPSK) constellation illustrated in Figure 2. For this constellation, the nonuniform spacing makes it much easier for a receiver to correctly recover the first bit than the second bit. Thus, the first bit can be used to send a basic message that is intended for a less-capable receiver or for all of a radio’s neighbors, while the second bit is used to convey an additional message that can only be recovered by more-capable receivers. Note that the spacing of the points in the constellation can be chosen so that there is very little performance degradation if the nonuniform QPSK constellation is used to convey the basic message in place of a uniform binary PSK (BPSK) constellation with the same symbol energy.

Simulcast transmission can also be achieved through a variety of other unequal error protection techniques. These include other types of nonuniform modulation [11], [12], [13], [14] unequal error-protection coding [15], [16], [17], [18], [19], [20], combined modulation and coding schemes [21], [22], [23], [24], [5], and space-time coding [25]. For the results presented in this paper, we do not wish to focus on a particular approach to simulcasting; rather, we are interested in the necessary modifications and the performance of the network when simulcasting is used. To do this, we assume that each transmission can include at most two classes of message: a basic message packet and an additional message packet. All packets are assumed to be of the same length. In
addition, we abstract the physical-layer simulcast transmission scheme in terms of parameters that characterize the effects of simulcasting on the performance of the basic and additional messages.

In [3], [4], two important parameters are introduced that can be used to simply characterize simulcast transmission schemes that carry only two classes of messages. The parameters are the degradation and the capability disparity. Both of these parameters are typically specified in decibels. In general, these parameters must be specified in terms of the target error probabilities for the basic and additional messages. In this work, the target error probabilities for these messages are assumed to be equal. By using a simulcast signaling scheme instead of a traditional signaling scheme that only conveys one basic message, the performance of the basic message must be degraded. The degradation measures the additional amount of energy that must be received to achieve the same performance for the basic message with a simulcast signaling scheme as is achieved with a traditional signaling scheme. The capability disparity, or simply disparity, is a measure of how much more capable a receiver must be in order to recover an additional message in comparison to a receiver that only recovers the basic message. It can be calculated as the amount of additional energy that is required at a more-capable receiver to recover the additional message at the target error probability in comparison to the amount of energy required at a less-capable receiver to recover the basic message at the target error probability. Typical values for the degradation and disparity from [4] are 0.5 dB and 9.1 dB, respectively.

In the context of an ad hoc network, the concepts of more-capable and less-capable receivers must be revised, as each radio may act as a transmitter or receiver at different times. When a radio is acting as a receiver, its capability level will depend on its link (channel) from the transmitting radio. Therefore, we define the radio links as being more-capable or less-capable links. For the results presented in this paper, we assume that the only differences in link qualities are caused by differences in propagation distance. This also implies that links are symmetric, so if the link from radio 1 to radio 2 is a more-capable link, then so is the link from radio 2 to radio 1. Radios are able to discover the capabilities of neighboring radios during network maintenance or during regular packet transmission.

An example link map from our simulation is illustrated in Figure [3]. The diagram in Figure [3] actually shows the link capabilities for two different values of degradation and disparity, as explained below. The maps are based on typical degradation and disparity values from [4] and exponential path loss proportional to the fourth power of distance. The figure illustrates the link capabilities
for two scenarios: 1) degradation of 0.5 dB and disparity of 9.1 dB, and 2) degradation of 0.3 dB and disparity of 11.4 dB. For the scenario 1, the solid lines represent the less-capable links, and the dashed lines (including those links shown with two dashed lines) represent the more-capable links. For the more stringent requirement on the degradation and the higher disparity of scenario 2, the links shown with two dashed lines are the more-capable links, and all the other links are less-capable.

As previously mentioned, we assume that the basic and additional messages require the same error probability. In fact, we consider a packet communication scheme in which any packet may be transmitted as either a basic or additional message, depending on the availability of more-capable links. The fact that a packet has been transmitted as one class of message over a link does not affect the class to which it will be assigned on later links. Thus, a packet may start out as an additional message, be transmitted as a basic message over some intermediate links, and be sent over the final link to its destination as an additional message again. The only requirement that we place on the transmissions is that additional messages should be transmitted whenever possible in order to improve the network efficiency. This approach differs from the approaches in [4], [5], [12], [26], in which nonuniform signaling techniques are used to transmit different classes of multimedia messages that may have different requirements on the packet error probability.

B. Routing Algorithm

In this paper, we consider a form of minimum-hop (min-hop) routing [27] in which the routing tables are modified to effectively utilize the capability of simulcasting. Our approach to including simulcasting in the network is designed to allow the transmission of an additional message whenever possible. As previously mentioned, we allow any packet to be sent as an additional message if an appropriate link is available. Whether a packet can be sent as an additional message will depend on the packet’s destination and the link capability of the first link on any minimum-hop route to that destination.

The new routing tables are a superset of the standard min-hop routing tables. The standard min-hop routing table is always used for selection of the next-hop radio for the basic message. To this routing table is added a set of simulcast entries. For a routing table entry to be a valid simulcast entry, it must have a first hop that is a more-capable link and it must be a minimum-hop route. It is not required that the links after the first link be more-capable links. Thus, as previously mentioned,
a packet that is transmitted as an additional message over one link may be transmitted as a basic message over other links.

To illustrate the modified routing table, consider the simple four-node network shown in Figure 4. In this figure, the more-capable links are shown as dashed lines, and the less-capable links are shown as solid lines. In Table I we present an example routing table for radio A. The routing table is formed as follows. The simulcast entries are specified first. Note that there will be no simulcast entry for destination radio B because there is no minimum-hop route that starts with a more-capable link. However, there are simulcast entries for destination radios C and D. Both destinations C and D can be reached in the minimum number of hops by first sending the packet over the more-capable link A → C. The routing table entries that are used to determine the routes for the basic messages are labeled “Normal Entries” in Table I and are selected from the possible min-hop routes in the usual way. For the results presented in this paper, the routing table entries for a particular destination are allowed to be identical, even if other min-hop routes exist.

C. Packet-Selection Algorithm

The packet-selection algorithm should also be modified to ensure efficient use of the simulcast capability. At each time that a radio transmits, it will attempt to utilize a more-capable link if one is available. By doing so, the link throughput can be increased because two packets are sent simultaneously by a radio in a single packet transmission interval whenever possible. An important feature of the simulcasting technique is that the basic and additional messages in a transmission do not have to have the same next-hop radio. Thus, for the network illustrated in Figure 4, radio A can simultaneously send a basic message to radio B at the same time that it sends an additional message to radio C.

The packet-selection algorithm determines which packet(s) in a radio’s buffer will be transmitted in any given packet transmission interval. The packet-selection algorithm is a modified first-in, first-out (FIFO) algorithm that ensures that more-capable links are utilized whenever possible. It functions in the following way. Any radio that has any more-capable link will first try to select from its queue the first packet that can be sent as an additional message. This will not necessarily be the first packet in its queue. After the additional message (if available) is selected, then the radio will select the first packet from the remaining set of packets to be sent as a basic message.

A brief example serves to illustrate this packet selection algorithm. Suppose that radio A’s
packet buffer contains four packets. Each entry in the packet buffer consists of an ordered pair \((I, D)\), where \(I\) denotes the Packet ID and \(D\) denotes the Destination node. Then the packet buffer is an ordered set of such entries. Suppose that radio \(A\)'s buffer is given by

\[
(1, B), (2, B), (3, D), (4, C)
\]

Then during the first interval in which radio \(A\) will transmit, it first searches its buffer for the first packet that can be sent as an additional message. To do so, it compares the destination for each packet to the set of destinations in the simulcast entries in the routing table. In this case, the first packet that can be sent as an additional message to its next-hop radio is packet 3, which, based on the simulcast entry for destination \(D\) in Table I, will be sent to next-hop radio \(C\). Packet 1 is then selected for transmission as the basic message. So, when radio \(A\) transmits, it will simultaneously send messages to radios \(B\) and \(C\) using simulcast transmission. On radio \(A\)'s next transmission, packet 4 will be selected as the additional message, and packet 2 will be sent as the basic message. Note that this simulcast transmission scheme is significantly different than multicasting that occurs at the network or application layers, in which one message is distributed to a group of different receivers. In simulcasting, multiple messages are simultaneously transmitted to a group of receivers.

### III. Link Throughput Analysis

In a distributed wireless network, there are typically two sources of failure for packet transmissions: collisions with transmissions from other radios and random noise. In this section, we consider the throughput analysis for a fixed network topology with a noise-free channel. We apply the conventional techniques for analysis of slotted ALOHA \[8\]. Let \(E[D_i]\) be the expected value of the delay (in terms of number of slots) required for a packet transmitted by radio \(i\) to be successfully received by the designated next-hop radio. Then the link throughput at radio \(i\), \(S_i\), is defined by \(S_i = 1/E[D_i]\). Then the average link throughput for a network of \(N\) nodes is given by

\[
S = \frac{1}{N} \sum_{i=1}^{N} S_i.
\]

We evaluate (I) for two different scenarios. In unicast transmission, simulcasting is not allowed, and each radio sends at most one packet to one next-hop radio during a time slot. For simulcast transmission, two packets can be sent simultaneously by a radio during a time slot if that radio
has any more-capable links, as described in Section II-A. The link throughputs for unicast and simulcast transmission are denote by $S_{\text{uni}}$ and $S_{\text{sim}}$, respectively.

The link throughput will depend on several parameters. Define $G_i$ to be the attempt rate of the $i$th radio. Let $S_{\text{uni}}$ and $S_{\text{sim}}$ be the link throughput at radio $i$ for unicast and simulcast transmission, respectively. The throughput at radio $i$ radios will depend on the number of neighbor radios $N_{b_i}$, the probability of collision $P_{\text{col}}$, and the retransmission rate for unsuccessful packets $R_i$.

### A. Unicast transmission

For unicast transmission, a radio sends only a single message in a slot, and that message is intended for only one of its neighbors. In this case, the throughput for the $i$th radio can be determined as follows. The attempt rate must satisfy $G_i = S_{\text{uni}} + R_i$, where $R_i = G_i P_{\text{col}}$. So, $G_i = S_{\text{uni}} + G_i P_{\text{col}}$. Then the throughput is given by $S_{\text{uni}} = G_i (1 - P_{\text{col}})$, where, if radio $i$ has $N_{b_i}$ neighbors and $G$ is the average attempt rate over all radios, then

$$P_{\text{col}} \approx 1 - (1 - G)^{N_{b_i}}.$$  \hfill (2)

The approximation greatly simplifies the analysis, and our results show that it is a useful prediction of performance. The result in (2) is approximate in two ways. First, the probability of collision depends on the number of neighbors of the destination radio for each packet, not the number of neighbors of the source radio. Second, the offered load from the potential interferers is replaced by the average offered load. Using (2), the average link throughput $S_{\text{uni}}$ can be approximated by averaging over all radios.

### B. Simulcast transmission

Let $R_m$ be the proportion of radios that have at least one more-capable link, and let $N_m$ be the average number of more-capable links for a radio that has at least one more-capable link. For example, for the network topology illustrated in Figure 3, these parameters are given by

(a) $R_m = 7/10$, $N_m = 8/7$, and

(b) $R_m = 4/10$, $N_m = 1$.

For the case of long packet buffers, if the packet generation rate is sufficiently high, then a radio that has a more-capable link will always have a packet that can be sent as an additional message. Then the throughput for the $i$th radio with simulcast transmission, $S_{\text{sim}}$, can be approximated as $S_{\text{sim}} \approx 2S_{\text{uni}}$ if radio $i$ has a more-capable link and $S_{\text{sim}} = S_{\text{uni}}$, otherwise. Let $N$ be the
number of nodes in the network, and let \( M(i) \) be an indicator function such that \( M(i) = 1 \) if radio \( i \) has a more-capable link and \( M(i) = 0 \) otherwise. Then the throughput for simulcast transmission can be approximated by

\[
S_{\text{sim}} \approx \frac{1}{N} \sum_{i} \left[ 2S_{\text{uni},i}M(i) + S_{\text{uni},i}(1 - M(i)) \right] \\
= S_{\text{uni}}(1 + R_{m}).
\]

So, in the best scenario (long packet buffers), simulcast transmission has the capability to improve the throughput by a factor of up to \( R_{m} \).

For the channel models considered in this paper, the conditions that determine whether two radios are neighbors depend only on the signal-to-noise ratio at one of the radios when the other transmits to it. Since the only factor that affects the signal-to-noise ratio is exponential path-loss (no random fading or shadowing is considered), the constraints on connectivity can be directly mapped into constraints on distance between the receivers. Thus, the value of \( R_{m} \) can be calculated based on the assumed distribution of the radios in a network.

For example, suppose that \( N \) radios are uniformly distributed over a circular area with radius \( r \) and area \( \pi r^2 \). Let \( d_l < r \) be the maximum distance between two radios for which they can still be neighbors, and let \( d_m < d_l \) be the maximum distance between two radios for which they are still connected by a more-capable link. Then the probability that radio \( i \) and radio \( j \) are neighbors can be approximated by

\[
p_{\ell} \approx \frac{\pi d_l^2}{\pi r^2},
\]

and the probability that radio \( i \) and radio \( j \) are neighbors connected by more-capable links can be approximated by

\[
p_{m} \approx \frac{\pi d_m^2}{\pi r^2},
\]

where the approximations arise from ignoring the edge effects. Then the network degree (number of neighbors), \( N_{\text{deg}} \), and the proportion of radios with more-capable links can be approximated by

\[
N_{\text{deg}} \approx \sum_{i=1}^{N-1} \binom{N}{i} p_{\ell}^{i}(1 - p_{\ell})^{N-1-i}, \quad \text{and}
\]

\[
R_{m} \approx 1 - (1 - p_{m})^{N-1}.
\]
IV. MEDIUM-ACCESS CONTROL PARAMETERS

In the system that we consider, radios contend for the channel in a particular slot via slotted-ALOHA. We assume that the radios have long packet buffers such that every radio will always have a packet to transmit. When a radio suffers a collision, the radio will wait a random back-off time that is selected according to a geometric distribution. For the system parameters that we consider, the performance is dominated by the effects of contention. Thus, the way that the probability of retransmitting in each slot (or equivalently, the average number of slots that the system will back off after a collision) is determined can have a significant effect on the performance of the system.

The back-off parameters at different radios should be allowed to be different, as the number of other radios that compete for the same channel will depend on the number of neighbors of the next-hop recipient of the packet. We specify the parameters of the geometric back-off algorithm at radio \( i \) in terms of the mean time from collision until the packet is retransmitted, \( T_{B,i} \). Here the value of \( T_{B,i} \) is measured in terms of the number of slots before retransmission. Thus, after a collision, each radio will begin its retransmission in each of the following slots with probability \( \frac{1}{T_{B,i}} \).

The fact that the level of contention depends on the number of neighbors of a radio suggests several approaches for choosing the retransmission parameters at different radios. In addition, with simulcast transmission, some radios are capable of making more efficient use of the channel than others, as radios with more-capable links can transmit two packets in each slot. Radios that do not have any more-capable links can only transmit one packet per slot. We first begin by investigating the effects of adapting to the topology of the network. As radios that have many neighbors are also likely to have some more-capable links, it seems likely that the effects of adapting to such topology information may have a significant effect on the performance of the network that uses simulcast packet transmission.

In our baseline approach that we use to compare with other schemes, the retransmission probability is the same for every radio. For the simulation results, the value of this retransmission probability is varied to achieve a particular offered load. In the second and third approaches, we adapt to the number of neighbors of the next-hop recipient and the source radio, respectively. In the fourth approach, we consider priority schemes in which we assign a higher probability of retransmission to those radios that have a more-capable link and a lower probability of retransmission to those radios that have no more-capable links.
Changing the parameters of the MAC protocol has the potential to improve link throughput at the expense of fairness. For instance, the parameters can be such that a few radios will nearly always be able to transmit while the other radios are blocked. The link throughput increases because there are few collisions, but the network becomes useless as the end-to-end throughput decreases and most radios are unable to transmit any packets. Therefore, in comparing different back-off parameters, we also consider the fairness provided. We define the fairness $F$ as

$$F = \frac{\min(S_{uni_i})}{S_{uni}}.$$  \hspace{1cm} (3)

When $F = 1$, then all radios have equal link throughput and the network resources are in some sense shared fairly. When $F = 0$, then there is at least one radio that is unable to transmit any packets.

A. Case 1: Equal Retransmission Probability

For this case, the MAC protocol assigns equal probability of retransmission to all radios in a network. Thus at a certain average network attempt rate, $G$, every radio has equal back-off time $T_B$ when it suffers a collision.

B. Link-Adaptive Retransmission Probability

For the link-adaptive retransmission schemes, the retransmission parameters depend on the local topology of the network around the transmitter. We consider two different cases, depending on whether the retransmission probability depends on the number of neighbors of the next-hop recipient or the number of neighbors of the transmitting radio.

- Case 2: Based on Number of Neighbors of Next-hop Radio

For this case, the probability of collision is proportional to the number of neighbors of the next-hop radio for the packet intended for the less-capable receiver. We note that in order to minimize the probability of collision, the retransmission probabilities in a flat network that employs slotted ALOHA should be chosen to be inversely proportional to the number of radios in the network [9], [10]. In the local area of a receiver, an ad hoc network appear similar to a flat network, so it makes sense to choose the average back-off time to be proportional to the number of neighbors for the next-hop recipient of the basic message packet. Let $N_{deg}$ be the network degree, which is the average number of links at a radio, and let $N_{nxt}^i$ be the number of neighbors for next-hop radio $i$. 
Then, the back-off time $T_{B,i}^{\text{next}}$ is determined by

$$T_{B,i}^{\text{next}} = \frac{T_B}{N_{\text{deg}}^{\text{next}}} N_i.$$  

(4)

We note, however, that this approach does not quite equate with the approach in a flat network. To see this, consider some radio $i$ that is a next-hop recipient for a packet from one of its neighbors, radio $j$. The problem with the proposed approach is that the other neighbors of radio $i$ may have packets intended for other recipients and thus will choose their retransmission probabilities based on the neighbors of those radios. However, any transmissions from those radios still causes contention at radio $i$. This may result in much higher or lower contention than would be optimal based on the flat-network approximation. This motivates us to investigate other approaches to adapt to the local network topology, as in the next section.

- **Case 3: Based on Number of Neighbors of the Transmitting Radio**

  The second approach to adapting to the local topology of the network again uses the approach suggested above and in [9], [10]. However, in this section we choose the back-off time, $T_{B,i}^{\text{src}}$, to be proportional to the number of neighbors of the transmitting radio. So, if the number of neighbors of the transmitting radio is $N_i$, then

$$T_{B,i}^{\text{src}} = \frac{T_B}{N_{\text{deg}}} N_i.$$  

(5)

**C. Priority-based Retransmission Probability**

We consider a priority-based approach that attempts to improve the average link throughput by assigning a higher priority to the radios that can transmit more messages in a slot. Similar approaches have been investigated in the context of 802.11-type networks that employ carrier-sense multiple access with collision avoidance (CSMA/CA) [28], [29]. In these 802.11 networks, priority is controlled by adjusting the length of the contention window. For our slotted-ALOHA network, we can adjust the priority by assigning a higher retransmission probability to radios that have a more-capable receiver and a lower retransmission probability to those radios that have only less-capable links to their neighbors. Using this approach, it is hoped that the link throughput can be increased further, although we expect that the fairness may be decreased.

- **Case 4: Based on Number of Neighbors of Next-Hop Radio and Priority**

In this paper, we only consider adding priority to the scheme that adapts the retransmission probability to the number of neighbors of the next-hop recipient of a message. The results in Section V
indicate that for the network considered here, adapting the retransmission probability based on the number of neighbors of each transmitter provides a good compromise between increasing throughput and decreasing fairness.

We assign a higher chance of retransmission to packets that are intended for a more-capable receiver by adjusting the retransmission probability by a priority weight, $W_p$. Let $N_{M,i}$ be the number of more-capable receivers of radio $i$ and $N_{L,i}$ be the number of less-capable receivers of radio $i$. Furthermore, let $P_{L,i}$ denote the retransmission probability if radio $i$ only uses less-capable links and $P_{M,i}$ denote the transmission probability of radio $i$ also uses more-capable links (if it has any) to send additional messages. Then we wish to choose $P_{L,i}$ and $P_{M,i}$ such a way that

$$P_{M,i} = W_p P_{L,i}.$$ 

The expected number of back-off slots corresponding to these two probabilities is given by $T_{L,i}$ and $T_{M,i}$ for the use of only less-capable links and both types of links, respectively. Then in terms of our original expected back-off time $T_B$, the $T_{L,i}$ and $T_{M,i}$ are given by

$$T_{L,i} = T_B \frac{N_{M,i} W_p + N_{L,i}}{N_{L,i}},$$

and

$$T_{M,i} = \frac{T_{L,i}}{W_p}.$$ 

V. SIMULATION RESULTS

Monte Carlo simulations were conducted to evaluate the performance of simulcasting in ad hoc networks and the proposed protocol modifications. We used a custom simulation programmed in MATLAB because this provided us a simple approach to develop a simulation that incorporates the ability to transmit multiple packets to multiple different receivers in a single transmission slot and to adapt the link- and network-layer protocols to take advantage of the simulcasting capability.

We begin by consider the fixed network topology of ten nodes illustrated in Figure 3. The initial network degree, defined as the average number of links per radio, is 2.2. The results in Figure 5 show the throughput performance of the network with no mobility as a function of the average attempt rate. Solid lines represent the performance predicted by the analysis, and the markers illustrate the performance results from our simulation. The performance is illustrated for three different network configurations. For the results marked “Unicast”, the the nodes are constrained do not employ the simulcast signaling technique and thus each node transmits at most one packet in a time slot. For the results marked “Simulcast(NW1)”, simulcast transmission is used, where
the more-capable links are determined based on a degradation of 0.5 dB and a disparity of 9.1 dB.

The results marked “Simulcast(NW2)” illustrate the performance for a network with fewer more-capable links because the required capability disparity is increased to 11.4 dB, which corresponds to a degradation of 0.3 dB. The throughput for these fixed topologies with equal back-off times is illustrated in Figure 5. The results indicate that simulcasting can significantly improve the throughput in the ad hoc network. The simulation incorporates transmission in additive white Gaussian noise (AWGN), where the bit error probability at the maximum range is $10^{-4}$. It is assumed that the packet length is 1000 bits and an error-control code is used that can correct up to 10 bit errors. For this case of no mobility, we expect that there will be almost no performance degradation from the noise, as the transmission range for nodes to be considered neighbors is such that the packet error probability is very small. The simulation results match closely with the analytical results.

The results in Figure 6 illustrate the performance of the network when mobility is added. Here, we investigate the effect of having out-of-date information about the network links. Thus, a node’s link information may indicate that a node is a neighbor even though that node has moved out of range. Similarly, a node may believe that a link is a more-capable link even though the nodes movements have reduced the capability of a link to an extent that the packet error probability over that link degrades performance. We model these effects by only allowing for a periodic update of routing tables. We assume a slot time of 20 ms and a routing table update every 300 slots (6 s). We employed a random waypoint mobility model with various parameters for the mobile velocities. We present results for no mobility and constant velocity of 30 km/hr. We also consider two cases of random velocities with the velocities randomly distributed over some range. At each waypoint, a new velocity is chosen according to the specified distribution. We present results for uniform distributions on 10 km/hr to 30 km/hr and for the range of 30 km/hr to 70 km/hr. The routing table is refreshed at every 300 time slots by exchanging information between the radios that have a direct link to each other. The simulation results in Figure 6 show that the performance for both systems degrades, but simulcasting still provides a significant throughput gain. As expected, higher mobility levels generally result in lower throughput as routing table information is more likely incorrect. This is observed to be especially true at high average attempt rates.

The results in Figure 7 show the throughput performance of the different approaches to choosing the back-off parameters that are described in Section IV. For these results, the simulations used the static initial network NW1 under the assumption of a noise-free channel. By choosing
the parameters using the link-adaptive approach that adapts to the number of neighbors of the next-hop radio (case 2), the maximum throughputs of the unicast and simulcast transmissions are increased from approximately 0.12 to 0.15 and from 0.22 to 0.24, respectively, in comparison to equal back-off time (case 1). This represents gains of approximately approximately 25% for unicast transmission and 9% for simulcast transmission. By choosing the back-off time based on the number of links at the transmitting radio (case 3), the maximum throughput of unicast transmission is increased by approximately 50%, and the maximum throughput of simulcast transmission is increased by approximately 27% in comparison to case 1. Using the link-adaptive parameters can also have a significant effect on the fairness of the system. The results on the fairness of these various approaches are illustrated in Figure 9; however, we delay discussing them until we present the throughput results for the priority-based retransmission probabilities.

For the results presented in this paper, we only consider priority schemes based on modifying the scheme that adapts to the number of neighbors of the next-hop recipient for the basic message. The probability of retransmission for those radios that have a more-capable neighbor is set to a value that is \( W_p \) higher than for those radios that have the same number of neighbors but no more-capable neighbors. The results in Figure 8 show the average link throughput for various values of \( W_p \). By increasing \( W_p \), the average link throughput can be significantly increased. For the scheme that does not use priority retransmission, \( W_p = 1 \), the maximum throughput achieved with simulcasting is approximately 0.22. By assigning higher retransmission probabilities to those radios that have more capable receivers, the maximum throughput can be increased to approximately 0.29 for \( W_p = 2 \). This corresponds to almost a 32% increase in throughput. Using either \( W_p = 3 \) or \( W_p = 4 \) results in an increase in the maximum throughput to approximately 0.32. There was actually a slightly higher throughput measured for \( W_p = 4 \), but the difference was less than 0.004, thus the maximum throughput appears to saturate for \( W_p \geq 3 \). Note that the gain in throughput is only achieved by increasing the average attempt rate and thus may not be achievable in many networks. Furthermore, this increase in throughput is achieved at the expense of fairness, which we investigate below.

In Figure 9, we investigate the fairness of the various approaches to adjusting the retransmission probabilities. We begin by discussing the three approaches that do not incorporate priority retransmission. Recall that the retransmission probabilities are equal for case 1, adapted to the number of neighbors of the next-hop recipient of the basic message for case 2, and adapted to the
number of neighbors of the transmitting radio for case 3. The results indicate that the fairness is approximately equal for all of the retransmission schemes up to an average attempt rate of approximately 0.15. Below this point, we expect that collisions occur fairly infrequently, so changing the retransmission probabilities will not significantly affect the throughput. However, for an average attempt rate above 0.15, different changing the retransmission probabilities can greatly affect both the throughput and fairness. Thus, when comparing the performance of the various approaches without priority, the results of Figures 7 and 9 should be interpreted together.

The results in Figure 9 indicate that using equal retransmission probabilities (case 1) generally provides the highest fairness of all the approaches investigated. Case 1 provides the lowest throughput. Adapting to the number of neighbors of the next-hop recipient (case 2) has a lower fairness, and adapting to the number of neighbors of the transmitter (case 3) provides the lowest fairness of those schemes that do not use priority. As discussed above, case 2 provides a slightly higher maximum throughput, and case 3 provides the highest throughput. Thus, there is a clear trade-off between fairness and throughput.

As indicated by the results in Figure 8, assigning additional priority to the transmission from those radios with more-capable neighbors can significantly improve the maximum average throughput. However, the results in Figure 9 show that those throughput gains come at the expense of decreased fairness. For instance, all of the values of the weighting parameter \( W_p \) achieve approximately the same throughput and fairness at an average attempt rate of 0.28. Above this value, not using priority (\( W_p = 1 \)) provides a higher level of fairness, but the throughput decreases rapidly as the attempt rate is increased. The maximum throughput for \( W_p = 2 \) is achieved at an average attempt rate of 0.32. To achieve this, the throughput is reduced from approximately 0.51 for \( W_p = 1 \) (case 3) to 0.4 for \( W_p = 2 \). Further increasing the priority drastically decreases fairness. The maximum throughput for \( W_p = 3 \) is achieved at an average attempt rate of approximately 0.37. At this attempt rate, the fairness for \( W_p = 3 \) is 0.27 versus 0.46 for \( W_p = 1 \) and 0.37 for \( W_p = 2 \). Again, there is a clear trade-off between fairness and throughput. On the other hand, since the radios that have more-capable neighbors can transmit two messages in each slot, it makes sense to allow them greater access to the channel resources; however, our measure of fairness only compares the throughputs for the basic messages. The proper measure of fairness will depend on the particular types and sources of traffics expected in the network.
VI. CONCLUSION

In this paper, we introduced the use of simulcast transmission techniques for ad hoc networks. We applied a cross-layer approach in which the link- and network-layer protocols were modified to effectively utilize the new capability presented by simulcasting. We proposed some modifications to the routing, packet-selection, and collision back-off algorithms. The performance of simulcast signaling was analyzed and simulated for a network that employs slotted ALOHA. The analytical and simulation results confirm that simulcasting can significantly improve network throughput for static and mobile networks. The performance advantage of simulcasting is primarily determined by the number of nodes that have more-capable links available, which in turn is determined by the degradation and disparity of the simulcast transmission scheme. Modifications to the collision back-off parameters were also simulated. The results indicate that by adapting the retransmission probabilities to the number of neighbors of a radio, the average link throughput can be increased, although the fairness will be reduced. A priority-based MAC protocol was also investigated in which the retransmission probabilities were increased for those radios that have a more-capable receiver and decreased for those radios that have only less-capable links. Increasing the priority was found to allow a higher average link throughput to be achieved at high average attempt rates, but again, the overall fairness was reduced.
REFERENCES


Fig. 1

SIMPLE SCENARIO ILLUSTRATING SIMULCASTING AT THE LINK LEVEL.
Nonuniform 4-PSK that achieves different levels of error protection for each bit.
Fig. 3

Link capabilities for a ten-node wireless network. Solid lines indicate less-capable links. For degradation of 0.5 dB and disparity of 9.1 dB, all the links shown with dashed lines are more-capable links. For degradation of 0.3 dB and disparity of 11.4 dB, only the links shown with two dashed lines are more-capable links.
Fig. 4

EXAMPLE LINK MAP FOR A FOUR-NODE WIRELESS NETWORK.
<table>
<thead>
<tr>
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<th>Destination</th>
<th>Next Hop</th>
<th>No. of Hops</th>
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<td>1</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>B</td>
<td>2</td>
</tr>
</tbody>
</table>

**TABLE I**

**Routing table for radio A in Figure 4**
Throughput in AWGN for the network of ten nodes that is illustrated in Figure 3. For NW1, the degradation is 0.5 dB, and the disparity is 9.1 dB. For NW2, the degradation is 0.3 dB, and the disparity is 11.4 dB.
**Fig. 6**

Throughput in AWGN for a mobile network of ten nodes with degradation of 0.5 dB and disparity of 9.1 dB. The initial configuration is as illustrated in Figure 3.
Fig. 7

THROUGHPUT OF ADAPTING BACK-OFF PARAMETERS BASED ON LINK ENVIRONMENT.
Fig. 8

Throughput of priority-based approach to choosing the retransmission probabilities.
Fig. 9

FAIRNESS OF THE VARIOUS TECHNIQUES TO CHOOSE THE RETRANSMISSION PROBABILITIES.