Wireless Networks manuscript No.
(will be inserted by the editor)

Cooperative-Diversity Slotted ALOHA

John M. Shea, Tan F. Wong, and Wing-Hin Wong

Wireless Information Networking Group, University of Florida, Gainesville, FL 32611-6130, USA

The date of receipt and acceptance will be inserted by the editor

Abstract

We propose a cooperative-diversity technique for ad hoc networks based on the decode-and-forward relaying strategy. We develop a MAC protocol based on slotted ALOHA that allows neighbors of a transmitter to act as relays and forward a packet toward its final destination when the transmission to the intended recipient fails. The proposed technique provides additional robustness against fading, packet collisions and radio mobility. Network simulations confirm that under heavy traffic conditions, in which every radio always has packets to send, the proposed cooperative-diversity slotted-ALOHA protocol can provide a higher one-hop and end-to-end throughput than the standard slotted-ALOHA protocol can. A similar advantage in end-to-end delay can be obtained when the traffic is light. As a result, the proposed cooperative-diversity ALOHA protocol can be used to improve these measures of quality of service (QoS) in ad hoc wireless networks.

Keywords: cooperative diversity, relaying, MAC protocols, slotted ALOHA

1 Introduction

In ad hoc networks, multi-hop routing is used to deliver messages from a source to a destination. In the conventional approach, if a packet is not successfully delivered then the desired recipient will transmit back a negative acknowledgment (NACK) or fail to transmit a positive acknowledgment (ACK). However, other neighbors of the transmitting radio may have successfully received the packet and thus may be able to relay that message on to the desired recipient. By allowing these radios to act as relays for the packet, cooperative diversity [7, 4] can be achieved. Our approach is distinguished from these information-theoretic works in several ways. Schemes that rely on the decode-and-forward or amplify-and-forward [4] methods to improve diversity at the original intended receiver typically result in a reduction in bandwidth efficiency. Furthermore, in previous work contention among the relays is usually ignored under the assumption of ideal orthogonal transmission, which may be impractical for distributed networks. Our approach takes into account contention issues. Another significant difference between our approach and the work above is in the destination of the relaying. In [4] the relays transmit additional information to the original intended receiver of a message. This is an inherently suboptimal approach because the ultimate goal of any transmission is to propagate a message toward its end destination. Thus in the protocol we propose, a radio may relay a packet directly toward its end destination. Our approach depends on several key assumptions and modification to the usual division between link and network layers. We address these issues in the detailed description of the proposed algorithm in Section 4.

In this paper, we limit our scope to modifying the simple slotted-ALOHA MAC protocol [1] and to investigating the performance under the assumption of minimum-cost routing. In our proposed scheme, we provide additional mini-slots for control signaling to allow for another radio to take over responsibility for a packet when the transmission to the intended receiver fails. Thus a form of cooperative diversity is achieved. We note that a similar scheme, known as Selection Diversity Forwarding (SDF), is proposed by Larsson in [5]. We will compare the performance of our cooperative-diversity slotted ALOHA (CDSA) and Larsson's SDF schemes in Section 6.

2 System Model

We consider an ad hoc network that employs a MAC protocol based on slotted ALOHA and a minimum-cost routing protocol [6],[2]. The channel is modeled as a flat fading channel, where the fading is constant over each time slot. For a pair of radios separated by a distance of d m, the instantaneous SNR in a time slot is

$$\text{SNR} = \frac{a}{d^{\alpha}}\gamma_0, \tag{1}$$

where α is the exponential path loss order, a is an exponentially distributed random variable with unit mean, and γ_0 is a SNR reference. The value of α usually ranges from 2 to

5. The exponential random variable a is employed to model the effect of Rayleigh fading. With the assumption of ergodic fading processes, the *long-term average SNR* between a pair of radios separated by a distance of d m is

$$\overline{\text{SNR}} = \frac{1}{d^{\alpha}}\gamma_0. \tag{2}$$

We assume that the long-term average SNRs are measurable and are passed among the radios for use in routing. The value of γ_0 is determined by the transmission power of the radio and the noise spectral density. The primary effect of using different values for γ_0 is to change the level of connectivity in the network. We use the following model for network connectivity. Two radios will be considered *long-term neighbors* if the average SNR for communications between those radios is above some threshold, SNR_0. We also consider mobile networks, so the long-term neighbors of a radio can change.

We use the following simplified model for the physical layer. Two radios will only be able to communicate or interfere with each other if the instantaneous SNR between the two radios is greater than a threshold. In this case, we say that the radios are *instantaneous neighbors*. In this paper, we use the same threshold, SNR_0, to determine whether radios are long-term neighbors or instantaneous neighbors. We assume that in a specific time slot, the transmission of a packet will be successful only if *both* of the following conditions hold: (1) the receiving radio is an instantaneous neighbor of the transmitting radio in that time slot, and (2) no other transmitting radio, of which the receiving radio is an instantaneous neighbor, sends a packet in that time slot.

3 Cooperative Diversity Through Relaying

Our protocol is based on the observation that in a connected network, when a packet is not successfully received, one of the other neighbors of the transmitter may have overheard the packet and furthermore can relay the packet to its destination with a lower link cost than the transmitter. In our proposed scheme, each such radio decides whether it should attempt to act as relay based on whether it can provide a route to the destination as good as the route from the intended receiver to the destination. To know this information requires that information about the routing tables of neighboring radios be stored and made accessible to the link layer. Fig. 1 shows an example scenario for relaying. Suppose radio A has a packet intended for destination H and determines from its routing table that it should transmit the packet to D. However, during this time slot, the channel from A to D is in a deep fade. Meanwhile, the other instantaneous neighbors of A, radios B, C and E, can overhear the packet. All these radios try to check the packet header and decide whether they should help forwarding the packet. Node B determines that it can reach the packet's destination in 3 hops, whereas the intended receiver D can reach the destination in 2 hops, so it decides not to help forwarding the packet. Nodes C and E can reach the destination H in two hops, which is the same as the intended receiver, so they will attempt to act as relays.

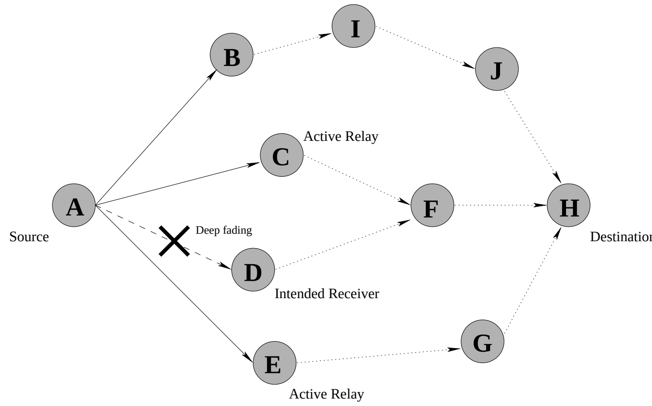

Fig. 1 Section of an ad hoc network that shows scenario for relaying. Solid lines connect instantaneous neighbors of transmitter. Dashed lines connect long-term neighbors that are not instantaneous neighbors.

4 Cooperative-Diversity Slotted ALOHA

We present a protocol based on slotted ALOHA that provides a method for a relay to take over responsibility for forwarding a packet to its destination. The protocol must provide several features. First, if the final destination can recover the packet even if it is not the intended receiver, there should be a means to cease any other forwarding by the intended receiver or other relays to avoid unnecessary network traffic. Second, it should provide a means for the intended receiver to acknowledge if it has received the packet correctly. Third, it should provide a means for the transmitter to inform the relays that relaying is required because the intended receiver did not correctly receive the message. Finally, there should be some method for selecting a relay to forward the packet on to its destination. The protocol we develop is called cooperative-diversity slotted Aloha (CDSA).

4.1 Routing Considerations

We consider the use of CDSA with a minimum-cost routing algorithm. The route cost is defined as a pair (H, L), where H denotes the hop count and L denotes the total link cost, which is given by

$$L = \sum_i \left(\overline{\text{SNR}}_i\right)^{-1}, \tag{3}$$

where $\overline{\text{SNR}}_i$ is the long-term SNR of the i^{th} link of the route. We explain this choice of link cost as follows. The probability density function of the instantaneous SNR of a particular link is given by:

$$f(s) = \left(\overline{\text{SNR}}\right)^{-1} e^{-s(\overline{\text{SNR}})^{-1}}. \tag{4}$$

The packet can be transmitted through this link successfully if the instantaneous SNR is larger than the threshold SNR:

$$\Pr(\text{SNR} > \text{SNR}_0) = \int_{\text{SNR}_0}^{\infty} f(s)ds = e^{-(\text{SNR})(\overline{\text{SNR}})^{-1}}. \tag{5}$$

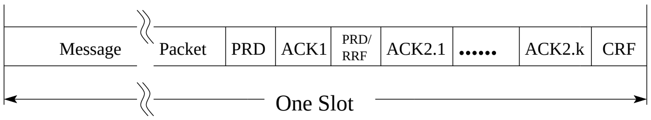

Fig. 2 Diagram showing subdivision of transmission slot for the CDSA protocol.

The packet can be transmitted through the whole path successfully without re-transmissions with probability

$$\exp\left\{-\mathrm{SNR}_0 \sum_i \left(\overline{\mathrm{SNR}}_i\right)^{-1}\right\}.$$

Thus in the absence of collisions, minimizing the proposed link cost is equivalent to maximizing the success probability of a packet transmission through the path. The link costs are ordered according to $(H_i, L_i) < (H_j, L_j)$ if $H_i < H_j$ or $(H_i = H_j) \cap (L_i < L_j)$, so that minimum-hop routing takes priority, but a route with a lower link cost is chosen when comparing two routes with the same number of hops.

The application of cooperative diversity implies the possibility of dynamically modifying the route of a packet. We refer to a radio that competes to forward a packet that the original recipient did not recover as a *routing relay (RR)*. A radio will only act as a RR if it meets all the following:

1. It is a relay. That is, it overhears a packet from the original transmitter and can decode the whole packet successfully.
2. It has a route to the packet's destination with hop count not larger than the path from the original transmitter.
3. Its link cost to the destination is less than that of the original transmitter.

The second and third conditions above correspond to requiring the RR to have a lower route-cost than the transmitter and are to avoid choosing an excessively long route and re-routing the packet back to the transmitting radio, respectively. There may be several radios that can act as RRs, but only one such RR can take over responsibility of delivering the packet to the final destination when the intended receiver does receive the packet. In the next section, we present a protocol to coordinate the selection of a RR.

4.2 MAC Protocol

The CDSA protocol segments each slot into the message packet portion followed by *five* [1] *or more* mini-slots, as illustrated in Figure 2. The five types of mini-slots are as follows:

1. The PRD mini-slot (Packet-Reached-Destination) is intended for the final destination of the packet to transmit an acknowledgment to the transmitter. When the original transmitter receives the PRD signal, it will also send a PRD signal in the third time slot as described below.
2. The ACK1 mini-slot is for the intended receiver (not the final destination) to acknowledge successful reception of the transmitted packet.
3. The RRF/PRD mini-slot is intended for the transmitter to send a Request-for-Relay-Forwarding (RRF) or a PRD signal depending on the following situations:
   (a) If the final destination sent a PRD in the first mini-slot, the transmitter will send a PRD signal here to inform the intended receiver (if it is not the destination) not to forward the packet further.
   (b) If the original transmitter did not receive the PRD signal but did receive the ACK1 signal, it will not transmit anything in this mini-slot.
   (c) If the transmitter received neither a PRD or ACK1 in the first two mini-slots, it will transmit a RRF signal to the RRs to request help in forwarding the packet.
4. One or more ACK2 mini-slots are used for RRs to compete to relay a packet. Upon hearing the RRF signal in the RRF/PRD mini-slot, a RR will verify whether the RRF signal matches the packet that it has correctly decoded.
   (a) If the RRF signal does not match the received packet, the RR will discard the packet.
   (b) Otherwise, the RR will determine whether it will complete with other RRs to forward the packet according to some relay forwarding resolution (RFR) algorithm. Examples of such algorithms are described later in the section.
      i. If the relay decides to help forward the packet, it will send out acknowledgment signal ACK2s to the transmitting radio in one or more of the ACK2 mini-slots. Using more than one mini-slot is to increase the probability of success during ACK2 contention.
      ii. Otherwise, the relay will discard the packet and remain idle until the next time slot.
5. The Clear-to-Relay-Forwarding (CRF) mini-slot is used for the original transmitter to select a RR to take over forwarding the packet toward the end destination. After sending out the RRF signal in the RRF/PRD mini-slot, the transmitting radio checks for acknowledgments in the ACK2 mini-slots.
   (a) If there is at least one ACK2 mini-slot in which a single RR transmits the ACK2 signal, the original transmitter will be able to select a RR to take over forwarding the packet. For those mini-slots in which one RR sends an ACK2 signal, the original transmitter can correctly decode the signal in that mini-slot. We call this a success in that particular mini-slot. Note that there may be multiple success in more than one mini-slot. The transmitter will pick the most favorable relay (lowest link cost to the final destination) and send a CRF signal in the CRF mini-slot to that relay.
   (b) If there are no mini-slots in which exactly one RR transmits the ACK2 signal, then the original transmitter cannot select a RR and thus will initiate the retransmission cycle. In each mini-slot, this can happen if no RRs send an ACK2 signal or if multiple RRs

[1] The use of PRD mini-slot is optional. If it is not used, then four or more mini-slots are needed

send an ACK2 signal, in which case the transmissions collide.

After sending the acknowledgment signals in one or more of the ACK2 mini-slots, a RR will wait for the CRF signal from the transmitting radio.

(a) If there is no CRF signal in the CRF mini-slot, the RR will discard the packet.

(b) If the CRF signal is present, the RR will check whether it matches the packet that the relay has stored *and* the relay's address is included in the CRF signal to indicate that this relay is supposed to forward the packet.

   i. If so, the relay radio will forward the packet.

   ii. Otherwise, it will discard the packet and prepare for the transmission cycle in the next time slot.

We note that the handshaking procedure involving the PRD, RRF and CRF signals is necessary because the RRs may not be able to hear the acknowledgment signals from each other or from the intended receiving radio. Also the use of the PRD mini-slot is optional. The protocol described above still works without the presence of this mini-slot. The resulting degradation in performance will be examined in Section 6.

4.3 Relay Forwarding Resolution Algorithm

A RFR algorithm is needed to resolve the contention from multiple RRs trying to forward the packet. One basic goal of such an algorithm is to maximize the probability that the transmitting radio successfully received at least one ACK2 signal in the ACK2 mini-slots. For simplicity we propose a RFR algorithm that does not make use of any network state information (such as channel state, radio queue length, etc) to decide whether to transmit ACK2s or not. We adopt a simple algorithm here: A competing relay will send an ACK2 acknowledgment in a particular mini-slot with probability q, independently from mini-slot to mini-slot. Thus the probability that there is exactly one ACK2 signal being sent in a particular mini-slot is:

$$P_s = N_{RR} \cdot q \cdot (1-q)^{N_{RR}-1}\ , \qquad (6)$$

where N_{RR} is the number of RRs that a transmitting radio has. To maximize the above expression we simply set $q = \frac{1}{N_{RR}}$. Since the relays may not know the instantaneous value of N_{RR}, we set q to be $\frac{1}{E[N_{AR}]}$ as a suboptimal solution. This expected number of relays is usually a long-term characteristic of the network and hence can be estimated and passed among the radios.

5 Analysis of One-hop Throughput

In order to perform mathematical analysis for the CDSA protocol, we consider the network topology and the traffic flows together. We elect to extract several representative parameters from the network topology coupled with the effect of channel fading, and use these parameters to completely describe the topology information. We can then perform analysis based on these parameters and the traffic model assumed. We assume that there are a total of N radios in the network distributed over a certain area. We extract the following parameters to represent the network topology coupled with the effect of channel fading at a fixed γ_0:

1. $E[N_{LT}]$: Expected number of long-term neighbors of a radio.
2. $E[N_{IN}]$: Expected number of instantaneous neighbors of a radio.
3. $E[N_{RR}]$: Expected number of RRs for a transmission to a random destination.
4. $\Pr[N_{RR} = i], i = 1, 2, \ldots, N$: The probability that there are exactly i RRs for a transmitting radio.
5. $\Pr[N_I = i | N_{RR} = j], j = 1, 2, \ldots, N, 0 \leq i \leq j$: The conditional probability that a radio other than the transmitting radio and the RRs will interfere with i RRs in a particular slot given that the radio transmits in that slot, conditioned on the presence of j RRs.
6. $\Pr[N_{IR} = i | N_{RR} = j], j = 1, 2, \ldots, N, 0 \leq i \leq j - 1$: The conditional probability that a RR will interfere with i other RRs in a particular slot given that the radio transmits in that slot, conditioned on there begin j RRs for that transmission.

For the analysis, these long term statistics are obtained by generating a random network topology along with a random fading channel realization for 10000 time slots and averaging the results.

We adopt a heavy traffic model, by which we mean that every radio is assumed to have a non-empty queue of packets waiting for transmission. A radio transmits a packet with a probability p independent of previous communications or communication by any other radios. Thus a uniform traffic pattern is obtained. We define the *one-hop throughput* as the average number of successful one-hop transmissions per radio per time slot. Defined in this way, the one-hop throughput is a measure of how well each radio utilizes the available time slots for successful transmissions.

To evaluate the one-hop throughput performance of the CDSA protocol, we focus on a particular radio that attempts to transmit a packet to a randomly chosen destination and estimate the probability that the packet can be successfully received by at least one of the RRs. We first condition on there being n RRs of which k are transmitting. The probability that this scenario occurs is

$$\Pr(n,k) = \Pr(N_{RR} = n) \cdot \binom{n}{k} p^k (1-p)^{n-k}. \qquad (7)$$

Next we can calculate the probability that the packet can reach at least one of the remaining $n-k$ non-transmitting RRs. Consider a particular subset of m relays out of the $n-k$ non-transmitting RRs, and denote the event that all of these m relays can correctly receive the packet by E_m. Then the probability that E_m occurs and is given by

$$\begin{aligned} &P_{m|n,k} \\ &= \Pr(k \text{ transmitting RRs do not interfere with the } m \text{ RRs}) \\ &\quad \cdot \Pr(\text{all other radios do not interfere with the } m \text{ RRs}), \end{aligned} \tag{8}$$

where

$$\begin{aligned} &\Pr(k \text{ transmitting RRs do not interfere with the } m \text{ RRs}) \\ &\approx \left[\sum_{\theta=0}^{n-1-m} \Pr[N_{IR} = \theta | N_{RR} = n] \cdot \frac{\binom{n-1-m}{\theta}}{\binom{n-1}{\theta}} \right]^k . \end{aligned} \tag{9}$$

This is an approximation because the event that a particular transmitting RR interferes with a particular set of m non-transmitting relays may be correlated with the event that another transmitting RR interferes with that set of m non-transmitting relays. Since the channel fading between a pair of radios is independent of the fading for any other pair, the correlation is only due to the geometrical location of radios. We have neglected this correlation here to simplify the calculation. Also,

$$\begin{aligned} &\Pr(\text{all other radio do not interfere } m \text{ RRs}) \\ &= \Bigg[(1-p) \\ &\qquad + p \cdot \sum_{\theta=0}^{n-m} \Pr[N_I = \theta | N_{RR} = n] \cdot \frac{\binom{n-m}{\theta}}{\binom{n}{\theta}} \Bigg]^{N-1-n} \end{aligned} \tag{10}$$

Since we have a total of $n-k$ non-transmitting RRs, for a particular m, we have $\binom{n-k}{m}$ different events E_m in which all m radios receive the packet. The event that at least one of the RRs can receive the packet is simply the union of all these E_m events for $m = 1, 2, \cdots, n-k$. Hence

$$\begin{aligned} \Pr(N_{RR} \geq i | n, k) &= \Pr(\text{at least i RR rec'd} | n, k) \\ &= \sum_{m=i}^{n-k} (-1)^{m-i} \binom{n-k}{m} P_{m|n,k}. \end{aligned} \tag{11}$$

So the probability that exactly i RRs can receive the packet successfully is given by

$$\Pr(N_{RR} = i) = \Pr(N_{RR} \geq i) - \Pr(N_{RR} \geq i+1). \tag{12}$$

If the CDSA protocol is equipped with an infinite number of ACK2 mini-slots, then the transmission succeeds when there is at least one RR that receives the packet successfully. Thus the one-hop throughput performance when there are an infinite number of ACK2 mini-slots can be expressed as

$$S_1\big|_{\text{ACK2}\to\infty} = p \cdot \sum_{n=1}^{N-1} \sum_{k=0}^{n-1} \Pr(N_{RR} \geq 1) \cdot \Pr(n, k). \tag{13}$$

If there are only a finite number k ACK2 mini-slots available, then the probability of successful transmission is

$$\Pr(\text{success}|n,k) = \sum_{i=1}^{n-k} \Pr(N_{AR} = i) \cdot \underbrace{\left\{1 - (1 - P_s|_{N_{AR}=i})^j\right\}}_{\geq 1 \text{ success in k ACK2 slots}} \tag{14}$$

where $P_s|_{N_{RR}=i}$ is the expression given by (6) with $N_{RR} = i$ and $q = \frac{1}{E[N_{RR}]}$, representing the probability of success of ACK2 contention in one particular mini-slot. Thus the corresponding one-hop throughput performance is:

$$S_1\big|_{\text{ACK2}=j} = p \cdot \sum_{n=1}^{N-1} \sum_{k=0}^{n-1} \Pr(\text{success}|n,k) \cdot \Pr(n,k). \tag{15}$$

6 Simulation Results

In this section, we present results from a simulation study to illustrate the performance of the proposed CDSA scheme. Unless otherwise stated, we assume that 100 radios are uniformly distributed over a square area of 1000m $\times$ 1000m. We set γ_0 to values ranging from 80 to 105dB. This results in different degrees of connectivity of the network, as expressed by the average number of long-term neighbors of a radio. We are mostly interested in the throughput performance of our CDSA protocol when the expected number of neighbors of each radio ranges from 6 to 8, the “magic” numbers often cited [3] for network efficiency and connectivity. The time-varying fading phenomenon is modeled by (1), as Rayleigh fading is assumed. We also consider mobility of the radios. The widely adopted random walk model [8] is used to model the mobility of radios after the initial deployment of the radios. The advantage of this mobility model is the uniform radio distribution, which is desired for our simulation.

Except in Section 6.4, we consider a heavy traffic model as mentioned in Section 5, in which every radio always has packets to transmit. The destination of a newly generated packet at a radio is randomly chosen to be a radio that is reachable according to the local routing table at the source radio. Minimum-cost routing is used, as described in Section 4. Routing table updates are sent periodically at 5 second intervals by every radio within the area.

In our simulation we assume that the control signals in all mini-slots are always successfully received. Although collisions could occur in the mini-slots because of the transmission of similar signals by other non-participating radios, we assume that the mini-slot signals can be designed to minimize the effect of such collisions. This assumption is justified by the fact that the amount of information contained in the signals in the mini-slots is small and hence powerful error correcting codes can be employed to protect these signals against collisions.

6.1 One-hop Throughput

The results in Fig. 3 illustrate the performance of the proposed CDSA protocol in comparison to conventional slotted

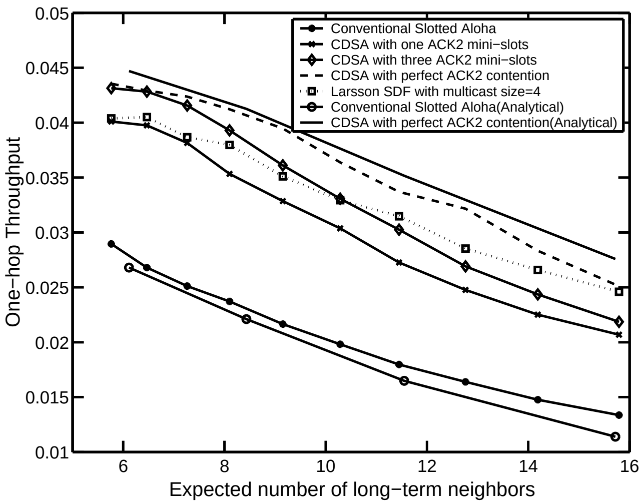

Fig. 3 One-hop throughput performance of CDSA, with no radio mobility

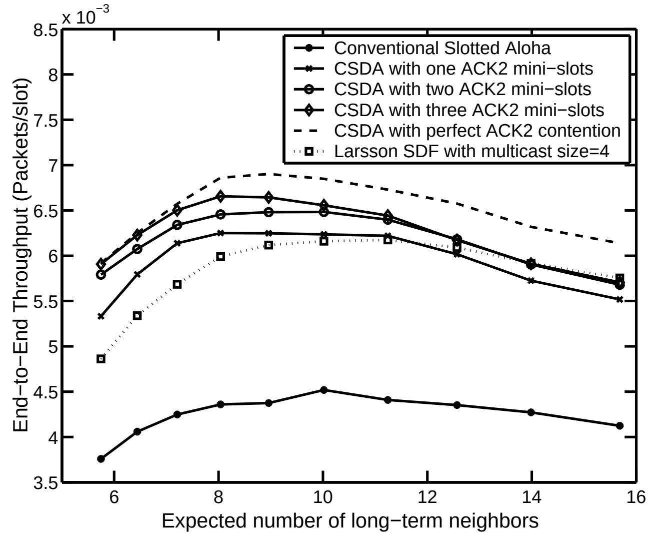

Fig. 4 End-to-end throughput performance of CDSA, with no radio mobility

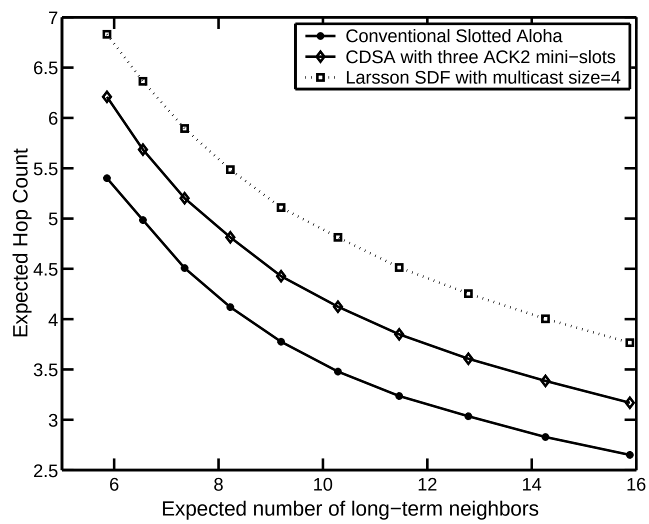

Fig. 5 Average hop count from a source radio to a random destination, with no radio mobility

ALOHA and Larsson's SDF scheme [5], when there is no radio mobility. Note that for the results on the CDSA protocol and Larsson's SDF, we do not account for the increase in overhead of the additional mini-slots required in comparison to simple slotted ALOHA. As the overhead will depend greatly on the particular physical-layer implementation, we have elected to leave such calculations to the interested systems engineer. We see that the one-hop throughput of CDSA is always about 50% larger than that of standard ALOHA. We observe that the CDSA protocol with three ACK2 mini-slots performs better than Larsson's SDF scheme [5] for $E[N_{LT}] < 10$, which is the usual range of interest, when a multicast group size of four is used for Larsson's SDF. We choose these design parameters since at such the CDSA and the SDF approach their asymptotic performance well. Any further increase in these parameters only improves the throughput performance marginally. CDSA outperforms SDF because in the CDSA protocol, all radios which are instantaneous neighbors of the transmitting radio can be RRs. In contrast, in SDF only a group of pre-selected radios can be relays. Thus the CDSA protocol provides a larger freedom of finding a more favorable relay to the destination. On the other hand, the disadvantage of the CDSA protocol is that the RFR algorithm may introduce a loss in throughput due to collision of the ACK2 signals from multiple RRs. The choice of 3 ACK2 slots tips the balance to the former beneficial effect over the latter detrimental effect of CDSA.

6.2 End-to-end Throughput

The results in Fig. 4 show the end-to-end throughput of CDSA, where again no radio mobility is assumed. End-to-end throughput is defined as the average number of packets successfully received at the final destination per radio per time slot. The results indicate that in terms of end-to-end throughput, CDSA has an advantage of approximately 50% and 10% over ALOHA and SDF, respectively, for $E[N_{LT}] \leq 10$. The end-to-end throughput first increases and then decreases as the expected number of long-term neighbors increases. The initial increase is due to the fact that the packets need to go through more hops to reach their final destinations when the connectivity of the network is low, and the decrease in throughput at high $E[N_{LT}]$ is due to increased congestion.

The results in Fig. 5 show the expected hop count from a source radio to a random destination with no radio mobility. The conventional slotted ALOHA scheme always has the lowest hop count since the network layer always chooses the path with minimum number of hops. For both CDSA and SDF, we allow a packet to be sent to a relay that has the same number of hops to the destination as the original transmitter if that relay has a lower link cost to the destination. This can increase the number of hops that a packet takes from the source to the destination, but we found that allow-

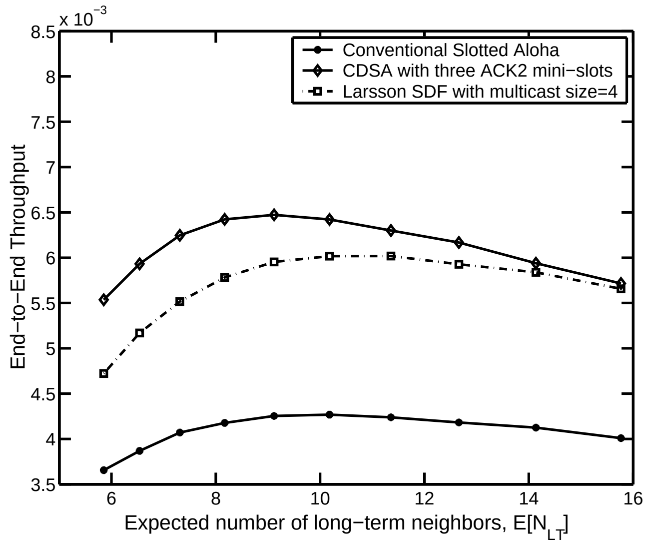

Fig. 6 End-to-end throughput performance of CDSA, with radio mobility (maximum radio moving speed = 3 m/s)

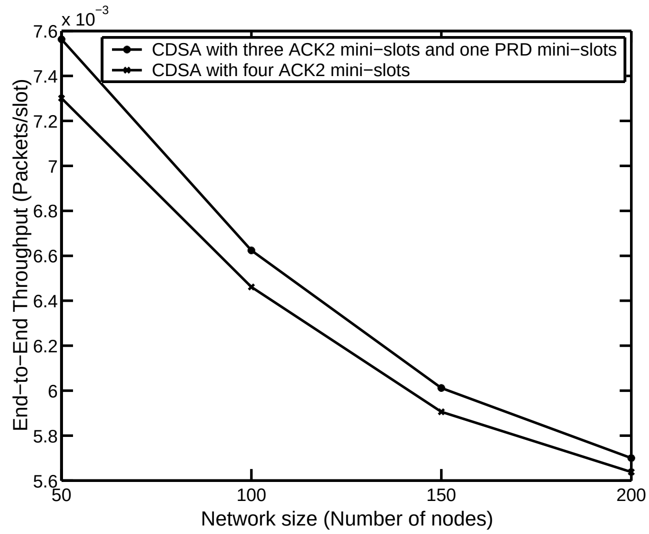

Fig. 7 End-to-End throughput versus network size, expected number of long-term neighbors = 8, with no radio mobility

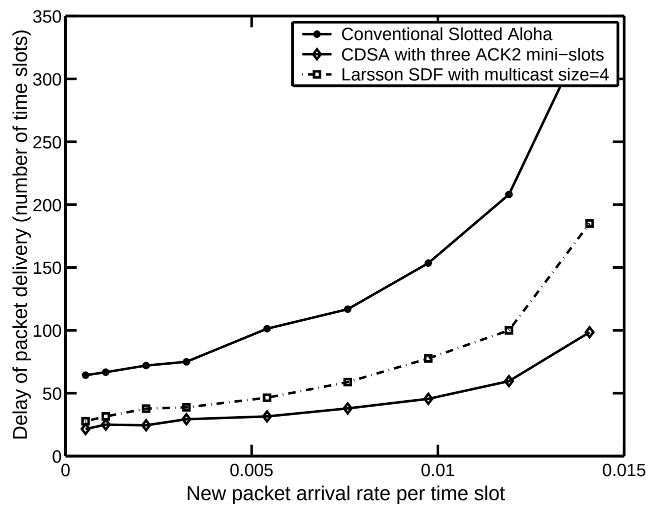

Fig. 8 Delay of end-to-end packet delivery, expected number of long-term neighbors = 8, with no radio mobility

ing this provides better performance by routing around poor-quality links. Meanwhile the CDSA protocol requires fewer hops than SDF since CDSA chooses the most favorable next-hop to the destination from the instantaneous neighbors of the transmitting radio, whereas SDF limits its choice of next-hop to the pre-selected multi-cast group. This explains why CDSA offers a better end-to-end throughput even though the one-hop throughput advantage is not obvious or even worse than SDF for the case with one ACK2 mini-slot.

The end-to-end throughput performance when there is radio mobility is demonstrated in Fig. 6. Since the radio distribution is uniform for the random walk model, no warm-up period is needed during the simulation. The maximum radio velocity is chose to be 3 m/s, which mimics fast moving pedestrians. As expected the throughput drops for all the protocols. Nevertheless, the CDSA scheme still maintains a throughput advantage of about 50% and 12% over ALOHA and SDF, respectively, at the usual operating range that the expected number of neighbors varies from 6 to 10. Thus, CDSA is more robust in a mobile environment.

6.3 *Effect of PRD mini-slot*

The PRD signal is designed to reduce unnecessary transmissions by the transmitter, the intended receiver, and the alternative relays if the final destination can overhear the packet. The elimination of these unnecessary transmissions decreases the overall traffic load of the network and increases the throughput. As discussed before, the CDSA protocol still works without the use of PRD. In the absence of PRD, the unnecessary transmissions mentioned above cannot be eliminated, resulting in a degradation in throughput. Here we try to study the extent of this degradation for different network sizes. For all network sizes that we consider, we change the number of radios such that the radio density remains the same. The effect of the PRD(Packet-Reached-Destination) acknowledgment signal is shown in Fig 7. With a network size of 100 radios, the use of PRD improves the throughput by 2.5% compared to that if the PRD mini-slot is replaced by an additional ACK2 mini-slot, when the expected number of long-term neighbors of each radio is 8. In the network of 200 radios, the use of PRD only increases the throughput by about 1.1%. This is expected since the PRD is only likely to be useful when the packet is close to the final destination. With a larger network size, the average hop count of each transmission increases, and the benefits of using the PRD signal are reduced.

6.4 *End-to-end Delay*

The results in Fig. 8 show the average delay of end-to-end packet delivery of various protocols, when the expected number of long-term neighbors is 8 and there is no radio mobility. Here we consider a light traffic scenario, in which a radio may not have packets to transmit at each slot. A new packet is assumed to arrive at a slot with a small arrival probability. The delay is plotted against this packet arrival probability in Fig. 8. We see that the CDSA protocol has an obvious advantage over SDF and slotted-ALOHA. The average delay using CDSA is several times less than that of ALOHA and about 25% less than that of SDF. In addition, the CDSA protocol can also tolerate a higher traffic load before the packet delay increases drastically.

7 Conclusion

We have presented a simple extension to the standard ALOHA protocol to achieve cooperative diversity in ad hoc networks. The proposed cooperative-diversity slotted ALOHA (CDSA) protocol improves throughput by taking advantage of the broadcasting nature of the wireless channel. The resulting cooperative diversity provides additional robustness against channel fading, collision, and radio mobility. Network simulations confirm that when every radio always has packets to send (heavy traffic), CDSA can provide significantly higher one-hop and end-to-end throughput than the standard slotted-ALOHA protocol. A similar advantage on the end-to-end delay can also be obtained when the traffic is light. As a result, the proposed cooperative-diversity ALOHA protocol can be used to improve these measures of QoS in ad hoc wireless networks.

References

1. N. Abramson. The throughput of packet broadcasting channels. *IEEE Trans. Commun.*, 25:117–128, Jan. 1977.
2. D. Bertsekas and R. Gallager. *Data Networks*. Prentice-Hall, 1991.
3. L. Kleinrock and J. Silvester. Optimum transmission radii for packet radio networks or why six is a magic number. In *Proc. National Telecom. Conf.*, pages 4.3.1–4.3.5, Birmingham, AL, Dec. 1978.
4. J. N. Laneman, D. N. C. Tse, and G. W. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Trans. Inform. Theory*, 50:3062–3080, Dec. 2004.
5. P. Larsson. Selection diversity forwarding in a multihop packet radio network with fading channel and capture. In *ACM SIGMOBILE Mobile Computing and Communication Review*, pages 47–54, Oct. 2001.
6. A. Leon-Garcia and I. Widjaja. *Communications Networks: Fundamental Concepts and Key Architectures*. McGraw-Hill, 2000.
7. A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity–parts I and II. *IEEE Trans. Commun*, 51:1927–1948, Nov. 2003.
8. D. Yu and H. Li. Influence of mobility models on node distribution in ad hoc networks. In *Proc. 2003 IEEE Int. Conf. Commun.*, pages 985–989, Apr. 2003.