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Multiple Routing for Simulcast in Ad Hoc Network

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Abstract

Depending on its simulcast capability for a transmit packet in ad hoc networks, each route is likely to have a different routing cost. Assigning a higher traffic rate on a route that has a larger simulcast capability may have an opposite effect between the larger amount of transmission due to its simulcast capability and the queue delay increase due to its heavy traffic load on a route. In this paper, the properties of a multiple routing scheme in ad hoc networks, based on a simulcast transmission that allocates randomly unequal transmission rates on multiple links according to the simulcast capabilities, are investigated.

Keywords*: Multiple routing, Simulcast, Ad hoc network*

1. Introduction

In ad hoc networks, the neighbors of a transmitter often experience very different propagation and channel conditions, and therefore these neighbors will differ in their ability to recover information from a transmitted message. Thus, when a radio transmits, it can include additional messages for neighbors with better channel conditions at very little cost in performance for neighbors with less capability in receiving messages. We call this technique simulcast, which transmits multiple packets simultaneously to different receivers of different link capabilities by adapting different link conditions in wireless networks. We also call a receiver that has a better link capability, enabling it to accommodate a simulcast transmission, a more-capable receiver, and a receiver that has a poor link capability, enabling it to only receive basic messages, a less-capable receiver [1-3]. We define more-capable link and less-capable link as the links connected to a more-capable receiver and less-capable receiver, respectively. In our previous work [4], we demonstrated that simulcast can significantly increase link and end-to-end throughputs in an ad hoc network at the expense of a slight decrease in the probability that a random network is connected.

Multiple routing strategies to achieve high performance in wireless ad hoc networks have gained a lot of attention recently. Tsirigos and Haas [5] proposed a routing scheme that uses multiple paths simultaneously by splitting the information among the multitude of paths to increase the probability that the essential portion of the information is received at the destination of the original information. Das *et al.* [6] explored adaptive multi-path routing for a large volume of data packets, which performs preemptive route re-discoveries before route errors occur while transmitting a large volume of data by computing the link stability in consideration of signal strength, link distance, and node

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velocity in a dynamic environment. Jian and Lin [7] classified multiple routes into various sets. The ranked values to indicate routing efficiency, which are dynamically computed by considering resource constraints such as bandwidth, computing efficiency, power consumption, traffic load, and the number of hops, are assigned to each classified set. The ranked set of multiple routes collaborate in order to distribute the data packets along a different routing path with an aim to achieve a high transmission rate and optimal routing path distribution.

Previously, we evaluated how simulcast utilizes radio resources to increase both link and end-to-end throughputs. We have shown that modulation and coding schemes can be modified to allow the inclusion of an additional message for a more-capable receiver at very little cost to the performance at a less-capable receiver [1-3]. Later, we suggested MAC approaches to employ simulcast and have investigated its performance in a mobile ad hoc network that uses slotted ALOHA [4]. However, we did not consider a routing layer approach to exploit the simulcast capability in ad hoc networks.

In this paper, we investigate how the simulcast capability can be exploited as a network layer approach by adjusting the distribution of packets across multiple routes in a system employing multipath routing. Based on the modified min-hop routing for simulcast that we used in our previous works [4,8], we may have multiple routes that have the same number of hops from a source radio to a final destination. However, each route is still likely to differ in terms of its simulcast capability because of the different numbers of relay radios with more-capable links. Routes that have more relay radios with more-capable links will transmit more packets per transmission opportunity, and therefore will be more efficient in relaying a packet along the routes. If a radio has multiple routes to a destination, this effect should be considered when determining what proportion of packets to transmit on a route. We may want to allocate a larger transmission amount on the route with more simulcast capability. However, allocating a higher transmission rate on a route results in an increasing queue delay due to the heavy traffic load. Thus, there must be a tradeoff between the larger transmission amount due to larger simulcast capability on a route and the queue delay increase due to heavy traffic load by assigning the higher traffic rate on the route. In this paper, we provide a preliminary investigation of how the simulcast capability can be exploited in allocating transmit packets across multiple routes in the aspect of network layer [9]. We study such simulcast properties with varying transmit packet distribution across multiple routes with different simulcast capabilities for several network topologies.

2. Network Model

The example networks that we consider, shown in Figure 1, have source (S) and destination (D) radios connected by two routes with the same number of hops but different simulcast capabilities.

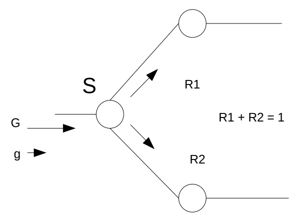

Figure 1. Packet Transmission from Source Radio to Randomly Selected Route Based on the *Simulcast* Capability

The three network topologies that we consider are shown in Figure. 2 to 4. In order to reduce the simulation complexity and run time, we do not simulate radios in a large network, other than those on the two routes from S to D as if they were part of a larger network. Every radio is modeled as having the same average attempt rate G and same number of neighbors N_b, which is defined as the network degree. Thus, given a transmission, the collision probability is

$$P_C = \sum_{i=1}^{N_b} C_i^{N_b} G^i (1-G)^{N_b - i}$$

Then, the link throughput by unicast is given by $S_U = G(1-P_C)$ and that by *simulcast* is $S_S \approx 2G(1-P_C)$, as discussed in [4]. These values determine the queue statistics, such as the arrival and service rates for the queue of a relay radio on a route. If a packet from a source radio collides with another transmission at one of the radios along the route, the packet will stay in the queue of the transmitting radio to wait for re-transmission.

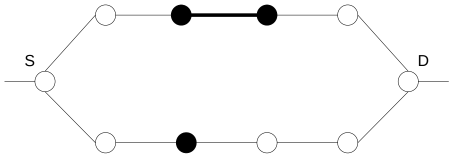

Figure 2. Topology 1 for Unequal Random Route Selection Based on the *Simulcast* Capability

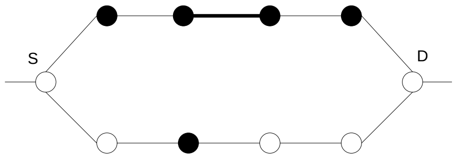

Figure 3. Topology 2 for Unequal Random Route Selection Based on the *Simulcast* Capability

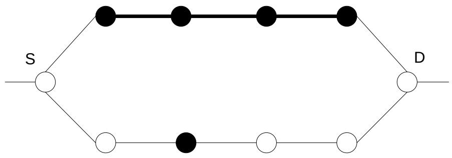

Figure 4. Topology 3 for Unequal Random Route Selection Based on the *Simulcast* Capability

We consider a multipath routing scheme in which packets from S are distributed randomly across the two routes, as illustrated in Figure 1. Source S transmits packets at attempt rate G to only destination D. The two routes have the same number of hops to D, but may have different simulcast capabilities. We define *more-capable route* as a route that has larger *simulcast* capability, and *less-capable route* as a route that has less *simulcast* capability. We distribute transmit packets across the routes with transmission rates of $R1$ for more-capable route and $R2$ for less-capable route, where $R1 + R2 = 1$. We also define *optimal route selection rate* as the route selection rate in which *more-capable route* achieves the maximum end-to-end throughput.

We model three network topologies of transmission routes in wireless ad hoc networks with identical wireless radios deployed within a two-dimensional geographical territory. There are two routes as we mentioned above. The two routes have the same number of hops from a source radio to a destination radio, but different simulcast capabilities due to the number of relay radios that are capable of simulcast, which means more-capable radios, or a different number of more-capable links along each route. In each of the three network topologies, the upper route represents a more-capable route, and the lower route represents a less-capable route. We assume that each route does not interfere with the other because they are not within transmission range. We measure the end-to-end throughput as the number of packets successfully transmitted from S to D per time slot. Figures 2 through 4 show the three topologies, the results of which are presented in Section IV. The filled circles represent radios that can utilize simulcast because they have more-capable neighbors, and the empty circles represent radios that can only unicast. The bold lines represent more-capable links, and the thin lines represent less-capable links. Topology 2 has more relay radios with simulcast on a more-capable route than on the more-capable route of topology 1, but the number of more-capable links is the same. Topology 3 has the same number of more-capable radios on a more-capable route as topology 2, but has more more-capable links. The conditions of less-capable routes are the same for all three network topologies.

3. Link Properties

In this section, we describe how we generate packets at the intermediate radios along multiple routes from *S* and *D* as if these radios were part of a larger network. We model the inflow and outflow of traffic to the queue of a radio along the routes, as illustrated in Figure 5. The states *n* and $n+1$ in the circles represent the number of packets in the queue, and *p* and *q* are the arrival and service rates, respectively. For the purpose of modeling packet arrivals and departures at the radios along the two routes, we treat arrivals and departures as independent. In fact, these are not independent, as a radio may not successfully transmit and receive simultaneously. However, we expect that this approximation will have little impact on our results. Then, *Q* is the probability of no change in the number of packets after one transmission time slot, which we approximate by

$$Q = pq + (1-q)(1-p) + (1-p)P(0),$$

where *P*(0) represents the probability that there is no packet in a queue at the current transmission time slot.

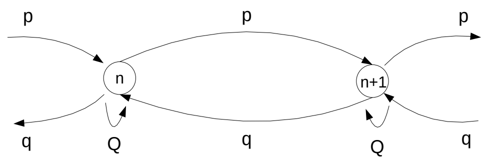

Figure 5. Markov Status Diagram for the Number of Packets in a Queue

The statistics of a queue status depend on the *simulcast* capability, which is determined by several network parameters such as the number of neighbors, the number of more-capable links of a radio, and the number of more-capable links on a route. Figures 6 through 10 illustrate the possible link statuses and their properties. The service rate *q* simply includes any outgoing packet from *S* to *D*. However, the arrival rate p_b includes only a basic incoming message by unicast, and the arrival rate due to additional incoming messages by *simulcast* is represented by the symbol p_a. The traffic generated according to probabilities p_b and p_a is not used to model the traffic from *S* to *D*, which is fully simulated. Total incoming rate *p* is equal to $p_b + p_a$. The dotted arrows in Figure. 9 and 10 represent additional messages other than those from the source radio that are received by *simulcast* at a radio along a more-capable route.

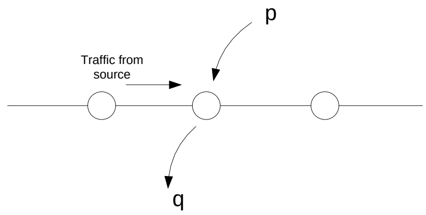

Figure 6. *Link Model* 1 for Analyzing the Queue Status in Random Route Selection Based on the *Simulcast* Capability. The Relay Radio does not have a More-Capable Link

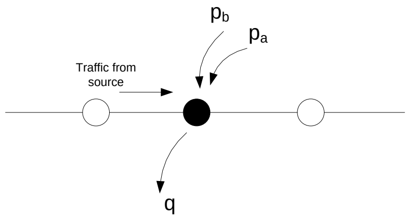

Figure 7. *Link Model* 2 for Analyzing the Queue Status in Random Route Selection Based on the *Simulcast* Capability. The Relay Radio has more Capable Links, but not on the Route

Figure 6 represents one of the possible link conditions, *link model 1*, in which a relay radio does not have a more-capable link. So, its arrival and service rates correspond to link throughput by unicast. However, because total arrival rate p does not include the traffic incoming from S, based on the assumption that every radio involved in the transmission in the network is identical, and sends packets uniformly on each branch, arrival rate p is related to the amount of incoming packets except from one branch among all N_b branches. Then,

$$p = \frac{N_b - 1}{N_b} S_U + g,$$

$$q = S_U.$$

Also, because a link on the route from S is a less-capable link, traffic from the source will be one packet at a time.

Figure 7 illustrates another possible link condition, *link model 2*, in which relay radios can *simulcast* but do not have a more-capable link on a route. Thus, its arrival and service rates correspond to the link throughput by *simulcast*. Service rate q is simply $2S_U$. Arrival rate p is figured out in a similar way with *link model 1*, but corresponds to the throughput by *simulcast*, and because this relay radio can *simulcast*, it includes the arrival rate for additional messages p_a. Relay radios do not have a more-capable link on the route, so based on the assumption that sending additional messages on each more-capable link is uniform and independent on the transmission of basic messages, p_a is $S_U\left(N_m / N_b^2\right)$. Then, with a similar analysis of *link model 1*, where N_m is the average number of more-capable links of a radio,

$$p = S_U\left(\frac{N_b - 1}{N_b} + \frac{N_m}{N_b^2}\right) + g,$$

$$q = 2S_U.$$

Because the link on the source side of a route is a less-capable link, the traffic coming from that direction arrives at a rate of one packet per transmission.

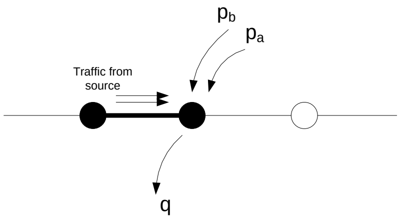

Figure 8. *Link Model* 3 for Analyzing the Queue Status in Random Route Selection Based on the *Simulcast* Capability. The Relay Radio has more Capable Links, and One of them is Included on the Source Side of the Route

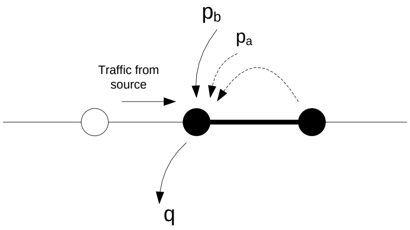

Figure 9. *Link Model* 4 for Analyzing the Queue Status in Random Route Selection Based on the *Simulcast* Capability. The Relay Radio has more Capable Links, and One of them is Included on the Destination Side of the Route

Figure 8 illustrates another possible link condition, *link model 3,* where relay radios can *simulcast* and have a more-capable link on the source side on a route. Thus, its arrival and service rates correspond to the link throughput by *simulcast*. Service rate q is simply $2S_U$.

The arrival rate p is figured out in a similar way as with *link model 2*. However, one additional message comes from the source side. Thus, the amount of additional messages included in p_a is lessened by the proportion of one branch out of N_m branches. Then, the arrival rate by additional messages is given by $S_U(N_m-1)/N_b^2$. Then,

$$p = S_U\left(\frac{N_b-1}{N_b}+\frac{N_m-1}{N_b^2}\right)+g,$$

$$q = 2S_U.$$

Because the link on the source side on the route is a more-capable link, traffic coming from that direction arrives at a rate of two packets per transmission.

Figure 9 illustrates another possible link condition, *link model 4*, where a relay radio can *simulcast* and has a more-capable link on the destination side of a route. The only difference with *link model 3* is that an additional message incoming to the radio is from the destination side of the route. Thus, the arrival rate by additional messages p_a includes additional messages coming from the radio on the destination side of the route. Then,

$$p = S_U\left(\frac{N_b-1}{N_b}+\frac{N_m}{N_b^2}\right)+g,$$

$$q = 2S_U.$$

Because the link on the source side of the route is a less-capable link, traffic from the source side will arrive at only one packet per transmission.

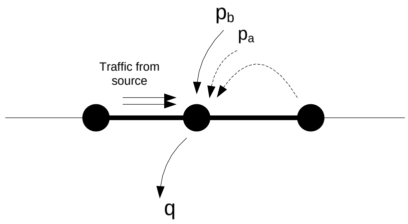

Figure 10. *Link Model* 5 for Analyzing the Queue Status in Random Route Selection Based on the *Simulcast* Capability. The Relay Radio has more Capable Links, and Two of them are Included at Both the Source and Destination Sides of the Route

Figure 10 represents the final possible link condition, *link model 5*, where relay radios can simulcast and have more-capable links to both neighbors on a route. The arrival rate by additional messages p_a in this condition is the same as with *link model 3*. Then,

$$p = S_U\left(\frac{N_b - 1}{N_b} + \frac{N_m - 1}{N_b^2}\right) + g,$$

$$q = 2S_U.$$

Because the link on the source side of the route is a more-capable link, the traffic from that direction will arrive at a rate of two packets per transmission.

In the above network models, we consider end-to-end throughput, which is measured as the number of packets successfully transmitted from a source radio to a destination radio per time slot. The statistics of queue delay at each relay radio for the traffic from a source radio will affect the end-to-end throughput. Now, we will investigate random multiple routing for *simulcast*, which randomly assigns unequal transmission rates from a source radio to each route in order to maximize the end-to-end *simulcast* performance in ad hoc networks.

As described above, data modeling is closely related to philosophical reasoning. Under this premise, if the center of philosophical reasoning moved in a certain direction, another important subject of research would be to examine how data modeling should incorporate the movement. In this study, this new research direction will be referred to as "event-centric approach" or the "E-C approach."

4. Simulation and Results

We performed separate simulations for each of the three network topologies discussed in Section II by applying the link properties discussed in Section III in various network densities along with the average number of more-capable links of a radio. Two different network density scenarios, N_b=8 and N_b=6, are investigated in each of the three network topologies. A source radio transmits packets at the same attempt rate with the rest of the radios in a network, and all the packets transmitted by the source radio are destined to the same destination radio. We randomly select one out of two routes in each network topology for a transmit packet, with probability of $R1$ for a more-capable route and $R2$ for a less-capable route. The transmission rates $R1$ and $R2$ are varied subject to $0 \le R1 \le 1$, $0 \le R2 \le 1$, and $R1 + R2 = 1$. The queue status of each relay radio is determined by the statistics mentioned in Section III. If a packet transmitted from a source radio is collided by the collision probability P_C in Section II at any relay radio on a route, the packet stays in the queue of the original radio in order to wait for retransmission to occur by the exponential back-off algorithm, as discussed in [4]. Simulation was performed on various attempt rates G ranging from 0 to 1. If a packet was successfully transmitted, it moves to the end of the arrival queue of the next radio. The packet selection algorithm was based on the modified FIFO as mentioned in [4]. Simulation is performed by running 100,000 time slots to count the numbers of packets that were transmitted from a source radio, and that arrived at a destination radio successfully for various transmission rates of *R*1 and *R*2.

Simulations were performed for a high-density network scenario in which the network degree is 8 and the average number of more-capable links of a radio is 4, and for a low-density network scenario in which the network degree is 6 and the average number of more-capable links of a radio is 3. Figures 11 and 12 show the simulation results for the maximum end-to-end throughput in a high-density network and low-density network, respectively, in each of the three topologies. The marks *, □, and ○ represent the simulation results of topology 1, topology 2, and topology 3, respectively. The simulation results of the low-density networks show the same patterns of end-to-end throughput as those of the high-density networks, but are 43.24%, 32.14%, and 26.79% higher than those of the high density networks in topologies 1, 2, and 3, respectively. This is considered to be because the low number of neighbors gives a lower collision probability at the receivers. Careful consideration is demanded in interpreting such effects. In general, a high network density might be caused by a large transmission range, and it reduces the number of hops for a transmit packet from a source radio to a final destination radio in wireless ad hoc networks, which increases the end-to-end throughput. Such effect is opposite of the effect of high collision probability occurring in high networks. In this simulation, only the varying collision probability according to different network densities is considered, but such effect should be related with various factors such as the transmission range, the network density, and the number of hops in a more practical sense. However, it is meaningful that we observe in this simulation, when excluding the aspect of varying relaying numbers due to varying the transmission range, how network density affects the network performance in wireless ad hoc networks in terms of end-to-end throughput.

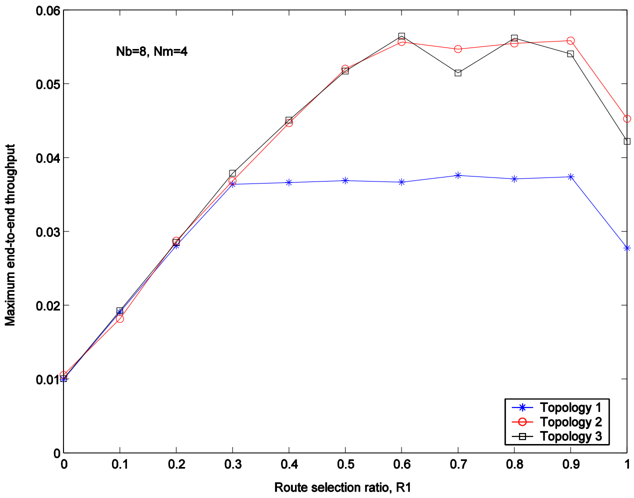

Figure 11. Maximum End-To-End Throughput versus Route Selection Ratio for Route 1 in a High Density Network

Figure 11 shows the simulation results for high-density networks with N_b=8 and N_m=4. The maximum end-to-end throughputs are improved by 270%, 450%, and 410% for network topologies 1, 2, and 3, respectively, by multiple routing compared to the case when we chose a less-capable route only. Compared to the case in which we chose a more-capable route only, the maximum end-to-end throughput improved 37.04%, 27.27%, and 33.33% for network topologies 1, 2, and 3, respectively, by multiple routing. The optimal route selection rates range from 0.6 to 0.9 for network topologies 2 and 3, and from 0.3 to 0.9 for network topology 1. The optimal route selection rates for network topology 1 spread within a larger range than in the case of network topologies 2 and 3. The maximum end-to-end throughputs are improved by about 10% from unequal multiple route selection at $0.6 < R1 < 0.9$ compared to equal route selection ($R1$=0.5) for network topologies 2 and 3. For network topology 1, it is hard to find the throughput gain yielded by unequal multiple routing. It is considered that the larger range of optimal route selection rate, and less gain by unequal multiple routing for network topology 1, indicate that unequal multiple routing has less impact on a less-capable route in terms of the end-to-end *simulcast* performance.

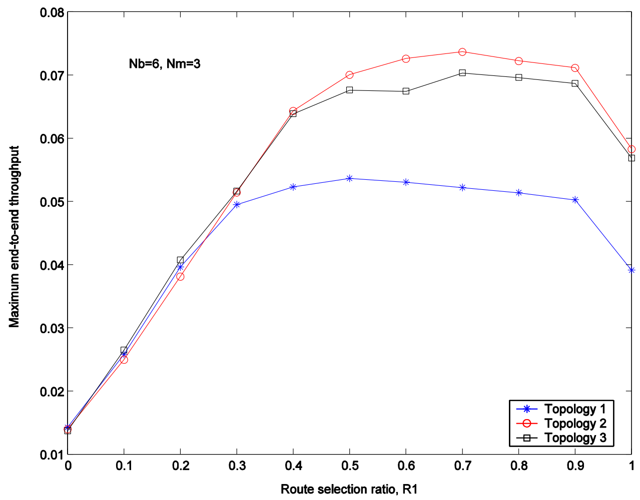

Figure 12. Maximum End-To-End Throughput versus Route Selection Ratio for Route 1 in a Low Density Network

Figure 12 shows the simulation results for low-density networks with N_b=6 and N_m=3. Like the high-density network cases, the maximum end-to-end throughputs are improved by 270%, 410%, and 390% for network topologies 1, 2, and 3, respectively, by multiple routing compared to the case in which we chose a less-capable route only. Compared to the case where we chose a more-capable route only, the maximum end-to-end throughputs improved by 33.3%, 24.1%, and 21.1%, for network topologies 1, 2, and 3, respectively, by using multiple routing. The maximum end-to-end throughputs are improved by about 15% from unequal multiple route selection at $R1 = 0.7$ compared to equal route selection ($R1 = 0.5$) for network topologies 2 and 3. For network topology 1, the throughput gain by unequal multiple route selection is not significant as in the case of a high-density network. The optimal route selection rates are around 0.7 for network topologies 2 and 3. For network topology 1, the optimal route selection rate is 0.5. However, the optimal route selection rate for network topology 1 spreads within a relatively large range of 0.2 to 0.9. Just like in the case of a high-density network, the simulation results indicate that a less-capable route undergoes relatively less influence from an unequal multiple routing scheme.

In the simulation results for the high-density networks shown in Figure 11, the maximum end-to-end throughput in network topologies 2 and 3 are around 52% higher than in network topology 1, but there is almost no difference between network topologies 2 and 3. The results for the low-density network in Figure 12 show that network topologies 2 and 3 yield 39.62% and 33.96% higher maximum end-to-end throughputs than in network topology 1, respectively, and the difference between network topologies 2 and 3 is as small as 4.23%. This indicates that end-to-end throughput using unequal multiple route selection is strongly dependent on the number of relay radios with *simulcast*, but not as much on the number of more-capable links on a route. It is considered that a more-capable radio itself surely has a positive effect in emptying a queue by transmitting more packets so as to reduce the end-to-end delay, but a more-capable link on a route also has the opposite effect of letting transmit packets pile up in a queue so as to increase the end-to-end delay. Thus, in counting the *simulcast* capability in a route for a transmit packet, it is deemed that the number of more-capable radios in a route has more impact on end-to-end throughput than the number of more-capable links.

5. Conclusions

In this paper, we investigated the *simulcast* capability to be exploited in ad hoc networks in the aspect of the network layer. By assigning unequal transmission rates on multiple routes according to the *simulcast* capabilities, which can be determined by the number of more-capable radios and links on a route, the *simulcast* performance apparently increases. The simulation results for both high-density networks and low-density networks show that the *simulcast* performance on multiple routes is strongly dependent on the number of relay radios that have *simulcast* capabilities. The simulation results indicate that the knowledge on the *simulcast* capabilities of radios along a route can be utilized in a network layer to improve the end-to-end throughput in a system employing multi-path routing.

Acknowledgement

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