THE RECEIVER'S DILEMMA

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Abstract In Mobile Ad Hoc Networks (MANETs), each node has the capacity to act as a router. The performance of the MANET relies on how well the nodes perform this function. In simulations, the receipt of a Route Reply (RREP) packet is evidence that the associated link is reliable, but in the real world of wireless links, it is not. Thus a node often has to decide whether the RREP indicates a reliable link or is due to an outlier in the distribution of received power. If the node accepts an atypical RREP when the link is not reliable, the subsequent attempt to communicate will fail. On the other hand, if it rejects a representative RREP, it will fail to use a reliable link. This paper examines this selection problem using a stochastic model of link behavior and explores some techniques that may be used to deal with the situation.

Keywords: MANET routing; wireless propagation; multipath fading; stochastic models; decision rules; power averaging.

1. Introduction

In a *Mobile Ad Hoc Network* (MANET), each node has the ability to act as a router, permitting adaptable multihop communications. Although simulations show that MANET protocols can support nets containing hundreds of nodes, practical considerations limit most implementations to five or fewer mobile nodes [1–4]. A significant cause of this disparity is the stochastic nature of wireless links. This paper describes this nature, demonstrates how it affects MANETs, and summarizes some promising directions for future study.

In this paper, Section 2 describes the basic problem, presents two test scenarios, and develops the basic evaluation measures. Section 3 outlines several strategies to deal with the problem and estimates their effectiveness. Section 4 presents a simulation of the impact of combining two particular strategies: unicast route replies and multiple attempts

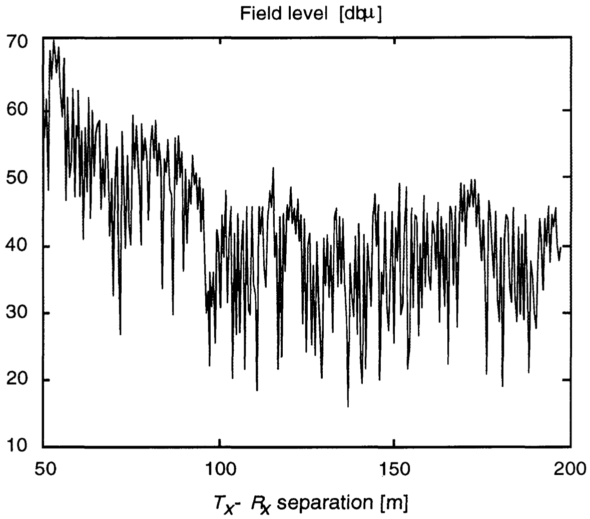

Figure 1. Field Measurements of Signal Levels from [5]

at the link level. Finally, Section 5 summarizes, draws conclusions, and outlines future work.

2. A Fundamental MANET Problem

As illustrated in Figure 1, wireless signals are subject to fine grained, high magnitude fluctuations which may cause two detrimental events:

1 A packet may be dropped over a reliable link, and

2 A packet may be received over an unreliable link.

This phenomena certainly impacts stub and cellular networks. However, in MANETS, it creates much more severe problems because , in addition to Event 1 causing data packets to be lost, the occurrence of either event may impact the stability of the MANET's routing mechanism.

Event 1 is liable to cause a node to conclude that a current route is no longer usable, when it actually is. The resulting unnecessary route search significantly reduces performance. A more serious difficulty arises when a node receives a *route reply* (RREP) over an unreliable link due to Event 2. This may cause the node to conclude that the link is reliable and to include it in the selected route. When the unreliable link fails, a new search becomes necessary, which degrades performance further. Not only that, the new search creates another opportunity for Event 2 to occur. This has proven to be a serious problem in the field [1, 2, 4].

In most MANET simulations and analysis, it is assumed that receipt of a RREP over a link is proof that it is reliable. However, in the real world, receipt of a RREP could indicate either a reliable route or that Event 2 has occurred. Thus, when a MANET node receives a RREP from another node, it is faced with a dilemma. If it chooses to use a link which is, in fact, unreliable, the subsequent attempt to transfer information will fail. On the other hand, if it rejects a link that is actually reliable, an opportunity to transfer information will be lost.

Because whether a node accepts or rejects a particular RREP, it may make a serious error, the performance of a MANET will depend greatly on how well each node guesses which links are reliable and which are not. Failing to account for this dilemma in protocol design will generally lead to poor performance in the "real world." Therefore, the manner in which this guessing occurs is an important MANET design consideration. This paper explores this dilemma as well as several methods to deal with it.

A Simple Stochastic Link Model

There are a number of models which can predict $\overline{p}(d)$, the average received signal strength as a function of distance [5–7]. In this paper, it is assumed that power decreases exponentially with distance. Thus,

$$\overline{p}(d) = p_0 \left(d_0/d\right)^c, \tag{1}$$

where d_0 is a reference distance, p_0 is the average power measured at d_0, and c is the rate of exponential decay. Assuming there are no other nodes transmitting in the vicinity, interference would be minimal and the probability of reception would be mainly a function of received power. In addition, letting $p_0 = p_{\min}$, the the minimum amount of power for reliable reception, means that d_0 is the nominal range. Finally, it is assumed that $c = 3$, a typical value [6, 7].

Given any model to predict $\overline{p}(d)$, the fine grain variations in received power can be represented as a stochastic process. This variability is chiefly due to effects of fading and shadowing, together with some other effects not completely understood [5–7]. Because multipath fading can cause signals to be stronger, as well as weaker, than expected, it plays a primary role in the occurrence of Event 2. There are several common multipath fading models. In this paper, the Rayleigh model is used. Although simple, this model is realistic [1, 5–7] and will serve to illustrate the fundamental difficulties induced by multipath fading.

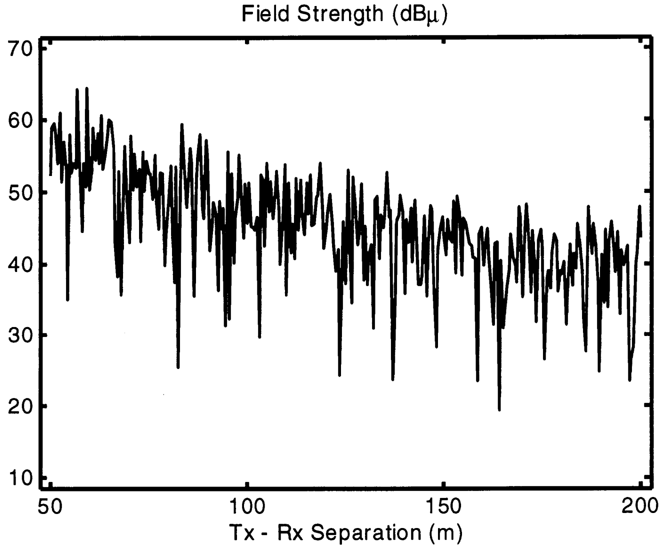

Figure 2. Synthetic Trace Generated by Eq. (5)

If Rayleigh fading is in effect, the probability that instantaneous received power (p_i) is at least p would be:

$$\begin{aligned}\Pr\{p_i(d) \geq p\} &= \int_p^\infty [1/\overline{p}(d)] \exp[-s/\overline{p}(d)]\, ds \\ &= \exp[-p/\overline{p}(d)]. \qquad (2)\end{aligned}$$

Substituting Eq. (1) into (2) leads to:

$$\Pr\{p_i(d) \geq p\} = \exp[-(d/d_0)^c (p/p_{\min})]. \qquad (3)$$

Finally, the probability of reception is:

$$\Pr\{p_i(d) \geq p_{\min}\} = \exp[-(d/d_0)^c]. \qquad (4)$$

To demonstrate the ability of this model to predict field measurements, a simulation was run in Scenario 1.

Scenario 1. This is a simple test in which a transmitter is initially 5m away from a receiver and then moves at a constant rate of 0.5m/s until it is 100m away. This scenario demonstrates the nature of reception over a range of separation distances. It is similar to tests in [1] and [5].

The inverse transform of Eq. (3)

$$p_i(d; d_0, p_{\min}, c) \quad = \quad -p_{\min}(d_0/d)^c \ln r. \tag{5}$$

was used to generate random received power levels. Here r is a random number uniformly distributed on (0,1) and $p_i(\cdot)$ is a random instance of received power. In this test, the transmitter sent one 1024 bit UDP packet each second. Power was adjusted to give a mean response similar to that in [5]. Figure 2 shows the simulated received power levels that resulted. The variation in these values is very similar to that in Figure 1.

Evaluation Model

The impact of each strategy discussed in the following section will be estimated in the context of Scenario 2.

Scenario 2. The layout for this scenario, shown in Figure 3, was inspired by a field test conducted in [2], except that in this scenario none of the nodes move. The task is for Node A to find a route to Node B. The nominal range is 50m. Also there are no other nodes in the vicinity. Assume the routing protocol seeks routes on demand and will select that route with the fewest number of hops. Note that if the originating node had perfect knowledge, it would choose the AXB two-hop route. This scenario, therefore, focuses on the impact of uncertainty.

As each strategy is introduced, the probability of selecting the better route and the probability of successfully transmitting five data packets are estimated analytically. Let the probability of a control packet being received over either link AX or XB be p_1 and that for Link AB be p_2. The three possible ways in which Node A could receive a RREP are listed in Table 1. This table also states their probabilities in terms of p_1 and p_2. From Eq. (4),

$$p_1 = \exp(-0.6^3) \approx 0.806 \quad \text{and} \quad p_2 = \exp(-1.2^3) \approx 0.178. \tag{6}$$

This leads to the values listed in Table 1.

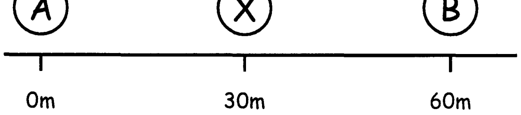

Figure 3. Relative Position of Nodes A, B, and X in Scenario 2

Table 1. Possible ways of A receiving a RREP for a Path to B

Possibility	RREQ Path	RREP Path	Probability Expression	Value
a	AXB	BXA	$p_a = p_1^4$	0.421
b	AB	AB	$p_b = p_2^2$	0.032
c	AXB	AB	$p_c = p_1^2 p_2$	0.115
b or c	AXB or AB	AB	$p_{c \cup b} = \left(p_1^2 + p_2 - p_1^2 p_2\right) p_2$	0.126

In the cases that follow, for Case n, let $P_{\text{SAXB}n}$ denote the probability of selecting the more reliable AXB route and $P_{\text{S}n}$ be the probability that a five-packet message will be transmitted successfully.

Case 1: Baseline. It is assumed that Node A will accept a RREP from either B or X, regardless of the route the RREQ followed. Hence,

$$P_{\text{AXB1}} = \frac{p_a \left(1 - p_{b \cup c}\right)}{1 - \left(1 - p_a\right)\left(1 - p_{b \cup c}\right)} \approx 0.744.$$

Thus, the poorer route will be selected about 25% of the time. Under the simplifying assumption that $p_{\min}$ is independent of packet size, and ignoring the various delays associated with route searches,

$$P_{S1} = P_{\text{AXB1}}\, p_1^{10} + (1 - P_{\text{AXB1}}) p_2^5 \approx 0.086.$$

Although this baseline model is not very good, it serves to illustrate the basic computations. The following section discusses possible improvements on this simple protocol.

3. Some Strategies to Deal with Fading

This section discusses five general approaches that can help reduce the severity of this problem, organized by OSI level.

The MANET Protocol

Two possible MANET protocol modifications are unicasting RREP packets and specifying a minimum reliability.

Case 2: Unicasting rrep Packets. A simple improvement to the basic protocol is to require that RREPs be unicast back to the node from which the RREQ came. This simple change has been implemented in a number of protocols [8, 9]. Requiring that the RREP be unicast back to the source eliminates the third possibility in the baseline scenario. Thus

$$P_{\mathrm{AXB2}} = \frac{p_a\,(1 - p_b)}{1 - (1 - p_a)\,(1 - p_b)} \approx 0.928.$$

Although this improves P_{AXB2} appreciably, it only increases P_{S3} to about 0.107. However, combining this strategy with other strategies leads to further improvement. This will be explored further in Section 4.

Case 3: Minimum Reliability Criterion. Another approach is to include a minimum reliability value in the RREQ. In this scheme, nodes continually estimate the probability that they will be able to communicate with their one-hop neighbors. If Node B knows that its link to A is not sufficiently reliable, it would not reply to a RREQ from A, even if it receives one. A simple rule could be that unless two packets from A are received in a row, do not reply, but other rules are possible. The strategy of having nodes curtail their RREPs reduces the consequences of Event 3 and the number of RREPs on the channel. The primary disadvantage is that this requires some pre-existing traffic to work.

It is difficult to state how this would impact the probability of success, since it depends on the method chosen to estimate reliability. However, assuming the simple two-in-a-row rule, the probability of two successes in a row AB link is $p_2^2 \approx 0.032$. For the AXB path, the probability of two successes is $p_1^4 \approx 0.649$. So, $P_{\mathrm{AXB3}} \approx 0.927$ and $P_{\mathrm{S3}} \approx 0.466$.

The Link Level

A common strategy in wireless nets is to retry packets at the link level up to some limit (R) times before reporting a failure to the higher levels.

Case 4: Up to R Retries. If a packet will be sent up to R times, there will have to be $R + 1$ failures in a row before the MANET layer is advised of the failure. In each attempt, there could be a failure in the packet transmission or in the receipt of the ACK. Thus, the probability of success on a single link is:

$$P(R) = 1 - (1 - p^2)^{(R+1)}, \tag{7}$$

where p is the probability of success for a single attempt. Note that this assumes that the transmitter will wait for an ACK after the last attempt. That is, the case in which $R = 0$ is not the same as in Case 1.

Key probabilities are listed in Table 2 in Scenario 2 for several values of R. Note that while $P_1(R)$ increases with R, the probability of Event 2 also rises. As a consequence, $P_{\mathrm{SAXB4}}(R)$ decreases. In addition, P_{S4}

Table 2. Effect of R on Success in Scenario 2

R	$P_1(R)$	$P_2(R)$	$p_a(R)$	$P_{b\cup c}(R)$	$P_{\mathrm{SAXB3}}(R)$	$P_{S3}(R)$
0	0.649	0.032	0.178	0.014	0.927	0.012
2	0.957	0.092	0.838	0.085	0.901	0.579
4	0.995	0.148	0.979	0.147	0.851	0.806
6	0.999	0.201	0.997	0.201	0.799	0.794

seems to peak around $R = 4$. However, there are other detrimental effects, such as an increase in the number of packets attempted and mean packet delay, which influence the optimal choice of R. The impact of these factors will be explored in further in Section 4.

The Physical Layer

The layer with the greatest knowledge of what is happening is, of course, the physical layer.

Case 5: Power Averaging. In [1], the authors employed an exponentially-smoothed average of received power to estimate the reliability of the link. In such a scheme, $\widehat{P}_i$, the i-th estimate of average received power, is defined to be:

$$\widehat{P}_i \;=\; \alpha p_i + (1-\alpha)\widehat{P}_{i-1} \tag{8}$$

where p_i is the $i - th$ observed power level and $0 < \alpha < 1$ is the exponential smoothing parameter. This average is equivalent to a weighted average of all observations to date, with greater emphasis on the most recent [10, p. 594], reducing the impact of node movement on the estimate. The expectation of $\widehat{P}$ is $E[P]$ and its variance is $\alpha/(2-\alpha)V[P]$.

Let $\alpha = 0.5$, and the minimum threshold for a usable link be $\widehat{P} > Fp_{\min}$ where F is a factor chosen to improve the chances of reception on a selected link. Here, let $F = 1.05$. Approximating $\widehat{P}$ by a normal random variable with mean $E[\widehat{P}(d)] \approx Fp_{\min}\,(d_0/d)^c$ and standard deviation equal to 0.58 $E[\widehat{P}(d)]$, yields a probability of about 0.945 of accepting the AX or XB links and about 0.134 of selecting AXB. Combining this with the probabilities of receiving RREPs, leads to $P_{\mathrm{AXB5}} \approx 0.989$ and $P_{\mathrm{S5}} \approx 0.114$. The effectiveness depends on a number of technical factors, such as bandwidth and rate of node movement [1].

Case 6: hello Messages. A major problem with reliability estimation and power averaging is that one must have traffic present. Most wireless networks employ HELLO messages to establish the degree of local connectivity. Unfortunately, due to differences in data rate and packet size, one cannot directly infer reliability for message packets from that of HELLO packets [2]. However, this is not the case for power averaging. Thus, one can estimate receive power (or SNR) with any packet. The main difference is that if each HELLO packet generates a single estimate of p_i, then data and other longer packets should generate more estimates.

HELLO packets have another advantage for power averaging. Because HELLO packets are transmitted on a schedule, the receiver can detect missing HELLO packets and use that information to generate more accurate estimates of the average received power. Alternatively, one can simply count the number of HELLO messages received with $p_i > p_{\min}$ or some other critical value that would indicate proper reception of data packets. This would reduce the need to estimate power levels, reducing the computational load.

This approach requires each node to estimate and store link reliability values, even if that link is not needed. However, HELLO messages are very short and this need only be done in the one-hop neighborhood. The information is propagated to others by the simple means of not replying to RREQs from nodes sharing unreliable links. Since HELLO packets are normally send only when other traffic is not present, they would only be useful at very light loads in Scenario 2. However, they would be more useful in larger nets.

4. Simulation Analysis

There are some effects that were not considered in the Section 3. In this section, the combination of unicast RREPs and retries at the link level are explored by means of simulations. These simulations are performed in OPNET[1] using a modified wireless lan model in which the exponential decay factor is 3 and Raleigh fading is employed. Details of this modification are in [11].

Figure 4 illustrates the impact of retries for $R = 0$, 2, and 6 in Scenario 1 with a generation rate of 10 packets/s. The dotted line is the performance predicted by by considering only $\overline{p}(d)$. Note that while increasing R can increase reliability on $(0, d_0)$ to nearly that predicted by the non-fading model, large values of R also increase the probability of Event 2. However, this analysis is at a very light load and does not consider such things as the impact of the repeated transmissions of failed packets.

Figure 5 shows the relative throughput for a range of offered loads in Scenario 2 using unicast and several values of R on a one Mbit channel. The MANET protocol is AODV. Here the relative offered load is the ratio of the number of bits in data packets received to that of data

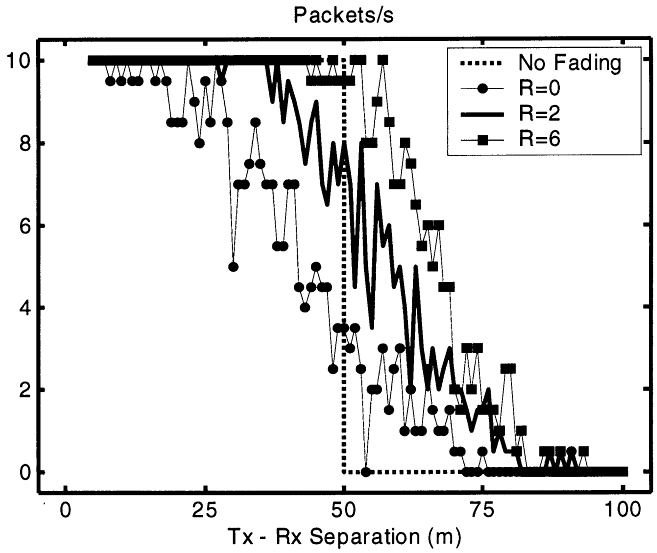

Figure 4. Simulated Effect of Range and the Number of Retries on Throughput

packets sent. The simulation consisted of two replicates, each consisting of a 500 second run for each value of offered load and R. The replicates were consistent with each other, roughly indicating sufficient run length. The values Figure 5 are the averages from the two replicates.

The results indicate that while having some number of retries improves performance, having too many is also detrimental. This is likely because of the increased utilization of the channel due to the multiple transmissions. It appears that for this particular situation, Either $R = 1$ or $R = 2$ is indicated. The smaller value yields lower overall throughput, but more consistency, while $R = 2$ brings higher performance at the cost of less stability. It also appears that an offered load of more than 10% of channel capacity will sharply decrease relative throughput and that the best one can expect in this configuration is between 70% and 80% of the packets to get through. This agrees with results in [2].

5. Summary and Conclusions

When searching for routes, a MANET node can make two sorts of errors: 1) rejecting a reliable link on the basis of an unusually weak signal and 2) accepting an unreliable link on the basis of an unusually strong one. Although either error has significant consequences, because it may lead to the need for a new route search, the second is more

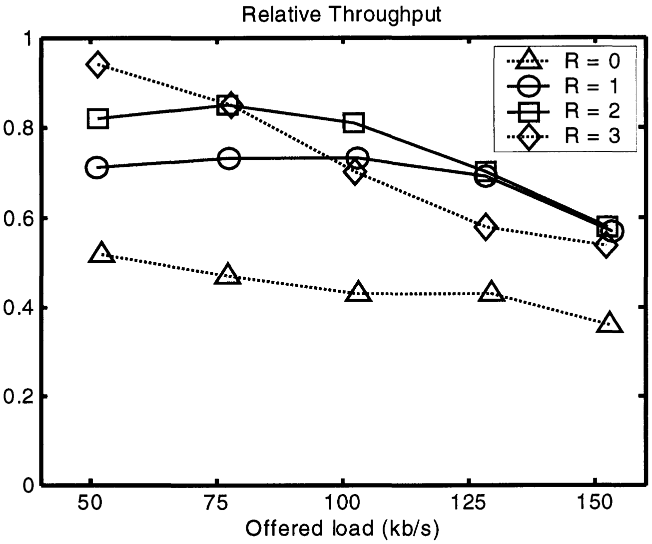

Figure 5. Effect of the Number of Retries on Throughput

serious than the first. Because the power of a received packet is a random variable, it is not possible for a node to anticipate, on the basis of a single packet, how reliable a route is likely to be. It is essential that some sort of repeated measures be incorporated to achieve acceptable throughput. The probability of selecting a better path over a shorter, but less reliable, one under several rules is summarized in Table 3. While some seem to work better than others, each introduces its own problems and requires some thought about parameter settings. Additionally, it is likely that the ultimate solutions to this problem will involve combinations of two or more basic approaches. For example, in [3] the authors describe an integrated approach that uses the number of retransmissions as the route selection metric, rather than shortest-path. This seems promising, if for no other reason than they have a working MANET containing 29 nodes.

There are many possibilities to consider. Doubtless, the unreliability problem will be mollified to some degree by technological advances at the physical and link levels, but there will still be a residual problem at the MANET level. In the end, however, the most important thing may be to develop more analytical and computer simulation models that will permit the consideration of the impact of this high magnitude, fine grained stochastic link behavior in MANET design.

Table 3. Impact of Strategies

Case	Strategy	P_{SAXB}	P_{S}	Notes
1	None	0.744	0.086	Baseline
2	Unicast RREPs	0.928	0.107	Typical?
3	R_{min}	0.927	0.466	Reduces excess RREPs, too.
4	Link retries	0.901	0.579	Using $R = 2$.
5	Power Averaging	0.989	0.114	Has side effects.

Notes

1. OPNET is a registered trademark of OPNET Technologies, Inc.

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