Impact of Multipath Fading in Wireless Ad Hoc Networks

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ABSTRACT

This paper examines several MANET behaviors and suggests root causes using a stochastic model of received power. It focuses specifically on MANET mechanisms most impacted by fine-grain variations in signal strength. Specifically, it examines 1) the impact of MAC retries on performance, 2) a possible cause of excessive route persistence, 3) route stability in MANETs, and 4) difficulties in estimating the mean SNIR in a MANET. It does so through mathematical analysis, simulation and comparisons to published field results.

Categories and Subject Descriptors

C.4 [**Computer Systems Organization**]: Performance Of Systems; J.7 [**Computer Applications**]: Computers In Other Systems

General Terms

Performance, Theory

Keywords

MANET routing protocols, Wireless propagation, Multipath fading, Stochastic models, Modeling fidelity, Rayleigh fading, AODV, DSR, SNIR, Cross-layer issues

1. INTRODUCTION

1.1 Motivation

In his keynote address to the 2004 conference on Mobile and Wireless Communications Networks (MWCN 2004), Charles Perkins pointed out that certain common issues were arising in the field of *Mobile Ad hoc Network* (MANET) protocol design and suggested that it is time to look to modular solutions that can be used by numerous protocols, rather than repeatedly addressing the problems in each individual protocol [16]. This paper is written in that vein.

A significant problem in MANET protocol design is that performance in physical experiments differs substantially from that predicted by mathematical analysis or simulation [4, 3, 5, 10]. Several have indicated that the problem is in the representation of the physical layer [20, 7]. This paper suggests that mathematical analysis and simulation of MANETs can be greatly improved with only a little effort by employing a stochastic model of multipath fading that is on the order of sophistication of the corresponding propagation model. It then uses this model to suggest underlying causes of some MANET behaviors observed in the field.

1.2 Scope

This paper explores several phenomena reported in published MANET test bed and field tests. It is specifically concerned with behavior that is the result of the interaction between MANET routing protocols and fine grain variations in signal strength. It attempts to assign causes of these phenomena in the MANET routing and lower layers. Because it seeks to find common causes, it employs a simple, yet fairly representative, stochastic propagation model. Although the issues presented here affect all MANET routing protocols, for the sake of brevity, the discussion is couched in terms of reactive protocols. Implications for proactive protocols are summarized in the conclusions.

This paper focuses specifically on MANET mechanisms that are most impacted by fine-grain variations in signal strength. In addition, it focuses on those that greatly affect MANET performance and not usually of concern in other forms of wireless communications. Simulation is carried out in OPNET v. 11.0[1], using standard models and default values, unless otherwise stated. Certain points are illustrated with the *Ad hoc On-Demand Distance Vector* (AODV) and *Dynamic Source Routing* (DSR) MANET protocols.

The specific issues examined in this paper are: 1) the impact of MAC retries on performance, 2)a possible cause of excessive route persistence, 3) route stability in MANETs, and 4) difficulties in estimating the mean *Signal to Noise plus Interference Ratio* (SNIR) in a MANET. Discussions include mathematical analysis, together with simulation and comparisons to published field results.

1.3 Previous Related Work

While there is no shortage of analytical work on MANET protocols [1, 6, 15, 19], there have also been numerous reports of field results differing in both magnitude and in rel-

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[1] OPNET Technologies, 7255 Woodmont Avenue Bethesda, MD, USA. http://www.opnet.com

ative order of performance [3, 4, 7]. This disparity is so significant that some even question the value of simulation in the design of MANET routing protocols [7]. A key problem seems to be that while fine grained variations in signal strength greatly impact MANET performance [3, 4, 15, 20], most analysis does not consider such variation [20, 7].

In previous papers, authors from the *Center for Stochastic Modeling* have described the ability of a Rayleigh fading model to greatly increase the fidelity of MANET simulations without incurring a significant penalty in modeling effort or simulation execution time [12], described the nature of the stochastic problem facing the receiver [14], and made some suggestions on how to deal with specific observed behavior [13, 11]. While those earlier works identified some of the phenomena discussed in this paper, they did not as fully explore possible root causes of those characteristics, as this paper does.

1.4 Content and organization of this paper

Section II describes the link model used in this paper and sketches some implications. It also serves as a reference for the later discussion. Section III briefly describes some key common functions of all MANET routing protocols and how fine-grain variations impact them. Section IV explores the four specific MANET issues mentioned above and presents some suggestions to deal with them. Section V summarizes, draws conclusions and indicates directions for further research. Finally, Appendix A derives some formulae that are used in the discussion, but whose development is not key to the discussion.

2. FIRST-ORDER PROPAGATION MODEL

Rather than attempting to model mean signal decay exactly, this paper employs a balanced model that approximates signal attenuation due to distance and signal variation to about the same degree. This is appropriate, since the goal is to identify common interactions of MANET protocols and signal variation, rather than behavior in a particular setting. It also allows mathematical analysis without sacrificing too much detail.

While shadowing is an important factor in signal variation and has been considered in analysis [2], as pointed out in [7], its effect tends to be autocorrelated. Multipath fading, on the other hand, has a great impact on signal variation, is relatively easy to model, and tends to be uncorrelated.

In spite of its simplicity, this model has been found to predict performance that is very close to observed performance in several test bed and field tests [12, 13].

2.1 Model development

The development is similar to that in [18], except that to keep notation consistent, some logarithmic expressions are replaced by their ratiomatic equivalents and expressions that refer to rms voltage are replaced by equivalent ones in terms of power.

2.1.1 Mean received power

The mean received signal power at R-T distance d is:

$$m_p(d; d_0, p_0, c) = p_0\,(d_0/d)^c \tag{1}$$

where d_0 is a reference R-T distance, p_0 is the mean power measured at d_0, and c is the path loss exponent. This is adapted from the Log-distance Path Loss Model [18, Eq. (4.68)]. In a free space model, c would be 2, but in practice, c is closer to 3 [18, 9]. To simplify comparisons in this paper, d_0 will be the nominal maximum range and p_0 the minimum power required for reception.

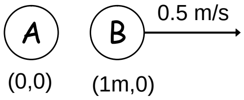

Figure 1: Scenario 1: Baseline

2.1.2 Instantaneous received power

Wireless received power exhibits a high level of variance [7, 15, 18, 9]. In this paper, such variation will be represented by the Rayleigh multipath fading model. This is a good first order approximation, especially since Rayleigh fading was observed in the two cases drawn on for the examples in this paper [4, 3]. In the Rayleigh fading distribution, instantaneous received power P is represented by an exponential distribution with mean $m_p(d)$. From [18, Eq. (5.49)],

$$\Pr\{P(d) \ge p\} = \begin{cases} \exp\left(\frac{-p}{m_p(d)}\right) & (d \ge 0) \\ 0 & (d < 0) \end{cases}. \tag{2}$$

Under the simplifying assumption that a packet will be received correctly if, and only if, $P(\cdot) \ge p_0$, the probability of reception would be:

$$\begin{aligned} p_R(d; d_0, c) &\overset{\Delta}{=} \Pr\{P(d) \ge p_0 | d_0, c\} \\ &= \exp\left[-\left(d/d_0\right)^c\right] \end{aligned} \tag{3}$$

For simulation, the inverse transform is

$$P(d; p_0, d_0, c) = -\ln(1-r)\,m_p(d; p_0, d_0, c) \tag{4}$$

where r is a random variable uniformly distributed on the interval (0,1).

2.2 Baseline Values

Simulations for this paper were carried out in the OPNET v. 11.0 MANET 802.11 model, with two modifications. One was that the default exponential decay value was changed from two to three. The second was to introduce the Rayleigh distribution. Details are in [12]. Transmission power was adjusted to 30 mW, yielding a nominal range of about 40 meters. Thus, $d_0 = 40$m and $p_0 = -62.67$dBμW, or about 0.54×10^{-12}W.

Figure 1 depicts the initial position of the first scenario. In this, Node B moves away from Node A at a constant rate of 0.5m/s while transmitting ten 1024-bit UDP packets per second to Node A. In Figure 2, the "Non Fading" line is the result of simulation without the Rayleigh model and the "RMP fading" is that with the Rayleigh model. The expectation plot is simply $10p_R(d)$. The Non Fading result considers the impact of BER, etc., while the RMP Fading plot considers everything the non-fading model does, plus fading.

The non-fading model shows a fairly definite maximum range with some rounding due to a high BER at extreme range. The RMP fading model, on the other hand, shows a much less definite range. Packets are lost even at fairly short ranges and packets are received, even at very large

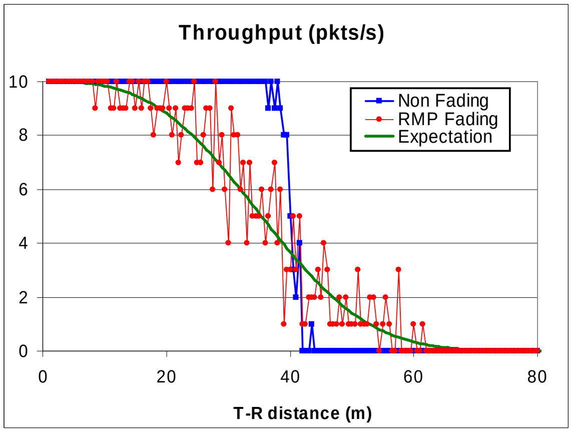

Figure 2: Simulated Throughput in the two models.

ranges. Also, the simple theoretical model seems to fit the RMP fading results well.

3. IMPACT OF FINE GRAIN SIGNAL VARIATION ON MANET PERFORMANCE

Fine grain variations exist, of course, in all forms of wireless communications. However, their effects on MANETs differ from those on other networks. A root cause of this difference in effect is a common function shared by all MANET protocols. That function is to identify and maintain routes through the network that will permit communication between nodes when a direct one-hop connection is not available [6, 17]. Toward this end, each node that is active in a reactive routing protocol repeatedly asks two questions:

1. For a link that is part of a current route, "Should I continue to use this link?"
2. For a link that may become part of a route, "Should I include this link in the route?"

The degree to which a routing protocol answers these two questions correctly greatly impacts how well the protocol works in practice.

If a reactive protocol assumes a link is no longer usable when it actually is, then it will initiate an unnecessary route search. This interrupts the current transmission and uses limited bandwidth to conduct the search. If, during a search, the protocol selects a link that is not actually usable, that will result in a faulty path, which when it fails, leads to a new search, and a risk of selecting the unusable link again. This latter possibility has been found to cause a very serious problem in the field [4].

Referring to Figure 2, under a non-fading model, receipt of a packet is very good evidence that a link will be good and failure to receive that it will be bad. But in the RMP fading model, packets can be lost on a good link and received on a bad one. By introducing variation similar to that found in wireless communications, the RMP fading model subjects the MANET protocol to issues that will occur in the field.

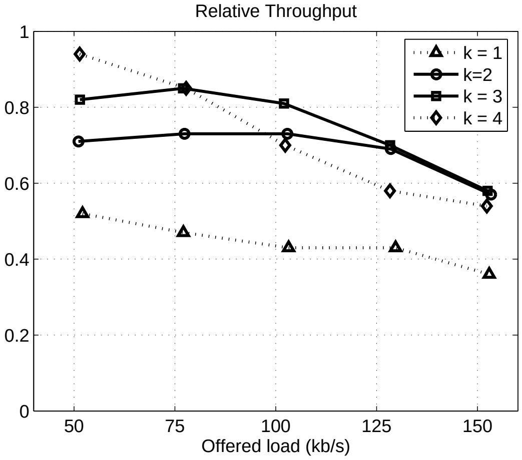

Figure 3: Relative Throughput as a function of k and offered load, from [13]

4. SOME MANET ISSUES

This section details some MANET performance issues that have been brought up in recent papers.

1. The impact of MAC retries on performance,
2. a possible cause of excessive route persistence,
3. route stability in MANETs, and
4. difficulties in estimating mean SNIR.

Discussions include a mix of mathematical analysis, together with simulation, and comparisons to published field results.

4.1 Impact of MAC retries on performance

One way to improve the probability of delivery on a link is to increase k, the number of times the MAC will attempt to transmit a packet before reporting a failure. The probability of success on a single attempt is p_R^2, ignoring the differences in probabilities for data and ACK packets. Thus, the probability of success for a given k is:

$$p_s(p_R, k) = 1 - (1 - p_R^2)^k. \qquad (5)$$

As k increases, p_s increases, reducing the risk of an unnecessary search. However, in [12, 13], it was noted that increasing k beyond two or three seemed to be counterproductive. Figure 3 displays the results of a simulation including twenty five mutually communicating nodes using the DSR protocol on a 1-Mbps channel. The results seem counterintuitive. Even at moderate loads, increasing k beyond two or three caused throughput to decrease. More than that, delay increased dramatically [13].

Figure 4 is a plot of $p_s(\cdot)$ vs. d for several values of k. As k increases, the probability of success at every distance is improved. However, increasing k also increases the load on the network.

To estimate this impact in the context of a MANET, assume that if a link fails to deliver a packet in k tries, the MAC will report a failure to the MANET protocol, which will initiate a search. Assume further that the network is dense enough that such a search will eliminate that link

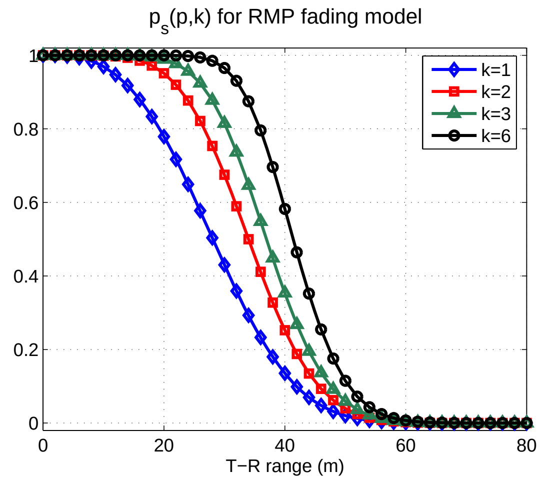

Figure 4: Throughput as a function of k

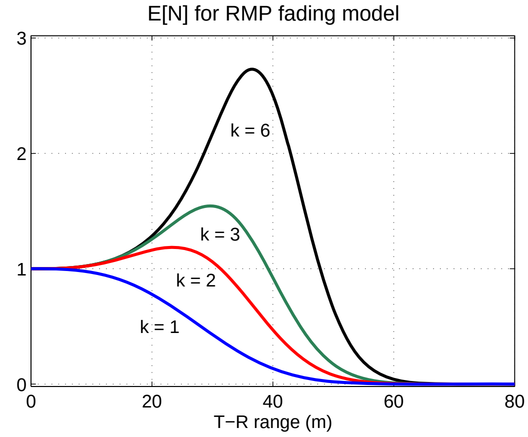

Figure 5: $E[N]$ as a function of d and k

with probability one. Thus, the probability that a link will be used in a path is just p_s.

Now, if a link is being used, the expected number of transmissions would be:

$$E[N|U] = k(1 - p_R^2)^k + \sum_{i=1}^{k} i\left(1 - p_R^2\right)^{i-1} p_R^2. \qquad (6)$$

The first term represents the case in which the link is not successful and the summation covers the cases in which it is. By conditioning on whether or not the link is in use, the expected number of transmissions on a random link would be

$$E[N] = E[N|U]p_s + 0(1 - p_s). \qquad (7)$$

$E[N]$ is illustrated in Figure 5 as a function of d and k.

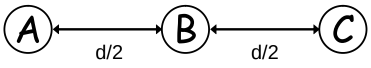

Figure 6: Scenario 2: Route Selection

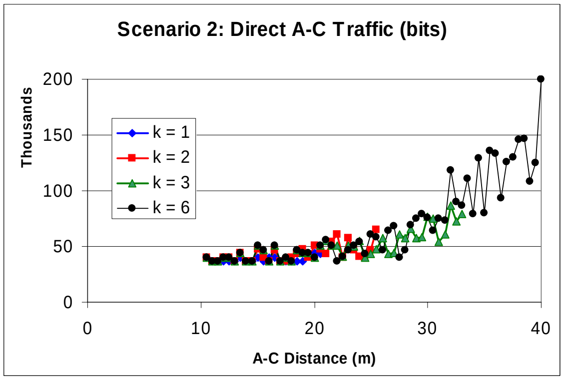

Figure 7: Scenario 2: Total Bits/s from Node A Sent Directly to Node C as a Function of d and k

Table 1: Changeover Range and Mean Traffic Load in Scenario 2

Statistic	Value of k			
	1	2	3	6
Changeover Range (m)	21	26	33	40
Mean load (Kbps)	38	44	50	70

To demonstrate this effect, consider Scenario 2, depicted in Figure 6. Node A transmits ten 1024-bit data packets a second to Node C. The channel properties are as in Scenario 1 with several values of k. Initially, the A-C distance is ten meters, but it increases at a rate of 0.5m/sec as the run progresses. At all time, Node B is exactly half way between nodes A and C. Figure 7 shows the total number of packets transmitted by Node A directly to Node C. The horizontal scale in this figure is only 40 meters because beyond that point, all traffic passes through Node B. The range at which the route changes from AC to ABC and mean bit traffic rate are summarized in Table 1. Note that as k increases, the changeover range increases, as expected. However, for $k = 6$, this increase in range comes at the expense of a very significant increase in the load on the channel. Although these statistics include all traffic from A to C, they do indicate the type of congestion predicted by Eq. 7.

Thus, increasing k tends to increase the offered load on the channel. In a MANET, this is especially troublesome, since re-transmission multiplies the effect as much as three times, due to the need to avoid data collisions on adjacent hops. In addition, as k increases, the probability of success goes up at longer ranges, meaning that the protocol is more likely to continue to use a poor link when a better route is available. Noting that the increase in $E[N]$ is especially large at the longer ranges, these two factors interact to make the problem even greater.

there is an upside to this situation. If a network is locally sparse, resulting in long local links, the protocol will repeatedly return to the mediocre, but usable, link. If this is the case, it might be advisable to have a large value of k, since the impact of $E[N]$ might be less than that of the repeated fruitless searches. Thus, one possibility to explore is a variable k, managed by the MANET routing protocol, keeping the value low for most links, but setting it high if the alternative is even worse performance or partition.

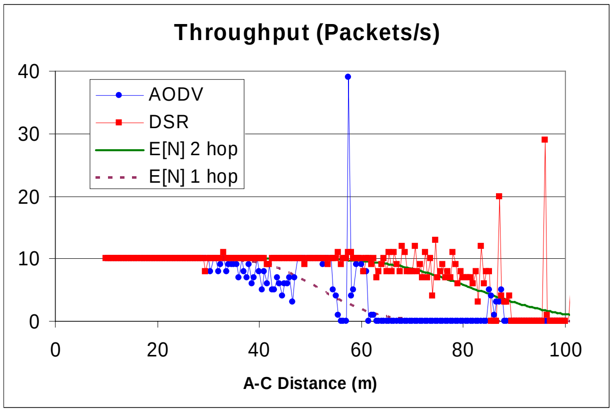

Figure 8: Throughput in Scenario 2

4.2 A possible cause of excessive route persistence

In [3] the authors noted that performance using AODV is considerably poorer than expected. They suggested that a problem was that the HELLO packets were transmitted at 1Mbps while data packets were sent at 11Mbps. Hence, by Shannon's Law, the HELLO packets would be received at a much greater distance than data packets. While this may be a factor, the following discussion offers an alternative explanation.

Reconsider Scenario 2, letting $k = 3$ and comparing the performance of AODV and DSR. Figure 8 shows throughput in this Scenario. As reported, AODV throughput decreases quite rapidly. In this same figure are the theoretical one-and two-hop throughput. The one-hop expectation is simply $Np_R(d)^2$, where N is the number of packets to be transmitted (10 in this case). For the two-hop situation, it is $Np_R(d/2)^4$. It appears that the problem is that AODV tends to use the AC direct route, instead of taking advantage of the ABC two-hop route, at longer ranges. This is confirmed by looking at the throughput for Node B, (See Figure 9.)

Certainly, HELLO packets could cause links to be retained too long. However, in this scenario, the HELLO interval one second and Node C would be transmitting up to ten ACKs per second, so no HELLO packets are generated until the link fails completely.

With a HELLO interval of one second and allowed HELLO loss of two packets, AODV will keep the AC link active as long as it receives at least one packet, HELLO or data, every two seconds. During two seconds, Node C may generate up to twenty ACK packets. Figure 10 shows the probability of success for several values of N. Note that at $N = 20$, the probability remains high until about 45 meters. Thus, although HELLO packets are not a factor, the HELLO interval is. At low traffic intensities, this is not likely to cause a problem, but if the traffic is sufficiently high, the value of HELLO Interval × Allowed HELLO Loss will cause AODV to remain on a poor link long after it should abandon it. Thus, the observed behavior can be explained in terms of multipath fading, even when HELLO packets are not involved.

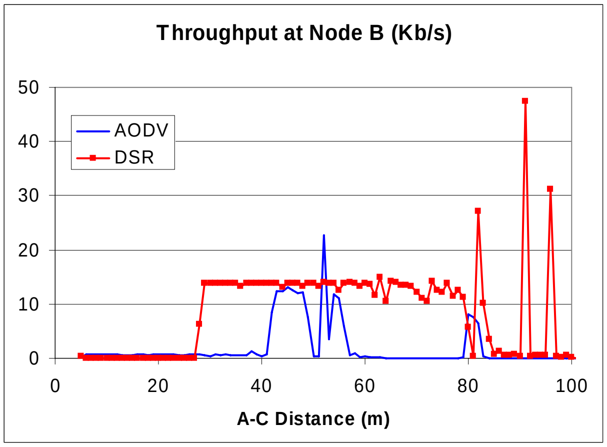

Figure 9: Throughput at Node B in Scenario 2

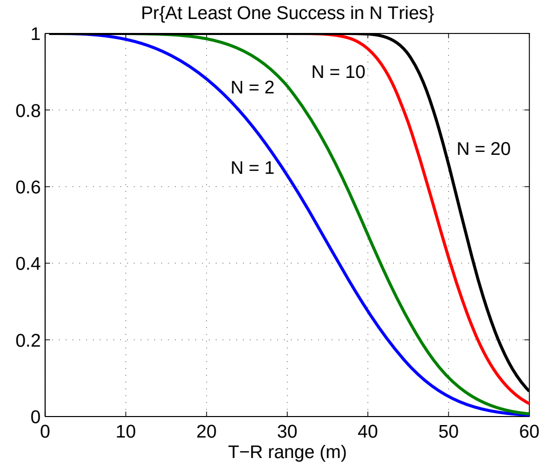

Figure 10: Pr{ **At Least One Success in** N **Tries**} **in Scenario 2**

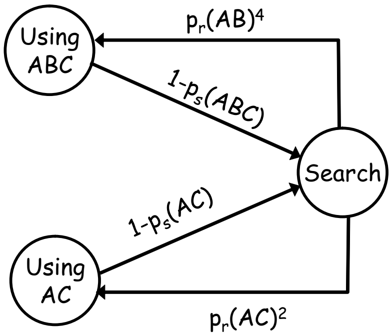

Figure 11: The Use-Search Cycle in Scenario 2

4.3 Route stability in MANETs

Referring back to the previous scenario, although DSR performed fairly well, its performance was affected by the fact that between 60 and 90 meters, it repeatedly alternated between the two possible routes. This alternation is due to two different interrelated probabilities. When a route is in use, there is a probability that it will fail, causing a search. The result of that search will be a path which will be used until it fails, and so on. Assuming the protocol will search until it finds a route, this situation is depicted in Figure 11.

Let $p_{SABC}(d)$ be the probability of selecting route ABC at A-C distance d and $p_{SAC}(d)$ that of selecting AC. Assuming the protocol will select the route with fewest hops and that RREPs are unicast, then from[14], at A-C distance d,

$$
\begin{aligned}
p^*_{SAC} &= \left[p_s\left(\frac{d}{2}\right)^2 + p_s(d) - p_s\left(\frac{d}{2}\right)^2 p_R(d)\right] && (8)\\
p^*_{SABC} &= p_s(d/2)^2 p_R(d/2)^2 \left[1 - P_{SAC}(d)\right] && (9)\\
p_{SAC} &= p^*_{SAC} / \left[p^*_{SAC} + p^*_{SABC}\right] && (10)\\
p_{SABC} &= 1 - p_{SAC}(d) && (11)
\end{aligned}
$$

where p^*_{SABC} and p^*_{SAC} are the probabilities that Routes ABC and AC, respectively, are selected in a single search and p_{SABC} and p_{SAC} are the corresponding probabilities, assuming the search is repeated until a route is found. Then, by conditioning on the route chosen, the probability of a route failing at A-C distance d in Scenario 2 is:

$$
\begin{aligned}
p_F(d,k) &= \left[1 - p_{s|ABC}(d;k)\right] p_{SABC}(d) \\
&\quad + \left[1 - p_{s|AC}(d,k)\right] p_{SAC}(d) && (12)
\end{aligned}
$$

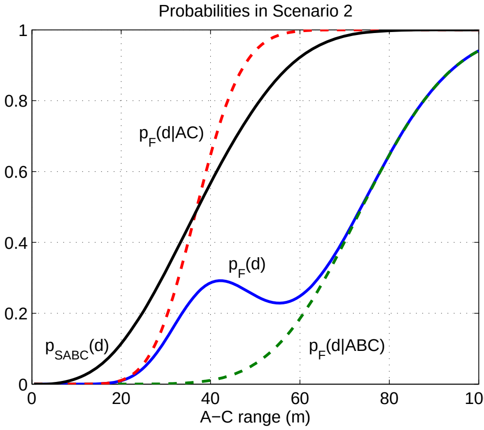

Figure 12: Probabilities in Scenario 2

Figure 12 shows these probabilities as functions of the A-C distance for $k = 3$ in Scenario 2. $p_F(d)$, the probability of a route failing at distance d is a weighted average of the failure probabilities for the two possible routes $P_F(d|ABC)$ and $P_F(d|AC)$). However, at any given time, the failure probability will be governed by the selected route. $P_F(d)$ remains low until about 60 meters. Although the probability of selecting ABC is high at this A-C distance, there is still a risk of selecting Route AC, which is very likely to fail. As $p_F(d)$ increases, there will be more and more opportunities for Route AC to be chosen, causing the system to alternate between the two roues until p_{SAC} becomes sufficiently small. One way to reduce this jitter is to require unicast RREP packets. This eliminates the possibility of a RREQ from A reaching C via node B, but the RREP traveling directly from C to A. The result, shown in Figure 13, is to cause the probability of selecting Route AC at moderate ranges, reducing the risk of jitter, as well as decreasing the overall probability of route failure.

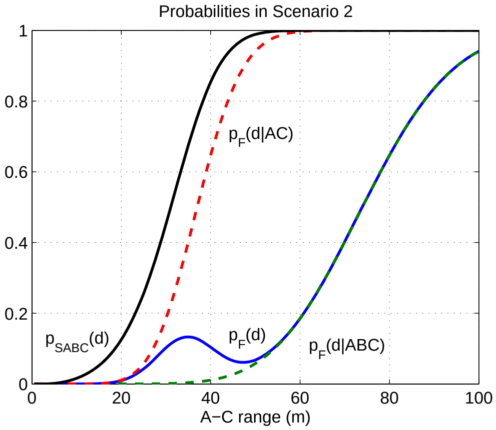

Figure 13: Probabilities in Scenario 2 When Route Reply Packets are Unicast

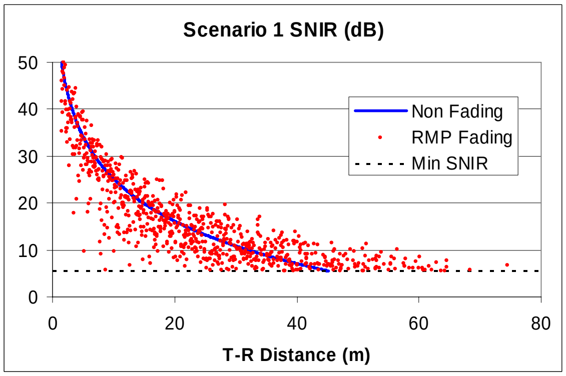

Figure 14: Observed SNIR in Scenario 1

4.4 Estimating Mean SNIR

To a great extent, the problems discussed so far are due to difficulty estimating the merit of a particular link. Several authors have noted that mean *Signal to Noise plus Interference Ratio* (SNIR) is a good predictor of success and suggest that average SNIR be a basis for link selection. Several researchers have met with some success using this scheme, but, as noted in [4], there seems to be some measurement error. That error can be explained in terms of signal variation.

4.4.1 *A source of bias*

Ignoring interference for now, Figure 14 illustrates the individual estimates of S/N ratio for Scenario 1. Note that as d increases, the number of observations decreases because if received power is too low, the receiver cannot identify the

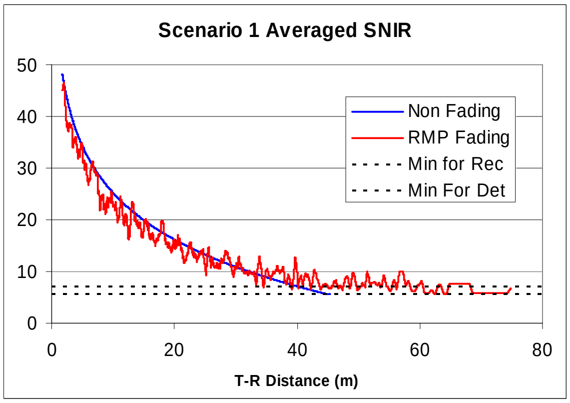

Figure 15: Estimated SNIR in Scenario 1

transmitter. Even if it can estimate the S/N ratio, it cannot associate that estimate with a particular link. Thus, only the higher ratios are observed and estimates based on those observations become more and more biased. This is illustrated in Figure 15, in which the mean S/N ratio is estimated by means of exponential smoothing with $\alpha = 0.2$. Note that from about 45 meters on, the estimate is essentially constant and that at no time does it fall below the minimum S/N required. For this reason, some sort of offset needs to be assumed [4].

4.4.2 *Considering interference*

In a MANET, because nodes share a common channel, interference usually has a greater impact than noise. In addition, thanks to in-band transmissions from nodes that are out of range, but near, as well as crosstalk from near-band transmissions, the interference level can have large, rapidly-changing values. Hence, the remainder of this section focuses on the SNIR, rather than the S/N ratio. Scenario 3 addresses the issue. As shown in Figure 16, Nodes A and B are as in Scenario 1. However, three pairs of mutually communicating nodes are now arranged around Node A. Each "X" node is 50m away from Node A and is paired with the node indicated by the solid double arrow. During the simulation run, all nodes, except A, generate ten 1024-bit packets per second.

Figure 17 shows the results. Because the node pairs are further than 40m from A, the non fading model shows almost no impact of their transmissions. The RMP fading model, on the other hand, shows about a 10 dB drop in the SNIR. However, as before, the exponentially-smoothed average estimate of SNIR is too optimistic. Because of the interference, the actual effective range of the AB pair is about 15m, but the uncorrected estimate (red) does not consistently drop below the 9 dB line until about 40m. Thus, using uncorrected estimates of SNIR can cause the MANET to accept a link that may be of very poor quality.

This figure also displays a simple correction to the estimate in which each value that is too small to estimate is replaced by half the minimally detectable level, 4.14 dB, instead of being ignored. While this estimate (green) yields a more realistic values, it is not practical in a MANET. Because nodes in a MANET share a common channel, the receiver would not know which transmitter was active and, therefore, would be unable to tell which link to associate the correction with. This is complicated further when data collisions are taken into account, for in that case, the failure to decode the packet was due to a random coincidence, rather than the quality of the link.

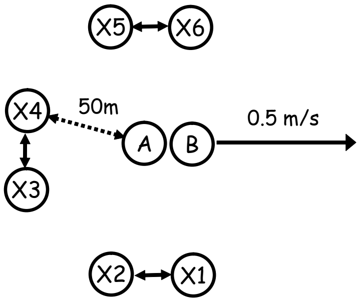

Figure 16: Layout for Scenario 3

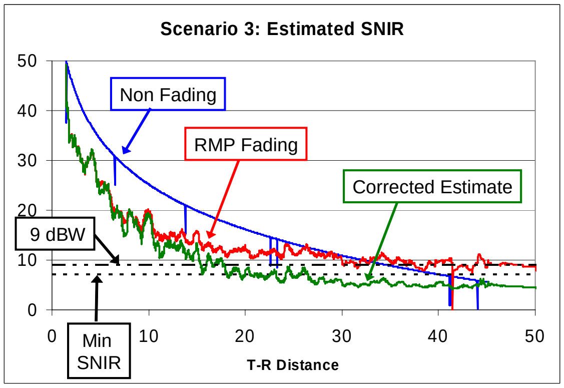

Figure 17: Estimates of SNIR in Scenario 3

Although use of the SNIR could greatly improve MANET performance, estimating its level in a MANET presents a number of difficulties. Aside from the censoring problem described above, received power and interference power tend to change for different reasons. Received power tends to decrease as T-R distance increases while interference is a function of in-band and near-band emissions of other nodes in a vicinity of the receiver. Hence, an increase in local traffic can cause the SNIR to decrease enough to prevent reception, even though the received power is moderately high. Because power and interference vary randomly, it is very difficult to estimate their ratio. At this time, the Center for Stochastic Modeling is examining this problem and seeking reliable solutions.

5. CONCLUSION

5.1 Summary

This paper examined 1) the impact of MAC retries on performance, 2)a possible cause of excessive route persistence, 3) route stability in MANETs, and 4) difficulties in estimating the mean SNIR in a MANET. It did so using the Rayleigh multipath fading model to represent fine-grain fluctuations in signal strength. It suggested 1) it is counterproductive to retry transmissions more than a few times in a MANET, 2) the HELLO interval in AODV is a likely cause of excessive route persistence, 3) route stability can be improved by reducing the risk of selecting bad routes, and 4) uncorrected estimates of SNIR will be biased with bias increasing with T-R distance.

5.2 Conclusions

Fine-grained variations in signal strength affect MANET protocols in ways that differ from that in other network architectures. This difference implies that one should use caution when applying a method or result developed to describe behavior in a cellular or stub network to a MANET. The results above deal specifically with reactive protocols, but apply in a similar fashion to proactive ones. For example, if a node falsely concludes a link is broken, it will propagate that topology change. The fact that communications may fail at any distance means propagation must consider connectivity information may not be propagated completely. Also, because a packet may be received at great T-R distances, there is a risk that a false link will be identified as good and included in the routing tables.

In spite of its simplicity, the stochastic model presented here predicts a remarkable amount of observed behavior with reasonable accuracy. While there has been a great deal of emphasis on improving the ability of propagation models to predict mean received signal strength, the impact of signal variation on MANET performance would indicate that models of signal variation should be of comparable complexity to better predict behavior. Without this sort of model, the protocol developer is deprived of effective diagnostic and modeling tools.

5.3 Further work

At this time, the Center for Stochastic Modeling is exploring the problem of estimating SNIR reliably. One promising direction is the use of techniques employed for censored observations, as in [8]. More generally, it will continue exploring phenomena that impact classes of protocols, rather than particular ones.

In general, the MANET protocol development could be greatly increased if developers had access to better predictive and simulation models. The model presented here is useful at the most abstract levels of analysis and design, but such models are also needed particular applications.

6. ACKNOWLEDGEMENTS

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