Achieving Robust Protocols for Mobile Ad Hoc Networks

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Abstract

A Mobile Ad Hoc Network (MANET) is a self-organizing and self-contained communications network that requires no fixed infrastructure. Such a network is a logical choice to establish a communications network under emergency conditions, during a temporary assemblage, or even in the home. The current practice in testing the design of MANET routing protocols is to assume a very simple radio propagation model, together with specific movement scenarios to model the offered load and other demands. While this approach is useful in finding some weaknesses in protocol design, it fails to predict some problems that lead to serious difficulties in the field. This paper describes a technique which uses Response Surface Methodology, together with stochastic radio propagation models, to more realistically predict protocol performance in an attempt to achieve more robust MANET protocols.

Keywords: MANET routing, wireless propagation, fading, shadowing, stochastic models, network reliability, decision rules, power averaging.

1 Introduction

A *Mobile Ad Hoc Network* (MANET) is a communications network formed by nodes that are likely to be mobile and may, from time to time, opt to not participate in the net. Because the topology frequently changes, a MANET has no fixed infrastructure. Instead, communications between nodes that are far apart is effected by intermediate nodes acting as routers. The purpose of the MANET routing protocol is to maintain the virtual backbone created by these routers, in spite of the nets dynamic topology [1, 2].

At this time, virtually all development of MANET protocols assumes that if two nodes are within a given range (r_0) of each other, they can communicate directly, but if at a greater range they cannot. The main focus is on carefully modeling the protocol behavior, node movement, and the expected value of r_0 [3, 4, 5, 6, 7]. However, while these matters are important, this analysis ignores the fact that radio signal strength is highly variable [8, 7, 9] and, as evidenced by recent field experiments, this variability introduces serious performance issues in the field [10, 11, 12, 13].

This paper outlines a different approach to MANET protocol evaluation which considers the stochastic nature of radio wave propagation. In this approach, protocol design parameters are selected to provide stable performance over the expected range of radio link behavior.

2 Background

2.1 How a MANET Routing Protocol Works

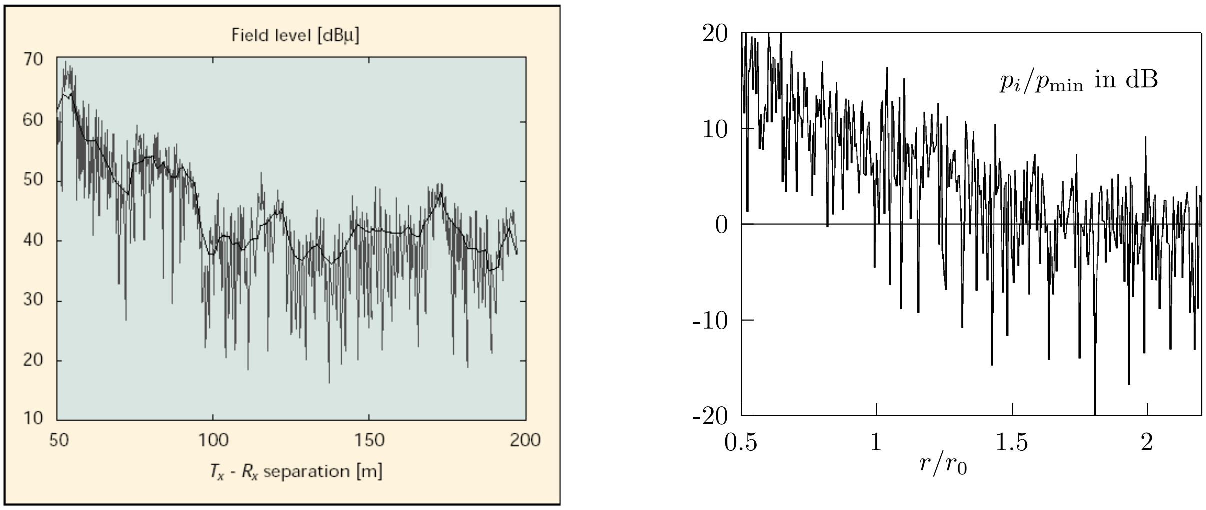
There are numerous MANET protocols [1, 2]. In this paper, the *Ad hoc On-Demand Distance Vector* (AODV) [14] will be used as an example, but a similar approach would be possible with any of the others. In the AODV, nodes only maintain active routes and do not attempt to maintain knowledge of the full topology. When a node needs to send data to another node and has no current route in its table, it broadcasts a *Route Request* (RREQ) packet. Nodes receiving this packet will pass it on. If a node that is either the desired destination or has a valid route to that destination receives the RREQ, it will unicast a *Route Request Reply* (RREP) packet back towards the originator of the request. This RREP will contain the list of nodes on the route. When the originator receives a RREP it considers valid, it will update its routing table and begin to send packets on that route. Because there may be more than one route to the destination, the originator may receive more than one RREP to its RREQ. If it later receives a valid RREP indicating a route with fewer hops, it will update its table and begin using the shorter route.

2.2 The Stochastic Nature of Radio Wave Propagation

As illustrated in Figure 1a, received power is an extremely variable and noisy function of distance. This variation is chiefly due to effects of fading and shadowing, together with some other effects not completely understood [7, 8, 9, 10, 15, 16]. Thus, there is no r_0, as described above, but instead, there is a non-zero probability of communications success at any range. Nevertheless, there are models which can describe this phenomena. One such model is:

$$F_p(p; r, r_0, c, F, p_{\min}) \;=\; \Pr\{P \le p | r_0, c, F, p_{\min}\} \;=\; 1 - \exp\left[-\left(\frac{r}{r_{_0}}\right)^c \left(\frac{p}{F\, p_{_{\min}}}\right)\right] \tag{1}$$

where r is the distance between the nodes, r_0 is the nominal maximum range, c is the exponential decay factor, F is the fading factor, and $p_{\min}$ is the minimum power required for reception. (This equation is derived in Appendix A). Figure 1b illustrates a pseudorandom signal produced by the inverse transform of Eq. (6). One can see by comparing the two parts of this figure that this model captures key elements of received signal strength.



a) Actual Measurements, from [7]

b) Synthetic Trace Generated from Eq. (6)

Figure 1: Actual and Simulated Received Power Levels

3 The Basic Problem

In one recent study, the authors identify two serious consequences of receive power variability. The first is that due to a random drop in signal strength, a packet may be lost on a reliable link, falsely indicating that the link has failed. A second, more serious, problem is there is a fairly high probability that, in response to a request for a route (RREQ), a node will receive a route request reply (RREP) from a distant node. Since most protocols prefer routes with fewer links, this “shortcut” is selected over the longer, more reliable, path. However, when the path is used to transmit data, it is likely to fail, leading to an interruption and the need for a new path search. This made it nearly impossible to communicate over just three or four hops [10, p. 53]. A similar phenomena was noted in [13].

3.1 An Example

To illustrate this problem, consider Figure 2. Assume Node A needs to find a route to Node B, which is at a distance of $2r_0$. Node C is located between them so that the AC and CB distances are both equal to r_0. Assume no other nodes are in the vicinity. When A broadcasts a RREQ for a route to Node B, exactly one of four things can happen. 1) Node A receives only a RREP from Node B, 2) Node A receives only a RREP from Node C 3) Node A receives a RREP from both nodes, or 4) Node A receives no RREP. Under the fixed range assumption, only Event 2) is possible, but in reality, any of the four could occur.

For Node A to receive the RREP from Node B, first Node B must receive the RREQ directly from Node A, then Node A must receive the RREQ directly from Node B. This requires two successful transmissions over

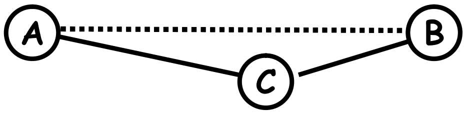


Figure 2: A Request for a Route from Node A to Node B

the distance $2r_0$. For Node A to receive a RREP from Node C, Node C must receive the RREQ from Node A, Node B must receive the RREQ from Node C, then Node C must receive the RREP from Node B, and Node A must receive the RREP from Node C. This requires four successful transmissions over the distance r_0.

Given a stochastic propagation model, one can calculate the probability that power will equal or exceed $p_{\min}$ by integrating p over the range $[p_{\min}, \infty)$. In the case of the simple model above, the result is:

$$\Pr\{\text{Success}\} \;=\; \Pr\{P \geq p_{\min} | r_0, c, F, p_{\min}\} \;=\; \exp\left[-\left(\frac{r}{r_0}\right)^c \left(\frac{1}{F}\right)\right] \tag{2}$$

Table 1 summarizes the probabilities of the four cases listed above, assuming $c = 3$, and $F = 100$. In this table, p_1 is the probability of success for a single hop, n is the number of hops, and p_e is the probability of the event.

Table 1: Possible Probabilities of Events in the Example

Event	Description	p_1	n	p_e
1	A receives only a RREP from B	0.923	2	0.033
2	A receives only a RREP from C	0.990	4	0.142
3	A receives both RREPs	—	—	0.819
4	A receives neither RREPs	—	—	0.006

The probability of five packets successfully passing over the ACB route is $(0.990)^10 \approx 0.90$ while the probability of success over the AB route is only $(0.923)^5 \approx 0.67$. However, because the protocol favors shorter routes, the ACB route will be selected only if Event 2 occurs, which will happen only about 14% of the time. The poorer route will be selected 85% of the time. This highly probable event is completely ignored by the fixed-range model.

4 Seeking Robust Protocols

Either Response Surface Analysis or the Taguchi method could be used to seek a stable design. IN this approach, a system model is subjected to a range of offered loads similar to those expected in use. In addition, design factors are selected to determine how design choices affect system stability. The objective is to select a combination of design factors that would work well over the full range of offered loads and stresses.

In the simple model above, there is one design factor, F. In addition, there is one environmental factor, c. More precise models would add more design and environmental factors. For example, there are other kinds of fading and the MANET protocol itself could be a design choice. The example below serves to illustrate the method, but is not a complete analysis.

4.1 Environmental Model

Only two environmental factors were considered: the exponential decay (c) and the effects of Rayleigh fading. The values of c were included in the sample design at levels 2, 3, and 4. The stochastic fading effects were produced by simulation.

4.2 Optimizing Fading Margins

In other applications, such as cellular telephone, the primary concern is increasing the reliability of routes for which $r \leq r_0$. However, in MANETS, high values of F also increase the risk of a spurious RREPs from more distant nodes. To estimate the effect of different fading margins, the design includes points at $F = 25$, 100, and 400.

4.3 Power Averaging

In [10], the authors employed an exponentially-smoothed average of received power. This approach balances the need to estimate the likely reliability of the link against the affects due to changes in distance. In such a scheme, $\widehat{P}_i$, the i-th estimate of average received power is defined to be:

$$\widehat{P}_i \;=\; \alpha p_i + (1-\alpha)\widehat{P}_{i-1} \tag{3}$$

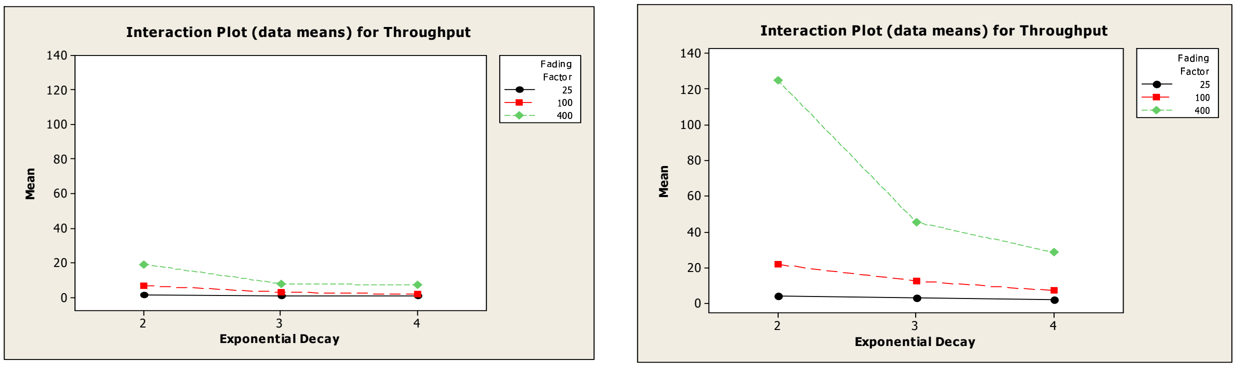
where p_i is the $i-th$ observed power level and $0 < \alpha < 1$ is the exponential smoothing parameter. This average is equivalent to a weighted average of all observations to date, with greater emphasis on the most recent [17, p. 594]. The expectation of $\widehat{P}$ is $E[P]$ and its variance is $\alpha/(2-\alpha)V[P]$. In this technique, a node receiving a RREP will check to see if $\widehat{P} > kp_{\min}$ for that link. If this is not the case, the RREP is ignored.

4.4 RSM Sample Implementation

The original (mirrored) protocol described in Section 3 and the power averaging protocol of Section 4.3 with $\alpha = 0.5$ and $k = 10$ are considered by this sample RSM procedure. In both cases, the average power distribution was approximated by a normal random variable with mean

$$E[\widehat{P}(r)] \;\approx\; Fp_{\min}\left(\frac{r_0}{r}\right)^c$$

and standard deviation equal to $0.58E[\widehat{P}(r)]$. These results are displayed in Figure (3. While the results of the earlier field test of [10] and this simulation both look promising, its effectiveness depends on a number of technical factors, such as bandwidth and rate of node movement [10]. For the power averaging protocol, k should also be considered as another design factor.



a) Original Results

b) Power Averaging

Figure 3: Throughput in Packets per Second

5 Conclusion

5.1 Summary

Virtually all simulation of MANET protocol performance ignores the stochastic elements of wireless communications. This leads to a serious difference between simulated and field behavior. At the Center for Stochastic Modeling, we are developing tools to more accurately predict MANET protocols by considering the impact of stochastic variable link behavior and through Response Surface Analysis. This paper illustrates the framework for this effort using simple propagation models.

5.2 Further Work

The model shown here is purposely simple to focus on the central concepts: 1) the importance of considering fading and 2) the potential of Response Surface Analysis in this area. The team at the CSM plans the following to further this work.

First of all, the simulation models used here were very simple. More realistic communications models will be generated using OPNET and ns2. The first step in this portion of the work is to develop modules to use in these languages that will incorporate the stochastic link behavior.

The RF propagation model considers only c at this time. Future models will incorporate other forms of fading. A key aspect of this step will be to explore the interactions between fading type and the exponential fading factor.

There are many more design choices than those outlined here. Others would include existing protocols and new protocols. As mentioned above, the value of k is a factor for power averaging. Other rules could also be investigated, similar to those in statistical process control.

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A Derivation of the Propagation Model

There are a number of propagation models that will predict the average received power, p_A, at a given distance, r. One such model is

$$p_A(r, r_0, p_0, c) \;=\; p_0\left(\frac{r_0}{r}\right)^c, \tag{4}$$

Where p_0 is the average power measured at the reference distance r_0 and c is the exponential decay coefficient. This simple model does not consider large obstructions and such, but regardless of the nature of the model, the result is p_A, an average power level [7, 8, 16].

In MANETS, antennas are often low and obstruction is likely. In such a case, Rayleigh fading would not be unusual [7, 8, 16]. In this case, the probability distribution of instantaneous power, p_i would be:

$$F_p(p_i; r, r_0, c, p_0) \;=\; \Pr\{P_i \le p_i | r_0, c, p_0\} \;=\; 1 - \exp\left[-\left(\frac{p}{p_A}\right)\right] \;=\; 1 - \exp\left[-\left(\frac{r}{r_0}\right)^c \left(\frac{p}{p_0}\right)\right] \tag{5}$$

Finally, let r_0 be the nominal range and $p_{\min}$ be the minimal power for reception. Since the distribution of received power varies about the average level, a fading factor, F is selected so that the average power at r_0 is $Fp_{\min}$. This fading factor is chosen to have a sufficiently large expectation that r_i will exceed $p_{\min}$ at r_0. Thus, the probability distribution of instantaneous power at range r :

$$\Pr\{P_i \le p_i | r_0, c, F, p_{\min}\} \;=\; 1 - \exp\left[-\left(\frac{r}{r_0}\right)^c \left(\frac{p}{F\,p_{\min}}\right)\right]. \tag{6}$$

The exponential decay factor is typically equal to 3, but often ranges from 2 to 4 [8, 16]. $p_{\min}$ depends on a number of factors, including bandwidth, date rate, type of encoding, and receiver noise. However, for a given configuration, it can be assumed to remain relatively constant. The fading factor is a design choice which determines the average reliability of a link within range. This essentially compensates for the variability of received signal strength. A typical value is 100, or 20dB.