Link Ratio for Ad Hoc Networks in a Rayleigh Fading Channel

Haley M. Jones *Haley.Jones@anu.edu.au*
Sanlin Xu *Sanlin.Xu@anu.edu.au*
Kim Blackmore *Kim.Blackmore@anu.edu.au*

Department of Engineering
Australian National University
Canberra ACT 0200

***Abstract*—**
Mobility metrics have been widely recognised as a useful tool in comparing the performance of different mobility models of nodes in ad hoc networks. Most mobility metrics studied to date have been used in conjunction the *transmission range* model of communication. That is, it is assumed that if two nodes are within a given distance, r, then it can be said that a communications *link* exists between them. This assumption is based on the model of a wireless channel in which the only impediment to signal strength is attenuation related to, usually the square of, distance. This model is used extensively in both theoretical and simulation work which, naturally then, agree, bringing about a *perceived* strengthening of the validity of such a model.

A more realistic view of the wireless channel is to assume that the signal is affected by multipath, giving a Rayleigh, Ricean or even Nakagami signalling environment. Such a view brings an entirely different perspective of signal transmission in ad hoc networks. The separation distance between a pair of nodes being within transmission range no longer guarantees that a communications link exists. This more practical approach requires a fresh look at mobility metrics. We consider the *link duration*, find it inappropriate for such a transmission environment and, instead, introduce a new metric, the *link ratio*.

Keywords: Mobile Ad Hoc Networks, Rayleigh Fading, Mobility Metrics, Link Duration, Link Ratio, Path Link Ratio

I. Introduction

Recent advances in wireless technology have enhanced the feasibility and functionality of wireless mobile ad hoc networks (MANETs). MANETs are networks in which multiple nodes, each possessing a wireless transceiver, form a network among themselves via peer-to-peer communication. In particular, there is no central controller (i.e., there is no entity equivalent to a base station in a cellular network). An ad hoc network can be used to both exchange information between the constituent nodes and to allow communication with remote sites that would be otherwise unreachable.

There has been significant research activity over the past 5-10 years into the performance of such networks with the view to developing more efficient and robust communication protocols. However, the vast majority of the research has concentrated on either developing appropriate mobility models for node movement [1], [2] or on developing performance metrics [3], [4]. The channel itself has been effectively ignored. In [4] a cluster based framework is presented for defining a strategy to dynamically organize an ad hoc network. Nodes are sorted into clusters based on the probability of path availability, α, between all nodes in the cluster over a given time interval t. The random walk mobility model is used in this work with a link between any pair of nodes being assumed to exist as long as the nodes are within a mutual transmission range, r.

In [5], given a network of dimension, d, and side length, l, the critical transmitting range is determined which ensures connectivity of the network. Connectivity is defined as meaning that each node in the network is able to communicate with each other node in the network via at least one multi-hop path (sequence of links). The range is determined first for stationary networks and then for networks with mobile nodes. While, in [6] the number of neighbours required for connectivity in a wireless network is examined.

In both [5] and [6] all calculations are based purely on geometry with no consideration given to channel properties. And, in many of the works on mobility metrics, the transmission range or threshold, r, is defined as being dependent upon many system dependent factors, including fading, but none actually addresses the issue of fading in any meaningful way.

We claim that such models are unrealistic and inadequate for properly describing the nature and performance of, in particular, wireless ad hoc networks. In this paper we consider a more realistic wireless channel model. In particular, we consider one of the most well-known wireless channel models, the Rayleigh fading channel model. The Rayleigh fading model is used to describe channels which have a number of *multipath* signal components caused by reflections from objects in the signal environment such as trees, hills and buildings, as in Figure 1. These components, then, destructively or constructively interfere, to varying degrees, at different locations in the transmission environment. In such a signal environment, then, even if a given pair of nodes are within possible transmission range of each other, signal fidelity cannot be guaranteed. The nature of the Rayleigh fading signal is determined by the signal environment and the positions of the communicating nodes.

Previously, [7], we have considered the *link duration* as a measure of communication performance between a pair of nodes in a mobile ad hoc network. We again use the link duration as a measure of communication performance and find it inadequate for describing the link performance of an ad hoc network operating in a Rayleigh fading channel. We then introduce the related measure, the *link ratio*, as a more appropriate measure. The link ratio gives a much better indication of the probability of a link being available at any given time for an ad hoc network operating in a Rayleigh fading channel.

In this paper, we begin by introducing the Rayleigh fading channel model in Section II. In Section III we revisit the link duration mobility model and then introduce the link ratio mobility model in Section IV. Simulation parameters and results are presented in Section V followed by conclusions in Section VI.

II. Rayleigh Fading Channel Model

The standard model for signal transmission in wireless ad hoc networks assumes that the only impediment to successful signal transmission and receipt is too large a distance between the transmitting and receiving nodes. Any channel effects, such as interference from other nodes' transmissions, noise or multipath are effectively ignored. This type of model is used for both theoretical work and the large amount of simulation work carried out to investigate and understand ad hoc networks.

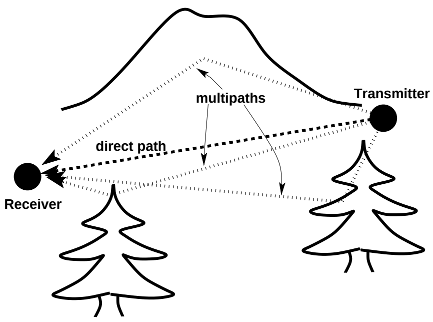

Fig. 1. Depiction of a multipath signaling environment with reflections of the signal from the transmitting node to the receiving node from trees and a hill.

Many authors have developed a number of network performance metrics such as link duration, link availability, path duration and path availability, [1], [3], [4]. We can find, in this work, no consideration of the effects of the wireless signalling environment, as described above. In our previous work [7], we developed mathematical expressions for the link duration based upon this "in-range" transmission model. We considered a pair of mobile nodes moving according to the Random Walk Mobility Model (RWMM). In this paper we again consider a pair of nodes moving according to the RWMM but, this time, we take into account other effects of the wireless channel. To this end, we model the channel using the well-known Rayleigh fading model. Again, we use the link duration as the performance metric.

The Rayleigh fading model comes about, primarily, due to the presence of multipath signals. By *multipath* we mean that the transmitted signal reaches the receiver via a number of different paths (multiple paths) due to reflections from obstacles in the signaling environment such as trees, people and buildings, as shown in Fig. 1 . Because these paths have different lengths, they have different phases upon reaching their destination and, therefore, destructively or constructively interfere causing stronger or weaker signals at different receiver locations. Where the signal strength is weak, the signal is referred to as being *faded*. The well-known Rayleigh fading model assumes no (dominant) direct path (the Rician model takes care of this case).

III. Link Duration

The link duration has been shown to be a useful mobility metric giving a good indication of protocol performance in ad hoc networks over a range of mobility models [2], [3]. In [7] we determined expressions for the probability distribution function (pdf) of the link duration in an ad hoc network where the nodes were assumed to be moving according to the RWWM.

The link duration is the average time that a communication link between a given pair of nodes lasts without breaking. It is a measure of stability of the link between these nodes. For the in-range model a link is said to exist between a given pair of nodes as long as they are within a distance r of each other, where r is the chosen link distance threshold. For a given system, r depends upon many system factors such as transmitted signal power, clutter in the signalling environment (e.g., hills and buildings), noise and interference. For the Rayleigh fading model, a communication link is said to exist between a given pair of nodes as long as the signal strength at each node is above a given threshold. For our purposes, it is assumed that this link is symmetric. The average link duration can be calculated as follows [8].

Consider a network of N nodes and take an arbitrary pair of nodes i and j. Let $\mathcal{L}_k(i,j)$ be an indicator variable which equals 1 if a link exists between these nodes at time step k and 0 otherwise. The *link time* $\mathrm{LT}(i,j)$ is the number of time steps for which the link has existed between the pair of nodes, over a period of K steps, where K is sufficiently large, such that

$$\mathrm{LT}(i,j) = \sum_{k=1}^{K} \mathcal{L}_k(i,j). \tag{1}$$

Let $C_k(i,j)$ be another indicator variable which has value 1 only when the link appears, i.e., $C_k(i,j) = 1$ iff $\mathcal{L}_k(i,j) - \mathcal{L}_{k-1}(i,j) = 1$. The number of *link changes* $\mathrm{LC}(i,j)$ is the number of times the link has existed during the K steps.

$$\mathrm{LC}(i,j) = \sum_{k=1}^{K} C_k(i,j) \tag{2}$$

The *average link duration* $LD(i,j)$ between the pair of nodes can be expressed as

$$\mathrm{LD}(i,j) = \begin{cases} \frac{\mathrm{LT}(i,j)}{\mathrm{LC}(i,j)} & \text{if } \mathrm{LC}(i,j) \neq 0 \\ 0 & \text{otherwise} \end{cases} . \tag{3}$$

If there are N nodes in the network, the average link duration LD for the network is simply the average of $\mathrm{LD}(i,j)$ over all $\frac{N(N-1)}{2}$ possible (symmetric) links.

$$\mathrm{LD} = \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} \mathrm{LD}(i,j). \tag{4}$$

If node locations are generated according to some random process, the average link duration LD will approach the expected link duration as $K \to \infty$, according to the law of large numbers.

In the following, we calculate the expected link duration for an arbitrary pair of nodes. As the movements of all nodes are i.i.d. and all nodes have identical transmission ranges, the expected link duration between a given pair of nodes is equal to the expected average link duration over all possible node pairs. This can be seen by considering the expectation of (4).

IV. Link Ratio

Due to the nature of the Rayleigh fading model, and the movement of the nodes, the signal strength fluctuates with movement of the nodes in a different way to the in-range model. It will be seen in Section V that the Rayleigh model performs poorly compared with the in-range model when the link duration is used as the performance metric. A typical variation in signal power with distance in a Rayleigh fading environment is shown in Fig. 2. We will discuss how this affects the link duration results in Section V.

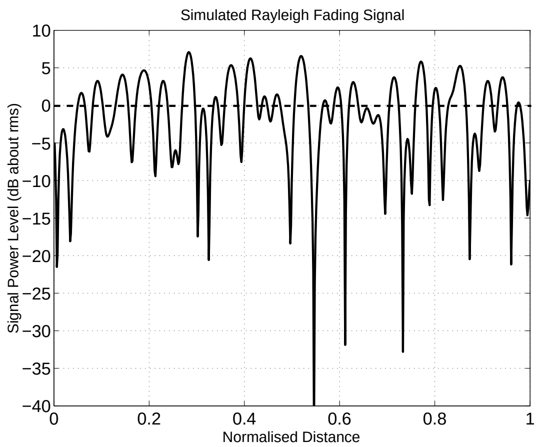

Fig. 2. Variation in signal power (dB) in a Rayleigh fading environment with distance from given, arbitrary, location.

Let the power threshold be chosen to be 0dB, for example, as shown by the dashed line in Fig. 2. It can be seen that a link would exist between two nodes for a significant amount of the time, however, the links would not necessarily last very long as the nodes move through the peaks and troughs of the Rayleigh fading environment. Thus, the *link duration* metric would not necessarily be a suitable indicator of communication link performance. We propose a new metric, the *link ratio* which is simply the ratio, given a suitable length of time, of the amount of time that a communication link exists between a pair of nodes, compared with the amount of time that the link is broken. We will see in Section V that the link ratio is, indeed, a more suitable metric for the Rayleigh fading environment that the link duration.

V. Results

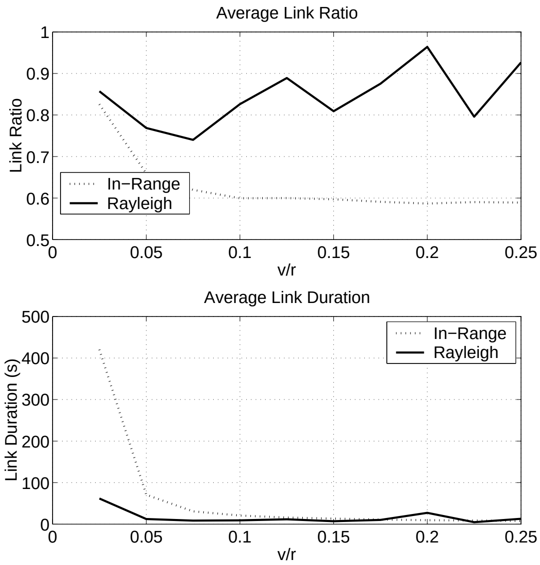

Fig. 3. Comparison of Link Duration and Link Ratio mobility metrics for the Rayleigh fading and "in-range" channel models for 2000 trials of 500 movements each. Movement is restricted to a circle of radius $r/2$ for the Rayleigh fading model and circle of radius r.

A. Simulation Parameters

We simulated the movements of two nodes within channel environments using, respectively, the Rayleigh fading and the in-range channel models. To try to make the result comparisons as meaningful as possible, the following system parameters were chosen.

For the in-range system, the two nodes were restricted to movement on a circle of radius r. A communication link was assumed to exist as long as the two nodes were, at most, a distance r from each other. No other impediments to the communication link were considered.

The system required to simulate a Rayleigh fading environment was slightly more complicated. Again, the movement of the nodes was restricted to being within a circle, this time with radius $r/2$, so that they could never be further than r apart. This radius was chosen so that no mixing of the two models was required. Then, the circle was partitioned into forty (40) sections, made up of four (4) concentric circles of radius $r/8$, $r/4$, $3r/8$ and $r/2$ with each of the resultant "rings" being divided into ten (10) partitions of equal angular range (i.e., 36° each). Each section was randomly assigned a power level according to a Rayleigh distribution generated from a pair of Gaussian random variables each of mean 0 and variance 1.

The assigning of power levels was done in this way to try to capture the fact that, in an actual wireless environment, the fading occurs in a gradual way rather than changing wildly from one position to the next, assuming the two positions in question are very close. That is, the Rayleigh power levels at two points which are close together are *correlated*.

B. Results Analysis

Simulation results for link duration and link ratio are shown for both the Rayleigh fading and in-range channel models in Figure 3. Each node was made to move according to the RWMM, moving a distance of v in each time step in a different, random, direction $\theta \in (0, 2\pi]$. The movements of the two nodes were i.i.d. Both the link duration and link ratio are plotted against the ratio of the node movement step-size, v to the in-range model link range, r. In general, it is assumed that the movement step size is much smaller than the communication link range, $v \ll r$. We have chosen a range of $v/r \in \{0.025, ..., 0.25\}$.

The results for the in-range model are similar to those in [7] and show a smooth, gradual decrease in both link duration and link ratio as v/r increases, as would be expected. However, for the Rayleigh fading channel model, the results are quite different. It can be seen that, for smaller values of v/r the Rayleigh fading model performs quite poorly compared with the in-range model. Further, while the results for both channel models are of a similar value for larger values of v/r, the link duration does not degrade gracefully for the Rayleigh fading model as it does for the in-range model.

If we now consider the results for the link ratio, it can be seen that the Rayleigh fading model performs much better than the in-range model. In this case there appears to be no correlation between link ratio and v/r for the Rayleigh fading model. So, for the signal power threshold chosen for the Rayleigh fading model the amount of time that the two nodes are actually connected is much greater for the Rayleigh fading model than for the in-range model. This important factor cannot be told, at all, from the link duration results.

Some applications may require longer communication links while others, presumably in the majority, will require a greater guarantee overall of a communication link existing. It is clear that the link ratio is a much more appropriate measure than the link duration for applications which fall into the latter category.

VI. Conclusions

We have considered a more realistic channel model for ad hoc networks, taking into account actual channel effects such as multipath. We have chosen a Rayleigh fading model to capture the effects of the multipath. A comparison of the performance of an ad hoc network operating in a Rayleigh fading channel with the more commonly used in-range channel model has shown that the *link duration* mobility metric is inadequate for describing the performance of the Rayleigh fading channel model for most applications of interest. We have introduced the *link ratio* as a more appropriate performance metric which provides a more intuitive indication of link availability (in a general sense) in ad hoc networks operating in a Rayleigh fading channel environment.

We will develop this work using a more sophisticated model for the Rayleigh fading channel. Different mobility models will be considered for the movement of the nodes to determine the efficacy of the link ratio as a mobility metric across a range of mobility models. We expect that the link ratio will be appropriate as a link performance measure across all mobility models for ad hoc networks operating in Rayleigh fading models. We hope to further develop this work by establishing rules for efficient communication protocols in such environments.

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