Optimizing Wireless Network Protocols Using Real-Time Predictive Propagation Modeling

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Abstract

A common feature of all wireless mobile data networks is the dynamic nature of the propagation environment. Our work introduces a new level of intelligence into wireless networks by creating a real-time prediction model that runs independently on each mobile node. Such a prediction can assist the routing protocol in making hand-offs or in choosing the best route to a destination, taking into account future RF propagation conditions.

1 Introduction

In areas where there is little or no communication infrastructure wireless mobile users may still be able to communicate through the formation of an *ad hoc network*. In such a network, each mobile node operates not only as a host but also as a router, forwarding packets for other mobile nodes in the network that may not be within direct wireless transmission range of each other. Each node participates in an ad hoc routing protocol that allows it to discover "multi-hop" paths through the network to any other node. Some examples of the possible uses of ad hoc networking include soldiers relaying information for situational awareness on the battlefield [1] and emergency disaster relief personnel coordinating efforts after a hurricane or earthquake.

One of the major challenges for multi-hop wireless ad hoc network routing protocols is rapid adaptation to topological change so that users of the ad hoc network experience minimal packet loss and delay when topological change occurs. However, if changes in the network topology can be *predicted*, the job of the routing protocol becomes easier as it can reroute network traffic before topological change causes an existing route to break, and thereby avoid packet loss or delays that would otherwise be incurred.

We have designed and implemented a real-time predictive propagation model that uses terrain information, GPS position information for each node, movement modeling and prediction, and propagation modeling to estimate the signal strength and loss factor between each pair of nodes in an ad hoc network. The predictive aspects of this model are used to estimate when routes that are presently working will break and this estimation is then passed to the routing protocol so that it can adapt to impending changes in the network before they cause packets to be lost or delayed.

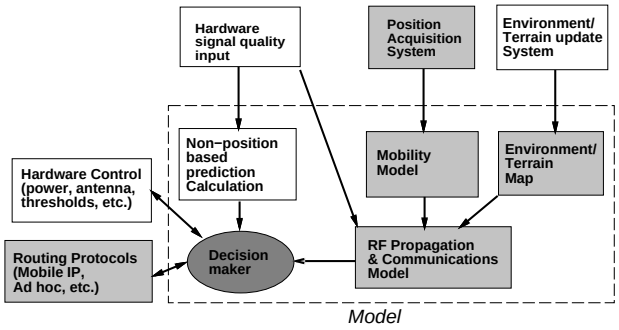

Figure 1 General structure of the prediction model and the model-protocol interaction

Our predictive model has been implemented and validated in a real ad hoc network testbed of 7 nodes [2] that was in regular use for 5 months from November 1998 through March 1999. Using this testbed we demonstrated that the use of real-time interaction between the routing protocols and a predictive model can improve the reliability and performance of multi-hop wireless ad hoc networks.

Section 2 provides a detailed description of the model's architecture. Section 3 has details of the implemented pieces of the architecture. Section 4 describes the testbed, while Section 5 describes the tests that we used to validate the accuracy of the model and demonstrate the usefulness of its interaction with ad hoc network routing protocols.

2 Prediction Model Design

The model uses node location information, knowledge of terrain characteristics, and an RF propagation calculation to compute a link quality metric between each pair of nodes in the network. The ad hoc network protocol uses these link quality metrics in route selection. Figure 1 describes the components of the prediction model in terms of inputs, outputs and prediction elements.

Inputs:

- *Position acquisition system:* This block provides location information of nodes to the prediction model. The position information may come from a GPS device, some feature inherent to the networking technology being used, or by other means specific to the scenario in which the

network is implemented. A node can pass along its movement information to other nodes either by explicit periodic notification or by appending this information to data packets.

- *Environment/Terrain update system:* In the case of a rapidly changing terrain, the prediction model may be kept up to date of such changes. If structural information of mobile nodes is available, terrain height can be inferred from the node location. Updated terrain information can also be obtained from radar or lidar images. This information can be provided to the prediction model as updates to a digital elevation map.
- *Hardware signal quality input:* If the wireless networking hardware provides some information about the signal strength, SNR, etc. at which data is being received from other nodes, this information can be used in multiple ways:
  - for a simple extrapolation based on recent values to predict a signal strength,
  - as a form of memory in case the network configuration is repeated in the future and
  - as validation and feedback to an RF Propagation Calculation.

Prediction Elements:

- *Non-position based prediction:* Even in the absence of position information, the presence of some form of hardware signal quality measurement allows prediction by extrapolation of these values.
- *Environment/Terrain Map:* The environment/terrain map kept by the model is needed to make a detailed RF Propagation calculation. It is updated by any information obtained about topographical changes.
- *Mobility Model:* The mobility model uses past and current information about node positions and velocities to predict probable future positions.
- *RF Propagation and Communications Model:* The RF Propagation and Communications Model computes link qualities between nodes based on node locations predicted by the mobility model, the information stored in the terrain map, feedback received about past predictions, and specifications about the wireless technology currently being used.
- *Decision Maker:* This block is the affecter of change in the network. It interacts with the network protocol to determine the links to be tracked, provides link quality information to the network layer and asserts physical control of the network hardware when appropriate.

Outputs:

- *Routing Protocols:* The prediction model makes estimates of link quality between different nodes. This information is used to guide the network protocol in either choosing routes or making hand-off decisions.
- *Hardware:* The prediction model can control the wireless network hardware directly by regulating power levels, setting signal thresholds and effecting any positive control on the antenna if possible. It may not always be possible for the prediction model to do this due to real-time constraints. An alternative is to provide the necessary information to the network layer which can then control the hardware on a packet by packet basis.

3 Implementation Details

At present the shaded blocks in Figure 1 have been implemented and tested. We used an implementation of the Dynamic Source Routing *ad hoc network* protocol to test our ideas. This protocol was designed and implemented by the Monarch Project at Carnegie Mellon. This section provides further detail about the operation of the DSR protocol, the interface between DSR and the prediction model, the mobility model, and the RF propagation model.

3.1 Dynamic Source Routing

The Dynamic Source Routing protocol (DSR) [3, 4, 5] works by discovering and using *source routes*. That is, the originator of a packet first learns the complete, ordered sequence of network hops necessary to reach the destination, and each packet sent carries this list of hops in its header. The key advantage of a source routing design is that intermediate nodes do not need to maintain up-to-date routing information in order to route the packets that they forward, since the packets themselves already contain all of the routing decisions. This fact, coupled with the *on-demand* nature of the protocol, eliminates the need for the periodic route advertisement and neighbor detection packets present in other protocols [6].

The DSR protocol is composed of two mechanisms: *Route Discovery* and *Route Maintenance*. Route Discovery is the mechanism by which a node **S** wishing to send a packet to a destination **D** obtains a source route to **D**. To perform a Route Discovery, the source node **S** broadcasts a ROUTE REQUEST packet that is flooded through the network in a controlled manner and is answered by a ROUTE REPLY packet from either the destination node or another node that knows a route to the destination. To reduce the cost of Route Discovery, each node maintains a cache of source routes it has learned or overheard, which it aggressively uses to limit the frequency and propagation of ROUTE REQUESTS.

When sending or forwarding a packet to some destination **D**, Route Maintenance is used to detect if the network topology has changed such that the route used by this packet has broken. When a route breaks, the detecting node returns a ROUTE ERROR packet to the original sender **S** of the packet. The sender **S** can then attempt to use any other route to **D** that is already in its route cache, or can invoke Route Discovery again to find a new route.

3.2 Model/Protocol Interface

A routing socket interface is used for communication between the DSR networking layer and the prediction model, which runs as a user program. The prediction model provides the network layer with a "quality metric" for a multi-hop route. In

an ad hoc network with a sizeable number of nodes, keeping track of each end-to-end path can be computationally intensive. The prediction model should only keep track of the routes of interest to the network layer. Choosing a limited set of routes to track requires input from the network layer. The network layer may request the prediction model to keep track of source/destination pairs or a specified hop-by-hop route.

To this end an interface has been tested to allow the network protocol layer to send requests to the prediction model, but in the experiments described below, the prediction model kept track of all possible links so that we could collect more data points for analysis.

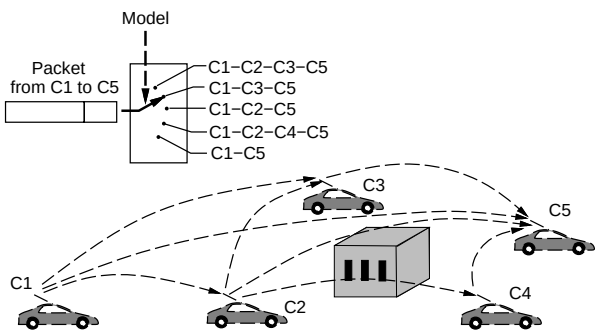

Figure 2 Model and Routing Protocol Interaction. The model provides route quality metrics to the protocols to aid in selecting the best route from the route cache.

In the current implementation the prediction model provides the network protocol layer with a "quality metric" for pairs of nodes. The ad hoc protocol layer combines these quality metrics to compute a single metric for each multi-hop route so that it can choose the "best" route (Figure 2).

3.3 Mobility Model

In the current implementation, the location of each node is tracked by a Global Positioning System device located on each node. These devices are also capable of receiving differential GPS updates which can be sent over the wireless network. Without differential GPS, a node will still provide position information but with a degraded accuracy. Each node advertises its GPS information (location, speed and heading) in the packets it originates. These packets may use multiple hops to reach their final destination. Any other node overhearing a packet in transit can record the GPS information of the source. This information is collected by the network layer and provided to the prediction model. The mobility model on each node keeps track of the location history of all nodes. Using this information, it can perform path prediction to approximate the location of a node some time into the immediate future. In the case that the node is following a cyclic pattern, this is recognized and information from previous cycles is used to improve current prediction. The best prediction of future location of nodes is provided to the propagation model to make signal connectivity predictions. These predictions take the form of "link quality metrics" that are sent to the network layer.

3.4 RF Propagation Model

We use a site-specific three-dimensional propagation model. This model can be called "$N + 2$ ray + diffraction" model since it takes into account a direct ray, a ground-reflected ray, and rays reflected off N objects, as well as diffraction from these objects. Objects considered in the model are arbitrarily oriented buildings of simple shape. A vehicle can also be described as an object whose location is known from the GPS information contained in the packets that it transmits. The model takes as an input the locations and heights of the transmitter, the receiver, and the buildings. Multipath is computed deterministically, assuming interference of the direct ray and single specular reflections from the ground and buildings. The geometrical optics approximation that allows us to use ray-tracing is valid because typical obstacle size in our experiment is much larger than the wavelength.

The power received is computed by the following expression:

$$P_r = P_t G_t G_r \Gamma_c \frac{\lambda^2}{(4\pi)^2} \cdot \left| \frac{\Gamma_d e^{-j\frac{2\pi}{\lambda}d}}{d} + \sum_{l=2}^{N+2} \frac{\Gamma_{d_l} \Gamma_l e^{-j\frac{2\pi}{\lambda}d_l}}{d_l} \right|^2 \quad (1)$$

where P_t is the transmitter power, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, Γ_c is the loss factor for antenna leads, λ is the wavelength, Γ_d is the coefficient of diffraction losses along the direct path, d is the direct path length, Γ_{d_l} is the coefficient of diffraction losses for the l-th reflected ray, Γ_l is the reflection coefficient of the l-th reflecting object, and d_l is the path length of the l-th reflected ray. In the current version of the model, Γ_{d_l} is equal to either 1 or 0, depending on whether the ray reflected from the l-th object is blocked or not. The ground reflection is included into the summation above as the first term with $l = 2$.

Diffraction effects become important when the line of sight is obstructed or a building is present in the first Fresnel zone. The equivalent diffraction coefficient Γ_d is computed using a method similar to that described in [7] generalized to our geometry.

An exhaustive search for all sources of multipath can be computationally expensive. To make this computation as efficient as possible, we limit our search to the ellipsoid with foci colocated at the transmitter and receiver, that represents the maximum distance impacting our problem [8]. The size of this ellipsoid can be determined by the following factors:

- the distance at which the power drops below a certain level
- the maximum differential path delay corresponding to the chip rate of the radio for direct sequence spread spectrum

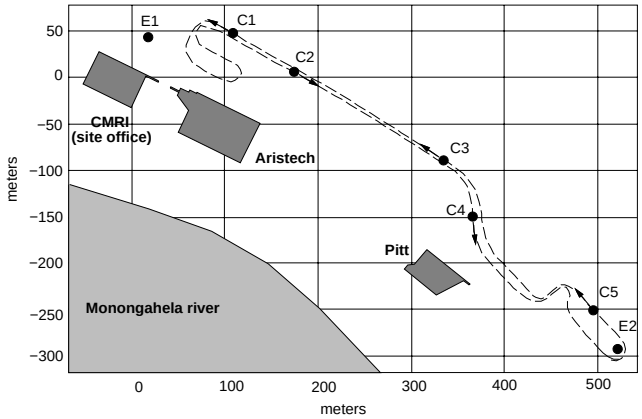

Figure 3 Map of the Ad Hoc Network Testbed. End nodes **E1**, **E2** remained stationary as cars **C1-C5** followed a cyclical path (dashed line) with an average speed of 20 mph.

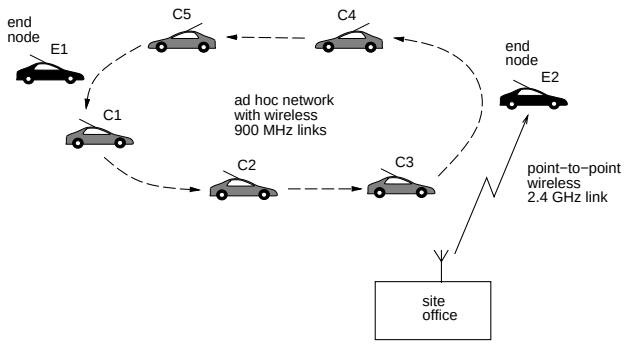

Figure 4 Network Diagram. The site office also provided connectivity to the campus network and the Internet.

- the maximum differential path delay corresponding to the channel hopping rate for frequency hopping spread spectrum

The Doppler shift resulting from the movement of vehicles was not included in the model.

Theoretically our model allows computation of propagation conditions for an arbitrary terrain represented as a digital elevation map. Depending on the elevation profile, diffraction and multipath calculations can become quite challenging. In our experiment the testbed site was relatively flat and we used flat ground terrain in our model.

4 Testbed Description

An experimental testbed was constructed for evaluating the performance of the ad hoc network protocol and to test the ideas described in this paper. An area of approximately 700 m by 300 m was chosen on the map shown in Figure 3. Five mobile nodes and two stationary end nodes were used in different scenarios. A stationary GPS receiver was set up as a reference base-station for differential corrections at the site office which provided an accuracy on the order of a few centimeters. The network architecture of the system is shown in Figure 4.

Each mobile node (car) was equipped with an IBM Thinkpad 560X notebook, a WaveLAN 900 MHz PCMCIA card, and a Trimble 7400 series GPS receiver. The equipment and power supply were housed in a rack on the front passenger seat. The antennas for the WaveLAN card and the GPS receiver were mounted separately on the top of the car. The Thinkpad notebook ran FreeBSD 2.2.7 with DSR (see section 3.1) implemented by the Carnegie Mellon Monarch Project.

The WaveLAN radio (External Antenna Module) is a Direct Sequence Spread Spectrum card (DSSS) with a power output of approximately 250 mW (measured) and a raw data rate of 2.0 Mbps [9].

The chip rate of the WaveLAN card is 11 MHz, which means that the reflections arriving with a delay of 91 ns beyond the direct path are off by one chip. This limits the area of search for significant sources of reflections to the ellipsoid defined by the differential time delay of 91 ns (path difference 27.3 m), as described in Section 3.4. Experimentally, however, a differential delay of about 30 ns or less was needed to significantly impact the received signal strength. This reduces the ellipsoid to one representing a path difference of 9 m.

The average speed of the cars in the experiments was 20 mph (9.3 m/s). This corresponds to a maximum Doppler shift of ± 57 Hz at 915 MHz. This shift had no noticeable impact on the performance of the WaveLAN radios. Additional information about the testbed can be found in [2].

5 Experimental Results

5.1 Model Validation

In the typical operation of the testbed, five vehicles (**C1-C5**) followed each other on the loop course shown in Figure 3. Two stationary nodes, **E1** and **E2**, were positioned at the far ends of the course. Figure 5 shows the experimentally measured power received by node **C1** from node **C2** and the power level predicted by the model. The experimental values were obtained from the WaveLAN hardware. The peaks in the signal strength occur when the cars periodically pass each other on the road, moving in opposite directions. Similarly, the minimum signal strength occurs when the cars are farthest apart. This typically occurs when the cars are traveling in the same direction on the middle portion of the loop (Figure 3).

The large-scale signal level predicted by the propagation model is in good agreement with the experimental data (Figure 5). However, there are significant differences in the fine structure between the model and the measurements. The fine structure in the predicted signal strength primarily results from interference between the direct and ground-reflected rays. As mentioned previously, only reflections with a differential path delay in excess of 30 ns are included in the model. This eliminates almost all of the building reflections at our test site. In contrast, the experimental curve generally has more fluctuations than the theoretical curve, suggesting the presence of multi-path components not included in the model. To explore this possibility, swept frequency channel

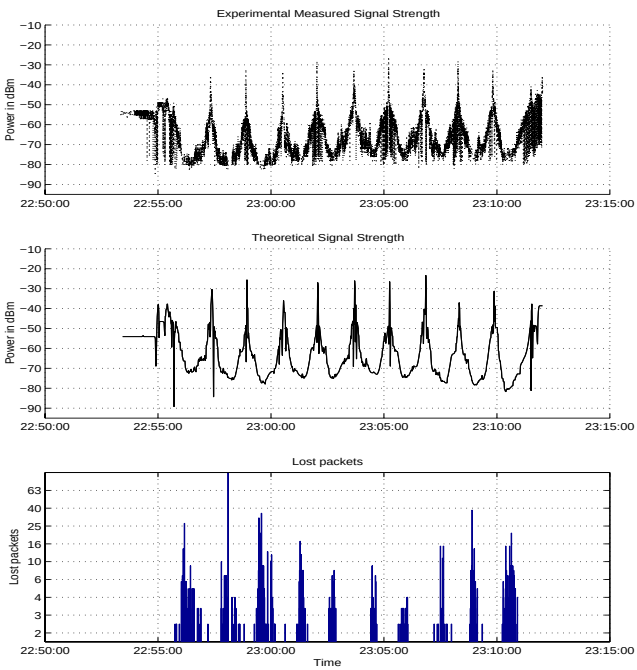

Figure 5 Experimentally measured signal strength, theoretically predicted signal strength and count of lost packets for a pair of two mobile nodes in the wireless ad hoc network.

measurements were made from the parking lot in front of the Aristech building (Figure 3) using two antennas connected to a network analyzer. This location was selected since it is where the paths of the cars come closest to a building. Delay spread curves obtained by taking the Fourier transform of the swept frequency measurements confirmed a relatively clean response with building reflections comfortably outside the 30 ns window. Consequently the cause of the rapid fluctuations in the measured signal strength is unclear. Other possible sources of reflections include the trunks and hoods of the cars themselves [10].

It is important to note, however, that packet losses were generally associated with the large-scale minima in the signal strength rather than the rapid fluctuations (bottom plot in Figure 5). Thus the model generally gave good results in our tests, in spite of the remaining questions related to the accuracy of modeling multi-path propagation effects.

5.2 Validation of Model - Protocol Interaction

Figure 6 shows the experimental setup used to verify the interaction of the prediction model with the network protocol. The simplified test involved three nodes. Nodes **1** and **3** were stationary. Node **2** was mobile and equipped with the prediction model running in real time. Figure 6 shows the trajectory of node **2** with respect to nodes **1** and **3**. Node **2** was in constant communication with node **3**. Initially it started out close to node **3**. It then moved closer to node **1**, passed it and then drove into an area sheltered from communication with node **3** before finally returning to its original position.

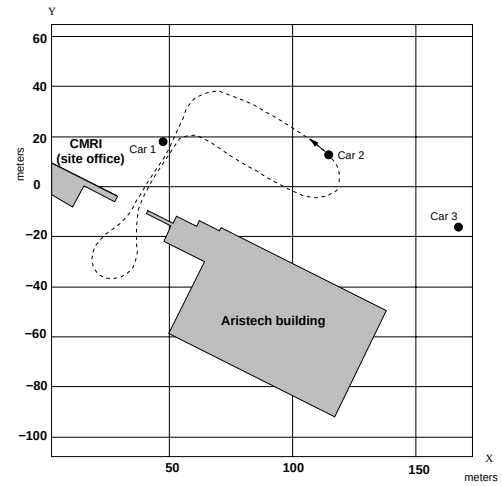

Figure 6 Trajectory of node 2 and locations of nodes 1 and 3

In this test, instead of the model defined by Equation 1, a simplified propagation model was used. Depending on the distance d between the nodes, the power received was determined by either a free-space or an approximate 2-ray ground reflection model as follows [11]:

$$P_r = P_t G_t G_r \Gamma_c \Gamma_d \cdot \begin{cases} \frac{\lambda^2}{(4\pi d)^2} & \text{if } d < \frac{4\pi h_t h_r}{\lambda} \\ \frac{h_t^2 h_r^2}{d^4} & \text{if } d > \frac{4\pi h_t h_r}{\lambda} \end{cases} \quad (2)$$

where h_t and h_r are the heights of the transmitter and receiver respectively. In the test we used $\Gamma_d = 1$ when the line of sight was clear and $\Gamma_d = 0.3$ whenever the model determined that the line of sight was blocked. This value was empirically obtained by signal strength measurements.

Figure 7 shows the theoretically predicted power of the signal received by node **2** from nodes **1** and **3** and the link quality factor for the two routes. The first route is a one-hop route *node* **2** $\leftrightarrow$ *node* **3**, and the second one is a two-hop route *node* **2** $\leftrightarrow$ *node* **1** $\leftrightarrow$ *node* **3**. The link quality factor L for the route consisting of M hops was defined as

$$L = \prod_{s=0}^{s=M} \left(1 - Q((P_{pred_s} - P_{th})/\sigma)\right) \quad (3)$$

where $Q(x)$ is a standard Q-function, P_{pred_s} is the theoretically predicted power received by the s-th node from the $(s-1)$-th node, P_{th} is the receiving threshold and σ is the variance of signal variations (a Gaussian model is assumed). In other words, the link quality factor is the product of probabilities computed for each hop that at the certain time moment in the future the signal level will be above the receiving threshold. We used a simple linear position extrapolation based on the current GPS position and velocity information to estimate the positions of all nodes 1 second in the future. These positions, along with Equation 2, were used to obtain P_{pred} . We used $\sigma = 6$ dB and $P_{th} = -60$ dBm.

The prediction model periodically updates the DSR protocol with the link quality factor values for each route. The route

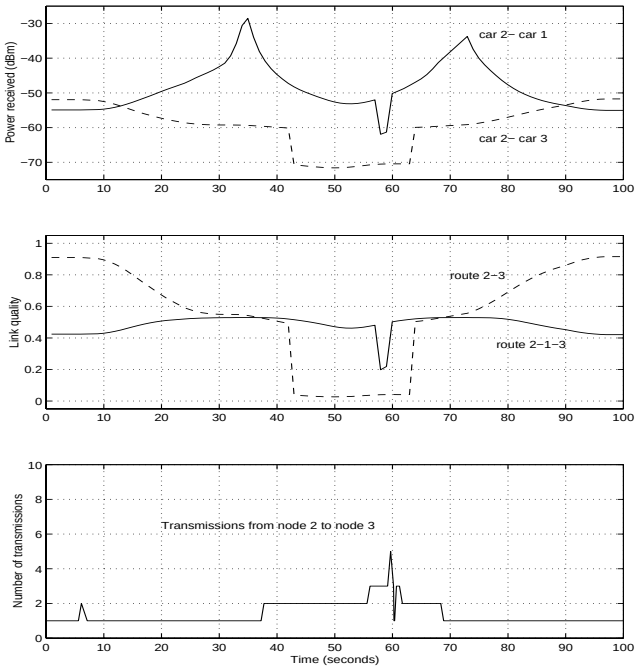

Figure 7 Theoretically predicted signal strength, the link quality factor and experimentally measured transmissions per packet

with the larger link quality factor is chosen by the protocol as the source route on a packet-per-packet basis.

The bottom plot in Figure 7 shows the number of transmissions on the air for a packet sent from node **2** to node **3**. The number of transmissions can include retransmissions due to packet loss (which has a bursty nature on the graph). In steady state (in the absence of losses), the number of transmissions reflects the number of hops taken to get to node **3**. The number of transmissions starts out at 1 since the packets are being sent directly from node **2** to node **3**. As advised by the predicted link quality (Figure 7) from the model, the DSR protocol starts using the two hop route available to it, then switches back to a one hop route when the line-of-sight to node **3** is restored.

This experiment demonstrates the ability of the prediction model to influence the network protocol. It was performed to verify the interaction between the model and the protocol. The advantage to using the prediction model is that routes do not have to fail before a new one is chosen.

6 Summary and Conclusions

We have described how a predictive model can interact with packet protocols in real time to improve performance and reliability. The basic concepts were demonstrated using an ad hoc network testbed constructed at Carnegie Mellon University. The demonstration showed the successful interaction between a custom predictive model and the Dynamic Source Routing protocol.

Failures in a wireless data network take the form of increased delays and the inability to satisfy quality-of-service guarantees. The advantage of a predictive model is in preventing failures instead of repairing them.

7 Acknowledgement

The CMU ad hoc network testbed was the product of the work of many other people, but special recognition is due to David A. Maltz, Jorjeta Jetcheva, Qifa Ke, and Ben Bennington. We are also grateful for the efforts of the other members of the research team, including David B. Johnson, Satish Shetty, Michael Lohmiller, Yih-Chun Hu, Sam Weiler, and Jon Schlegel.

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