A New Multipath Routing Protocol for Ad Hoc Wireless Networks

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Abstract— **An ad-hoc wireless network is a collection of mobile nodes that form a network which does not require any centralized administration for its operation. For certain types of applications, it is important to minimize end-to-end packet delays, while we may be willing to trade-off some extra bandwidth by using multiple paths in the network. This becomes especially useful in wireless networks, given that packet error rates are higher than those experienced in traditional wired networks.**

In this paper, we analyze the impact of using multiple paths and the effects of various parameters on the delay-bandwidth tradeoff. It is seen that in most cases, sending packets simultaneously over 2 to 3 paths provides the optimal solution. A new routing protocol, Dynamic Multipath Source Routing (DMSR) is proposed by extending the existing Dynamic Source Routing (DSR) protocol to send packets simultaneously over multiple paths. Performance of DMSR and DSR are compared using the ns-2 network simulator for various network loads, and results show a good performance gain at low network loads.

I. Introduction

Wireless networks are getting increasingly popular over the past few years. In particular, ad-hoc wireless networks have become more and more relevant in certain situations. They are very quickly deployable making them useful for a whole range of applications like internet connectivity in buildings, connecting computers at a conference and video-conferencing between people in different rooms. They are also useful for wireless sensor networks used to monitor atmospheric parameters like pressure and temperature because in such situations infrastructure networks become very costly given that nodes are distributed in a very sparse manner. Their applications also extend to military communications and providing emergency services in case of fire or flood.

In ad-hoc networks with several nodes, there often exist multiple paths between any two mobile nodes. In fact, if only one path existed, the routing protocols would be uninteresting and much simpler. The various paths have different bandwidth and delay characteristics, and it is often important to choose the right path to obtain optimum performance.

Certain interactive applications, like telnet or voice communication, place stringent demands on the end-to-end delay requirements. These applications may be willing to utilize extra bandwidth to achieve reduced network delays. Due to the nature of the wireless medium, packets suffer relatively high error rates during transmission, and multiple transmissions may be required before the packet reaches the destination successfully. This setup provides a good platform to exploit the bandwidth-delay tradeoff by sending multiple copies of a packet in order to reduce the expected end-to-end delay. Existing routing protocols typically transmit the data over only a single path in order to keep the bandwidth usage to a minimum. Our work extends one of these routing protocols[12] to use multiple paths from a source to a destination node.

The remainder of this paper is organized as follows: Related work is described in section II. The problem statement and analytical framework are presented in section III, and the theoretical analysis and DMSR protocol are presented in section IV. Simulation results are presented in section V, followed by conclusions in section VI and future work in section VII.

II. Background

As we are planning to use multiple paths in the network to reduce delays, the analysis requires understanding of loss models for wireless networks. Losses in wireless networks have been extensively studied over the years. Eckhardt et al. [8] (1996) and Anderson et al. [2] (1995) have given extensive descriptions of the different sources of wireless errors and studied the effects of variations of some of these parameters.

Nguyen et al. [19] (1996) have used a trace-based approach for modeling wireless channel behavior. Using the AT&T WaveLAN, their results indicate average packet error rate of 2 to 3 percent. Furthermore, they derive an improved two-state model to characterize these errors based on the distribution of the error and error-free length of packet streams. Their model contains a combination of two exponential curve segments for the error length distribution and a combination of two pareto and one exponential curve segments for the error-free length. Also, Konrad et al. [13] (2001) propose a Markov based channel model for wireless networks. Their results are based on traces collected over GSM digital wireless cellular network and their key observation is that time-varying effects on wireless channels result in non-stationary wireless traces. So, they present an algorithm that divides traces into stationary components and provides an analytical channel model that represents error characteristics more accurately than traditional approaches.

With regards to using multiple paths for packet transmission, some old relevant work includes Maxemchuk's work

on dispersity routing [17], [16] (1975) and Rabin's work on information dispersal [23] (1989). More recently, Apostolopoulos [3] (2001), [4] (2002) looked at reliable video communication over lossy packet networks using multiple state encoding and path diversity. His work involves encoding a video into multiple streams and sending different streams over different paths to see an average path behavior and achieve better video performance. Also, Liang et al. [15], [14] (2001) have looked at multi-stream voice communication over the internet using path diversity. Their work involves an experimental setup in which they send packets over two paths using a relay server. They also simulate sending two CBR voice streams via two paths using the *ns* simulator.

With regards to current ad-hoc wireless routing protocols, a review has been performed by Royer and Toh[24]. The authors have characterized these protocols into two types - *table-driven* and *source-initiated on-demand*. The table-driven routing protocols require each node to store one or more tables containing routing information at each node. They try to maintain consistent up-to-date information from every node to every other node in the network. Table-driven routing protocols include Destination-Sequenced Distance Vector Routing(DSDV)[22], Clustered Gateway Switch Routing (CGSR)[6] and the Wireless Routing Protocol (WRP)[18]. In contrast, source-initiated on-demand protocols create routes only when desired by the source node. Routing protocols of this type include Ad Hoc On-Demand Distance Vector Routing (AODV)[21], Dynamic Source Routing (DSR)[12], Temporally Ordered Routing Algorithm (TORA)[20], Associativity-Based Routing (ABR)[25] and Signal Stability Routing (SSR)[7].

III. Problem Statement and Analytical Framework

A. Problem Statement

As discussed in section II, prior work has looked at sending different streams over different paths or sending redundant streams over two paths. But, none of the prior work has looked at the impact of using extra paths on bandwidth, the tradeoff between reduction in delay and increase in bandwidth, the optimal number of redundant paths, and application to routing protocols. Also, according to our knowledge, there has been no prior work dealing with these issues in terms of a reliable end-to-end transport protocol (like TCP), where sender timeouts could be very expensive.

We first propose a delay-bandwidth metric for evaluating the amount of extra bandwidth that may be used to achieve a certain reduction in delay. Then we identify the important parameters and study the effect of their variations on delay, bandwidth and the delay-bandwidth metric. Based on this analysis we also determine the optimal number of redundant paths. Next, we propose the Dynamic Multipath Source Routing (DMSR) protocol which is an extension of the existing Dynamic Source Routing (DSR) protocol to send packets simultaneously over multiple paths. Finally, we perform simulations to validate the results.

B. Analytical Framework

Here we present a formal framework for analysis of the delay-bandwidth tradeoff for the multipath problem. First we choose a simple probability loss model for the wireless channels. We mentioned two trace-based models for wireless channels in section II, but they are too complicated and have very specific parameters as they are based on actual traces making them inappropriate for such an analysis. Also, actual distribution of losses are non-uniform and they include burst losses and outages for which there is very strong correlation between the probabilities of loss of consecutive packets. So, if we consider a more accurate loss model, and apply the same model to all links, then the probability of bursts or outages will be same over all links, while the delay gain when there is a burst on the default path will be much more than the loss of bandwidth when there is burst on an alternate path. Thus, the gain of using multiple paths will only be greater and a simple probability loss model will give a lower bound on the gain obtained by using multiple paths.

Also, when we use multiple paths, we consider that they are disjoint and independent of each other to simplify the analysis. In a more practical scenario, it is possible for two paths to have some links in common. In such cases, these paths can be decomposed into the common parts and disjoint parts, and then the current analysis could be extended to such scenarios.

Now let us formalize the network model in terms of delay and bandwidth of the links and the notation used. Consider end-to-end transmission from source S to destination D. Let us look at a topology consisting of m end-to-end paths from S to D. For simplicity, let us assume that all paths go over n hops. Let d_{kl} denote the expected delay of the link over the l^{th} hop of the k^{th} path, and let b_{kl} denote the bandwidth of the link. Then $\sum_{i=1}^{n} d_{ki}$ is the expected end-to-end delay over path k when there are no losses, which we denote by d_k. Also, if we consider transmission of one packet over a link of bandwidth b as equal to a bandwidth usage of b, then $\sum_{i=1}^{n} b_{ki}$ is the total bandwidth used for one end-to-end transmission over path k, which we denote by b_k. The paths are numbered in order of increasing expected end-to-end delay, i.e. $d_1 < d_2 < .. < d_m$. So, the default routing path choosing minimum delay will have end-to-end delay of d_1 and bandwidth usage of b_1. For simplicity, we assume that all other paths also use an end-to-end bandwidth of b_1, i.e. the bandwidth of the end-to-end path with minimum expected delay. This can be justified because other paths have delays higher than d_1 and hence would most probably be using either lower bandwidths if extra delay is due to difference in transmission time or nearly equal bandwidths if extra delay is due to queuing delays. So, by choosing bandwidths of these paths to be equal to b_1 we will be giving an over-estimate of bandwidth used for the multipath case and hence giving only a lower bound on the delay-bandwidth

gain.

In order to quantify the reduction in delay obtained by utilizing extra bandwidth, we propose to use a metric called delay-bandwidth product, which is calculated as

$$DBP = expected\ endtoend\ delay \times total\ BW$$

where,

$$total\ BW = \sum_{all\ links} E[\#\ transmissions_{link}] \times BW_{link}$$

This metric effectively captures both expected end-to-end delay and the expected total bandwidth used for successful transmission of each packet.

IV. Analysis and DMSR Protocol

A. Analysis

Now, we present an analysis of the effect of using multiple paths on the delay-bandwidth tradeoff. Apart from the number of paths to be used for transmission, other important parameters include loss probability over each wireless link, end-to-end timeout before retransmissions, average number of hops over each path and additional delay of alternate path(s) as compared to the default path.

Let us first analyze the simpler case of two paths using n hops each and then extend the analysis to multiple paths. As described in section III, let the expected delay of the default path be d_1 and let the expected delay of path 2 be $d_2 = k_2 d1$, where $k_2 \geq 1$. Let p denote the loss probability over a wireless link and T denote the ratio of the end-to-end timeout to d_1. Let p_{s1} denote the probability of a packet transmitted at the source to be successfully reaching the destination when using only one end-to-end path. Then, $p_{s1} = (1-p)^n$. Also, let $p_{e1} = 1 - p_{s1}$ be the probability of a packet getting dropped when using only one end-to-end path. Then it can be shown that for the default path, the expected delay,

$$E[d] = d_1 \left[1 + \left(\frac{1-p_{s1}}{p_{s1}}\right) T\right]$$

the expected bandwidth used,

$$E[b] = \frac{b_1}{p_{s1}}$$

and the delay-bandwidth product,

$$DBP = E[d] \times E[b]$$

When we use two paths simultaneously, let p_{s1} and p_{e1} be defined as before and let p_s be the probability of a transmitted packet to be successfully reaching the destination when using two paths. Then $p_s = 1 - p_{e1}^2$. Also, it can be shown that the expected delay,

$$E[d] = \frac{d_1}{p_s}\left[p_{s1} + p_{s1}(1-p_{s1})k_2 + (1-p_s)T\right]$$

and the expected bandwidth used,

$$E[b] = \frac{2b_1}{p_s}$$

Now let us consider the case of m paths using n hops each. The expected delay and bandwidth for the default case remains unchanged. Let p_{s1} and p_{e1} be defined as before and let p_s be the probability of the packet successfully reaching the destination when using m paths. Then, $p_s = 1 - p_{e1}^m$. The expected delay,

$$E[d] = \frac{d_1}{p_s}\big[p_{s1} + p_{s1}(1-p_{s1})k_2 + p_{s1}(1-p_{s1})^2 k_3 + ...+$$

$$p_{s1}(1-p_{s1})^{m-1}k_m + (1-P_s)T\big]$$

and the expected bandwidth used,

$$E[b] = \frac{mb_1}{p_s}$$

In order to effectively study the effect of variation of the various parameters, we assume that the delays of all paths other than the first path are equal, i.e. $k_2 = k_3 = ... = k_m, k_2 \geq 1$. Then the expression for expected delay reduces to

Before we discuss the effects of variation of various parameters, note that in all figures, expected delay refers to the ratio of the expected end-to-end delay for successful transmission using multiple paths to that using the default path. Similarly, expected bandwidth refers to the ratio of expected bandwidth used for successful end-to-end transmission using multiple paths to that used by the default path. In both cases, values less than 1 indicate a better performance of multiple paths.

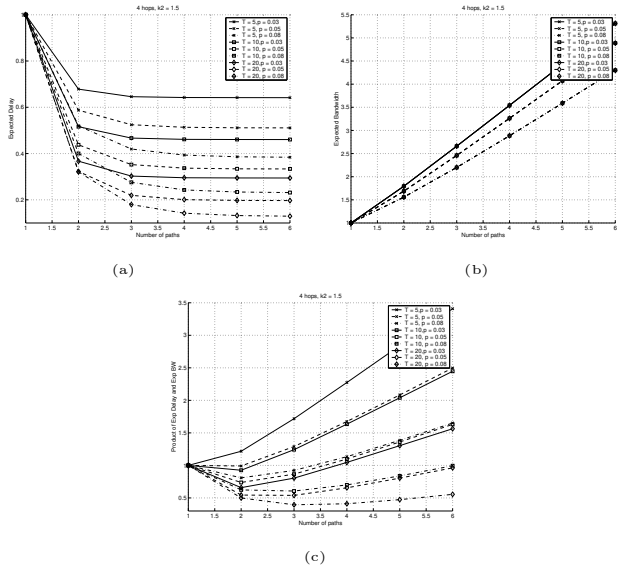


Fig. 1. Effect of variation of the number of paths on (a)expected delay, (b)expected bandwidth usage, (c)DBP

We first look at the effect of variation of the number of paths on the delay-bandwidth tradeoff. For this purpose

we select the number of hops, $n = 4$ and $k_2 = 1.5$. As defined before, k_2 is the ratio of the expected delays of all paths other than the default path to the expected delay of the default path. As seen in figure 1a, there is a significant gain when we increase the number of paths from 1 to 2 or 3, but the gain saturates beyond that. Also, the gain is higher for higher timeouts and higher probabilities of losses. Figure 1b illustrates that although the bandwidth increases almost linearly with increase in the number of paths, the slope is less than 1, which is important because if we use (say) 6 paths then the expected bandwidth is only 4 to 5 times that required for the default path depending on other parameters. This is because as the number of paths used increases, the probability of a successful end-to-end transmission increases which in turn reduces the expected number of retransmissions and bandwidth usage. This can also be seen from the fact that expected bandwidth loss is lower when there is a higher probability of losses. The variation of the delay-bandwidth product with number of paths is shown in figure 1c. It is important to note that for most values of T and p, the delay-bandwidth product is less than 1 when the number of paths used is 2 or 3. This observation coupled with the nature of the graph indicates that it is optimal to use 2 or 3 redundant paths to achieve results better than using only the default path.

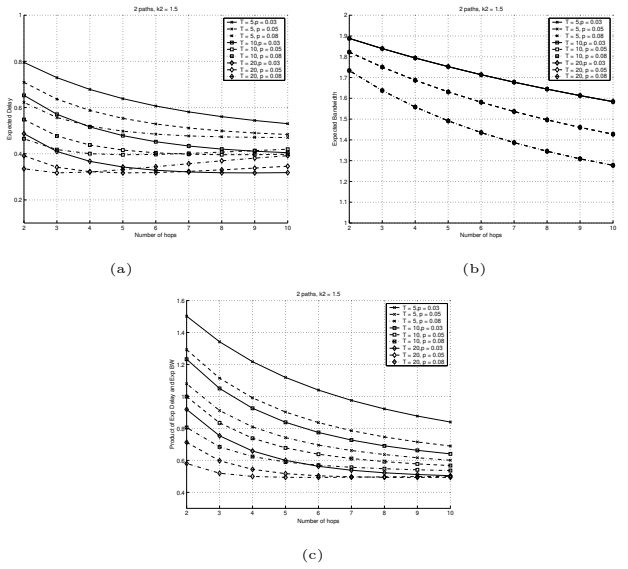


Fig. 2. Effect of variation of the number of hops in a path on (a)expected delay, (b)expected bandwidth usage, (c)DBP

Next we look at the effect of variation of the number of hops, n on the delay-bandwidth tradeoff. For this purpose, we select the number of paths, $m = 2$ and $k_2 = 1.5$. As seen in figures 2a and 2b, there is a gain in terms of both reduction of expected delay and expected additional bandwidth used as the number of hops increases. This can be intuitively explained by the fact that although the probability of successful end-to-end transmission decreases for both single-path and multi-path cases when the number of hops increases, the probability decreases more rapidly for the single-path case. In turn, this requires lesser number of timeouts and retransmissions for the multipath case, giving a reduction in both delay and additional bandwidth used. Also, results get better when either the timeout value or the probability of loss over a link increases. Figure 2c shows the variation of the delay-bandwidth product with number of hops, and although 2 to 3 paths gives an optimal solution for a given number of hops(Fig 1), it can be seen that the gain in terms of the delay-bandwidth product is greater for more number of hops.

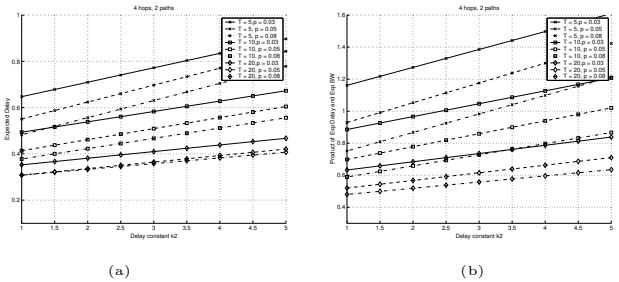


Fig. 3. Effect of variation of the additional delay of alternate paths on (a)expected delay, (b)DBP

Lastly, we look at the effect of variation of the additional delay incurred over the alternate paths on the delay-bandwidth tradeoff. We study this by varying the constant k_2 described above. We select the number of paths, $m = 2$ and the number of hops, $n = 4$. As can be seen from figure 3, there is an increase in the expected delay and the delay-bandwidth product with increase in the delay of the alternate path(s). But, when we vary k_2 from 1.5 to 3, all curves show an increase in the delay-bandwidth product of less than 0.2, and still most values of the delay-bandwidth product remain less than 1, indicating that even if the delay of the alternate path is upto 3 times that of the default path, there is potential for gain in terms of the delay-bandwidth trade-off.

Based on the variation in delay-bandwidth product with number of paths, and sensitivity of the delay-bandwidth product to other parameters, it seems that 2 to 3 redundant paths will almost always give an optimal solution.

B. Dynamic Multipath Source Routing (DMSR)

Now we use the above analysis to propose a new ad-hoc wireless routing protocol that sends packets across multiple paths in the network. In section II, we saw some existing ad-hoc routing protocols. Here, we propose a modification to the Dynamic Source Routing (DSR) protocol to take advantage of multiple paths. DSR is an on-demand routing protocol, and as such has lower routing overhead than table-based schemes since route discovery is only initiated when a required route is not known. Source routing means that the complete route selection is done at the source node, and no per-hop processing is needed at the intermediate nodes.

DSR nodes contain a cache of source routes that the node is aware of. The route discovery mechanism in DSR

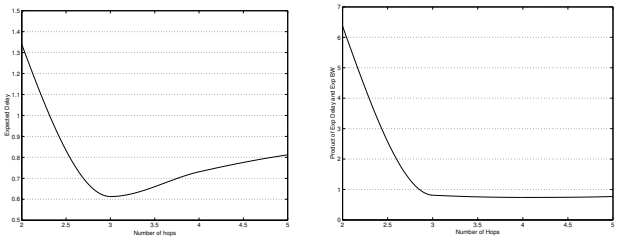
already allows the nodes to have route information for multiple paths between nodes. In contrast, other protocols like AODV would require modifications to the route discovery mechanism to take advantage of multiple paths. Our new protocol, Dynamic Multipath Source Routing (DMSR) is a modification to the DSR protocol. Route discovery and maintenance are achieved in the same fashion as before. Since we are still using source routing, only the source nodes need to have information about the multiple paths that can be followed. For m-path DMSR, copies of the packet are made at the source node, and sent along the m best (shortest) paths that the node has in it's route cache. The subsequent nodes in the path do not need to do anything special for DMSR, and simply forward the packet to the next node according to the source route in the packet header.

V. Simulations

The results obtained from the analysis were further validated by simulations using the ns-2 simulator[1] with the CMU/Monarch wireless extensions. This provides an implementation of the DSR protocol, which we modified to implement the 2-path DMSR protocol. The intent of the simulations was to study the delay-bandwidth tradeoff for end-to-end error-recovery protocols. For this purpose, we used TCP as a reliable end-to-end protocol, that would perform the necessary retransmissions when a packet is lost in the network. Since our analysis showed that the optimum solution uses 2 or 3 paths, we have implemented DMSR with 2 paths for the simulations. We present some results here that show the effect of the number of hops on the delay and delay-bandwidth product for 2 path DMSR as compared to single path DSR. We also look at how variation in the network load affects these metrics.

There are a number of parameters that had to be chosen in the simulation setup. Apart from TCP having its own sender timeouts, the 802.11 MAC layer specification provides for link-layer retransmissions in case of losses and has its own timeouts and maximum retry limits. This make the choice of these parameters very important, otherwise the link layer retransmissions can interfere with the end-to-end error recovery mechanism [9], [10]. The timeout values for the retransmission, and the maximum number of retransmissions are not defined strictly. Appropriate choice of these parameters has been studied as a research problem by itself, but for the purpose of our simulations we set the number of retransmissions to a very low number (2), as our focus is on end-to-end error recovery schemes and not link layer recovery schemes.

In the past, people have simulated the performance of wireless ad-hoc networks by considering topologies having around 50 nodes and 10 to 30 sources placed in a uniform random manner [5],[11]. But for such topologies, the multiple paths tend to have many common links in their path. As mentioned in the analytical framework in section III, our analysis assumes that the multiple paths are disjoint and independent of each other. So, to verify our results, we set up a deterministic 19-node system in a manner that

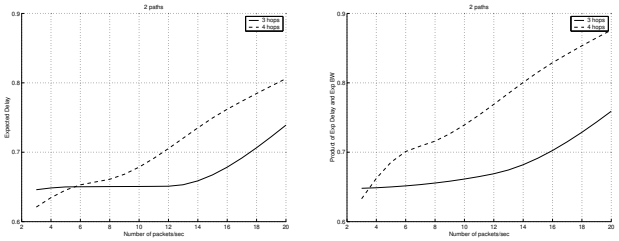


(a) (b)

Fig. 4. Effect of variation of the number of hops in a path on (a)delay, (b)DBP as determined by simulation

the number of common links between multiple paths is reduced. But there are still some common links because of the manner in which costs are assigned and paths are chosen by the network simulator.

We send traffic across various paths of different lengths to obtain the results shown in figure 4. The 2 hop case actually shows an increase in delay, but this is because of increased congestion in a shared part of the two paths. Other than that, for all paths of length 3 to 5 hops there is a reduction in delay by using two paths. For 3 or more hops, we also notice that the delay-bandwidth product is less than 1. Thus using 2 paths performs better than using a single path for paths of any length. While we expect performance to get better as the number of hops increases, the simulation results appear to be stabilizing at a fixed value. This may be due to shared links, and complete independence of paths would result in better performance for longer paths.



(a) (b)

Fig. 5. Effect of the variation of network load on (a)delay, (b)DBP as determined by simulation

Figure 5 shows the variation of delay and delay-bandwidth product with the rate of the stream. We see that using two paths as compared to using a single path consistently yields a reduced delay and delay-bandwidth product less than 1. But, as the network load increases, the extra bandwidth used gives rise to more congestion. This in turn increases both the delay and the bandwidth used. So, while there is still a performance gain for DMSR as compared to DSR, the amount of gain reduces with increase in network load.

VI. Conclusion

In this paper we show that the use of multiple paths to send packets over ad-hoc wireless networks leads to a lower expected delay for reliable end-to-end delivery. This reduction in delay can be achieved without a significant increase in bandwidth requirements. In fact, for most values of system parameters, the delay-bandwidth product is less than one. This result suggests that the extra bandwidth used is more than offset by the reduction in delay.

By using multiple paths, delay reductions and lower delay-bandwidth products are obtained for paths of all lengths, but the benefits increase as the number of hops in the paths increases. The gain is mainly due to the increase in the probability of successful transmission and hence reduction in the number of retransmissions due to timeouts. But the maximum gain in terms of probability is when we increase from one path to 2 or 3 paths, after which there are diminishing returns in terms of delay reduction, while the increase in bandwidth usage is much more, thus leading to an increase in the delay-bandwidth metric. Thus, we find that the optimal solution is provided by sending the packets over 2 or 3 paths.

The results of this analysis can be implemented as the Dynamic Multicast Source Routing (DMSR) protocol. This protocol uses source routing to send copies of the packets across multiple paths of the network. To validate our analysis, we presented results from simulations performed using the ns-2 network simulator for 2-path DMSR, with TCP as the reliable end-to-end delivery protocol. At low network loads, DMSR is found to perform better than DSR as shown by the expected delay and delay-bandwidth metrics, although performance gain decreases with increase in the network load. This protocol appears to be easy to implement as it takes advantage of the existing DSR protocol.

VII. Future Work

There are a number of directions in which this work can be carried forward from it's current state. We have performed simulations on a deterministic topology; a random topology would be a more practical scenario in which the number of shared paths would be higher and it is important to quantify the gain of using multiple paths in such a setup. As indicated in section III, such scenarios can be analyzed by breaking the shared paths into common parts and disjoint parts. So it would be interesting to understand the effect of having non-disjoint paths on the performance of multipath routing protocols.

We have shown that in most cases the optimal number of paths is 2 or 3, but it may be possible to design an *intelligent* DMSR algorithm that makes the optimal choice of number of paths by looking at the number of hops, network load and other parameters. Other work could also look at the performance of DMSR at higher network loads and propose an algorithm which can adapt to varying network conditions with regards to choosing appropriate multiple paths.

References

[1] Ns (network simulator). http://www.isi.edu/nsnam/ns/.

[2] T.S.; Yoshida S. Andersen, J.B.; Rappaport. Propagation measurements and models for wireless communications channels. In *IEEE Communications Magazine , Vol.33, Iss.1, 1995 Pages: 42- 49*.

[3] J. Apostolopoulos. Reliable video communication over lossy packet networks using multiple state encoding and path diversity, 2001.

[4] J. Apostolopoulos, W. Tan, S. Wee, and G. Wornell. Modeling path diversity for multiple description video communication, 2002.

[5] Josh Broch, David A. Maltz, David B. Johnson, Yih-Chun Hu, and Jorjeta Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Mobile Computing and Networking*, pages 85–97, 1998.

[6] C. Chiang, H. Wu, W. Liu, and M. Gerla. Routing in clustered multihop, mobile wireless networks, 1997.

[7] R. Dube, C. Rais, K. Wang, and S. Tripathi. Signal stability based adaptive routing (ssa) for ad hoc mobile networks, 1997.

[8] David Eckhardt and Peter Steenkiste. Measurement and Analysis of the Error Characteristics of an In-Building Wireless Network. In *SIGCOMM*, pages 243–254, 1996.

[9] David A. Eckhardt and Peter Steenkiste. Improving wireless LAN performance via adaptive local error control. *Proceedings of IEEE ICNP '98*, 1998.

[10] Gavin Holland and Nitin H. Vaidya. Analysis of TCP performance over mobile ad hoc networks. In *Proceedings of IEEE/ACM MOBICOM '99*, pages 219–230, August 1999.

[11] Per Johansson, Tony Larsson, Nicklas Hedman, Bartosz Mielczarek, and Mikael Degermark. Scenario-based performance analysis of routing protocols for mobile ad-hoc networks. In *Proceedings of the fifth annual ACM/IEEE international conference on Mobile computing and networking*, pages 195–206. ACM Press, 1999.

[12] David B Johnson and David A Maltz. Dynamic Source Routing in Ad Hoc Wireless Networks. In Imielinski and Korth, editors, *Mobile Computing*, volume 353. Kluwer Academic Publishers, 1996.

[13] Almudena Konrad, Anthony D. Joseph, Reiner Ludwig, and Ben Y. Zhao. A Markov-Based Channel Model Algorithm for Wireless Networks.

[14] Y. Liang, E. Steinbach, and B. Girod. Multi-stream voice over IP using packet path diversity, 2001.

[15] Y. Liang, E. Steinbach, and B. Girod. Real-time Voice Communication over the Internet Using Packet Path Diversity, 2001.

[16] N. F. Maxemchuk. Dispersity Routing. In *International Conference on Communications*, pages 41–10 41–13, 1975.

[17] N. F. Maxemchuk. Dispersity Routing in Store and Forward Networks, 1975.

[18] Shree Murthy and J. J. Garcia-Luna-Aceves. An efficient routing protocol for wireless networks. *Mobile Networks and Applications*, 1(2):183–197, 1996.

[19] Giao Thanh Nguyen, Randy H. Katz, Brian Noble, and M. Satyanarayanan. A Trace-Based Approach for Modeling Wireless Channel Behavior. In *Winter Simulation Conference*, pages 597–604, 1996.

[20] Vincent D. Park and M. Scott Corson. A highly adaptive distributed routing algorithm for mobile wireless networks. In *INFOCOM (3)*, pages 1405–1413, 1997.

[21] C. Perkins. Ad-hoc on-demand distance vector routing, 1997.

[22] Charles Perkins and Pravin Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, pages 234–244, 1994.

[23] M. O. Rabin. Efficient Dispersal of Information for Security, Load Balancing, and Fault Tolerance., 1989.

[24] E. Royer and C. Toh. A Review of Current Routing Protocols for Ad-Hoc Mobile Wireless Networks, 1999.

[25] C. Toh. Associativity-based routing for ad-hoc mobile networks. In *Wireless Personal Communications Journal, Special Issue on Mobile Networking and Computing Systems*, March 1997.