Multipath Routing in the Presence of Frequent Topological Changes

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ABSTRACT

In this article we propose a framework for multipath routing in mobile ad hoc networks and provide its analytical evaluation. The instability of the topology (e.g., failure of links) in these types of networks, due to nodal mobility and changes in wireless propagation conditions, makes transmission of time-sensitive information a challenging problem. To combat this inherent unreliability of these networks, we propose a routing scheme that uses multiple paths simultaneously by splitting the information among the multitude of paths, to increase the probability that the essential portion of the information is received at the destination without incurring excessive delay. Our scheme works by adding some overhead to each packet, which is calculated as a linear function of the original packet bits. The resulting packet (information and overhead) is fragmented into smaller blocks and distributed over the available paths. Our goal is, given the failure probabilities of the paths, to find the optimal way to fragment and then distribute the blocks to the paths so that the probability of reconstructing the original information at the destination is maximized. Our algorithm has low time complexity, which is crucial since the path failure characteristics vary with time and the optimal block distribution has to be recalculated in real time.

INTRODUCTION

In this article, we consider the problem of routing data over multiple disjoint paths in an ad hoc network. One of the well-known approaches to multipath routing is *diversity routing* [1]. In [2] another multipath scheme is proposed, *diversity coding*, in order to achieve self-healing and fault tolerance in digital communication networks. In [3] a per-packet allocation granularity for multipath source routing schemes was shown to perform better than a per-connection allocation. An exhaustive simulation of the various trade-offs associated with dispersity routing was presented in [4]. The inherent capability of this routing method to provide a large variety of services was pointed out.

The application of multipath techniques in mobile ad hoc networks seems natural, since multipath routing allows to diminish the effect of unreliable wireless links and the constantly changing topology. The *on-demand multipath routing* scheme is presented in [5] as a multipath extension of *dynamic source routing* (DSR) [6], in which alternate routes are maintained so that they can be utilized when the primary one fails. In *AODV-BR* [7], an extension of *AODV* [8], multiple routes are maintained and utilized only when the primary root fails. However, traffic is not distributed to more than one path. *Multiple source routing* (MSR) [9] proposes a weighted round-robin heuristic-based scheduling strategy among multiple paths in order to distribute load, but provides no analytical modeling of its performance. *Split multipath routing* (SMR), proposed in [10], focuses on building and maintaining maximally disjoint paths; however, the load is distributed only in two routes per session. In [11] the positive effect of *alternate path routing* (APR) on load balancing and end-to-end delay in mobile ad hoc networks has been explored. In an interesting application [12], *multipath path transport* (MPT) is combined with *multiple description coding* (MDC) in order to send video and image information in a multihop mobile radio network.

In our article we propose a multipath scheme for mobile ad hoc networks based on *diversity coding* [2]. Data load is distributed over multiple paths in order to minimize the packet drop rate, achieve load balancing, and improve end-to-end delay. The routing paradigm is depicted in Fig. 1, where three different paths are utilized at the same time in order to send data from a source to a destination node. As we explain in the next section, each data packet is split into multiple pieces, which are distributed among the available paths. We evaluate our scheme by calculating the probability that a transmission from the source results in successful packet reception at

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the destination. The probability function of successful reception is analytically derived and data is split over multiple paths in such a way that the function is maximized.

The model we are using in order to evaluate our scheme is developed under the assumption that the mean time of packet transmission is much smaller than the mean time between variations in network topology. If this assumption holds, we can assume that the probability that one or more path links fail is constant during the transmission of a packet. In other words, one can assume that the topology of the network will not change significantly while a packet is being transmitted.

Our article is organized as follows. We first provide a description of the proposed scheme and the definition of the successful transmission probability function P_{succ}, the function used for the evaluation of the scheme. Then we derive an analytical formula for P_{succ} and its approximation. Finally, we conclude the work and set some goals for our research in the future.

Description of Our Scheme

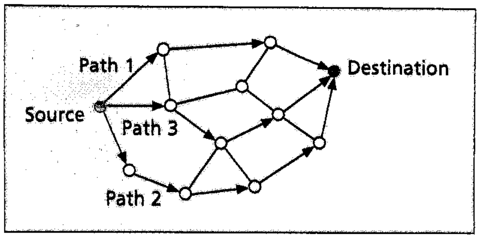
In this section, we describe how our scheme exploits the multitude of paths, in order to offer increased protection against path failures. Data packets are sent from source to destination over these paths, making use of *diversity coding* [2], which we explain later in this section.

In our network model, we assume that n_{max} paths are available for the transmission of data packets from a source to a destination node. All paths are mutually disjoint, that is, they have no nodes in common. Each path, indexed as i, $i = 1..n_{max}$, is assigned a probability of failure p_i, which is the probability that path i is down at the time that the source attempts to transmit. In addition, each path is treated as a pure erasure channel: either no information reaches the destination through path i (with probability p_i), or all the information is received correctly (with probability $1-p_i$). Since there are no common nodes among the paths, they are considered independent in the sense that success or failure of one path cannot imply success or failure of another.

Without loss of generality, the failure probabilities of the available paths are organized in the probability vector $p = [p_i]$, $i = 1..n_{max}$, in such a way that $p_i \leq p_{i+1}$, that is, the paths are ordered from the "best" one to the "worst" one. Given p we also define $q = [q_i]$, $q_i = 1 - p_i$, $i = 1..n_{max}$, which is the vector of the success probabilities.

The failure probability vector $\underline{p}$ reflects the network topology and the quality of the available routes, no matter what the node mobility pattern is. There exist various protocols, such as *associativity-based routing* (ABR) [13], that quantify the stability of the routes in a network using various criteria, based on network measurements. Our goal is to develop a method for the fast calculation of the optimal solution defined later in this section so that our scheme can respond (i.e., recalculate the optimal solution) to rapid changes in $\underline{p}$, that is, changes in the network topology.

Let's suppose that the proposed scheme has to send a packet of X information bits utilizing the set of available independent paths in such a way as to maximize the probability that these



■ **Figure 1.** *Using multiple paths in an ad hoc network.*

bits are successfully communicated to the destination. This probability is denoted as P_{succ}. In order to achieve this goal, we employ a coding scheme in which Y extra bits are added as overhead. The resulting B bits ($B = X + Y$) are treated as one network-layer packet. The extra bits are calculated as a function of the information bits in such a way that, when splitting the B-bit packet into multiple equal-size nonoverlapping blocks, the initial X-bit packet can be reconstructed given any subset of these blocks with a total size of X or more bits. First, we define the overhead factor r:

$$r = \frac{B}{X} = \frac{b}{x}, \tag{1}$$

where b and x take integer values and the fraction b/x cannot be further simplified; that is, the greatest common divisor of b and x is 1.

The key decision we have to make is how the B bits will be distributed over the available paths. For this reason, we define the vector $\underline{v} = [v_i]$, where v_i is the number of equal-size blocks allocated to path i. Clearly, some of the paths may demonstrate such poor performance that there is no point in using them at all. This means that we might need to use only some of the available paths. If n is the number of paths we have to use in order to maximize P_{succ}, it would be preferable to define the block allocation vector $\underline{v}$ as a vector with a variable size n, instead of fixing its size to the number of available paths (i.e., n_{max}). Given the fact that the probability vector is ordered from the best path to the worst one, a decision to use n paths implies that these paths will be the first n ones. Based on these observations, the allocation vector $\underline{v}$ has the following form:

$$\underline{v} = (v_1, v_2, \ldots, v_n), n \leq n_{max}.$$

If the block size is w, then

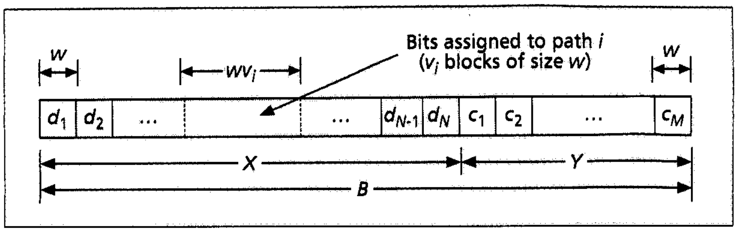
$$w \cdot \sum_{i=1}^{n} v_i = B = rX.$$

Therefore, the total number of blocks into which the B-bit packet is fragmented is

$$a = \sum_{i=1}^{n} v_i = \frac{rX}{w}. \tag{2}$$

From $p_i \leq p_{i+1}$ follows that $v_i \geq v_{i+1}$, because a path with higher failure probability cannot be assigned fewer blocks than a path with a lower failure probability. As a convention, we also set v_n to 1; that is, the last path we use receives one block.

In our article, we propose a multipath scheme for mobile ad hoc networks based on Diversity Coding. Data load is distributed over multiple paths in order to minimize the packet drop rate, achieve load balancing, and improve end-to-end-delay.



■ **Figure 2.** *Information and overhead packet fragmentation.*

In Fig. 2 we can see the B-bit packet and its relation to the original X-bit packet (gray area). We also show how the B-bit packet is fragmented into equal-size nonoverlapping blocks of size w. The original X-bit packet is fragmented into N w-size blocks, $d_1, \ldots, d_N$, and the Y-bit overhead packet into M w-size blocks, $c_1, \ldots, c_M$. Path 1 will be assigned the first v_1 blocks of the B-bit sequence, path two will receive the next v_2 blocks, and so on. Thus, path i will be assigned v_i blocks, each block of size w.

We can derive the expressions for N and M from Fig. 2:

$$N = \frac{X}{w} = \frac{a}{r}, \tag{3}$$

$$M = \frac{Y}{w} = (r-1)N = \frac{r-1}{r}a. \tag{4}$$

This is a typical case where *M-for-N diversity coding* can be applied. In [2] Ayanoglu *et al.* have proven that if M or less blocks are lost out of the $N + M$ total data and overhead blocks, the original N information blocks can be recovered using appropriate linear transformations. The overhead blocks c_i, $i = 1..M$, are also calculated as a linear transformation of the information blocks d_i, $i = 1..N$.

The optimization algorithm we developed is used to determine the optimal number of paths and the optimal allocation vector, given the path probability vector $\underline{p}$ and the overhead factor r. The details of this algorithm are explained in [14] and will be omitted here because of space limitations. The optimization process involves the maximization of P_{succ}, the definition of which we give shortly.

If v_i is the number of blocks we send over path i, and z_i is the number of blocks that actually reach the destination through path i, then:

- $Pr\{z_i = v_i\} = q_i\}$
- $Pr\{z_i = 0\} = p_i\}$

because we assume that if a path fails, all the blocks sent over the path are lost (recall the pure erasure channel assumption). M-for-N diversity coding can reconstruct the original X-bit information packet, provided at least N blocks reach the destination. Therefore, we can define P_{succ} in terms of the number of paths that are actually used and the corresponding allocation vector:

$$P_{succ}(n, \underline{v}) = \Pr\left\{ \sum_{i=1}^{n} z_i \geq \frac{a}{r} \right\}, \tag{5}$$

where we expressed N as a function of a and r using Eq. 3.

Evaluation of the Function P_{succ}

In the section below we use the definition in Eq. 5 in order to provide an analytical formula for P_{succ} and to estimate its complexity. We also present a formula that approximates P_{succ}, and based on that formula we explain how an optimal allocation of blocks to the paths can be obtained. We then present the evaluation results.

Formula and Complexity of P_{succ}

In this section we present a formula for the calculation of the probability of success P_{succ}, given the probability vector $\underline{p}$, overhead factor r, and allocation vector $\underline{v}$. We also give an estimation of the complexity of this function in terms of the number of multiplications involved in its calculations.

According to our network model, each of the n paths used by our scheme is subject to two distinct events:

- The event of failure to transmit the assigned packets (probability p_i)
- The event of successful attempt to transmit the packets (probability q_i)

We define an n-dimensional vector $\underline{s}$, which reflects the state of the n paths:

- $s_i = 0$, if path i failed
- $s_i = 1$, if path i succeeded

The associated probabilities are:

- $Pr\{s_i = 0\} = p_i$
- $Pr\{s_i = 1\} = q_i = 1 - p_i$

The probability $t(\underline{s})$ of the n paths being in state $\underline{s}$ is easily calculated as

$$t(\underline{s}) = \prod_{i=1}^{n} p_i^{1-s_i} \cdot q_i^{s_i}. \tag{6}$$

Each different state corresponds to a different set of paths succeeding in transmitting packets. All possible states describe all combinations of such sets, thus covering the whole space of events (2^n events in total). Since a transmission is successful, when at least N blocks arrive at the destination, each term $t(\underline{s})$, defined in Eq. 6, can contribute to P_{succ} only if the number of blocks sent over the set of paths described by $\underline{s}$ is more than or equal to N. By making this observation and by replacing N using Eq. 3, we can write P_{succ} as[1]

$$P_{succ}(n, \underline{v}) = \sum_{\underline{s}} t(\underline{s}) \cdot u(\underline{s} \cdot \underline{v} - \frac{a}{r}), \tag{7}$$

where $\underline{s} \cdot \underline{v}$ is the inner product of vectors $\underline{s}$ and $\underline{v}$, and equals the total number of successfully received blocks allocated to the subset of paths described by the state vector $\underline{s}$. The function $u(\cdot)$ in Eq. 7 is the unit step function defined as

$$u(x) = \begin{cases} o, x < 0 \\ 1, x \geq 0 \end{cases}$$

Given the probability vector p and the overhead factor r as parameters, we are looking for the optimal number n^* of paths (out of the n_{max}

[1] *The reader is reminded that* $a = \Sigma_{i=1}^{n} v_i$.

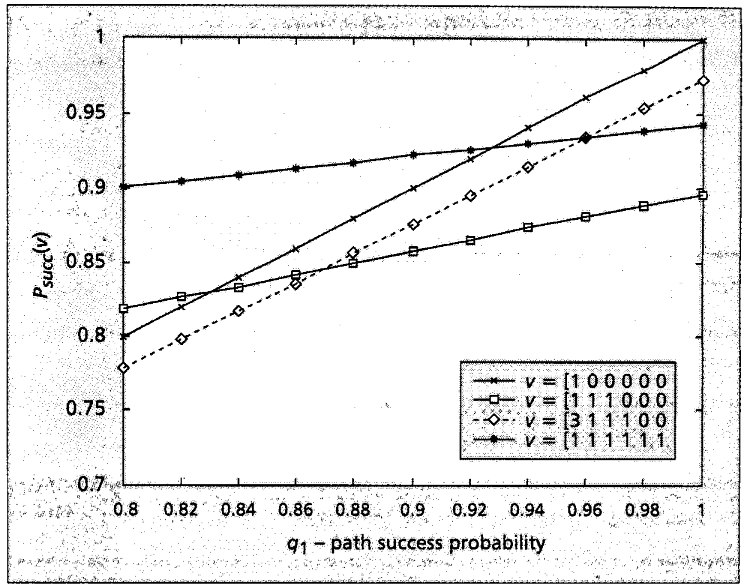
available ones) as well as the optimal allocation vector b^* over the n^* paths, so that P_{succ} is maximized.

Equation 7 is a complex formula, which makes it impossible to apply analytical maximizing techniques such as Lagrange multipliers, primarily because of the presence of the unit step function. Let us estimate the cost of exhaustively testing all combinations of the allocation vector $\underline{v}$, in order to find the maximum of P_{succ}. The number of possible allocations of B bits to n paths is $\binom{B+n-1}{n-1}$. The cost in multiplication operations of calculating P_{succ} using Eq. 7 is $n \cdot 2^n$, and thus exponential, because the total number of states is 2^n and each term is a product of n terms. Therefore, the total cost is

$$C = \sum_{n=1}^{n_{\max}} n 2^n \binom{B+n+1}{n-1}. \qquad (8)$$

It is clear that the cost of brute force optimization of P_{succ} is exponential. Even for a small number of paths (e.g., 10 paths), testing all the valid combinations will take an unacceptably long time, making optimization of P_{succ} impossible to implement in real time. Even if programming techniques such as dynamic programming are employed, the size of the search space remains exponential with respect to n. Moreover, the computation of P_{succ} itself requires exponential time; therefore, even if we knew the optimal solution, it would take a long time to calculate the value of P_{succ} for that solution. The reader is reminded that in an ad hoc network the probability vector $\underline{\mathbf{p}}$ will not be constant with time, and therefore the optimization process of P_{succ} must be repeated when the network topology changes.

In Fig. 3 we give a numerical example in the case where $r = 3/2$ and $n_{max} = 6$ paths. The probability vector is $q = [q_1, 0.8, 0.8, 0.8, 0.8, 0.8]$, where $0.8 \leq q_1 \leq 1$. We plot the probability of success for four allocation vectors, as shown in the legend of the graph. We can see that for $q_1 < 0.92$, the optimal allocation is $v = [1, 1, 1, 1, 1, 1]$, whereas for $q_1 > 0.92$ it is $v = [1]$. If only three paths are available, then for $q_1 < 0.83$, the optimal allocation is $v = [1, 1, 1]$, whereas for $q_1 > 0.83$ it is $v = [1]$.



■ **Figure 3.** *Comparing different allocation vectors.*

APPROXIMATION OF P_{SUCC}

From the analysis presented in the previous section it is evident that neither the optimal number of paths nor the optimal allocation vector can be calculated in the general case where the probability vector is nonuniform. The main problem is the complexity of P_{succ} in terms of continuity and the required computation time. Since P_{succ} is not continuous because of the presence of the unit-step function in its formula, its derivative is not defined everywhere. Moreover, the time required to calculate P_{succ} is exponential, which means that real-time computation is impossible to achieve.

To address the above problem of P_{succ} evaluation, we will present an approximation of P_{succ} based on the following observations:

- The binomial distribution can be approximated by the normal distribution.
- The sum of n independent normally distributed random variables follows the normal distribution.

We assume n paths with the path probability vector $\underline{p}$ and the block allocation vector $\underline{v} = [v_i]$. Vector $\underline{p}$ follows an ascending order, and therefore $v_i \geq v_{i+1}$, because a path with higher failure probability ($p_{i+1} \geq p_i$) cannot receive more blocks than the blocks sent to a path with a lower failure probability. Also, without loss of generality, we assume that $v_n = 1$. P_{succ} can be approximated by the following equation, as shown in [14]:

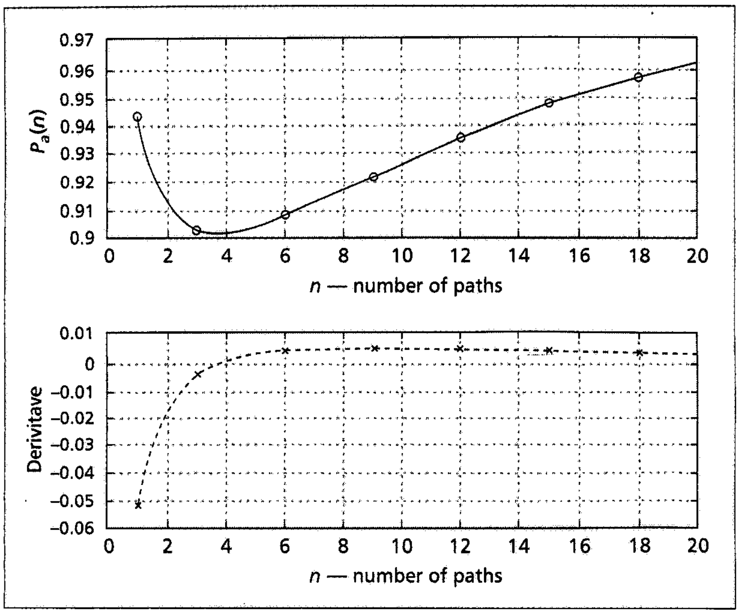
$$P_a(\underline{v},n) = \frac{1}{2} + \frac{1}{2} \cdot erf\left(\frac{\mu(\underline{v}) - \left\lceil \frac{1}{r} \sum_{i=1}^{n} v_i \right\rceil + 1/2}{\sigma(\underline{v})\sqrt{2}} \right), \qquad (9)$$

where

$$\mu(\underline{v}) = \sum_{i=1}^{n} v_i q_i, \quad \sigma(\underline{v}) = \sqrt{\sum_{i=1}^{n} v_i^2 p_i q_i}.$$

For a discussion on the validity of the approximation see [14]. Also, for more details on the normal approximation to the binomial distribution and the condition under which this approximation is satisfactory see [15].

Our goal is to maximize P_a with respect to $\underline{v}$ and $\underline{n}$. First, we observe that the expression inside the ceiling function in Eq. 9 must take on an integer value. If the latter is not true, the effective overhead ratio r' (i.e., the number of total blocks sent, divided by the minimum required number of blocks that must be received, so the original information can be reconstructed) would be less than the overhead ratio r employed by the scheme



■ **Figure 4.** P_a *and derivative for* $r = 3/2$ *and* $q = 0.8$.

$$r' = \frac{\sum_{i=1}^{n} v_i}{\left\lceil \frac{1}{r}\sum_{i=1}^{n} v_i \right\rceil} < \frac{\sum_{i=1}^{n} v_i}{\frac{1}{r}\sum_{i=1}^{n} v_i} = r.$$

The allocation vectors $\underline{v}$ for which $r' = r$ represent the points at which P_a has its local maxima.

In this article, due to limited space, we only present the calculation of the optimal number of paths n^*, assuming a uniform allocation of one block per path, that is, $v_i = 1$, for $i = 1..n^*$. The local maxima in this special case are found at $n = k \cdot b$, where b is defined in Eq. 1. An optimization technique for both $\underline{v}$ and n is developed in [14]. If one block is sent per path, P_a can be simplified to

$$p_a^{(u)}(n) = \frac{1}{2} + \frac{1}{2} \cdot erf\left(\frac{\sum_{i=1}^{n} q_i - \lceil n/r \rceil + 1/2}{\sqrt{2\sum_{i=1}^{n} p_i q_i}} \right). \quad (10)$$

The function $erf(\cdot)$ (i.e., the error function) is a monotonically ascending function; so in order to maximize P_a, it is sufficient to maximize its argument. Therefore, the optimal number of paths is given by the following expression:

$$n^* = \max_{n=kb}{}^{-1} = \left\{ \frac{\sum_{i=1}^{n} q_i - \lceil n/r \rceil + 1/2}{\sqrt{2\sum_{i=1}^{n} p_i q_i}} \right\}. \quad (11)$$

In the next section, we show some interesting evaluation results of the derivations presented here.

Results and Graphs

In this section, we present some results for the case in which one block is allocated to each path. In Fig. 4, we have drawn P_a and its derivative, for $q_i = 0.8$, $1 \le i \le 20$, and $r = 3/2$. As expected, the derivative is zero at the value of n that minimizes P_a.

Interesting results are obtained when the probability vector is uniform, that is, all paths exhibit the same probability of success $q_i = q$, $i = 1..n_{max}$. In this case, there is a threshold value $q_+(r)$ beyond which P_{succ} is increasing as the number of used paths increases. This threshold is approximated by the following equation:

$$q_+(r) = \frac{1}{2(b+1)} + \frac{1}{r}. \quad (12)$$

In Fig. 5, we compare q_+ and its approximation described by Eq. 12.

The main conclusions are:

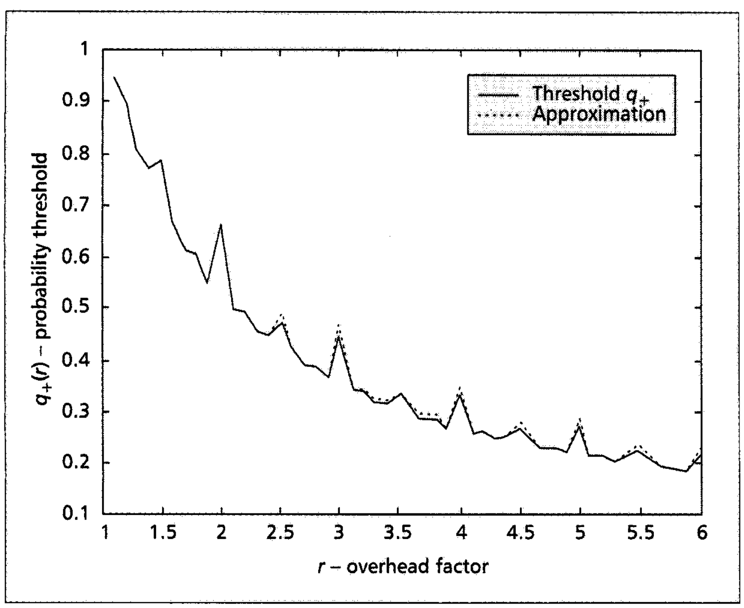
- If $q \ge q_+(r)$, then P_a is ascending for $n > b$, and therefore the optimal number of paths is the number of available paths (all paths should be used). However, we have to take into account that P_{succ} encounters local maxima at positions kb, where $k \ge 1$, so if the number of available paths is n_{max}, then the optimal number of paths is

$$n^*(r) = b \cdot \left\lfloor \frac{n_{max}}{b} \right\rfloor.$$

- If $q < 1/r$, then P_a is descending with respect to n and so is the set of local maxima of P_{succ}. The optimal number of paths for this case is $n^*(r) = b$.
- If $1/r \le q < q_+(r)$, then P_a has a minimum at

$$n_0(r,q) = \frac{1}{2(q - 1/r)}.$$

These conclusions can be verified from Fig. 6, in which we plot P_{succ} (overhead factor $r = 2$) against the number of paths $n = k \cdot b$, $k = 1..20$,



■ **Figure 5.** *Threshold* q_+ *and its applications.*

for different values of the path success probability. Incidentally, we note that $q_+(2) \approx 0.7$, whereas from Eq. 12 we find the exact value: $q_+(2) = 0.67$.

For the general case where the probability vector is arbitrary, we note that if $q_i > 1/r$,

$$\lim_{n \to +\infty} P_{succ}(n) = 1,$$

and therefore it is advantageous to use a large number of paths, so as to achieve a probability of success close to 100 percent.

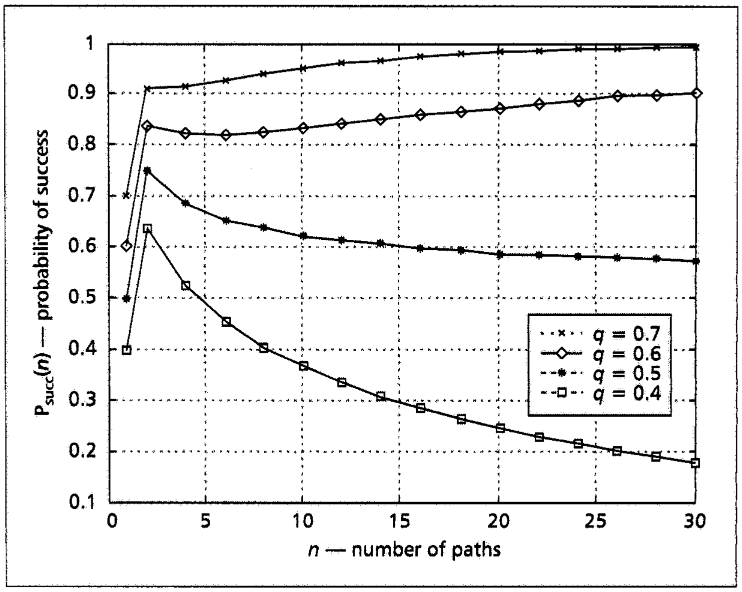
Conclusions and Future Work

In this article, we propose a new scheme for multipath routing in mobile ad hoc networks. Our goal was to apply multipath techniques in an environment that has continuously changing topology and no infrastructure so that the typical problems associated with nodal mobility and wireless links (unreliable transmissions, fading, etc.) will be alleviated. We argue that, if the mean time of packet transmission is much smaller than the mean time between variations in network topology, we can fairly assume that the probability that one or more path links fail is constant during the transmission of a packet.

Under these assumptions, we consider the general case of multipath transmission, in which $n_{\max}$ disjoint paths are available for a packet transmission. Each path is treated as a pure erasure channel and is associated with some failure probability p_i, defined as the probability that, at transmission attempt time, the path is down. Based on the work done in [2], we use M-for-N diversity coding. This scheme splits the original packet into N blocks, adds M blocks of overhead (calculated using linear transformations from the original N blocks), and, finally, allocates one block to each one of $N + M$ paths. M-for-N diversity coding offers protection against at most M lost blocks out of the total $N + M$ blocks. In our scheme, rather than allocating one block per path, we assume an allocation of v_i blocks to path i, $i = 1..n_{\max}$. Thus, we show what the optimal distribution of these blocks to the $n_{\max}$ disjoint paths should be so that P_{succ} is maximized.

Given the path failure probabilities, the overhead factor, and the allocation of the original and overhead blocks to the n_{max} paths, we develop an analytical formula for the probability function P_{succ}, namely, the probability that no more than M blocks are lost. This is the probability that the original N blocks can be reconstructed at the destination, and, as a consequence, the transmission is successful. We show how to maximize P_{succ} (in terms of the block allocation) fast enough (see an earlier section) so that the requirement for a real-time recalculation of the optimal solution due to topology changes could be met.

Our scheme proposed here offers increased protection against route failures. Under some constraints on the path failure probabilities, it was found that the probability of a successful communication of packets between source and destination increases with the number of used paths and can, in the limit, approach 100 percent. Moreover, this would effectively reduce transmission delay and traffic congestion through load balancing.



■ **Figure 6.** *Behavior of* P_{succ} *for different values of* q.

The proposed scheme can also be used to enforce error rate quality of service requirements, whenever the characteristics of the offered paths make it possible. In that case, we do not have to maximize P_{succ}, but, instead, simply set it to the required probability (indicated by the QoS requirements) and then find the number of paths and the block allocation that satisfies it. This could make real-time data transmission feasible in an environment that is hostile to such types of communication. Moreover, by keeping track of the probability of success and constantly comparing it with the QoS requirement, we obtain a metric that may be used in order to trigger new route discoveries, for example, if P_{succ} drops below the requirement. By extending the definition of the path failure probabilities, we could enforce different classes of QoS requirements, such as maximum delay requirements. This can be done by simply defining the path failure probability as the probability that a packet will not arrive on time, that is, within the maximum delay time, and as a result we assume it is lost.

Our goals for future research include:

- Evaluation of the proposed scheme when used for achieving load balancing and satisfying delay constraints
- Development of algorithms in order to estimate the probability vector $\underline{p}$ on a real-time basis
- Derivation and optimization of P_{succ} in the case of correlated paths
- Implementation of our scheme on top of existing routing protocols and comparative performance evaluation

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Biographies

ARISTOTELIS TSIRIGOS (at71@cornell.edu.) is a graduate student at New York University, New York. His research interests include mobile networking and computational biology. He received his B.S. in electrical engineering and computer science from the National Technical University of Athens, Greece, in 1998, and his M.S. in electrical and computer engineering from Cornell University, Ithaca, New York, in 2001. Currently, he is working towards his Ph.D. on Computational Biology.

ZYGMUNT J. HAAS [SM] (haas@ece.cornell.edu) received his B.Sc. in EE in 1979 and M.Sc. in EE in 1985. In 1988, he earned his Ph.D. from Stanford University and subsequently joined AT&T Bell Laboratories in the Network Research Department. There he pursued research on wireless communications, mobility management, fast protocols, optical networks, and optical switching. From September 1994 till July 1995 he worked for the AT&T Wireless Center of Excellence, where he investigated various aspects of wireless and mobile networking, concentrating on TCP/IP networks. As of August 1995, he joined the faculty of the School of Electrical and Computer Engineering at Cornell University. He is an author of numerous technical papers and holds 14 patents in the fields of high-speed networking, wireless networks, and optical switching. He has organized several workshops, delivered tutorials at major IEEE and ACM conferences, and serves as editor of several journals and magazines, including *IEEE Transactions on Networking*. He has been a guest editor of three *IEEE JSAC* issues (Gigabit Networks, Mobile Computing Networks, and Ad-Hoc Networks). His interests include mobile and wireless communication and networks, personal communication service, and high-speed communication and protocols.

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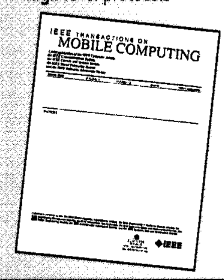

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