

# Rate Allocation with Minimized Packet-Loss in Multi-Hop Wireless Ad Hoc Networks

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**Abstract.** Due to time-varying topological changes in a wireless ad hoc network, it is a challenging issue to provide stringent QoS requirements of most real-time applications. Each real-time application requires a specific set of QoS parameter guarantees (such as delay, jitter, packet loss...). As multipath routing has the potential of reducing the congestion and increasing the throughput of the user traffic in multi-hop wireless networks, it is assumed that multiple paths are available in advance between each source-destination pair. In the current work, those subsets of real-time applications (such as Video On Demand), which require minimized packet loss and a lower bound on the delivered bandwidth, are taken into account. Using a constrained optimization framework and trying to minimize the packet loss, an optimal rate is allocated to each source-destination path of the real-time application. Simulation results verify the enhanced performance of the proposed method in terms of the packet error rate.

### INTRODUCTION

Ad hoc wireless networks are collections of wireless mobile nodes that self-configure to form a network without the aid of any pre-established infrastructure [1]. Due to the dynamic nature of these networks, traditional routing protocols are useless. So, special proactive/reactive multi-hop routing protocols (such as DSDV/AODV), route packets through intermediate nodes towards their final destination. Multi-hop routing can reduce interference, improve connectivity and allow distant nodes to communicate efficiently [2]. In addition, multi-path routing, where a source node uses multiple multi-hop routes or paths through the network to send data to a given destination, allows a higher throughput between these nodes than if just one path was used. On the other hand, using multiple paths between any source-destination pair can improve the important reliability and availability features of the routing strategy. Multi-path routing can provide both diversity and a multiplexing gain between a source and destination. However, multi-hop and multipath routing can also increase the total packet loss between the source and destination, especially if there is congestion in the paths or if the bit error rate of the

paths are high due to bad wireless link conditions (i.e. existence of high noise or interference levels). Thus, supporting multimedia data with a stringent maximum loss requirement over multi-hop ad hoc networks with multi-path routing is an important and challenging research area. In this paper, we assume the packet loss is only due to the wireless link conditions and also assume that all of the nodes have an adequate buffering capability (theoretically infinite buffer size), so the congestion related loss can be ignored.

The rest of the paper is organized as follows: First, an overview is given about the related work in this area. Then, the proposed optimization framework is introduced in detail. Following that, the simulation results and some concluding remarks and hints regarding further work are given.

# **RELATED WORKS**

Sending multimedia traffic over wireless ad hoc networks is a challenging issue and many active research areas exist that all try to resolve the problem.

Some researchers such as those in [3-4] try to use adaptive link layer techniques for throughput optimization. The authors in [4] propose a mathematical framework in which they vary adaptively the constellation size of a MQAM modulator, in order to maximize the single user throughput.

In [5-6], a congestion-minimized stream routing approach is adopted. In [6], the authors analyze the

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benefits of an optimal multi-path routing strategy, which seeks to minimize congestion on the video streaming in a bandwidth limited ad hoc wireless network. They also predict the performance in terms of rate and distortion, using a model which captures the impact of quantization and packet loss on the overall video quality.

Some researchers such as Agarwal [7], Adlakha [8] and Zhu [9] follow some congestion-aware and delayconstrained rate allocation strategies. Agarwal et al. [7] introduce a mathematical constrained convex optimization framework, by which they can jointly perform both rate allocation and routing in a delayconstrained wireless ad hoc environment.

Adlakha et al. [8] extend the conventional layered resource allocation approaches by introducing a novel cross-layer optimization strategy in order to more efficiently perform the resource allocation across the protocol stack and among multiple users. So, they show that their proposed method can support simultaneous multiple delay-critical application sessions such as multi-user video streaming.

For multi-path video streaming over ad hoc wireless networks, the received video quality is influenced by both the encoder performance and the delayed packet arrivals due to a limited bandwidth. So, Zhu et al. [9] propose a rate allocation scheme to optimize the expected received video quality, based on simple models of encoder rate-distortion performance and network rate-congestion tradeoffs.

As the wireless link quality varies, the video transmission rate needs to be adapted accordingly. In [10], measurements of packet transmission delays at the MAC layer are used to select the optimal bit rate for video subsequently enforced by a transcoder. The benefit of cross-layer signaling in rate allocation has also been demonstrated in [11], where adaptive rate control at the MAC layer is applied in conjunction with an adaptive rate control during live video encoding.

The authors in [12] propose a media-aware multiuser rate allocation algorithm in multi-hop wireless mesh networks that can adjust the video rate adaptively based on both video content and network congestion, and show the benefits of their work with respect to the well-known TCP Friendly Rate Control (TFRC) [13].

In the current work, a similar approach as in [7], is being adopted by which a constrained optimization framework is introduced for optimal rate allocation to some subsets of the real-time applications, which require a minimized packet loss. In [14], the authors do a similar optimization, but they take the average congestion of the overall network as the QoS criterion and minimize it to find the optimal solution for rate allocation on the available paths using simulations. Our work differs from [7] and [14] in terms of the QoS criterion used, which for us is the overall probability of packet loss in multi-path routing based rate allocation to a real-time application with stringent maximum packet loss and minimum bandwidth requirements such as Video On Demand (VOD).

We also have used a penalty function approach for solving the proposed constrained optimization problem such as those introduced in [15-16].

## PROPOSED OPTIMIZATION FRAMEWORK

Consider the multi-hop wireless ad hoc network depicted in Figure 1.

Assume that the existing multi-path routing protocol (e.g. AOMDV [15]) introduces N disjoint multihop paths between source-destination pair (S,D), periodically. Each path is associated with a traffic flow and these multiplexed flows are aggregated in the destination node to produce the initial source-generated traffic stream. The number, N, is selected, based on the assumption of availability of the current paths throughput information for the source node, S, and the sufficiency of the aggregate estimated throughput for the traffic's minimum bandwidth requirements.

We assume a simple strong Line Of Sight (LOS) with BPSK signaling for the node's wireless transmissions and also neglect the interfering effect of wireless transmissions between different paths [1]. In reality, the lack of interference would correspond to the use of perfectly orthogonal spreading codes in each multi-hop route, or to the use of disjoint frequency bands in the active multi-hop communication routes.

We also assume that the underlying routing protocol is fast enough, such that it can capture the nodes mobility and, with the assumption of the existence of routed paths, the proposed rate allocation method works properly as if it is in a static scenario. It also must be assumed that the nodes mobility is slow



Figure 1. A typical multi-hop wireless ad hoc network.

enough such that it doesn't change the propagation model of the nodes into fading or shadowing ones.

Each path *i* contains  $\lambda_i$  wireless links from source to destination for  $1 \leq i \leq N$ . We also assume that the transmitted data is fragmented in equal length packets of length *L* bits enabled with FEC error correction capability up to *M* bits.

It is assumed that the nodes have sufficient buffering capability in such a way that the congestion-related packet losses can be ignored and the packet loss is only affected by physical Bit Error Rate (BER) properties of the wireless link.

According to [1], the BER of the i'th flow in link j can be represented for a simple strong LOS propagation model with BPSK signaling as follows:

$$b_{ij} = Q\left(\frac{\eta_{ij}}{\sqrt{r_{ij}}}\right),$$
  

$$1 \le j \le \lambda_i, \quad 1 \le i \le N,$$
(1)

where:

$$\eta_{ij} = k_{ij} \cdot \sqrt{TP_{ij}}, \quad \forall i, j \in \Re_i$$
$$Q(y) \triangleq \frac{1}{\sqrt{2\pi}} \int_y^\infty e^{-\frac{y^2}{2}} dy,$$

where  $k_{ij}$  is a physical constant,  $\Re_i$  is the (nonempty) set of wireless links associated with the *i*th flow and  $TP_{ij}$  is the transmitted power along the *j*th link of the *i*th flow.  $r_{ij}$  is the total transmission data rate associated with the *j*th link of the *i*th flow. We assume that  $TP_{ij}$  is fixed during transmission, and so does not depend on the transmission data rate,  $r_{ij}$ .  $r_{ij}$ consists of two parts: one is the traffic rate allocated to the *i*th flow, which is denoted by  $x_i$  and another part is associated with the time-varying *j*th link cross (background) traffic, which is denoted by  $f_{ij}$ . Thus, we have:

$$r_{ij} = x_i + f_{ij}, \quad \forall i, j \in \Re_i.$$

With the assumption of the independent link bit error rate, the total bit error rate along the i'th path can be calculated as follows:

$$B_i = 1 - \prod_{j=1}^{\lambda_i} (1 - b_{ij}), \quad \forall i.$$
 (3)

If the FEC induced error correction capability of a packet with length L bits is M bits (M > 1) with the assumption of independent bit errors (lack of burst errors), the Packet Error Rate (PER) along the *i*'th path (flow) can be calculated as:

$$p_{i} = 1 - \sum_{m=0}^{M} {\binom{L}{m}} B_{i}^{m} (1 - B_{i})^{L-m}, \quad \forall i.$$
(4)

The total PER of the source-destination pair with the assumption of independent path packet losses can be written as:

$$p_T = 1 - \prod_{i=1}^{N} (1 - p_i).$$
(5)

We are now in a position that can start the formulation of the proposed constrained optimization problem as follows:

Minimize 
$$p_T$$
. (6)

Subject to:

$$\sum_{i=1}^{N} x_i \ge n_{\min},\tag{7}$$

$$x_i \ge 0, \quad \forall i, \tag{8}$$

in which  $x_{\min}$  is the minimum required bandwidth for the real-time application.

As the constraint set is convex, in order for the constrained optimization problem (Relations 6-8) to have a unique optimal solution vector  $x = (x_1, x_2, \dots, x_N)$ , it is necessary and sufficient that the following Lagrangian equations have positive second derivatives with respect to all of the  $x_i$  variables [16].

$$\Im \triangleq p_T - \nu \left( \sum_{i=1}^N x_i - x_{\min} \right). \tag{9}$$

From Equation 2, one can write:

$$\sum_{j=1}^{\lambda_i} r_{ij} = \lambda_i \cdot x_i + \sum_{j=1}^{\lambda_i} f_{ij}, \quad \forall i.$$
(10)

Before continuing the derivation of the second derivative of the Lagrangian function, we make the following simplifying conjecture.

#### Conjecture

If we neglect the congestion-related packet losses by infinite buffer size nodes, we have:

$$\frac{\partial r_{ij}}{\partial x_i} \cong 1, \quad \forall i, j \in \Re_i.$$
(11)

As we have neglected the congestion-related packet losses by infinite buffer size nodes, the conjecture (Relation 11) seems reasonable because target traffic  $x_i$  and cross traffic  $f_{ij}$  do not contend for the wireless channel capacity.

We will show in the corollary that in the case where conjecture (Relation 11) is not true, we can still have a unique solution vector for the optimization problem (Relations 6 to 8).

# Theorem

Consider a typical multi-hop wireless ad hoc network. Assume that  $L \gg 1$  and that the following holds:

$$0 \le B_i < \frac{1}{L}, \quad \forall i. \tag{12}$$

Then, there exists some M such that the optimization problem (Relations 6 to 8) has a unique and optimal solution vector.

#### Proof

First, it must be shown that the Lagrangian (Relation 9) have positive second derivatives with respect to all of the  $x_i$  variables.

Based on Relations 9 to 11, we have the following relations:

$$\frac{\partial \mathfrak{F}}{\partial x_i} \cong \frac{1}{\lambda_i} \cdot \sum_{j=1}^{\lambda_i} \frac{\partial \mathfrak{F}}{\partial r_{ij}} \cdot \frac{\partial r_{ij}}{\partial x_i}$$
$$= \frac{1}{\lambda_i} \cdot \sum_{j=1}^{\lambda_i} \frac{\partial p_T}{\partial r_{ij}} - \nu, \quad \forall i.$$
(13)

From Relations 5 and 13, we have:

$$\frac{\partial \Im}{\partial x_i} = \frac{1}{\lambda_i} \cdot \sum_{\substack{j=1\\m\neq i}}^{\lambda_i} \prod_{\substack{m=1\\m\neq i}}^N (1-p_m) \frac{\partial p_i}{\partial r_{ij}} - \nu, \ \forall i.$$
(14)

Similarly, from Relations 11 and 14, we can write:

$$\frac{\partial^2 \Im}{\partial x_i^2} = \frac{1}{\lambda_i^2} \sum_{j=1}^{\lambda_i} \sum_{k=1}^{\lambda_i} \prod_{\substack{m=1\\m\neq i}}^N (1-p_m) \frac{\partial^2 p_i}{\partial r_{ij} \partial r_{ik}}, \ \forall i.$$
(15)

From Equation 4, we have:

$$\frac{\partial p_i}{\partial r_{ij}} = -\frac{\partial B_i}{\partial r_{ij}}\varphi_i, \quad \forall i, j \in \Re_i,$$
(16)

where:

$$\varphi_i \triangleq \sum_{m=0}^{M} \binom{L}{m} (m - L \cdot B_i) B_i^{m-1} (1 - B_i)^{L-m-1}.$$
(17)

Similarly, we can write:

$$\frac{\partial^2 p_i}{\partial r_{ij} \partial r_{ik}} = -\varphi_i \frac{\partial^2 B_i}{\partial r_{ij} \partial r_{ik}} - \psi_i \frac{\partial B_i}{\partial r_{ij}} \frac{\partial B_i}{\partial r_{ik}},$$
  
$$\forall i, j, k \in \Re_i, \tag{18}$$

where for each i we have:

$$\psi_{i} = \frac{\partial \varphi_{i}}{\partial B_{i}} \triangleq L(L-1)(1-B_{i})^{L-3}((L-1)B_{i}-1)$$

$$+ \sum_{m=2}^{M} {\binom{L}{m}} B_{i}^{m-2}(1-B_{i})^{L-m-2}$$

$$[m(m-1) - 2mB_{i} + L(L-1)B_{i}^{2}].$$
(19)

From Equations 1 and 3, we can write:

$$\frac{\partial B_i}{\partial r_{ij}} = \left[\prod_{\substack{k=1\\k\neq j}}^{\lambda_i} (1-b_{ik})\right] \frac{\eta_{ij} \cdot e^{\frac{-\eta_{ij}^2}{r_{ij}}}}{2\sqrt{2\pi}} r_{ij}^{-3/2},$$
$$\forall i, j \in \Re_i, \tag{20}$$

$$\frac{\partial^2 B_i}{\partial r_{ij} \partial r_{ik}} = -\left[\prod_{\substack{m=1\\m\neq j,k}}^{\lambda_i} (1-b_{im})\right]$$
$$\cdot \frac{\eta_{ij} \cdot \eta_{ik} \cdot e^{\frac{-\eta_{ij}^2}{r_{ij}}} e^{\frac{-\eta_{ik}^2}{r_{ik}}}}{8\pi} r_{ij}^{-3/2} r_{ik}^{-3/2},$$
$$\forall i, j, k \in \Re_i, j \neq k, \tag{21}$$

and also:

$$\frac{\partial^2 B_i}{\partial r_{ij}^2} = \prod_{\substack{k=1\\k\neq j}}^{\lambda_i} (1 - b_{ik}) \\
= \frac{\eta_{ij} \cdot r_{ij}^{-7/2} \cdot e^{\frac{-\eta_{ij}^2}{r_{ij}}}}{2\sqrt{2\pi}} (\eta_{ij}^2 - \frac{3}{2}r_{ij}), \\
\forall i, j \in \Re_i.$$
(22)

Based on Relation 12, it can easily be shown that:

$$\frac{\partial B_i}{\partial r_{ij}} > 0, \quad \forall i, j \in \Re_i, \tag{23}$$

$$\frac{\partial^2 B_i}{\partial r_{ij} \partial r_{ik}} < 0, \quad \forall i, j, k \in \Re_i, \quad j \neq k.$$
(24)

Also, we can write:

$$\frac{\partial^2 p_i}{\partial r_{ij}^2} = -\varphi_i \frac{\partial^2 B_i}{\partial t_{ij} \partial r_{ik}} - \psi_i (\frac{\partial B_i}{\partial r_{ij}})^2,$$
$$\forall i, j, k \in \Re_i.$$
(25)

We make the following definitions:

$$\begin{split} \Phi_i^{jk} &\triangleq \frac{\partial^2 p_i}{\partial r_{ij} \partial r_{ik}}, \quad \Phi_i^j \triangleq \frac{\partial^2 p_i}{\partial r_{ij}^2}, \\ \forall i, j, k \in \Re_i. \end{split}$$

It is clear from Equations 17 to 22 and 25 that both  $\Phi_i^{jk}$  and  $\Phi_i^j$  are continuous functions of parameter  $B_i$ .

For proving the theorem, we consider two different cases:

#### a) Consider the case $j \neq k$ :

Based on Equations 18, 20 and 21, we can write:

$$\Phi_i^{jk} = \frac{\partial^2 B_i}{\partial r_{ij} \partial r_{ik}} (\varphi_i - (1 - B_i)\psi_i).$$
(26)

Consider the following functional:

 $T(B_i) \triangleq \varphi_i - (1 - B_i)\psi_i.$ 

By considering M = 2, for each *i* we have:

$$\varphi_i = -\frac{L(L-1)(L-2)}{2}B_i^2(1-B_i)^{L-3},\qquad(27)$$

$$(1 - B_i)\psi_i = -L(L - 1)(L - 2)$$
  
 $B_i(\frac{L - 1}{2}B_i - 1)(1 - B_i)^{L - 3}.$  (28)

Thus, based on assumption in Relation 12, we can write:

$$T(B_i) = -L(L-1)(L-2)$$
$$B_i(\frac{L}{2}B_i - 1)(1 - B_i)^{L-3} > 0.$$
(29)

From Equations 26 and 29, it can be deducted that:

$$\frac{\partial^2 p_i}{\partial r_{ij} \partial r_{ik}} > 0, \quad \forall i, j, k \in \Re_i.$$
(30)

b) Consider the case j = k:

First, from Equations 27 and 28 we can write:

$$\varphi_i, \psi_i < 0, \quad \forall i. \tag{31}$$

As we have  $L \gg 1$ , from Relation 12, it can be concluded that  $B_i \ll 1$ . From Equation 3, it can be easily concluded that  $b_{ij} \leq B_i \ll 1$  for each i, j, and based on Equation 1, we have:

$$b_{ij} \ll 1 \Rightarrow \frac{\eta_{ij}}{\sqrt{r_{ij}}} > \sqrt{\frac{3}{2}}, \begin{cases} 1 \le j \le \lambda_i \\ 1 \le i \le N. \end{cases}$$
 (32)

From Equations 22, 25, 27, 28 and 32, it can be concluded that:

$$\frac{\partial^2 p_i}{\partial r_{ij}^2} > 0, \quad \forall i, j, k \in \Re_i.$$
(33)

From Relations 30, 33 and 15, we can write:

$$\frac{\partial^2 \Im}{\partial x_i^2} > 0, \quad \forall i. \tag{34}$$

From Relation 34 and the convexity of the constraint set (Relations 7 and 8), it can be resulted that the constrained optimization problem (Relations 6 to 8) has a unique and optimal solution vector  $x^*$  [16].

#### Corollary

Under assumption in Relation 12 and if conjecture (Relation 11) is not valid, the optimization problem (Relations 6 to 8) still has a unique and optimal solution vector.

#### Proof

If conjecture (Relation 11) is not valid, we have:

$$\frac{\partial r_{ij}}{\partial x_i} = 1 + \frac{\partial f_{ij}}{\partial x_i}, \quad \forall i, j \in \Re_i.$$
(35)

We can partition the wireless links in  $\Re_i$  to two disjoint sets. One set is related to the congested links, which we denote by  $\Re_i^c$  and the other is associated with noncongested ones, i.e.  $R_i | R_i^c$ .

For non-congested links, the conjecture (Relation 11) is true, but for congested links, we can simply write:

$$\frac{\partial f_{ij}}{\partial x_i} = -1 \Rightarrow \frac{\partial r_{ij}}{\partial x_i} = 0, \quad \forall i, j \in \Re_i.$$
(36)

The general form of Equation 14 would be:

$$\frac{\partial \Im}{\partial x_i} = \frac{1}{\lambda_i} \sum_{j=1}^{\lambda_i} \prod_{\substack{m=1\\m\neq i}}^N (1 - p_m) \\ \left(1 + \frac{\partial f_{ij}}{\partial x_i}\right) \frac{\partial p_i}{\partial r_{ij}} - \nu, \quad \forall i.$$
(37)

From Relations 11 and 36, we can write:

$$\frac{\partial \mathfrak{F}}{\partial x_i} = \frac{1}{\lambda_i} \prod_{\substack{m=1\\m\neq i}}^N (1-p_m) \sum_{j \in \mathfrak{R}_i \ \mathfrak{R}_i^c} (1+\frac{\partial f_{ij}}{\partial x_i}) \frac{\partial p_i}{\partial r_{ij}} - \nu,$$
  
$$\forall i. \tag{38}$$

By adopting similar mathematical relations such as those described in the previous theorem for the non-congested links, we can deduct the convexity of the Lagrangian function and also the optimality and uniqueness of the solution vector.  $\blacksquare$ 

Now, for finding the analytical solution of Relations 6 to 8, we must have:

$$\frac{\partial \Im}{\partial x_i}, \quad \forall i.$$
 (39)

From Relation 13, we have:

.. .

$$\sum_{j=1}^{\lambda_i} \frac{\partial p_T}{\partial r_{ij}} = \lambda_i \nu, \quad \forall i.$$
(40)

From Equations 5, 16 and 20, for each i we have:

$$\varphi_{i} \cdot \sum_{j=1}^{\lambda_{i}} \prod_{\substack{m=1\\m\neq i}}^{N} \prod_{\substack{k=1\\k\neq j}}^{\lambda_{i}} (1-b_{ik})(1-p_{m})$$
$$\frac{\eta_{ij}}{2\sqrt{2\pi}} e^{-\frac{\eta_{ij}^{2}}{r_{ij}}} r_{ij}^{-\frac{3}{2}} + \lambda_{i}\nu = 0.$$
(41)

It is clear that Equation 41 is a transcendental function of  $x_i$  and cannot be solved analytically, so we try to use an iterative approach for finding the optimal solution vector,  $x^*$ .

Many iterative methods have been proposed that lead to the optimal solution of constrained optimization problems (Relations 6 to 8) [16]. From these methods, we have selected the penalty function approach.

Consider the following penalty function:

$$g(y) = \begin{cases} 0 &, \quad y \ge 0 \\ -y &, \quad y < 0. \end{cases}$$
(42)

The solution of the optimization problem (Relations 6 to 8) is equivalent to the solution of the following unconstrained problem when  $\alpha \to +\infty$  [16].

Minimize 
$$\Gamma \triangleq p_T + \alpha.g(\sum_{i=1}^N x_i - x_{min}).$$
 (43)

As we can see from assumption in Relation 8, for guaranteeing the uniqueness of the solution vector in optimization problems (Relations 6 to 8), it is necessary that the  $x_i$  variables must be non-negative. So, we must solve a projected version of unconstrained optimization (Relation 43) [16]. The iterative gradient descent solution for solving the unconstrained problem (Relation 43) is as follows (for each *i*):

$$x_{i}[n+1] = \{x_{i}[n] - \ell_{i} \frac{\partial \Gamma}{\partial x_{i}}|_{x_{i}=x_{i}[n]}\}^{+},$$
(44)

where:

$$\{y\}^+ \triangleq \max(0, y),$$

and  $\ell_i$  is some positive and sufficiently small constant that guarantees the convergence [17].

#### SIMULATION RESULTS

#### Part I: Static Scenario

Consider a sample simulation scenario that has been consisted of 50 nodes randomly distributed in a 10 m  $\times 10$  m area.

The nodes mobility has been neglected by the assumption of a static network topology.

A multi-path routing protocol [15] is enabled and introduces 4 disjoint paths for carrying the sourcedestination pair's traffic.

An important point that must be mentioned here is the fact that by using a proper feedback mechanism such as the Real-Time Control Protocol (RTCP), Equation 44 can easily be implemented in a distributed and end-to-end manner with minimal complexity; because each end node only needs the feedback information for computing optimal rates,  $x_i$ in Equation 44 and the allocation of these rates to each path. This fact is an important issue for the implementation of such algorithms in power limited ad hoc networks.

The average variable bit rate (VBR) cross traffic is selected to be 20 kbps for each wireless link. The  $\eta_{ij}$ parameters in Equation 1 are listed in Table 1. We have selected a simplified LOS propagation model for the wireless medium. We have selected an error correction capability up to 2 bits (M = 2), 4 disjoint paths (N =4), a packet size of 512 bits (L = 512) and a minimum bit rate ( $x_{min}$ ) of 128 kbps. We assume that the 1st, 2nd, 3rd and 4th paths consist of 5, 4, 4 and 3 wireless links, respectively.

 $\ell_i$  in Equation 44 is selected to be 0.0001 for each i.

The rate allocated to each path and the aggregate rate allocated to the source-destination pair are depicted in Figures 2 and 3 and are compared therein.

As can be verified from Figure 2, the allocated rates have fluctuations. These fluctuations are the direct consequence of competition between the rates allocated to the paths and the VBR cross traffic for consuming the link capacities.

After taking a summary of the average packet loss in each path, we have concluded that the percentage of the PER in paths 1, 2, 3 and 4 are approximately 40%, 32%, 18% and 10% of the total PER. Now, we can conclude that the result of the further allocated

**Table 1.** Values of the  $\eta_{ij}$  parameters.

$\eta_{ij}$	Link 1	Link 2	Link 3	Link 4	Link 5
Path 1	1	2	1.5	3	1
Path 2	1	2	3	1.7	
Path 3	4	2	1	1	
Path 4	2.1	1.2	1.3		



Figure 2. Rate allocated to each path in the proposed method.



Figure 3. The aggregate rate in the proposed method.

rate to path 4 is the result of less packet error rate associated with this path. In other words, the rate allocation algorithm in Equation 44 further penalizes those paths with higher levels of packet error rate.

We also calculated the paths' bit error rates  $(B_i)$  for each *i* and the resulting  $B_i$ 's are 0.00192, 0.00157, 0.00091 and 0.00045 for paths 1, 2, 3 and 4, respectively. As *L* is selected to be 512 based on Relation 12, these  $B_i$ 's must be less than 0.00195, in order for the optimization problem (Relations 6 to 8) to have an optimal solution.

The aggregate allocated rate to source-destination pair is depicted in Figure 3. It can be seen that, as specified in Constraint 7, the total allocated rates to all of the paths tend to the target value  $x_{min} = 128$ kbps.

The total PER performance of the proposed method is compared against a scenario in which equal

rates are allocated to each path in Figure 4. As the reader can verify, the proposed method outperformed the equal-share scenario.

#### Part II: Dynamic Scenario

For this part, we use the ns-2 network simulator, due to its extensive support for MANETs. Again, we generate scenarios with 50 mobile nodes distributed over a 10 m  $\times$  10 m area. We distribute the nodes, each with a transmission range of 1 m, according to the stationary distribution of the random waypoint mobility model [18]. This ensures that the stationary distribution of the nodes from the start of the simulation. The nodes are moving with the average speed of 1 m/s. Again, the multipath routing is enabled which introduced 4 disjoint paths for carrying the sourcedestination pair's traffic.

Each flow established from a source to a destination is (VBR), using an implementation of proposed iteration (Equation 44) as a transport protocol.

 $x_{\rm min}$  is selected to be 128 kbps. Paths' 1-4 capacities are considered to be equal to 50 kbps, 75 kbps, 30 kbps and 85 kbps, respectively, and their associated cross traffics are VBR sources with average rates of 7 kbps, 20 kbps, 8 kbps and 30 kbps, respectively. The 1st, 2nd, 3rd and 4th paths each consist of 5, 4, 4 and 3 wireless links. The simulation time is selected to be 100 sec.

As in part I, the  $\eta_{ij}$  parameters in Equation 1 are listed in Table 1 and  $\ell_i$  in Equation 44 is selected to be 0.0001 for each *i*.

In Figure 5, the total PER performance of the proposed method is compared with three other scenarios.

In one scenario, which we have specified in Fig-



Figure 4. Total PER comparison between the two methods.



Figure 5. Total PER comparison between the different methods.

ure 5 by *Fair share*, the rates are allocated in a dumb manner and are based on the percentage of the average-weighted available link's bandwidth. These average available bandwidths of paths 1, 2, 3 and 4 are 43 kbps, 55 kbps, 22 kbps and 55 kbps, respectively.

For example, the allocated rate to path 1 would be:

$$x_1 = \left(\frac{43}{43 + 55 + 22 + 55}.128 \text{ kbps}\right)$$
  

$$\cong 31.45 \text{ kbps}. \tag{45}$$

It is clear that this method cannot adapt itself to the channel PER conditions and this leads to the higher PER in Figure 5.

In another scenario, we have used the optimization algorithm proposed by Setton et al. [6]. We have denoted this method by *Minimum congestion*, as specified in [6]. This method attempts to minimize network congestion, focusing on congestion-related packet losses and paying less attention to wireless-related ones; this leads to worse total PER performance in comparison with the proposed method. The total PER associated with this method is depicted with the green line in Figure 5.

Another important strategy is the one proposed by Agarwal et al. [7]. They try to solve an optimization problem and their main objective is to assign some optimal rates to delay constrained data. It is clear that the final objective of this strategy is far apart from minimizing the total PER of the video traffic and only focuses on those subsets of applications that require a guaranteed maximum end-to-end delay. We have implemented this method and depicted that with the red line in Figure 5. It can be verified that its total PER performance is worse than the proposed and minimum congestion methods. Finally, we have computed the average total PER of each method in Figure 5. The average PER for the proposed, minimum congestion, delay constrained and fair-share methods are 1.7%, 1.82%, 1.88% and 1.94%, respectively, which denotes that the proposed algorithm outperforms conventional methods even in a dynamic scenario.

#### CONCLUSION

In the current work, a mathematical framework is introduced by which the rate allocation to each path of a multi-path wireless ad hoc network can be performed in such a way that the total PER is minimized. The main application of such algorithms is in rate allocation to those subsets of real-time traffic, which requires stringent maximum packet loss and minimum bandwidth (e.g. VOD). As we have used a simple LOS propagation model for the mobile, a more powerful algorithm, which can support more general multi-path fading propagation models, can be considered for future research. On the other hand, only the non-congestion related packet losses are used in the proposed method and introducing a more general framework incorporating congestion related packet losses can be regarded as another open research area.

#### REFERENCES

- Tonguz, O.K. and Ferrari, G., Ad Hoc Wireless Networks, A Communication Theoretic Perspective, John Wiley (2006).
- Royer, E.M. and Chai-Keong Toh "A review of current routing protocols for ad hoc mobile wireless networks", *IEEE Personal Communications*, pp. 46-55 (April 1999).
- Webb, W.T. and Steele, R. "Variable rate QAM for mobile radio", *IEEE Trans. on Commun.*, 43, pp. 2223-2230 (July 1995).
- Yoo, T., Lavery, R., Goldsmith, A. and Goodman, D. "Throughput optimization using adaptive technique", *Technical Report*, Wireless Systems Lab, Stanford University, CA, USA (2004).
- Setton, E. and Girod, B. "Congestion-distortion optimized scheduling of video over a bottleneck link", *IEEE International Workshop on Multimedia Signal Processing*, (MMSP'04), Siena, Italy, pp. 179-182 (Sept. 2004).
- Setton, E., Zhu, X. and Girod, B. "Congestionoptimized multi-path streaming of video over ad hoc wireless networks", *IEEE International Conference on Multimedia and Expo*, (*ICME'04*), 3, Taipei, Taiwan, pp. 1619-1622 (June 2004).
- Agarwal, R. and Goldsmith, A. "Joint rate allocation and routing for multi-hop wireless networks with delayconstrained data", *Technical Report*, Wireless Systems Lab, Stanford University, CA, USA (2004).

- Adlakha, S., Zhu, X., Girod, B. and Goldsmith, A. "Joint capacity, flow and rate allocation for multiuser video streaming over wireless ad-hoc networks", Proc. IEEE International Conference on Communications (ICC'07), Glasgow, Scotland (June 2007).
- Zhu, X., Han, S. and Girod, B. "Congestion-aware rate allocation for multipath video streaming over ad hoc wireless networks", *IEEE International Conference on Image Processing*, (ICIP'04), 4, Singapore, pp. 2547-2550 (October 2004).
- van Beek, p. and Demircin, M.U. "Delay-constrained rate adaptation for robust video transmission over home networks", *IEEE International Conference on Image Processing*, (ICIP'05), 2, Genova, Italy, pp. 173-176 (Sept. 2005).
- Haratcherev, L., Taal, J., Langendoen, K., Lagendijk, R. and Sips, H. "Optimized video streaming over 802.11 by cross layer signaling", *IEEE Communica*tions Magazine, 44(1), pp. 115-121 (Jan. 2006).
- Zhu, X. and Girod, B. "Media-aware multi-user rate allocation over wireless mesh networks", Proc. IEEE First Workshop on Operator-Assisted (Wireless Mesh) Community Networks, (OpComm'06), Berlin, Germany, pp. 1-8 (September 2006), Invited Paper.

- Handley, M., Floyd, S., Pahdye, J. and Widmer, J., TCP FriendlyRate Control (TFRC): Protocol Specification, RFC 3448 (Jan. 2003).
- Setton, E., Zhu, X. and Girod, B. "Congestion based multipath routing of multimedia data over ad hoc networks", *ICME*, Taipei-Taiwan (2004).
- Marina, M.K., Das, S.R. "On-demand multipath distance vector routing in ad hoc networks", *Proceedings* of the International Conference for Network Procotols (2001).
- Bertsekas, D. and Tsitsiklis, J., Parallel and Distributed Computation., Englewood Cliffs, NJ: Prentice-Hall (1989).
- Kelly, F.P., Maulloo, A.K. and Tan, D.K.H. "Rate control for communication networks: Shadow prices, proportional fairness and stability", *J. Oper. Res. Soc.*, 49(3), pp. 237-252 (Mar. 1998).
- Navidi, W. and Camp, T. "Stationary distributions for the random waypoint mobility model", *IEEE Transactions on Mobile Computing*, 3(1), pp. 99-108 (2004).