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DIFFERENTIATED QOS BASED ON CROSS-LAYER OPTIMIZATION IN WIRELESS AD HOC NETWORKS

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Generally, real time applications needs different levels of the Quality of Service (QoS) which must be guaranteed by the underlying network infrastructure. Wireless Ad Hoc networks introduce many technological challenges in guaranteeing these stringent QoS requirements which must be addressed. Many optimization theoretic based bandwidth allocation strategies have been developed for guaranteeing some levels of QoS for some classes of competing real-time users in wireless ad hoc networks. The rapid increase in the development of different real-time applications with stringent maximum packet loss requirements in such environments and the existence of difficulties in satisfying the pre-specified QoS limits, is a great motivation for designing some type of differentiated QoS guaranteeing mechanisms that can satisfy the demands of this class of the real-time traffics. In the current work, a cross-layer optimization framework is being developed in which, based on the packet loss information from the lower layers, optimal bandwidths are assigned to the real-time applications which need some levels of the maximum packet loss guaranties. As, each real-time application needs a different level of maximum packet loss guarantee, a weighted aggregate packet loss objective function is being introduced. The weights are proportional with the importance of the packet loss mitigation for a specific application and may be associated with some negotiated Service Level Agreement (SLA). The simulation results verify the claims.

Keywords: QoS, BER, PER, MANET, SLA
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1 Introduction

The theory of convex optimization is an important tool for many bandwidth allocation algorithms in wireline or wireless networks. Wireless ad hoc networks are computer networks in which the communication links are wireless. The network is ad hoc because each node is willing to forward data for other nodes, and so the determination of which nodes forward data is made dynamically based on the network connectivity. This is in contrast to wired network technologies in which some designated nodes, usually with custom hardware (variously known as routers, switches, hubs, and firewalls), perform the task of switching and forwarding the data. Ad hoc networks are also in contrast to managed wireless networks, in which a special

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node known as an access point manages communication among other nodes. Ad hoc networks can form a network without the aid of any pre-established infrastructure [1].

A specific set of QoS parameters (delay, jitter, packet loss, etc) must be guaranteed for each real-time application. However, for most real-time applications of wireless ad hoc networks, intrinsic time-varying topological changes provides challenging issues in guaranteeing these stringent QoS requirements.

Due to dynamic nature of these networks, traditional routing protocols are useless. So, special proactive/reactive multihop routing protocols such as DSDV/AODV are developed. Some of these routing protocols introduce more than one feasible path for a source-destination pair. These category of routing algorithms are called multipath routing algorithms [2]. Multipath routing scheme can reduce interference, improve connectivity, and allow distant nodes to communicate efficiently [2]. In multipath routing, multiple multihop routes or paths are used to send data to a given destination. This allows a higher spatial diversity gain and throughput between source and destination nodes. On the other hand, it is obvious that inherent load balancing feature of the multipath routing algorithms has the capability of reducing the congestion as well as increasing the throughput of the user traffic in multi hop wireless ad hoc networks. Moreover, using multiple paths between any source-destination pair can improve the important reliability and availability features of the routing strategy. Multipath routing can provide both diversity and multiplexing gain between source and destination.

Sending multimedia traffic over wireless ad hoc networks is a challenging issue and many active research areas exist that all try to propose a solution to the problem from different points of view.

In [3, 4] a congestion-minimized stream routing approach is adopted. In [4] the authors analyze the benefits of an optimal multipath routing strategy which seek to minimize the 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 [5], Adlakha [6] and Zhu [7] follow some congestion-aware and delay-constrained rate allocation strategies. Agarwal et al. in [5] introduce a mathematical constrained convex optimization framework by which they can jointly perform both rate allocation and routing in a delay-constrained wireless ad hoc environment. Adlakha et al. 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. They showed that their proposed method can support simultaneous multiple delay-critical application sessions such as multiuser video streaming [6].

In [4] setton et al. analyzed the benefits of optimal multipath routing on video streaming in a bandwidth limited ad hoc network. They show that in such environments the optimal routing solutions which seek to minimize the congestion, are attractive as they make use of the resources efficiently. For low latency video streaming, they propose to limit the number of routes to overcome the limitations of such solutions. To predict the performance in terms of rate and distortion, they develop a model which captures the impact of quantization and packet loss on the overall video quality.

In [8], 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 [9], where adaptive rate control at the MAC layer is applied in conjunction with adaptive rate control during live video encoding. The authors in [10] propose a media-aware multi-user rate allocation algorithm in multihop 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) [11].

Differentiated QoS enforcement is discussed in different papers such as [12, 13, 14]. In all of these papers, the objective is to optimize some parameters such as self-organization overhead and warm-up time, throughput, hand-off speed etc. which is different from the total packet error rate. By the best of our knowledge, allocating some optimal rates based on minimizing the total weighted packet loss has not been performed previously.

In the current work, a similar approach such as [5] is being adopted by which a constrained optimization framework is introduced for optimal rate allocation to the real-time applications. In [4], 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.

The presented work in this paper differs from [5] and [4] in that we have used the aggregate weighted packet loss as a QoS metric in place of the constrained-delay and the congestion level criteria used in [5] and [4] respectively. In order to compute the total packet loss, we have assumed that multiple sources use the same wireless ad hoc medium for transmission and their associated losses are additive [4]. On the other hand, the presented work differs from [5] in considering more than one (and possibly interfering) multipath-routed sources which compete for the available bandwidth in a bandwidth limited wireless ad hoc network.

The paper's objective is to develop an optimal bandwidth allocation framework bases on which, the overall weighted packet loss of all of the sources is minimized. We also have used a penalty function approach for finding an iterative solution algorithm for the proposed constrained optimization problem such as those introduced in [15, 16].

The major contributions of this paper can be summarized as follows:

First, we formulate the so-called *aggregated weighted packet loss* in wireless ad hoc networks mathematically. Second, we solve the resulting optimization problem for converging to an optimal solution.

2 Proposed Optimization Framework

2.1 Preliminary Concepts

Consider the multihop wireless ad hoc network depicted in the Figure1. Assume that there exist $\mathcal{N}$ sources and the existing multipath routing protocol introduces n_k disjoint multihop paths between each source-destination pair (S_k, D_k) periodically $(1 \leq k \leq \mathcal{N})$. 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_k is selected based on the assumption of availability of the current paths throughput information for the source node S_k and the sufficiency of the aggregate estimated throughput for the traffic's minimum bandwidth requirements. Each path j related to the source k contains $\mathcal{M}_{jk}$ wireless links

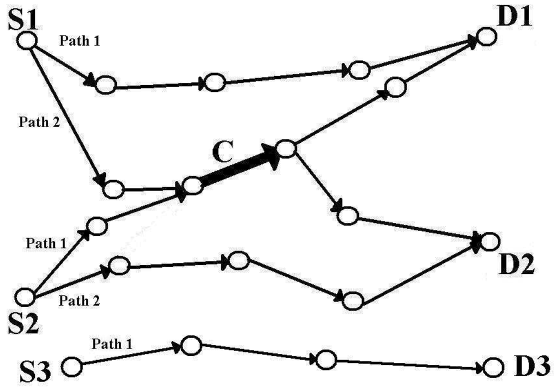

Fig. 1 Three competing multipath-routed sources

from source to destination for $1 \leq j \leq n_k$.

We assume a simple strong Line Of Sight (LOS) with BPSK signaling for node's wireless transmissions and also neglect the interfering effect of wireless transmissions between different paths [1]. The mentioned assumption can be realised by using the BPSK Direct Sequence Spread Spectrum (DSSS) with different spreading code in the physical layer of each path. As the Bit Error Rate (BER) performance of the BPSK spread spectrum system in an AWGN environment is identical to that of conventional coherent BPSK system [17], it is sufficient to calculate the latter performance for evaluating the BER of the proposed system.

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 and this leads to the coding gain γ.

In the current paper, the main objective is to minimize the aggregate weighted packet loss associated with multiple real-time sources. Thus, a mathematical formulation must be presented that express the packet loss of each source in terms of its allocated bandwidth. In the following paragraphs, the packet error rate computation method is presented.

The BER of the link i in the j'th path of the k'th video source can be represented for a simple strong LOS propagation model with BPSK signaling as follows [1]:

$$b_{ijk} = \frac{1}{\sqrt{2\pi}} \int_{\frac{\eta_{ijk}}{\sqrt{r_{ijk}}}}^{\infty} e^{-x^2/2} dx \qquad \forall j, k, i \in \mathcal{R}_{jk} \tag{1}$$

η_{ijk} is a function of physical environment and the transmission power. $\mathcal{R}_{jk}$ is the (nonempty) set of wireless links associated with the j'th flow of the k'th video source and r_{ijk} is the the total transmission rate associated with the i'th link in the j'th flow of the k'th source respectively. We assume that the transmitted power is fixed during transmission and therefore do not depends on the transmission data rate r_{ijk}.

Assume that $\mathcal{R}_{jk}$ can be partitioned in two disjoint subsets. One subset is associated with those wireless links that are common between more than one video sources which we denote by $\mathcal{R}^c_{jk}$ (it is assumed that this subset is not empty) and the other set contains non-common wireless links which we denote by $\mathcal{R}^{nc}_{jk}$.

We represent the set cardinality operator by $|.|$, so we have $|\mathcal{R}_{jk}| = \mathcal{M}_{jk}$. We also assume that $|\mathcal{R}^{nc}_{jk}| = \mathcal{O}_{jk}$ and thus we have $|\mathcal{R}^{c}_{jk}| = \mathcal{M}_{jk} - \mathcal{O}_{jk}$.

The r_{ijk} consists of two components: one is the traffic rate allocated to the j'th flow of the k'th source which is denoted by x_{jk} and another part is associated with the time-varying i'th link's cross (background) traffic a_{ijk}. Thus we have:

$$r_{ijk} = x_{jk} + a_{ijk} \qquad \forall k, j, i \in \mathcal{R}_{jk} \tag{2}$$

So, the available capacity (throughput) is denoted by e_{ijk} and is equal to $e_{ijk} = \mathcal{C}_{ijk} - a_{ijk}$. Where $\mathcal{C}_{ijk}$ is the capacity of the link i in the j'th path of the k'th video source.

In some cases (as is depicted in Figure1), two or more multi-path video sources may compete for a common wireless link (in the Figure1 this link is shown by bold line). Therefore, the available capacity of the common link must be shared between the competing flows in an optimal manner.

Assume that for each common link $i \in \mathcal{R}^{c}_{jk}$ there exists an associated set $\mathcal{S}^{i}_{jk}$ which represents the set of all ordered pairs (*path,source*) that use the common link i in the path j of the source k (for example, in Figure1, the path 1 of source 2 share the common link **C** with the path 2 of source 1). So the ingress and egress nodes associated with this common link are common between more than one flows.

For common links we assume that background traffic is composed only of those flows which are in $\mathcal{S}^{i}_{jk}$, i.e. we can write:

$$a_{ijk} = \sum_{(u,v)\in\mathcal{S}^{i}_{jk}} x_{uv} \qquad \forall k, j, i \in \mathcal{R}^{c}_{jk} \tag{3}$$

With the assumption of independent links' bit error rate, the total bit error rate along the j'th path of the k'th source can be calculated as follows:

$$\mathcal{B}_{jk} = 1 - \prod_{i=1}^{\mathcal{M}_{jk}} (1 - b_{ijk}) \qquad \forall j, k \tag{4}$$

The total Packet Error Rate (PER) of the j'th path of the k'th video source is composed of the congestion-related and Non congestion-related (wireless link) losses which we denote by $p^{\mathcal{Q}}_{j,k}$ and $p^{\mathcal{R}}_{j,k}$ respectively.

If the FEC induced error correction capability of a packet with length L bits is M bits ($M > 1$) and with the assumption of independent bit errors (lack of burst errors), the wireless link-related PER along the j'th path (flow) of the k'th source can be calculated as:

$$p^{\mathcal{R}}_{jk} = 1 - \sum_{m=0}^{M} \binom{L}{m} \mathcal{B}^{m}_{jk} (1 - \mathcal{B}_{jk})^{L-m} \qquad \forall j, k \tag{5}$$

Now we are in a position that must compute the congestion-related part of the PER.

First, assume that the end-to-end queueing delay of the j'th path of the k'th source can be represented with a random variable with the probability density function (*pdf*) $\beta_{jk}(t)$.

By adopting the same approach as in [5], it can be assume that congestion-related packet loss occurs when the end-to-end queuing delay of the j'th path of the k'th source exceeds a predetermined threshold Δ_{jk}. In mathematical terms the mentioned fact can be represented as follows:

$$p^{\mathcal{Q}}_{jk} = \int_{\Delta_{jk}}^{\infty} \beta_{jk}(t)dt \qquad \forall j,k \tag{6}$$

As in [5] simple M/M/1 queueing model and First In First Out (FIFO) service discipline are adopted for the nodes. With the assumption of M/M/1 queueing model, the service time of each queue is an exponentially distributed random variable [18]. We also assume that these service times are independent. On the other hand, the end-to-end delay of each path j belonging to the video source k is equal to the sum of these independent random variables. Ignoring the source and destination nodes (hops), the total number of nodes in $\mathcal{R}_{jk}$, the number of non-common nodes in $\mathcal{R}^{nc}_{jk}$ and common nodes in $\mathcal{R}^{c}_{jk}$ would be $\mathcal{M}_{jk}-1$, $\mathcal{O}_{jk}-2$ and $\mathcal{M}_{jk}-\mathcal{O}_{jk}+1$ respectively for each j,k.

Based on [19], for the nodes in $\mathcal{R}_{jk}$, the delay distribution (*pdf*) can be represented by *exponential* distribution as follows:

$$f_{ijk}(t) = \frac{e^{-t/\alpha_{ijk}}}{\alpha_{ijk}} \qquad \forall k,j,i \in \mathcal{R}_{jk} \tag{7}$$

where we can write as in [6]:

$$\alpha_{ijk} = \begin{cases} (e_{ijk} - x_{jk})^{-1} & \forall j,k,i \in \mathcal{R}^{nc}_{jk} \\ \left(\mathcal{C}_{ijk} - \sum_{(u,v)\in\mathcal{S}^{i}_{jk}} x_{uv} - x_{jk}\right)^{-1} & \forall k,j,i \in \mathcal{R}^{c}_{jk} \end{cases} \tag{8}$$

Thus the probabilistic distribution function of the end-to-end delay ($\beta_{jk}(t)$) is the convolution of all of these *pdf*'s [18]. On the other hand, we can write:

$$\beta_{jk}(t) = \overbrace{f_{1jk}(t) * \cdots * f_{njk}(t)}^{\mathcal{M}_{jk}-1} \qquad \forall j,k \tag{9}$$

where $n = \mathcal{M}_{jk} - 1$ is the number of nodes in $\mathcal{R}_{jk}$, $*$ is the *convolution* operator and $f_{1jk} \cdots f_{njk}$ are the *pdf*'s associated with all of the nodes which reside in $\mathcal{R}_{jk}$.

The total PER related to the j'th flow of the k'th source can be simply shown that is equal to:

$$p_{jk} = 1 - (1 - p^{\mathcal{R}}_{jk})(1 - p^{\mathcal{Q}}_{jk}) \qquad \forall j,k \tag{10}$$

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

$$p^{k}_{T} = 1 - \prod_{j=1}^{n_k}(1 - p_{jk}) \qquad \forall k \tag{11}$$

We assume that the aggregate weighted packet loss can be computed as follows:

$$\mathcal{P}_T \triangleq \sum_{k=1}^{\mathcal{N}} \xi_k \cdot p^{k}_{T} \tag{12}$$

where $\xi_k > 0$ are the weights associated with the priority of each real-time application.

2.2 Optimal Rate Allocation

The main objective of the current paper is to design an optimal rate allocation algorithm which minimizes the weighted total packet loss associated with multiple competing video sources. The formulation of the proposed minimum weighted total packet loss rate allocation problem can be formulated as follows:

$$\min \mathcal{P}_T \tag{13}$$

subject to:

$$\sum_{j=1}^{n_k} x_{jk} \geq x_{k,min} \qquad \forall k \tag{14}$$

$$0 \leq x_{jk} \leq \min_i (e_{ijk}) \qquad \forall j,k,i \in \mathcal{R}_{jk} \tag{15}$$

in which $x_{k,min}$ is the minimum required bandwidth for the k'th real-time source.

We must now remind our previous assumption that, the parameter n_k is assumed to be large enough such that the constraint (14) is met for all k.

Suppose that the optimal solution vector of the system (13-15) be defined as follows:

$$\chi^* \triangleq \left(x^*_{11}x^*_{21}...x^*_{n_1 1}...x^*_{1\mathcal{N}}...x^*_{n_\mathcal{N}\mathcal{N}}\right) \tag{16}$$

Now, we propose two theorems by which the existence and uniqueness of the solution vector χ^* for the optimization problem (13-15) can be guaranteed.

Theorem 1: Consider a typical multihop wireless ad hoc network. Assume that the following assumption holds:

$$0 \leq \mathcal{B}_{jk} < \frac{1}{L} \qquad \forall j,k \tag{17}$$

Then, there exist some M such that the following holds:

$$\frac{\partial^2 p^{\mathcal{R}}_{jk}}{\partial r_{mjk} \partial r_{njk}} > 0 \qquad \forall k,j,m,n \in \mathcal{R}_{jk} \tag{18}$$

Proof: See Appendix A.

Theorem 2: Assume $\mathcal{M}_{jk} - 1 > 1$ and consider that there exists the possibility of multiple congested links in path j of the source k. Based on the assumption (17) in the theorem 1 and the following assumption, there exists a unique and optimal solution vector for the optimization problem (13-15).

$$\Delta_{jk} > \frac{-\frac{\partial \sigma_{jk}}{\partial x_{jk}} + \sqrt{\left(\frac{\partial \sigma_{jk}}{\partial x_{jk}}\right)^2 - \sigma_{jk}\frac{\partial^2 \sigma_{jk}}{\partial x^2_{jk}}}}{\sigma_{jk}} \qquad \forall j,k \tag{19}$$

in which:

$$\sigma_{jk} \triangleq \prod_{i=1}^{\mathcal{M}_{jk}-1} (\alpha_{ijk})^{-1}$$

Proof: See Appendix B.

Many iterative and optimal rate allocation algorithms have been proposed which lead to the optimal solution of constrained optimization problem (13-15) [16]. From these algorithms we have selected the penalty function approach. A typical convex penalty function must be convex.

It is shown in [16] that for solving the mentioned constrained optimization problem it is adequate to solve the following unconstrained one:

$$\mathcal{V}(\chi) \triangleq \mathcal{P}_T + \sum_k \int_0^{x_{kmin}-\sum_j x_{jk}} q(y)dy \tag{20}$$

Theorem 3: Assume that (18) is true and consider the following update rule:

$$\frac{d}{dt}x_{jk} = -\delta_{jk}\frac{\partial}{\partial x_{jk}}\mathcal{V}(\chi) \qquad \forall j,k \tag{21}$$

where $\delta_{jk} > 0$ is a small positive constant. Then, the function $\mathcal{V}(.)$ is a Lyapunov function for the mentioned system (21) to which all the trajectories converge.

Proof: See Appendix C.

As we can see from assumptions (17) and (19), for guaranteeing the uniqueness of the solution vector in optimization problem (13-15), it is necessary that the x_{jk} variables remain in the constraint set ζ. So, we must solve a projected version of unconstrained optimization (20) [16]. The iterative gradient descent solution for solving the unconstrained problem (20) would be the discrete-time version of (20) as follows:

$$x_{jk}[n+1] = \left\{ x_{jk}[n] - \delta_{jk}\frac{\partial \mathcal{V}}{\partial x_{jk}}\bigg|_{x_{jk}=x_{jk}[n]} \right\}_{x_{jk}[n]\in\zeta} \qquad \forall j,k \tag{22}$$

where δ_{jk} is some positive and sufficiently small constant. Again, it must be stressed that the iterative algorithm in (22), allocates some rates to each path j of the video source k. By selecting the δ_{jk} parameters small enough, these allocated rates eventually converge to the optimal solution vector χ^* [15].

3 Numerical Analysis

For this part, we use the ns-2 network simulator due to its extensive support for Mobile Ad hoc NETworks (MANETs) [20]. We generate an experimental scenarios with 50 mobile nodes distributed over a $20^m \times 20^m$ area. We distribute the nodes, each with a transmission range of 2^m, according to the stationary distribution of the random waypoint mobility model [21]. This ensures that the distribution of the nodes remains stationary from the start of the simulation. We have used the BonnMotion tool for random waypoint mobility model generation. This ensures that the distribution of the nodes remains stationary from the start of the simulation. The nodes are moving with the average speed of $4^{m/s}$. AOMDV multipath routing protocol

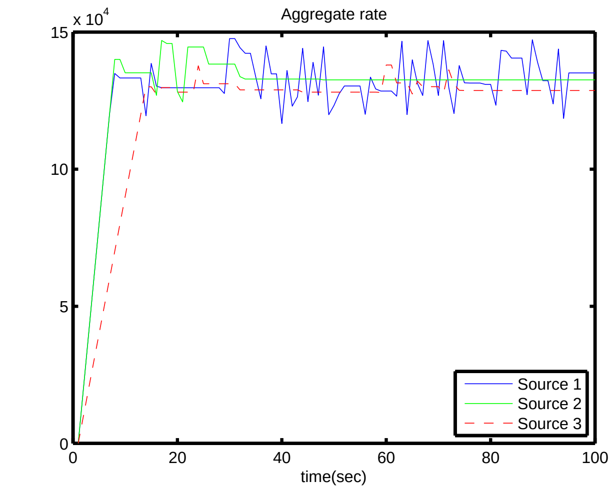

Fig. 2 Aggregate rate of sources 1, 2 and 3

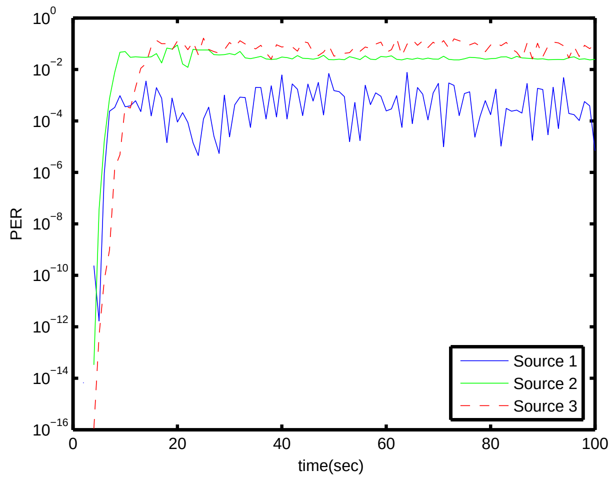

Fig. 3 PER of sources 1, 2 and 3

has been implemented [22]. The simulation setup is consisted of 3 video source-destination pairs and the routing protocol introduces 4 disjoint paths for each video source. Each flow established from a source to a destination uses an implementation of the proposed iteration (22) as a transport protocol. x_{min} is selected to be 128^{kbps} for each video source. Wireless link bandwidth is selected to be 90^{kbps}. There exist 12 VBR sources-destination pairs with average rate of 60^{kbps} which behave like cross traffics. Other simulation parameters are listed in the Table 1.

The simulation results are obtained after averaging between 100 independent runs of the simulation by properly setting the PRNG seed [20]. The aggregate allocated rate to source-

Table 1 Simulation parameters of dynamic scenario

Parameter	***Value***
MAC standard	802.11
Antenna type	Omni
Interface queue type	Drop tail
Mobility model	Random waypoint
Propagation model	Two-ray ground
Routing protocol	AOMDV
Interface buffer size	50 packets
Packet size (L)	1000 bits
Average node speed	$4^{m/s}$
Simulation time	100^{sec}
x_{min}	128^{kbps}
Number of paths/video source (n_k)	4
Number of video sources ($\mathcal{N}$)	3
Number of simulation runs	100
Link bandwidth	90^{kbps}
Number of VBR sources	12
Average VBR rate	60^{kbps}
δ_{jk}	0.01
Δ_{jk}	5^{ms}
M	2
(ξ_1, ξ_2, ξ_3)	(11.9,2.1,.1)

destination pairs are depicted in Figure2. The average aggregate rate of sources 1, 2 and 3, are above the threshold $x_{min} = 128^{Kbps}$ (128.9^{Kbps}, 130.3^{Kbps} and 128.3^{Kbps} respectively). As can be verified from Figure2, the allocated rates have fluctuations. These fluctuations are the direct consequence of competition between the rates allocated to the paths and the VBR cross traffics for consuming the link capacities.

In Figure3, the average PER performance of three sources have been compared. As it can be verified, more attention is being paid to source 1 which have higher ξ value.

4 Conclusions

In the current work, an optimization framework is introduced by which the rate allocation to each path of a multipath wireless ad hoc network can be performed in such a way that the weighted total packet loss of multiple video sources resulting from the network congestion and wireless environment can be minimized.

Main application of such algorithms is in rate allocation to those subsets of real-time traffics which require a selective level of differentiation in the incurred quality level (packet loss). These differentiation can be performed by the network operator by setting some levels of SLA between operator and users based on some subscription prices. As we have used a simple LOS propagation model for the mobile nodes and considered the nodes mobility only through simulation, a more powerful algorithm which can support more general multipath fading propagation models and includes the impact of the mobility phenomenon in the rate allocation algorithm, can be considered for future research.

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Appendix A

From (5) we have:

$$\frac{\partial p_{jk}^{\mathcal{R}}}{\partial r_{mjk}} = -\frac{\partial \mathcal{B}_{jk}}{\partial r_{mjk}} \varphi_{jk} \qquad \forall k, j, m \in \mathcal{R}_{jk} \tag{A.1}$$

where:

$$\varphi_{jk} \triangleq \sum_{m=1}^{M} \binom{L}{m} (m - L \cdot \mathcal{B}_{jk}) \mathcal{B}_{jk}^{m-1} (1 - \mathcal{B}_{jk})^{L-m-1} - L \cdot (1 - \mathcal{B}_{jk})^{L-1} \qquad \forall i \tag{A.2}$$

Similarly we can write:

$$\frac{\partial^2 p_{jk}^{\mathcal{R}}}{\partial r_{mjk} \partial r_{njk}} = -\varphi_{jk} \frac{\partial^2 \mathcal{B}_{jk}}{\partial r_{mjk} \partial r_{njk}} - \psi_{jk} \frac{\partial \mathcal{B}_{jk}}{\partial r_{mjk}} \cdot \frac{\partial \mathcal{B}_{jk}}{\partial r_{njk}} \qquad \forall k, j, m, n \in \mathcal{R}_{jk} \tag{A.3}$$

where for each j, k we have:

$$\psi_{jk} = \frac{\partial \varphi_{jk}}{\partial \mathcal{B}_{jk}} \tag{A.4}$$

From (1) and (4) and taking simply the partial derivatives, we can conclude that $\forall k, j, m, n \in \mathcal{R}_{jk}, m \neq n$:

$$\frac{\partial \mathcal{B}_{jk}}{\partial r_{mjk}} > 0, \qquad \frac{\partial^2 \mathcal{B}_{jk}}{\partial r_{mjk} \partial r_{njk}} < 0 \tag{A.5}$$

and also:

$$\frac{\partial^2 \mathcal{B}_{jk}}{\partial r_{ijk}^2} = \left[\prod_{\substack{m=1 \\ m \neq i}}^{\mathcal{M}_{jk}} (1 - b_{mjk}) \right] \frac{\eta_{ijk} \cdot r_{ijk}^{-7/2} \cdot e^{-\eta_{ijk}^2 / r_{ijk}}}{2\sqrt{2\pi}} \cdot \left(\eta_{ijk}^2 - \frac{3}{2} r_{ijk} \right) \qquad \forall k, j, i \in \mathcal{R}_{jk} \tag{A.6}$$

For proving the theorem, we consider two different cases.

a) Consider the case $m \neq n$:
Based on (A.3) and the definition of $\mathcal{B}_{jk}$ we can write $\forall k, j, m, n \in \mathcal{R}_{jk}$:

$$\frac{\partial^2 p_{jk}^{\mathcal{R}}}{\partial r_{mjk} \partial r_{njk}} = -\frac{\partial^2 \mathcal{B}_{jk}}{\partial r_{mjk} \partial r_{njk}} \left(\varphi_{jk} - (1 - \mathcal{B}_{jk})\psi_{jk}\right) \tag{A.7}$$

By considering $M = 2$ and based on assumption (17) we can write $\forall j, k$:

$$\varphi_{jk} - (1 - \mathcal{B}_{jk})\psi_{jk} = -L(L-1)(L-2) \cdot \mathcal{B}_{jk} \cdot (\frac{L}{2}\mathcal{B}_{jk} - 1)(1 - \mathcal{B}_{jk})^{L-3} > 0 \tag{A.8}$$

From (A.7-A.8) it can be concluded that (18) is true for $m \neq n$.
b) Consider the case $m = n$:
First, from $M = 2$ and the assumption (17) it can be easily concluded from (A.2) and (A.4) that:

$$\varphi_{jk} < 0, \qquad \psi_{jk} < 0 \qquad \forall j, k \tag{A.9}$$

As usually we have $L >> 1$, from (17) it can be concluded that $\mathcal{B}_{jk} << 1$. From (4) it can be easily concluded that $b_{ijk} \leq \mathcal{B}_{jk} << 1, \forall k, j, i$ and based on (1) we have:

$$b_{ijk} << 1 \Rightarrow \frac{\eta_{ijk}}{\sqrt{r_{ijk}}} > \sqrt{\frac{3}{2}} \tag{A.10}$$

From (A.3), (A.6) and (A.9-A.10) it can be concluded that:

$$\frac{\partial^2 p_{jk}^{\mathcal{R}}}{\partial r_{ijk}^2} > 0 \qquad \forall k, j, i \in \mathcal{R}_{jk} \tag{A.11}$$

Which completes the proof $\square$.

Appendix B

Since the constraint set is convex, in order for the constrained optimization problem (13-15) to have a unique and optimal solution vector χ^*, it is necessary and sufficient that the following Lagrangian equation have positive second derivatives with respect to all of the x_{jk} variables [16].

$$\Psi(\chi) \triangleq \mathcal{P}_T - \sum_{k=1}^{\mathcal{N}} \lambda_k \left(\sum_{j=1}^{n_k} x_{jk} - x_{k,min} \right) - \sum_{k=1}^{\mathcal{N}} \sum_{j=1}^{n_k} \lambda_{jk} \left(\min_i (e_{ijk}) - x_{jk} \right) \tag{B.1}$$

where λ_{jk} and λ_k are the positive lagrange multipliers.
From (B.1) we can write:

$$\frac{\partial^2 \Psi}{\partial x_{jk}^2} = \frac{\partial^2 \mathcal{P}_T}{\partial x_{jk}^2} \qquad \forall j, k \tag{B.2}$$

From (12) we have:

$$\frac{\partial^2 \mathcal{P}_T}{\partial x_{jk}^2} = \xi_k \frac{\partial^2 p_{jk}}{\partial x_{jk}^2} \left[\prod_{\substack{u=1 \\ u \neq j}}^{n_k} (1 - p_{uk}) \right] + \sum_{\substack{v=1 \\ v \neq k}}^{\mathcal{N}} \xi_v \frac{\partial^2}{\partial x_{jk}^2} \left[\prod_{u=1}^{n_v} (1 - p_{uv}) \right] \qquad \forall j, k \tag{B.3}$$

If we assume that the congestion-related and wireless-link losses are small enough, the equation (10) can be simplified as follows:

$$p_{jk} \cong p_{jk}^{\mathcal{R}} + p_{jk}^{\mathcal{Q}} \qquad \forall j, k \tag{B.4}$$

From (B.4) we can write:

$$\frac{\partial^2 p_{jk}}{\partial x_{jk}^2} = \frac{\partial^2 p_{jk}^{\mathcal{R}}}{\partial x_{jk}^2} + \frac{\partial^2 p_{jk}^{\mathcal{Q}}}{\partial x_{jk}^2} \qquad \forall j, k \tag{B.5}$$

In general, from congestion point of view, we can partition the wireless links in $\mathcal{R}_{jk}$ to two other disjoint sets. One set is related to the congested links ($r_{ijk} = \mathcal{C}_{ijk}$) associated with common nodes in $\mathcal{R}_{jk}^c$ which we denote by $\overline{\mathcal{R}}_{jk}$ and the other is associated with non-congested ones ($r_{ijk} < \mathcal{C}_{ijk}$) and will be denoted by $\mathcal{R}_{jk} \setminus \overline{\mathcal{R}}_{jk}$.

Hence, by considering the above fact and the equation (2), we can write:

$$\frac{\partial r_{ijk}}{\partial x_{jk}} = \begin{cases} 0 & \forall k, j, i \in \overline{\mathcal{R}}_{jk} \\ 1 & \forall k, j, i \in \mathcal{R}_{jk} \setminus \overline{\mathcal{R}}_{jk} \end{cases} \tag{B.6}$$

From chain rule, (18) and (B.6) we can write:

$$\frac{\partial^2 p_{jk}^{\mathcal{R}}}{\partial x_{jk}^2} = \sum_{m \in \mathcal{R}_{jk} \setminus \overline{\mathcal{R}}_{jk}} \sum_{n \in \mathcal{R}_{jk} \setminus \overline{\mathcal{R}}_{jk}} \frac{\partial^2 p_{jk}^{\mathcal{R}}}{\partial r_{mjk} \partial r_{njk}} > 0 \tag{B.7}$$

From (6) it can be shown that:

$$\frac{\partial^2 p_{jk}^{\mathcal{Q}}}{\partial x_{jk}^2} = \int_{\Delta_{jk}}^{\infty} \frac{\partial^2 \beta_{jk}(t)}{\partial x_{jk}^2} dt \tag{B.8}$$

It is clear that the delay distribution function of each node has exponential form. Equation (9) can be re-written for $n = \mathcal{M}_{jk} - 1 > 2$ as:

$$\beta_{jk}(t) = \underbrace{\int_0^t \int_0^{t-\tau_{n-1}} \cdots \int_0^{t-\sum_{m=2}^{n-1} \tau_m}}_{n-1} \prod_{\substack{m=1 \\ m \neq 2}}^{n} f_{mjk}(\tau_{m-1}) \cdot f_{2jk}(t - \sum_{m=1}^{n-1} \tau_m) d\tau_{n-1} \cdots d\tau_1 \qquad \forall j, k \tag{B.9}$$

For $n = 2$ we have:

$$\beta_{jk}(t) = \int_0^t f_{1jk}(\tau_1) f_{2jk}(t - \tau_1) d\tau_1 \qquad \forall j, k$$

From preliminary calculus, (7) and (B.9) we have:

$$\beta_{jk}(t) = \prod_{i=1}^{\mathcal{M}_{jk}-1} s_{ijk} e^{-s_{1jk} t} \cdot \mathcal{A}_{jk}(t) \qquad \forall j, k \tag{B.10}$$

in which:

$$s_{ijk} \triangleq \alpha_{ijk}^{-1} \qquad \forall j, k, i$$

and for $n = \mathcal{M}_{jk} - 1 > 2$ we have:

$$\mathcal{A}_{jk}(t) \triangleq \underbrace{\int_0^t \int_0^{t-\tau_{n-1}} \cdots \int_0^{t-\sum_{m=2}^{n-1}\tau_m}}_{n-1} e^{-u_{jk}(t)} d\tau_{n-1} \cdots d\tau_1 \qquad \forall j,k \tag{B.11}$$

in which:

$$u_{jk}(t) \triangleq \sum_{m=3}^{n} (s_{mjk} - s_{1jk})\tau_{m-1} + (s_{2jk} - s_{1jk}) \cdot (t - \sum_{m=1}^{n-1} \tau_m) \qquad \forall j,k \tag{B.12}$$

for $n = 2$ we have:

$$\mathcal{A}_{jk}(t) \triangleq \int_0^t e^{-v_{jk}(t)} d\tau_1 \qquad \forall j,k$$

in which:

$$v_{jk}(t) \triangleq (s_{2jk} - s_{1jk})(t - \tau_1)$$

It can be deducted from (7) and (B.12) that $\mathcal{A}_{jk}(.) > 0$ is not a function of x_{jk}. So, in order for the equation (B.8) to be positive and based on (B.10), it is sufficient that we have:

$$\frac{\partial^2}{\partial x_{jk}^2} \prod_{i=1}^{\mathcal{M}_{jk}-1} s_{ijk} e^{-s_{1jk}t} = \frac{\partial^2}{\partial x_{jk}^2} \sigma_{jk} e^{-s_{1jk}t} > 0 \qquad \forall j,k \tag{B.13}$$

By taking derivatives, and considering the fact that $t \geq \Delta_{jk}$, for proving the positiveness of (B.13), it is sufficient that:

$$\frac{\partial^2 \sigma_{jk}}{\partial x_{jk}^2} + 2t \frac{\partial \sigma_{jk}}{\partial x_{jk}} + t^2 \sigma_{jk} > 0 \qquad \forall j,k \tag{B.14}$$

Since $\sigma_{jk} \geq 0$, it is sufficient that:

$$t > \frac{-\frac{\partial \sigma_{jk}}{\partial x_{jk}} + \sqrt{\left(\frac{\partial \sigma_{jk}}{\partial x_{jk}}\right)^2 - \sigma_{jk} \frac{\partial^2 \sigma_{jk}}{\partial x_{jk}^2}}}{\sigma_{jk}} \qquad \forall j,k \tag{B.15}$$

Which is valid when assumption (19) be true and also $t \geq \Delta_{jk}$.

From above relations it can be concluded that:

$$\frac{\partial^2 p_{jk}^{\mathcal{Q}}}{\partial x_{jk}^2} > 0 \qquad \forall j,k \tag{B.16}$$

From (B.5), (B.7) and (B.16) we can conclude that:

$$\frac{\partial^2 p_{jk}}{\partial x_{jk}^2} > 0 \qquad \forall j,k \tag{B.17}$$

Note that at this point, the first term of equation (B.3) is positive. Now, we must show that the second term of equation (B.3) is also positive.

It is obvious (by taking into account the assumption of independence between packet error rate associated with different paths) that if path u of the source v be disjoint from path j of the source k, we have:

$$\frac{\partial^2 p_{uv}}{\partial x_{jk}^2} = 0$$

Hence, from now on, we assume that path u of the source v be common with path j of the source k in some links.

Similar to equation (A.3) we can write:

$$\frac{\partial^2 p_{uv}^{\mathcal{R}}}{\partial r_{mjk} \partial r_{njk}} = -\varphi_{uv} \frac{\partial^2 \mathcal{B}_{uv}}{\partial r_{mjk} \partial r_{njk}} - \psi_{uv} \frac{\partial \mathcal{B}_{uv}}{\partial r_{mjk}} \cdot \frac{\partial \mathcal{B}_{uv}}{\partial r_{njk}} \qquad \forall u, v, k, j, m, n \in \mathcal{R}_{uv} \tag{B.18}$$

where φ_{uv} and ψ_{uv} can be defined as in (A.2) and (A.4) respectively.

Note that if $m, n \in \mathcal{R}_{uv}^c \bigcap \mathcal{R}_{jk}^c$ we have $r_{mjk} = r_{muv}, r_{njk} = r_{nuv}$.

On the other hand,if m or $n \notin \mathcal{R}_{uv}^c \bigcap \mathcal{R}_{jk}^c$ we have:

$$\frac{\partial^2 p_{uv}^{\mathcal{R}}}{\partial r_{mjk} \partial r_{njk}} = 0 \tag{B.19}$$

Similar to the results in the theorem 1 for $M = 2$ we have:

$$\frac{\partial^2 p_{uv}^{\mathcal{R}}}{\partial r_{mjk} \partial r_{njk}} = \frac{\partial^2 p_{uv}^{\mathcal{R}}}{\partial r_{muv} \partial r_{nuv}} > 0 \qquad \forall u, v, k, j, m, n \in \mathcal{R}_{uv}^c \bigcap \mathcal{R}_{jk}^c \tag{B.20}$$

If we define $\mathcal{W}_{uvjk} \triangleq \mathcal{R}_{jk}^c \bigcap \mathcal{R}_{uv}^c \setminus \overline{\mathcal{R}}_{uv}$, then similar to equation (B.7) we can write::

$$\frac{\partial^2 p_{uv}^{\mathcal{R}}}{\partial x_{jk}^2} = \sum_{m \in \mathcal{W}_{uvjk}} \sum_{n \in \mathcal{W}_{uvjk}} \frac{\partial^2 p_{uv}^{\mathcal{R}}}{\partial r_{muv} \partial r_{nuv}} > 0$$

(B.21)

Similar to the steps in (B.8-B.16) we can write:

$$\frac{\partial^2 p_{uv}^{\mathcal{Q}}}{\partial x_{jk}^2} \geq 0 \qquad \forall j, k, u, v \tag{B.22}$$

Thus we can write:

$$\frac{\partial^2 p_{uv}}{\partial x_{jk}^2} \geq 0 \qquad \forall j, k, u, v \tag{B.23}$$

Now, from equation (B.23) we can conclude that the third term in (B.3) must be positive and finally based on (B.3), (B.17) and (B.23) we have:

$$\frac{\partial^2 \mathcal{P}_T}{\partial x_{jk}^2} > 0 \qquad \forall j, k \tag{B.24}$$

From (B.24) and the convexity of the constraint set (14-15), it can be resulted that the constrained optimization problem (13) has a unique and optimal solution vector χ^* [16] $\square$.

Appendix C

First, we must show that $\mathcal{V}(.)$ is convex. From (B.24) and the convexity of function $q(.)$ we have:

$$\frac{\partial^2 \mathcal{V}}{\partial x_{jk}^2} = \frac{\partial^2 \mathcal{P}_{\mathcal{T}}}{\partial x_{jk}^2} + q' \left(x_{kmin} - \sum_j x_{jk} \right) > 0, \forall j, k \tag{C.1}$$

From equations (20-21) and the chain-rule we can write:

$$\dot{\mathcal{V}}(\chi) = \frac{d\mathcal{V}}{dt} = \sum_k \sum_j \frac{\partial \mathcal{V}}{\partial x_{jk}} \cdot \frac{dx_{jk}}{dt} = -\sum_k \sum_j \delta_{jk} \left(\frac{\partial \mathcal{V}}{\partial x_{jk}} \right)^2 \leq 0 \tag{C.2}$$

Thus, $\mathcal{V}(.)$ is a Lyapunov function for the continuous-time system (21) and the vector χ^* is an equilibrium point of the system (13-15) to which all of the trajectories converge $\square$.