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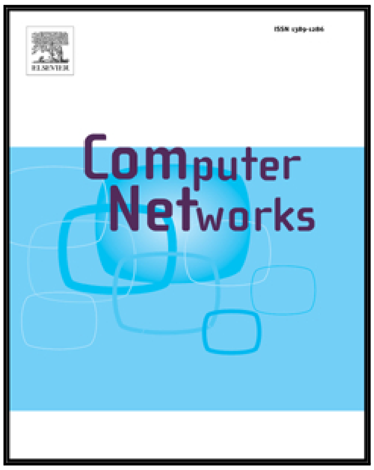

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Using Flow Cost to Globally Allocate and Optimize Limited Bandwidth in Multipath Routing

Junxiao He[1], Oliver Yang[1]and Yifeng Zhou[2]
[1]School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa,Canada
[2]Communication Research Centre, Ottawa, Ontario, Canada
E-mail: jhe052@uottawa.ca

Abstract—This paper studies a globally-aware optimization scheme for the allocation oflimited bandwidth in awireless ad hoc network using multipath routing. We assign a FC (Flow Cost) as a function of end-to-end delay, power consumption and hop distance so that we can select the best subset of multiple paths. Using the FC allowsus to consider not only the current local transmission, but also any global transmissionsfrom other parts of the networkthat converge at a CN (Crowded Node), hence providing an effective bandwidth allocation scheme for our multipath routing. In order to improve the routing discovery efficiency, we have proposedthe HCZ (Half-Circle Zone) scheme along with node-disjoint sorting to cut down the size of the RPT (Routing Path Table). Utilization factor is also used in the objective function of the optimization in order to take queueing performance into account. Some allocation evaluation by AIMMS (Advanced Integrated Multidimensional Modeling Software) is provided to demonstrate the capability of this algorithm.Implementation, simulation and performance evaluations/comparisons in Opnet 14.5have been carried out based on the optimization results.

Keywords—Wireless Ad hoc Network; Limited Bandwidth Allocation; Optimization; Globally-Aware Multipath Routing

1. Introduction

Wireless Ad hoc Network has attracted significant attention in recent years because no fixed infrastructure is required; its communicating nodes can cooperate to maintain network connectivity even when randomly distributed. While a node can communicate directly with others within itsradio transmission range, a sequence of intermediate nodes are used to relay messages to a destination node beyond its range. Thusmulti-hop routing is one important design challenge in order to provide adequate network services.

Time of action is one way to categorize the many existing works in multi-hop routing. In general, Reactive Routing computes routes when they are needed, and hence referred to as*on-demand routing* sometimes. Examples are DSR (Dynamic Source Routing) [JoMa96] and AODV (Ad hoc On-demand Distance Vector) [PeRo99]. In contrast, Proactive Routing needs to maintain/save the routing information/activitybetween two nodes. It is also called *table-driven routing* because a node keeps track of routes to all destinations and stores such information in a table. When a new route is required (such as when an application starts or when an old path is disrupted), a new route can be immediately/quicklyselected from the routing table. Examples are the DSDV (Destination Sequenced Distance Vector) Routing [PeBh94] and the WRP (Wireless Routing Protocol) [MuGa96]. Note that these two classes of routing protocols are usually used in uni-path routing with no consideration of bandwidth limitation.

In reality, link bandwidth is usually limited in a mobile ad hoc network, and a route along a single path may not have enough bandwidth to support the transmission requirements of an application. Therefore, it becomes more popular to use multipath routing to provide *additional*paths/bandwidth through a network [AlSe16, Gall77, BeGa84, TsMo06].There are several steps to follow. The first step is Route Discovery where a flooding approach is usually used. Zone-based routing [JoLu99] is proposed to improve the flooding efficiency by reducing the searcharea. However, the traditional zone-based methods(e.g., [GaMa07, JoLu99]) have some problems especially in the possibility of discarding useful nodes. The next step is to split data transmission into multiple data streams, each along a different path to the same destination. In this way, adequate bandwidth can be allocated to support total bandwidth requirement of a data transmission. A bandwidth reservation scheme has beenproposed to find multiple paths that collectively satisfy the bandwidth requirements [LiTs01]. However, it does not specify how the available link bandwidth is allocated.Apricing model

[QiMa03]has been proposed to associate each user with a cost consisting ofbandwidth, energy and interference, but no consideration is given to end-to-end delay and hop count thatare essential for bandwidth allocation in multipath routing. The DBACA (Dynamic Bandwidth Allocation with Collision Avoidance) scheme [JiZh06] uses a dynamical bandwidth allocation strategy to achieve efficient bandwidth usage, and a collision avoidance mechanism to get high throughput. However, it does not consider the issues of power consumption and delay The adaptive MSR (Multipath Source Routing) algorithm based on DSR (Dynamic Source Routing) is proposed to prove that multipath routing can decrease the network congestion quite well [WaZh01], but no consideration is given to the effect of finite bandwidth in bandwidth allocation and congestion. In recent years, GAMR (Globally Aware Multipath Routing) has been proposed to consider the available bandwidth between a pair of communicating nodes where the bandwidth is influenced not only by the communication activities at a given node, but also by ongoing communication in nearby regions of the network in order to account for the shared nature of the medium [KoAb06, HeYa15, HeYa17]. Its main purpose is to improve the routing performance such as throughput. However, no allocation of limited bandwidth is considered in these papers. The idea of generating routing paths based on the global network condition was also used in theNOC(Network-On-Chip) technology recently [ZhJi14] where one uni-path is chosen to carry the transmission but without any bandwidth optimization.

There has been much work on optimization approaches in wirelessad hoc network of which energy is one major concern[BhNa16, RoRa15, SaCa16]. One obvious objective is to minimize the power consumption by formulating the routing problem as a LP (Linear Programming) optimization model [KaTa11]. However, it usually leads to other problems such as the requirement to improve end-to-end delay while minimizing the power consumption during the optimization process [SiWo98]. Some works [e.g., BiKh10, MaMa14] have used Dynamic Route Optimization onAODV routing where continuous route optimization is performed to ensure an optimal path connection among thedynamic mobile nodes. Unfortunately, efficiency can become an issue as frequentroute optimization would decrease the routing efficiency.

In order to address the shortcomings reviewed above, we would like to study multipath routing where bandwidth is limited. We first definea flow cost as a function of several essential factors (such as energy consumption, hop count and end-to-end time delay) and use it to select the multiple paths. Specifically, we would like to formulate an optimum bandwidth allocation algorithm for multiple paths where each link has a limited bandwidth available. We would also like to capture the effect of queueing performance from other parts of the networkin our optimization model. For example, the queueing delay can probably benefit from proper bandwidth distribution which in turn can reduce the end-to-end delay.

In order to achieve our objectiveswe would like to first provide a network model for multipath routing in an ad hoc network where nodes with limited bandwidth can be shared by several network flows. For the path selection step in multipath routing, we introduce the HCZ (Half-Circle Zone) scheme to decrease the routing discovery area and use the node-disjoint concept to cut down the RPT (Routing Path Table) size. This is important for a large network when there can be many possible paths. Then we formulate an algorithm that would assign to every routing path in the network a FC (Flow Cost) as a function of end-to-end delay, power consumption, hop count and utilization factor. Theutilization factor at a node is considered because it is related to the queueing performance such as queue length and queueing delay. Whilst there are other factors contributing to queueing delay, we make use of the fundamental queueing knowledge that higher utilization usually results in longer delay. Unlike the assumption of unlimited (or big enough) bandwidth in many other algorithms, we would like to consider a more practical network with limited bandwidth which may result in congestion as a consequence due to the competition of limited bandwidth. We shall define a CN (Crowded Node) for each multiple routing path and formulate a LP (Linear Programming) optimization to obtain the minimum cost in all CNs. The optimization results allow us to choose the best bandwidth allocation scheme for the CNs. Of the several optimization packages available, we have chosen the AIMMS software[Aimm17] because its optimization software is readily available in our lab and is easy to use. We shall firstconsider the case of two multiple paths in order for us to understand fully the benefits of our bandwidth allocation algorithm. Then we will extend our study to three and more paths in order to demonstrate the compatibility of our optimization model. Some simulation results based on Opnet 14.5 [SeHn12] are provided to demonstrate the implementation and performance improvement.

The contributions of our paper are as follows: 1) Introducing the concept of FC(Flow Cost)as a general/inclusive approach in bandwidth allocation and path selection (as opposed to many traditional routing algorithms which only consider the shortest distance or lowest powerconsumption).2) Introducing the concept of globally-aware multipath routing and bandwidth distribution by defining a CN (Crowded Node) to account for the bandwidth taken up by transmissions from other parts of the network. As far as we know, there is no bandwidth allocation with this interaction carefully studied so far. 3) Using the utilization factor to account for queueing performance in the bandwidth optimization model when deciding the optimal bandwidth allocation. 4) Proposing a novel HCZ (Half-Circle Zone) scheme to improve routing discovery efficiency and decrease the flooding time. 5) Proposing the GLBAO (Globally-aware Limited Bandwidth Allocation Optimization) algorithm that incorporate the above and demonstrating its optimality. 6) Verifying the performance improvement via simulations.

The remainder of this paper is organized as follows: Section 2 presents the network model used in our research and the related assumptions. The common routing discovery procedure is also summarized in this part. Section 3 details the algorithms we propose/use in this paper. Section 4 exemplifies the optimization procedure in bandwidth allocationalgorithm and discusses the optimization results. Various multiple path schemes are used and their tradeoff is observed. Section 5 discusses Opnet simulation and its implementation.Section 6 summarizes our findings and future work. For the remainder of this paper, the following symbols and notations pertain.

C^{C}_{max}	Maximum capacity of the CN in k^{th} routing path.
C	Crowded node
D_S	Data rate from source node S.
D_{vu}	Link delay from node v to node u.
D_{max}	Maximum delay of all links in the network.
H_k	Number of hops of the k^{th} routing path.
k	Row number of RPT.
l	Number of links in the network.
M	Set of nodes located in the routing path.
n	Number of nodes in a network.
p	Number of multiple paths.
P_{vu}	Total power consumption from node v to node u.
P_{max}	Maximum transmission power.
R	Distance between the source node S and destination node D.
R'	Radius of the Half-Circle.
r	Maximum coverage distance of a node.
S	Source node
U	Total Flow Cost.
U_k	FC value of the k^{th} routing path.
U_{sc}	FC value for the path from node S to node C.
W_P	Weight of the power factor in the objective function.
W_D	Weight of the delay factor in the objective function.
W_H	Weight of the hop count factor in the objective function.
X_{SC}	Allocated bandwidth for the routing path from node S to node C.

2. Network Operation, Modeling and Assumptions

We consider a wireless ad hoc networkwith $n$nodes and l bidirectional links. Each node has a limited bandwidth and is equipped with an omni-directional antenna that has a maximum transmission power P_{max}. A link between two nodes would exist if they are within the transmission range of each other. Along each link (v, u), let P_{vu} be the total power required to deliver data (this consists of different components such as the transmission power and the processing power). Also let D_{vu}be the link delay consisting of the propagation delay and the processing delay. A routing path between a source and a destination consists of a concatenation of different links, and the path length H is measured in hops(called hop count).

Another measure is the end-to-end delay which is the sum of all link delays along the routing path. Likewise we can associate the total power consumed by all nodes along the data path. Among all nodes with intersecting flow paths, the node with the minimum available bandwidth is called the CN (Crowded Node) because congestion would likely occur when more flows are exceeding the capacity/bandwidth of the node.

2.1 Routing Discovery and Routing Table

Before a data packet is sent from the source to its destination, an end-to-end route must be determined. During its routing discovery phase [MaDa01, WaZh01], a source would initially flood the network with RREQ (Route REQuest) packets. Each intermediate node receiving an RREQ will reply with an RREP (Route REPly) along the reverse path back to its source if a valid route to the destination is available; else the RREQ is rebroadcast. Duplicate copies of the RREQ packet received at any node are discarded. When the destination receives an RREQ, it also generates an RREP. The RREP is routed back to the source via the reverse path. As the RREP proceeds towards the source, a forward path to the destination is established. In general, many more routes can be found as the network size increasesand the effectiveness of the algorithm would decrease during the routing discovery operation due to the increase in flooding time and memory usage. This will be the subject of improvement in our algorithm in a later section.

One can see that after each routing discovery process, an intermediate node can acquire all the related information (such as its downstream node in the routing path and the end-to-end delay from the source) from the RREP packets it received, and therefore can detect all the routing paths through it to a given destination. These paths will be saved in the RPT (Routing Path Table) in an increasing order of the end-to-end delays. Our optimization algorithm in Section 3 later will make use of this multipath information to update the RPT further using both the FC and any node-disjoint schemes.

Since congestion arises when a number of network flows would share the limited bandwidth of a CN at the same time, one would like to alleviate the high queuing length or delay at this CN. Our bandwidth allocation optimization will take advantage of the utilization factor (the ratio of packet arrival rate and queueing transmission rate) in the formulation to choose the best bandwidth allocation scheme.

2.2 Assumptions

Unless otherwise specified, the following assumptions pertain:

a) There is no link breakage during the transmission: This is because we would like to fix the channel conditions in this first stage of our research/analysis so that we need not consider various complications. This will be relaxed in our future research.
b) The number of network flows for the crowded nodeisknown (e.g. measured) and is fixedfor the current transmission.
c) The bandwidth (data rate) of a node is limited. This is practical because the total bandwidth of its outgoing links is limited. This important assumption is different from many other papers that assume the bandwidth is big enough for the transmission of all network flows in the network.
d) The end-to-end delay for each link is fixed until the next route discovery. In other words, we are considering the quasi-stationary of network operation where certain performance can remain constant over a short period of time.

3. Algorithms

Before carrying out bandwidth allocation optimization, we need to simplify the size of the RPT (Routing Path Table) as explained in Section 2.1 and then sort the paths in the RPT based on their FCs. After these steps, we can easily decide the multiple paths necessary for the transmission.

3.1 HCZ (Half-Circle-Zone) Scheme

The HCZ scheme allows us to reduce the flooding area to be explored by the RREQ packets and to avoid the disadvantage of discarding useful nodes in the zone-based routing as done in [JoLu99]. During the routing discovery (flooding) stage, since a node can obtain the location information of the source node from the RREQ packet it receives, it can calculate the distance and angle with respect to the source node. If the distance and/or the angle are outside the half-circle area, this node will discard the RREQ packet.

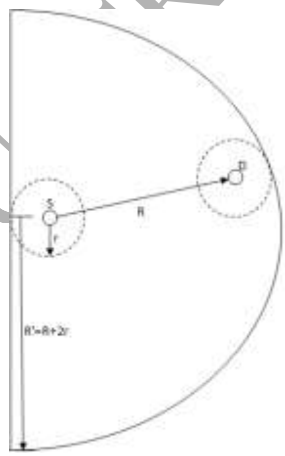


Fig. 1: Half-Circle Zone Scheme

As shown in Fig.1, R is the distance between the source node S and the destination node D. Let r be the maximum coverage distance for a node and R' be the radius of the Half-Circle. By automatically ignoring the RREQ packets from nodes outside the half-circle with radius$R'=R+2r$, we effectively limit our path exploration to within this half circle, thus reducing the number of nodes participating in the forwarding of the RREQ packets. Note that our HCZ scheme has already considered/included the maximum transmission range of both the source node and the destination nodes, and can provide more alternatepaths than the zone-based routing for the following considerations:

Although some nodes outside the half circle can probably provide a feasible route to the destination, such route is more likely to have a very high end-to-end delay or a large hop count, and therefore is a worse choice than those routes set up by the nodes within the half-circle.

The half-circlecan also include more potentially useful nodes than those in thecoverage areaused in the zone-based routing.To see this mathematically, let (X_S, Y_S) and (X_d, Y_d) be the coordinates of the source node S and the destination node respectively. The maximum area $A_Z$that can be covered by the zone-based scheme is

$$A_Z = (\frac{\sqrt{(Xd - Xs)^2 + (Yd - Ys)^2}}{\sqrt{2}})^2$$

$$= \frac{(Xd - Xs)^2 + (Yd - Ys)^2}{2}$$

For our HCZ scheme, the coverage area A_H is

$$A_H = \frac{\pi(R + 2r)^2}{2} = \frac{\pi(\sqrt{(Xd - Xs)^2 + (Yd - Ys)^2} + 2r)^2}{2}$$

which can be much bigger than A_Z due to the additional terms/components (in terms of r and π). Consequently, our HCZ scheme will not miss out so many useful nodes as the zone-based scheme.

3.2 RPT Simplification

Using the search results from the HCZ scheme, we will save the selected routing paths in the RPT. Although we have decreased the number of paths through the HCZ scheme, the size of the RPT can still be very largein a large network. Hence, we shall also make use of the concept of node-disjoint paths here, which is defined to be a set of paths with no common nodes except their source and destination. Node-disjoint paths can provide fault-tolerance by utilizing the most available network resources. When an intermediate node fails, only the path containing that failed node is affected with no impact on others in the set.

We shallidentify all available node-disjoint paths based on the Flow Cost consisting of the power consumption P_{vu}, the hop count $H$and the time delay D_{vu} as introduced in Section 2.

For the k^{th} routing path in the RPT, let $H_k \leq n\text{-}1$ *(k =1, 2, 3, ...)* be its path length in hops, and M be the set of nodes in the routing path such that $(v, u) \in$ Mis the set of concatenated links to form the path. Then we can formulate the Flow Cost U_k in terms of all these parameters from all links along the *kth* path as follows:

$$U_k = \sum_{(v,u)\in M}(W_p * \frac{P_{vu}}{P_{max}} + W_D * \frac{D_{vu}}{D_{max}}) + W_H * \frac{H_i}{n-1} \quad (1)$$

Since the power, delay and hop count take on different units and different magnitudes, we have normalized each parameter with respect to their highest values (i.e., P_{max}, D_{max}, and n-1 respectively) so that their contributions become values between 0 and 1. The variableW_p, W_D and W_H are the weights associated with their respective parametersin order for us to emphasize the contribution of a parameter in the FC. We shall use the default valuesof $W_p = W_D = W_H$=1in this research unless otherwise specified.

We can now sort/update all the paths in the RPT according to their FCs in their ascending order. The routing path with the smallest FC is saved in the first row of the RPT. Its path index number is 1. The routing path with the second smallest FC is saved in the second row with an index number 2, and so on and so forth. A smaller FC indicates a routing path with a combination of lower power consumption, lower time delay and smaller hop count.

After sorting allFCs in an ascending order, we shall eliminate those non-node-disjoint paths. By using therouting path information, we can compare all routing paths to see if they share the same node. When two routing paths share a node, we will delete the path with a higher FC (larger row number in RPT) until all the remaining routing paths are node-disjoint. For example, we will delete the second row from the RPT if its path has any nodes that are common with the first .row. This is repeated for the third row, fourth row…etc.

After the first iteration, all paths in the RPT will be node-disjoint with the first row. For simplicity of explanation, we shall renumber the row-numbers of the remaining paths sequentially in an ascending order. Then we begin our second iteration by comparing the second row with all rows below (i.e. third row and beyond) which at the end should produce all paths that are node-disjoint to the second row.This procedure (renumbering row index-numbers and comparing against the new rows below) is repeated until each row is node-disjoint with the pathswith lower row index numbers above. Note that ifthere are no node-disjoint paths in a network, we shall simply choose the first p ($p \geq 2$) routing paths from the first $p$rows.

3.3 Path Selection and the Crowded Node

After the HCZ scheme and node-disjoint paths selection, we arrive at a simplified Routing Path Table. However, it is possible that there can still be many routing paths in the RPT, and the efficiency of the algorithm will decreaseby considering all of them. Therefore, one can just take the first $p \geq 2$ routing paths. Some investigations and observations of different$p$values will be provided later.Finally, among all nodes along each path, it is also easy to determine the Crowded Node which is the node with the minimum available bandwidth.

3.4 The Optimization Model

For each of the p ($p \geq 2$)multiple routing paths selected in Section 3.3, let C^C_{max} be the maximum available capacity of the Crowded Node C that is shared by the intersecting path from various transmission sources.

For each of the *p*paths in our algorithm, let X_{SC} represent the bandwidth to be allocated to this path, and let U_{SC}represents its FC as given in (1). Different allocation scheme (different values of X_{SC}) can obtain different weighted sum. Let *U* be the total flow cost as a weighted sum of all U_{SC}selected in the RPT from all source nodes under consideration. Our aim is to find an allocation scheme so that the total Flow Cost is the minimum. Thus our objective function for optimum bandwidth allocation is formulated as follows.

$$\text{Minimize} \quad \mathrm{U} = \sum_{\mathrm{S,C \in M}} \mathrm{U_{SC}} * \frac{\mathrm{X_{sc}}}{\mathrm{C^{C}_{max}}} * \mathrm{X_{sc}} \qquad (2)$$

Subject to:

$$\sum_{\mathrm{s}} \mathrm{X_{sc}} < C^{C}_{max}\,,\ \forall\, \mathrm{s} \in \mathrm{M} \qquad (3)$$

$$\sum_{\mathrm{c}} \mathrm{X_{sc}} \geq \mathrm{D}_s\,,\ \forall\, \mathrm{c} \in \mathrm{M} \qquad (4)$$

$$\mathrm{X_{SC}} \geq 0 \qquad (5)$$

In the optimization process of the limited bandwidth allocation at the *p*CNs, we also have to be globally-aware of the traffic condition and bandwidth usage of other intersecting flows converging from anywhere in the network. This is done by using different values of X_{SC} so that the flow costs weighted by the utilization give the minimum total costs. .As introduced in the beginning, utilization is a good indicator for queueing delay (although there can be other factors contributing to the delay). Therefore, we use utilization factor combined with U_{SC} to measure the weight of bandwidth allocation. The more bandwidth allocated to one path (X_{SC}), the higher the flow cost and queueing delay. Different allocation scheme (using different values of X_{SC}) can result in different weighted sums. Our optimization is to find the optimal allocation scheme so that the Total Flow Cost isminimum.

Constraint (3) says that the sum of arrival rates from all network flows cannot exceed the maximum capacity (data rate) of a CN. Constraint (4) says that the sum of all outgoing path capacities supporting the flows from the same source should be greater than the source data rate. It also ensures that at least one *X*sc>0. Constraint (5) is just a regular condition to ensure the non-negativity of a flow value.

In summary, the purpose of this optimization is to jointly consider all the network flows going through the CNs for the optimization of a particular path. It then chooses the best bandwidth allocation *Xsc* for each flow from source *S* going through the crowded node *C*.The results of the optimization would allow us to choose the best bandwidth allocation scheme among all paths between a source-destination pair.

3.5 The GLBAO Algorithm

We can now summarize all the rationale and discussion of various issues above by proposingtheGLBAO (Globally-aware Limited Bandwidth Allocation Optimization) algorithm below. This algorithm will execute every time when a route discovery is initiated with the aim to optimize the allocation of the limited bandwidth available at a Crowded Node. It is a "global optimization" by taking into account the influence of flows that can arise from anywhere in the network.

1) Apply the HCZ scheme in the routing discovery algorithm in Section 2.1 to obtain all the possible routing paths for the present transmissionand save them in the RPT.
2) Renew and simplify the RPT according to the following schemes:
   a) Compute the FC of each path
   b) Update all paths of the RPT in an ascending order.
   c) Use the node-disjoint method in Section 3.2 to simplify the RPT.
3) Select $p \geq 2$multiple paths according to the requirement.
4) Identify the Crowded Nodes for each of the *p* paths in the RPT.
5) Identify all the othertransmissions sharing the Crowded Nodes and their data rates.
6) Carry out the optimization in Section 3.4 to obtain the optimal limited bandwidth allocation to each transmissionconverging in the Crowded Nodes.

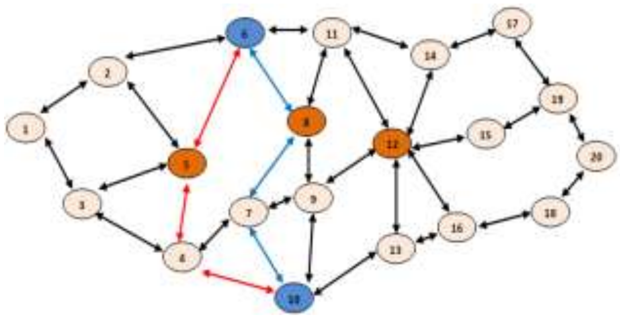


Fig. 2: A 20-Nodes Network Example

4. Optimization Analysis

We shall use the AIMMS (Advanced Integrated Multidimensional Modeling Software) solver [Aimm17] to solve our optimization problem.

Fig.2shows an example of n=20 node network. We will study different cases of p parallel paths.

4.1 Two Multiple Paths

We first use p=2 parallel paths to demonstrate how two transmissions interact with each other. One transmission goes from source node 6 to destination node 10. As shown in Fig. 2, there are two node-disjoint multiple routing paths: path *6-5-4-10* is shown in red and has the smallest FC value while path*6-8-7-10* is shown in blue with the second smallest FC value. The second transmission goes from source node 11 to destination node 4. It also has two node-disjoint paths of 11-6-5-4 and 11-8-9-7-4.

Table 1 illustrates the setup of the components in eqn. (1) for the first transmission. We use P_{max}= 100 mW and D_{max}= 100ms to normalize the components.We assume source node 6 is transmitting data at a rate of 60 Kbps. Furthermore, Node 5 is assumed to be the CN in the first path with the lowest available bandwidth of 80 kbps. Likewise, Node 8 is identified as the CN for the second path with the lowest bandwidth of 70 kbps. The hops for both paths are 3 and the maximum hop distance is n-1=19 as reflected in the 4th column of $H_i/(n-1)$.

Table 1: Sample Data for 1st Transmission

Source Node 6 to Destination Node 10 Ds=60 kbps	*CNs*	C^C_{max}	$\frac{H_i}{n-1}$	$\frac{P_{vu}}{P_{max}}$			$\frac{D_{vu}}{D_{max}}$		
6 - 5 - 4 - 10	5	80 kbps	3/(20-1)	Links in the routing path			Links in the routing path		
				6 - 5	5 - 4	4 - 10	6 - 5	5 - 4	4 - 10
				0.48	0.67	0.11	0.45	0.25	0.05
6 - 8 - 7 - 10	8	70 kbps	3/(20-1)	Links in the routing path			Links in the routing path		
				6 - 8	8 - 7	7 - 10	6 - 8	8 - 7	7 - 10
				0.61	0.56	0.79	0.14	0.22	0.25

The values of P_{vu}/P_{max}in the 5thcolumns are due to random/instantaneous measurements. They are all normalized with respect to their maximum values for use in eqn. (1). For example, suppose the consumed power of link 6-5 is P_{vu}= P_{65}=45mW, one obtains the normalized number of 0.45 as shown. Likewise for all normalized numbers indicated for links *(5,4), (4,10), (6,8), (8,7) and (7,10)*.

The entries of D_{vu}/D_{max} in the 6thcolumn are also normalized numbers. For example, if D_{68}=14 ms is measured for link *(6,8)*, then we obtained the normalized value of 0.14. Similarly for other links of *(6,5), (5,4), (4,10), (8,7) and (7,10)*.

Table 2: Sample Data for 2nd Transmission

Source Node 11 to Destination Node 4 Ds=40 kbps	*CNs*	$\frac{H_i}{n-1}$	$\frac{P_{vu}}{P_{max}}$				$\frac{D_{vu}}{D_{max}}$			
11 - 6 - 5 - 4	5	3/(20-1)	Links in the routing path				Links in the routing path			
			11-6	6-5	5-4		11-6	6-5	5-4	
			0.98	0.48	0.67		0.92	0.45	0.25	
11 - 8 - 9 - 7 - 4	8	4/(20-1)	Links in the routing path				Links in the routing path			
			11-8	8-9	9-7	7-4	11-8	8-9	9-7	7-4
			0.64	0.58	0.75	0.62	0.33	0.27	0.45	0.47

Similarly, Table 2 shows the setup of components in eqn. (1) for the second transmission with source node 11 transmitting at 40Kbp.To illustrate the process of optimization in bandwidth allocation, we assume the two parallel paths havethe same CNs (Nodes 5 and 8) as the first transmission from node 6 to node 10, and hence the same C_{max}^{C} values used in Table 1.

Note that the second path has$n$=5 nodes (4 hops) which is bigger than the hop counts of other paths in Tables 1 and 2. This is reflected in the calculation of$H_i/(n-1)$.Again, our P_{vu} and D_{vu} values are normalized under the P_{vu}/P_{max} and the D_{vu}/D_{max}columns in the table similar to Table 1.Using the same P_{max}= 100 mW and D_{max}= 100ms as in Table 1, the consumed power of link *11-6* is P_{vu}= P_{116}=76mW, which gives the normalized number of 0.76 as shown. Similarly the measureddelayofD_{116}=33 ms for link (11,6) gives the normalized value of 0.33. Likewise for all the other links.

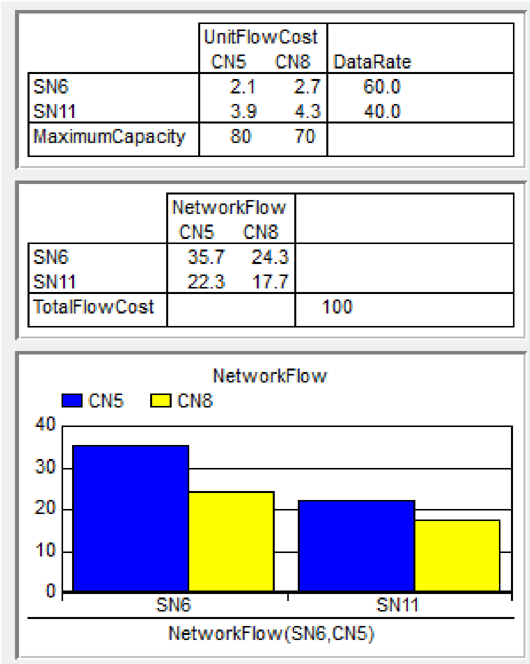


Fig. 3: Optimal Allocation Result for Two Paths

We can now globally optimize the bandwidth allocation among all 4 routing paths based on the information in Table 1 and Table 2. Fig. 3 shows the allocation results after running our optimization model in AIMMS. We can see that the Flow Cost for the two paths of the transmission from SN6 (Source Node 6) are 2.1 and 2.7, and those for transmission from SN11 (Source Node 11) are 3.9 and 4.3. Based on these FCs, the optimum allocation scheme is obtained at the minimum total flow cost of 100. The allocation for each flow is also presented in the bar chart. One can check that the total bandwidth (blue and yellow) allocated for Source Node 6 should be equal to or larger than the source data rate requirement of 60 kbps. Similar comment goes to Source Node 11 requirement of 80 Kbps. On the other hand, the total bandwidth allocated to the flows from SN6 and SN11should be less than or equal to the bandwidth available from CN5. Likewise for CN8.

Table 3: Other Random Allocation Schemes

	#1		#2		#3		#4		#5		#6	
	CN5	CN8	CN5	CN8	CN5	CN8	CN5	CN8	CN5	CN8	CN5	CN8
SN6	20	40	35	25	50	10	27	33	15	45	30	30
SN11	20	20	15	25	10	30	16	24	30	10	28	12
TotalFlowCost	116		106		130		109		134		105	

In order to verify the optimality of our result, we have used some other random allocation schemes as shown in Table 3. Take Allocation #1 for example, the row of SN6 says that one wants to allocate bandwidths 20 kbps and 40 kbps to the paths going through CN5 and CN8 respectively. Similarly, the row of SN11 says that bandwidths 20 kbps and 20 kbps are allocated to paths going through CN5 and CN8 respectively. The total flow cost is 116. The total flow costs of other random allocation schemes (#2 to #6) are all bigger than our optimum result of 100 as well when using the same FC assignments from Tables 1 and 2.

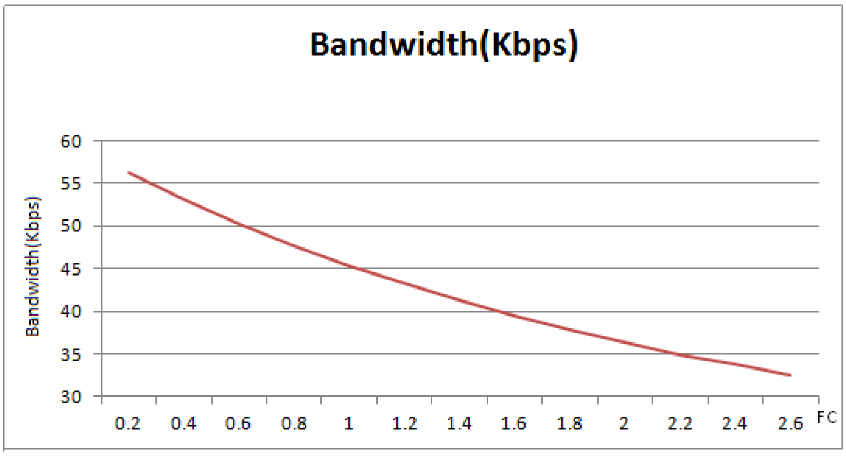


Fig. 4: Relationship between FC and Bandwidth

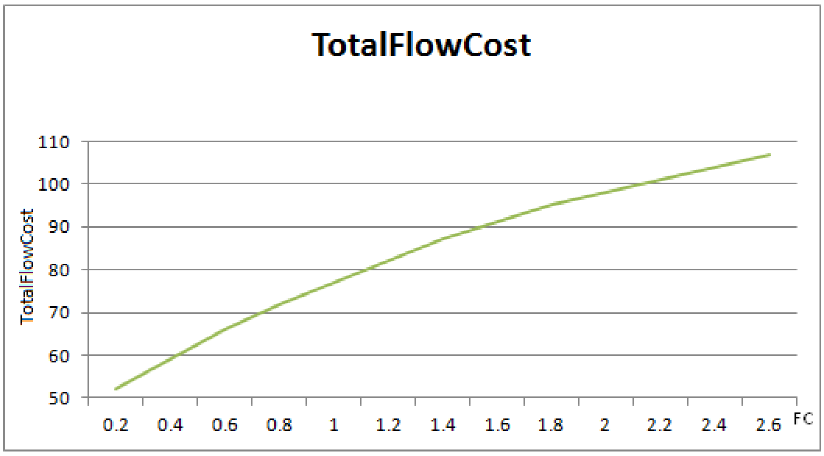


Fig. 5: TotalFlowCost of All Paths *vs* Cost Assignment of One Path

The optimization exercise in Table 3 above suggests that the FC of a path can play an important role in the behavior of various performance measures. For Figs. 4 to 7 below, we shall vary the FC of the first path while keeping the FC of the other 3 paths the same. Fig. 4 considers the transmission from Source Node 6 to Crowed Node 5. As the FC of the first path deviates from the current value of 2.1, the optimally allocated bandwidth is decreasing non-linearly. Fig. 5 shows that the "smallest total network FCs" (based on the unit FCs assigned to the 4 paths) is increasing non-linearly with respect to the FC value of the first path. In general, the larger the FC value of a path while keeping others the same, the higher the Total FC value.

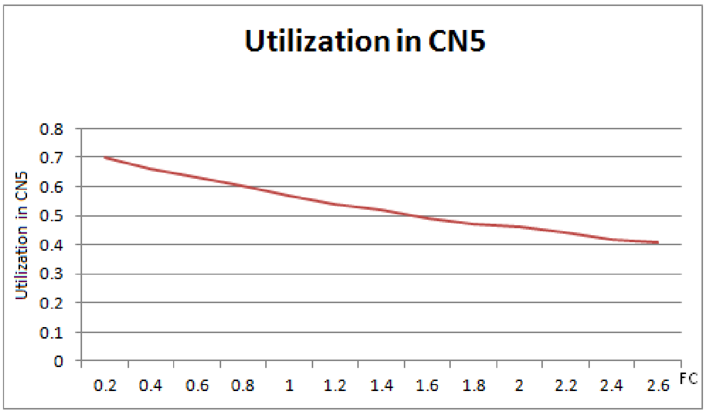


Fig. 6: Relationship between FC and Utilization in CN5

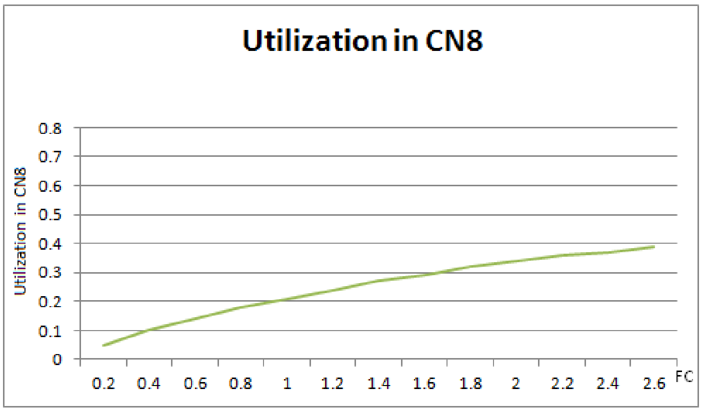


Fig. 7: Relationship between FC and Utilization in CN8

Fig. 6 shows that the utilization of CN5 is a decreasing function of increasing FC assigned to the first path. This is due to the decrease in the allocated bandwidth to that path as shown in Fig.4. According to the general queueing theory, we would expect the queueing performance to improve as the FC increases.For example, as less packets are transmitted through CN5, its queueing delay would decrease. On the other hand, Fig. 7 shows that the utilization of CN8 is an increasing function of the FC which means the queueing performance would worsen. This is due to more packets transmitted through CN8 in order to meet the constraint (4) in Section 3.2 of our optimization model.

4.2 More Than Two Paths

Our algorithms can also perform optimum bandwidth allocation to three or more paths. We offer below another example with *p*=3 multiple routing paths for each transmission.

Table 4: Information for Third Path

The 3rd Path	CN	C^{C}_{max}		$\frac{P_{vu}}{P_{max}}$				$\frac{D_{vu}}{D_{max}}$			
6-11-12-9-10	12	60Kbps	4/(20-1)	Links in the routing path				Links in the routing path			
				6-11	11-12	12-9	9-10	6-11	11-12	12-9	9-10
				0.57	0.64	0.7	0.45	0.11	0.24	0.37	0.19
11-12-13-10-4	12	60Kbps	4/(20-1)	Links in the routing path				Links in the routing path			
				11-12	12-13	13-10	10-4	11-12	12-13	13-10	10-4
				0.66	0.72	0.79	0.81	0.44	0.35	0.57	0.63

Table 4 gives the parametric information of additional paths added to the two transmissions in the same 20-node network of Fig.1. Specifically, we have 6-11-12-9-10 as a third path for the transmission between SN6 and DN10 (Destination Node 10) while 11-12-13-10-4 is the third path for transmission between SN11 and DN4.For illustration purpose, we shall use Node 12 as the additional CN with a maximum capacity of 60 Kbps.The data rates of thetwo sources remain the same at 60Kbps and 40Kbps respectively. We also use the same information for the other two paths in Tables 1 and 2. Altogether there are 6 paths to consider with 3 paths each to the modified Tables 1 and 2.

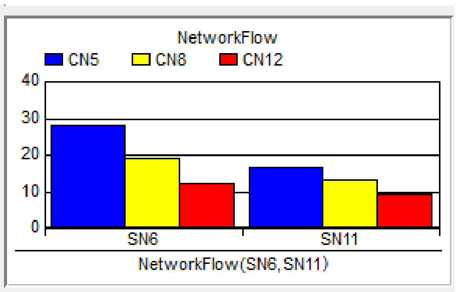


Fig. 8: Bandwidth Allocation Result for 3 Multiple Routing Paths

We can now run our optimization model to obtain the optimum allocation for each of the 6 paths.The FC values for the additional pathsare 3.5 for SN6 and 5.2 for SN11 based on the information of Table 4, while the FCs for the original 4 paths remain the same.

Fig. 8 shows the results of the optimum bandwidth allocation. Compared with Fig. 3, the allocated bandwidth for the first path is reduced from 35.7 Kbps to 28.2 Kbps, and the second path is reduced from 24.3 Kbps to 19.2 Kbps. The total allocated bandwidth remains the same at 60 kbps. Obviously, our algorithm has successfully changed the distribution from two paths to three paths, with the third path (through CN12) providing the extra bandwidth of 12.7 kbps. Similar observation and explanation go to the bandwidth allocation for the traffic requirement of 40 kbps from SN11. One also sees that using a total of 6 paths to carry the traffic of 2 transmissions has reduced the total flow cost from 100 to 77. Obviously, all these changes are due to the additional third path for each transmission.We have also tried some other random allocation schemes as done in the two-path study, and their results (not shown here) demonstrate that the total flow cost of 77 we obtained above is the minimum.

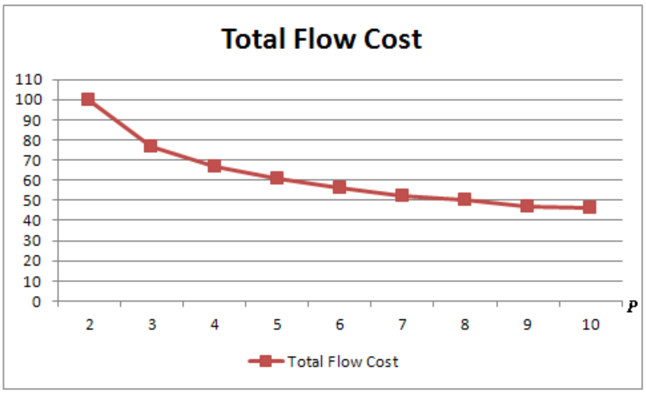


Fig. 9: Relationship between the Total Flow Cost with the number of paths *P*

One of the advantages of our algorithm is that it can provide bandwidth allocation for any number of p paths. This allows us to study easily the effect of providing more paths and transmission. For example, using p=4 multiple paths reduce the (smallest) totalflowcost to 67. The marginal gain (reduction in this total flow cost) is not as much as before. In fact, from the curve of the Total Flow Cost with respect to p in Fig. 9, one sees the marginal reduction is ever decreasing. Depending on the requirement of network design, there is a certain threshold (say p=5) beyond which there is not much more advantage. The limit can be used to cut down the amount of computation in optimization when deciding the number of parallel paths to achieve a given performance measure.

5. Simulation Implementation

We have also implemented the above algorithms in an Opnet 14.5 simulation.

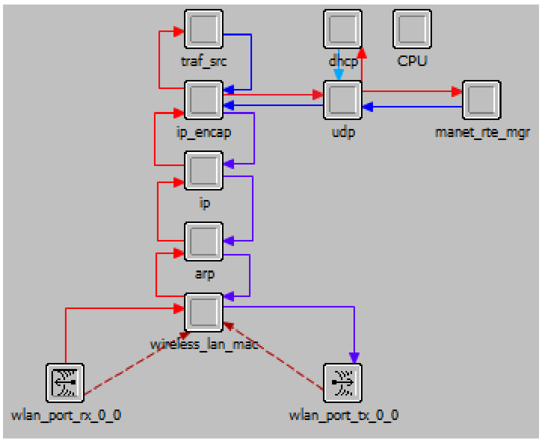
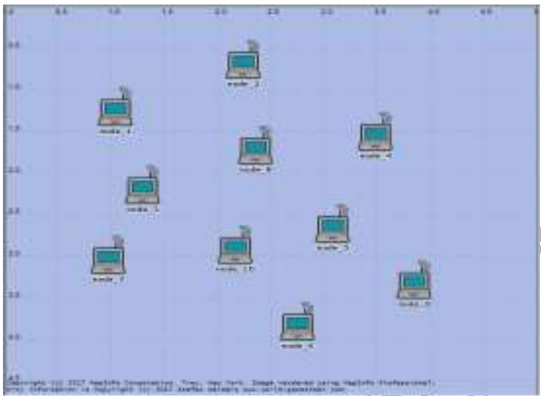


Fig. 10: Node Model

Fig. 11: Network Model for Simulation

Fig. 10 shows the node model/



implementation of a MANET (Mobile Ad hoc NETwork) station that we have modified from the Opnet library. The model consists of interconnected blocks called modules. Each module contains a set of inputs/outputs, and a process/method(not shown) for computing the module's outputs from its inputs and from its state memory (also not shown). Each module implements an entity of a protocol layer. The entity "wlan_port_rx/tx_0_0" implements the receiver and transmitter in the Physical Layer taking output/input from/to the MAC layer entity "wireless_lan_mc" for transmission in the wireless medium. Entities "arp", "ip" and "ip_encap" implement the Network Layer functions related to TCP/IP while other entities are data from different sources in the upper layers. The most interesting entity pertinent to our research is the "manet_rte_mgr". This is the MANET Routing Manager entity which can implement different routing protocols such as AODV routing. Our algorithms in Section 3 are coded in here as a new process.

To verify our performance improvement, we have created a wireless ad hoc network model with nodes running TCP/IP. There are n=10 randomly placed nodes within the 5*5 kilometers area as shown in Fig. 11.As an initial investigation, we make the nodes stationary.

In this simulation, we use two transmission flows (1→9 and 7→ 4), each of which has p=2 node-disjoint paths. As expected, our optimization algorithm in the "manet_rte_mgr" entity will globally analyze the FC of each path and then get the optimum allocation scheme. Our performance improvement demonstration is done in two parts: first comparing the throughput performance (without using optimization)oftwo paths withina single transmission, and then comparing the performance of the same transmission with and without optimization.

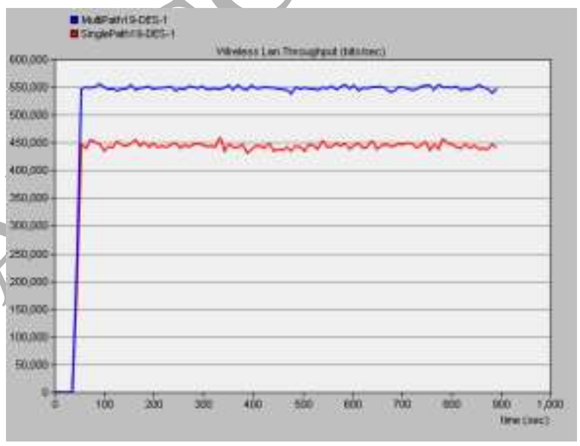


Fig. 12: Throughput Comparison for Source Node 1-Destination node 9

Fig. 12 show the instantaneous throughput (in bps) as time evolves when data is arriving at Source Node 1 at a rate of 1000 packets/s. Using a constant packet length of 1000 bits, the arrival rate of 1000 packets/s is equal to 1000000 bps. The red curve is the throughput of a single pathusing AODVwhile the blue shows total throughput of the two paths in our multipath routing without using optimization. We can see the steady throughput has increased from 450000 bpsto 550000bps (which is an improvement of 100000bps or 22.2%). Packets are lost due to the limited buffer size and/or some other reasons.Note the simulator has allowed the first 50 seconds for the system to perform routing discovery.

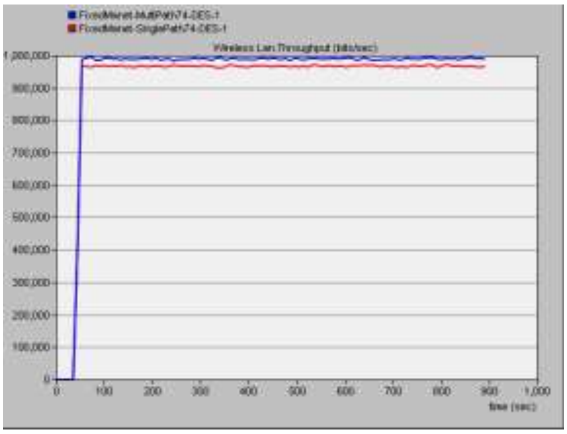


Fig. 13: Throughput Comparison for Source Node 7 to Destination Node 4

Similar to Fig. 12, Fig. 13 compares the instantaneous throughput of thetransmissionfrom source node 7 to destination node 4 using the same arrival rate and packet size. Higher throughput is achieved here due to shorter length (measured in hops) and higher bandwidth of the path.One can see the steady-state throughput is increased from 980000 bpsfor the single path case (shown in red) to 990000 bps for the multiple path case (shown in blue), which is ~1% improvement. The improvement percentage is less because the path is already supporting a throughput veryclose to the arrival rate.

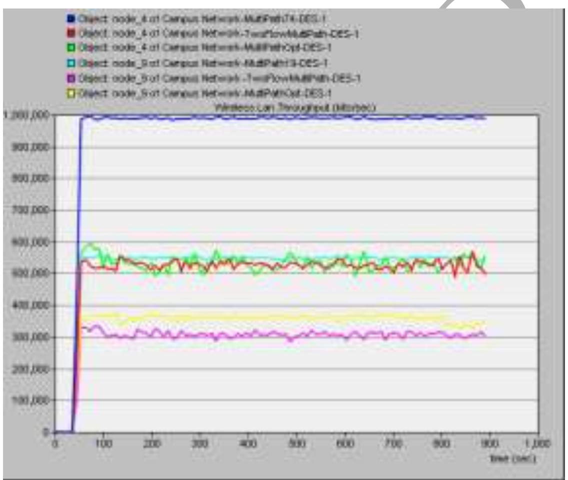


Fig. 14: Throughput Comparison

Unlike the same scenario of Figs. 12 and 13 where only one source-destination transmission flow is considered separately, we now investigate the throughput when the two source-destination flows (1→9 and 7→4, and each with 2 multiple paths to its destination.) are transmitting at the same time. Nodes 3 and 8 are the crowded nodes where these paths intersect. Without using any bandwidth optimization, Fig. 14 shows the total throughput of each transmission actually drops. For examples,the throughput of transmission flow1→9 has decreased from about 550000 bps (shown in light blue) to 300000bps (shown in pink) while the throughput of flow 7→4 has decreased from about 990000 bits/sec (shown in dark blue) to 520000 bits/sec (shown in red). This is because the limited bandwidth in Crowded Nodes 3 and 8 are not properly shared/allocated among the multi-paths supporting the two source-destination flows and therefore congestion has occurred.

After applying our optimization algorithm, the throughput for the flow1→9has increased from 300000 bits/sec (shown in pink) to 370000 bits/sec (shown in yellow) while the second flow 7→4 has increased from about 520000 bits/sec (shown in red) to 530000 bits/sec (shown in green). This demonstrates that our optimization can improve the throughput and therefore decrease the impact of congestion. The improvement for the 7→4 flow is not as big indicating congestionis still present. The observation is that our optimization can improve congestion via the optimization of bandwidth allocation but not built to solve the congestion problem.

6. Conclusion

In this paper, we have presented an optimization algorithm called GLBAO for the allocation of limited bandwidth in multipath routing. Using LP optimization, ourallocation scheme is globally-aware of the interactions withtransmissions from other parts of the network. Our optimization formulation takes queuing performance into account via the utilization factor in the objective function. We choose our node-disjoint multiple paths according to their FCs which is a combination of power consumption, delay and hop count. The optimization methodology proposed for limited bandwidth allocation in this paper has the potential to increase the reliability of the packet transmission and to decrease network congestion. Our performance evaluations in both AIMMS and Opnet have demonstrated the advantages of our algorithm.

As the first stage of our research, we are mainly concerned withthe improvement of the throughput in this paper.Future work will also study congestion control to improve throughput further as well as improving other performance such as queueing delay and overhead.

Acknowledgement

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Junxiao He received her B.S. degree in Automation and the M.S. degree in Control Science and Engineering from Central South University, China, in 2006 and 2009, respectively. From 2009 to 2012, she was a development engineer in the department of communication network optimization tools in ZTE Company, China. She is currently pursuing her Ph.D. degree in Electrical and Computer Engineering at University of Ottawa, Canada. Her research interests are in the design and performance issues of Internet services such routing, bandwidth allocation and congestion control of mobile ad hoc networks.

Oliver W.W. Yang received the PhD degree in electrical engineering from the University of Waterloo, Ontario, Canada. He is now Professor Emeritus in the School of Electrical Engineering and Computer Science at the University of Ottawa, Ontario, Canada. He has worked for Northern Telecom Canada Ltd. and has done various consulting. He has served on the editorial board of IEEE Communication Magazine, and IEEE Communication Surveys & Tutorials, as well as an associate director of the OCIECE (Ottawa-Carleton Institute of Electrical and Computer Engineering). His research interests are in the modeling, analysis, and performance evaluation of computer communication networks, their protocols, services, and interconnection architectures. The CCNR Lab under his leadership has been working on various projects in the switch architecture, traffic control, traffic characterization, and other traffic engineering issues in both wireless and photonic, the results of which can be found in more than 400 technical papers. Dr. Yang is a senior member of the IEEE.

Yifeng Zhou received his PhD degree in electrical engineering, in 1995, from McMaster University, Hamilton, Ontario, Canada. Currently, Dr. Zhou is a research scientist at the Communications Research Centre (CRC) Canada. Before that, he was a defence scientist at Defence R&D Canada (DRDC). Dr. Zhou's research interests are in the areas of statistical signal processing, data fusion and mobile ad hoc networking. He publishes actively in these areas.