Multipath Routing Optimization with Interference Consideration in Wireless Ad hoc Network

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Abstract. This paper proposes a multipath routing optimization algorithm for allocating bandwidth resources to nodes that are subject to interference from flows in other parts of the network. The algorithm consists of three steps: path discovery, path selection and load distribution. In addition to delay, power and hop count, the routing metric also takes into account the interference of flows from other parts of the network during path selection and load distribution. An optimization model is formulated based on the flow cost and the bandwidth usage by the other flows. The AIMMS package is used to solve the optimization problem to obtain an optimal solution with the minimum total flow cost. Finally, we use computer simulations to assess the performance and effectiveness of the proposed routing technique.

Keywords: Optimization · Multipath routing · Interference · Wireless ad hoc network

1 Introduction

In contrast to the infrastructure wireless networks, where each user directly communicates with an access point or based station, the wireless ad hoc network does not rely on a fixed infrastructure for its operation [HoMo14]. When a node tries to send information to other nodes out of its transmission range, one or more intermediate nodes are needed. Many research works have been studied in this area, e.g., [KoAb06, LuLu00, TsMo06].

Routing protocol is one of the most important challenges in wireless ad hoc network. The goal is to find the appropriate paths from source to destination. Generally speaking, the routing protocols can be classified into two categories: Unipath Routing and Multipath Routing as shown in Fig. 1 [AaTy13, MuTs04, YiJi07].

There are already many works in routing protocols such as Proactive routing protocols and Reactive routing protocols. Proactive routing such as DSDV (Destination Sequenced Distance Vector) Routing [PeBh94] and WRP (Wireless Routing Protocol) [MuGa96] is also called Table-Driven routing because they keep track of routes for all

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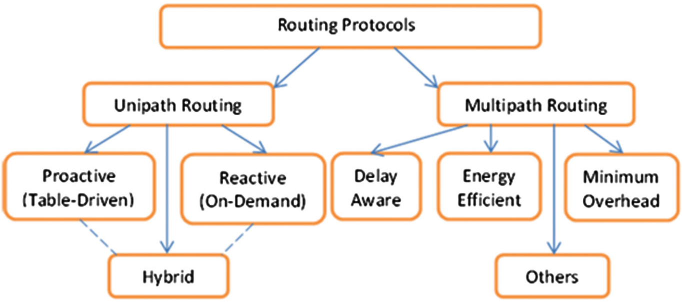

Fig. 1. Classification of routing protocols

destinations and store the route information in tables. When the application starts, a route can be immediately selected from the routing table. Reactive routing such as DSR (Dynamic Source Routing) [JoMa96] and AODV (Ad hoc On-demand Distance Vector) [PeRo99] is also known as On-Demand routing protocol because it does not need to maintain the routing information or routing activity if there is no transmission between two nodes. Routes are only computed when they are needed. These two classes of routing protocols are usually Unipath routing which do not consider the bandwidth limitation along the path. Since the bandwidth is usually limited in wireless ad hoc networks, routing along a single path may not provide enough bandwidth for transmission. This is why Multipath Routing is becoming more and more popular. This routing technique uses multiple alternative paths through a network, which can yield variety of benefits such as increasing fault tolerance, bandwidth aggregation, minimizing end-to-end delay, enhancing reliability of data transmission and improving security [BeGa84, Gall77, TsMo06]. The multiple paths computed might be overlapped, edge-disjointed or node-disjointed with each other [Wiki15b].

There are three fundamental components when designing the multipath routing: Path Discovery, Path Selection and Load Distribution. These three have always been the most important issues in the multipath routing. However, many papers are just concerned with only one or two of these issues. For examples, the SMR (Split Multipath Routing) protocol is an on-demand MSR (Multipath Source Routing) protocol that is concerned with the path discovery and path selection [LeGe00]. Some papers are mainly concerned with the path selection [MaDa01, MaDa06]. Based on the AOMDV (Ad hoc On-demand Multipath Distance Vector) [YeKr03], an NS-AOMDV (AOMDV based on the node state) protocol [ZhXu13] was proposed to choose the path with the largest path weight from the node state for data transmission. All of the above papers do not discuss how to allocate the bandwidth to different multiple paths because once several multiple paths are selected; an algorithm is required to distribute the load. Early papers usually assume an unlimited bandwidth, e.g. [GiEp02, Vand93]. A distributed routing and scheduling algorithm based on link metric is proposed [GiEp02] to decrease the consumption of limited resources such as the power. However, it does not take into account of limited bandwidth. An arbitrarily large bandwidth is also assumed in the derivation of the lower and upper bounds of a uniform capacity in a power-constrained wireless ad hoc network [ZhHo05].

There has been much work on optimization approaches in wireless ad hoc network. Since energy is a major concern, one obvious objective is to minimize the power consumption by formulating the routing problem as a LP (Linear Programming) optimization model [KaTa08]. It usually leads to other problems such as the need to improve the end-to-end delay while minimizing the power consumption during optimization [SiWo98]. There has been optimization work based on limited resources such as [KrPa06, LeCi98]. However, those papers do not consider the interference of transmissions from other parts of the network.

Based on the above short comings, we would like to study a multipath routing algorithm where bandwidth is limited, and to assign a Flow Cost as a function of several essential factors which can be used during the path selection step. In the third step of the multipath routing (load distribution). We would like to formulate an optimum bandwidth allocation algorithm for the multiple paths under the constraint of limited bandwidth available at each link. At the same time, we will also consider about the interference from the other network flows in the network during our optimization model.

In order to achieve our objectives, we would like to first provide a network model for multipath routing in a wireless ad hoc network where nodes with limited bandwidth can be shared by several network flows. For the path selection step of the multipath routing, we would formulate an algorithm that assigns to every routing path in the network a FC (Flow Cost) as a function of 4 different factors: interference in addition to end-to-end delay, power consumption and hop count. The interference can come from flows receiving influence from other parts of the network, but not just the physical interference from other nodes like the noise. Our algorithm is designed for more practical networks where bandwidth is limited so that congestion can arise due to the competition of limited resource. A CN (Crowded Node) is identified for each multiple routing path with the purpose to formulate a LP (Linear Programming) optimization model and to obtain the minimum cost in all CNs. The optimization results allow us to choose the best bandwidth allocation scheme for the CNs.

The contributions of our paper as the following: (1) Accounting for interference from other flows in the network in addition to the traditional power consumption, end-to-end delay and hop count. (2) Taking into account the bandwidth usage and the interaction of other network transmission in the CNs. As far as we know, there is no bandwidth allocation with this interaction carefully studied so far. (3) Solving the optimization model in AIMMS and using the optimization results to obtain the bandwidth allocation trend related with the flow cost.

The remainder of this paper is organized as follows: Sect. 2 presents the network model used in our research and the related assumptions. Section 3 explains the 3 steps of the multipath routing we propose/use in this paper. Section 4 provides the optimization procedure for use in the bandwidth allocation algorithm and discusses the optimization results. Section 5 summarizes our findings and future work. For the remainder of this paper, the following symbols and notations pertain.

C^k_{max} Maximum capacity of the CN in k^{th} routing path.

C^k_u Occupied bandwidth by other network flows in the CN of k^{th} routing path.

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_{vu}	Total power consumption from node v to node u.
P_{max}	Maximum power consumption.
R	Distance between the source node S and destination node D.
R'	Radius of the Half-Circle.
r	Maximum coverage distance of a node.
U_k	FC value of the k^{th} routing path.
X_k	Allocated network flow rate of the k^{th} routing path.

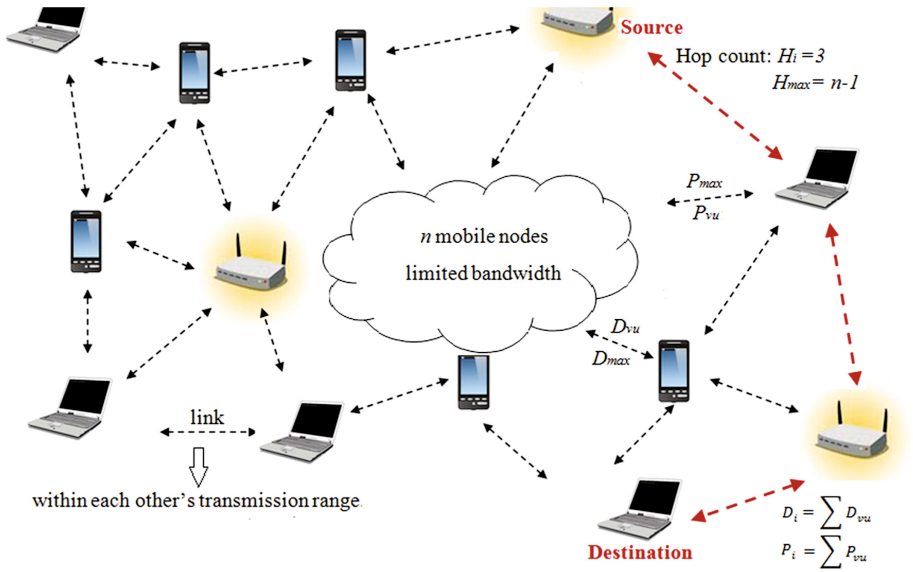

Fig. 2. Network model

2 Network Operation, Modeling and Assumptions

As shown in Fig. 2, we consider a network with n mobile nodes, each with a limited bandwidth. The nodes are equipped with Omni-directional antenna that has a maximum transmission power P_{max} and maximum interference I_{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 (such as the transmission power and the processing power) required to deliver data. Also let D_{vu} be the link delay consisting of the propagation delay and the processing delay; I_{vu} be the interference which can be anything that alters, modifies, or disrupts a message (e.g., noise) as it transmits the data from node v to node u. A routing path between a source and a destination consists of the concatenation of different links, and its length can be measured in hops H (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 a total power and total interference consumed along the path. The node with the minimum available bandwidth is identified as the CN (Crowded Node) which is most likely to have congestion in the presence of many network flows.

Unless otherwise specified, the following assumptions are pertained:

(a) There is no link breakage during the transmission: This allows us to focus on the channel conditions in this first stage of analysis without various complications. This will be relaxed in our future research.
(b) The number of network flows and their occupied bandwidths for the crowded node are known for the current transmission.
(c) The bandwidth 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 which 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.

3 Multipath Routing Algorithm

This section provides the details of the 3 steps of the multipath routing: path discovery, path selection and load distribution. During our path selection step, we not only consider the delay, power and path length, but also take the interference into consider. In the load distribution, we create a LP (Linear Optimization) model to optimally distribute the limited bandwidth to different multiple paths.

3.1 Path Discovery

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.

One can see that after each routing discovery process, an intermediate node can acquire all the related information (such as its next-node number 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 the increasing order of the end-to-end delays initially.

3.2 Path Selection

Before selecting the appropriate paths, the first step we need to do is to sort all the paths in the RPT based on their FCs which consists of the following 4 parameters:

(a) P_{vu}: the total link power consisting of factors such as transmission power and processing power.
(b) H_k: the path length of a route saved in the k^{th} row in RPT. Obviously, we have $H_k \leq n-1$ $(k = 1, 2, 3, \ldots)$.
(c) D_{vu}: link delay as introduced in the network model.
(d) I_{vu}: interference when transmitting packets from node v to node u.

We can now determine the FC of k^{th} routing path in the RPT as the total contributions of all the above parameters from all links along the path. Let U_k be the Flow Cost of the k^{th} path in the RPT and M be the set of nodes in the routing path such that $(v, u) \in$ M is the set of concatenated links to form the path. Then we have

$$U_k = \sum\nolimits_{(v,u) \in M} \left(\frac{P_{vu}}{P_{max}} + \frac{D_{vu}}{D_{max}} + \frac{I_{vu}}{I_{max}} \right) + \frac{H_k}{n-1} \tag{1}$$

Since the interference, power, delay and hop count take on different units and different magnitudes, we have normalized each parameter with their respective maximum value (i.e., P_{max}, D_{max}, I_{max} and $n-1$ respectively) so that their contributions become values between 0 and 1.

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 interference, lower time delay and smaller hop count.

After the first step of updating the RPT, we can get new routing path information in the table which is in an ascending order of FC. Thus, our second step is to simplify the table by the procedure of node-disjoint scheme. We will compare all the routing paths to see if they share the same node. When two or more routing paths share one same node, we will delete the path with higher FC (larger row number in RPT) until all the remaining routing paths are node-disjoint. For example, we firstly obtain the node numbers in the first routing path (the one in the first row with lowest FC), then we compare it with the node numbers saved in the second row. If they have one or more same node numbers, we will delete the second row from the RPT. Next, compare the node numbers with the third row, fourth row, etc. After the first iteration, all the paths in RPT will be node-disjoint with the first row. So we begin our second iteration to compare the second row with the others with larger row numbers. Then third iteration to compare the third row with the others with larger row numbers, the fourth iteration, etc., until all the paths in RPT are node-disjoint.

After the above two steps, we can obtain a simplified Routing Path Table. Every path in the table is node-disjoint with the others and the paths are in an ascending number according to their FCs. Assume there are k rows in total in the table. We use U_1 as the FC value for the first routing path saved in the first row in RPT; U_2 as the FC value for the second routing path saved in the second row in RPT; etc. U_k as the FC value for the k^{th} routing path saved in the last row in RPT. There are usually many routing paths in the RPT even after the node-disjoint selection scheme. If we consider all these paths, the efficiency of the algorithm will decrease. Therefore, we just consider the first 2 routing paths here (it's easy to expand the 2 routing paths to more).

3.3 Load Distribution

For each of the two multiple routing paths selected in Sect. 3.2, we need to distribute the limited bandwidth to different paths. For each path, we can find a Crowded Node with minimum available bandwidth. We attempt to optimize the bandwidth allocation of the limited bandwidth available at the two CNs by taking into account the usage of bandwidth by the other flows that can arise from anywhere in the network. In addition, we plan to use the utilization factor (packet arrival rate/transmission rate) combined with the FC in the optimization objective function to find the optimum bandwidth allocation scheme which can achieve the minimum flow cost. The results of the optimization would allow us to choose the best bandwidth allocation scheme among all paths between a source-destination pair.

We use U as the total flow cost and U_k as the flow cost of k^{th} path. Because we just choose the first two paths in RPT, so k can be equal to 1 or 2. If we want to bring in more multiple paths, we just extend the values of k. We assume the occupied bandwidth for the CN in k^{th} path is C_u^k and its maximum capacity is C_{max}^k. The bandwidth will be allocated to the k^{th} path is X_k. Then the optimization formulation is as the following.

$$\text{Minimize } U = \sum\nolimits_{k=1,2} U_k * \frac{C_u^k + X_k}{C_{max}^k} * X_k \tag{2}$$

Subject to:

$$C_u^k + X_k \leq C_{max}^k,\ k = 1, 2 \tag{3}$$

$$\sum\nolimits_k X_k \geq D_s,\ k = 1, 2 \tag{4}$$

$$X_k \geq 0,\ k = 1, 2 \tag{5}$$

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. Constraint (5) is just a regular condition to ensure the non-negativity of a flow value.

4 Optimization Performance

We shall use the AIMMS-CPLEX (Advanced Integrated Multidimensional Modeling Software) solver to solve our optimization problem. We will take a 20 nodes network for example as shown in Fig. 3.

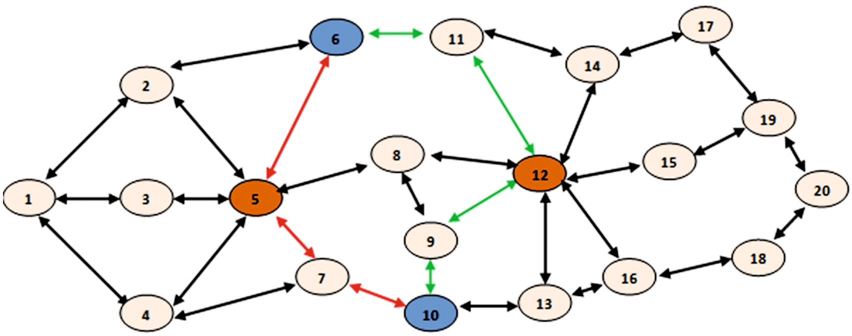

Fig. 3. A 20-nodes network example. (Color figure online)

Assume we have decided the two node-disjoint routing paths from source node 6 to destination node 10: the first one with smallest FC is *6-5-7-10* (red path); and the second path is *6-11-12-9-10* (green path). The two Crowded Nodes for these two multiple paths are Node 5 and Node 12. For node 5, we assume there are two other flows is using this node when we transmit the packets from node 6 to node 10, they are *1-3-5-7* and *4-5-8*. These two flows occupy $C_u^1 = 120$ Kbps. For node 12, we assume there are three other flows is using this node for transmission: *13-12-14, 9-12-15-19 and 8-12-16.* These three flows occupy $C_u^2 = 145$ Kbps . The maximum capacity for these two routing paths is 200 Kbps. The data arrival rate for current transmission (from source node 6) is D_S = 60 Kbps. Based on the above data information, we can create an optimization model in the AIMMS to solve the problem and obtain the optimal bandwidth allocation to the two multiple routing paths. We give some random values of Flow Cost for the first and second routing path. After running the model in AIMMS several times, we can get the different allocation results with different FC values as shown in Table 1 below.

Table 1. Allocation optimization results

The 1st routing path		The 2nd routing path		Total FC
FC	Allocated Bandwidth	FC	Allocated Bandwidth	
1.4	48.3 Kbps	1.8	11.7 Kbps	73
2.7	50.0 Kbps	3.6	10.0 Kbps	143
3.2	50.4 Kbps	4.3	9.6 Kbps	169
3.6	53.7 Kbps	5.2	6.3 Kbps	193
4.0	54.7 Kbps	5.9	5.3 Kbps	215
4.3	55.9 Kbps	6.5	4.1 Kbps	231
4.7	53.8 Kbps	6.8	6.2 Kbps	252
5.5	47.8 Kbps	7.0	12.2 Kbps	288
6.4	41.9 kbps	7.2	18.1 kbps	323

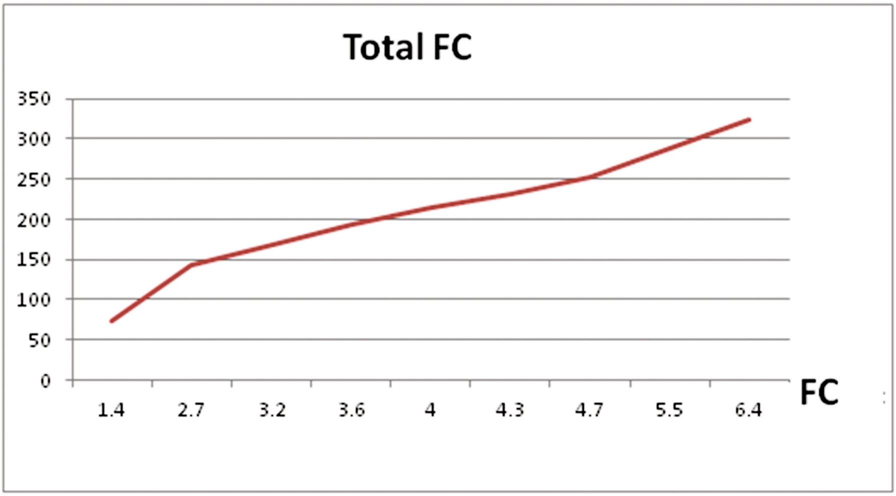

Fig. 4. Relationship between FC and total FC

From the table, it is obviously to see that the higher FC values for the two multiple paths, the higher Total FC as shown in Fig. 4.

The allocated bandwidth to a path is not an increasing function of FC as illustrated in Fig. 5 for the first multiple paths. A smaller FC does not guarantee to obtain more bandwidth because there is a FC for which a maximum bandwidth is obtained. So this relationship tells us that we need to find the more appropriate values for two multiple paths in order to optimally allocate the bandwidth according to our specific requirements.

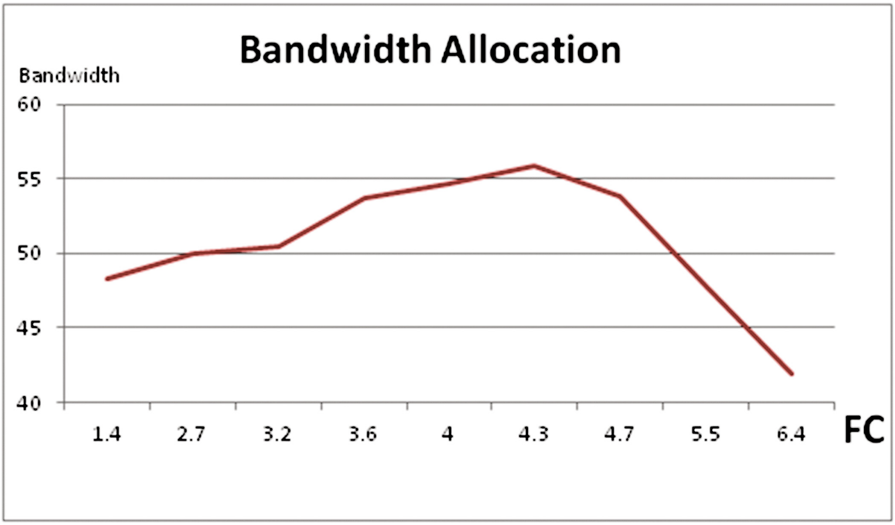

Fig. 5. Relationship between FC and allocated bandwidth

Table 2. Other random allocation schemes

	Bandwidth for 1st routing path	Bandwidth for 2nd routing path	Total FC
FC = 1.4 for the 1st routing path FC = 1.8 for the 2nd routing path	20 Kbps	40 Kbps	86
	15 Kbps	45 Kbps	91
	35 Kbps	25 Kbps	76
	30 Kbps	30 Kbps	79
	40 Kbps	20 Kbps	75
	10 Kbps	50 Kbps	97

In order to demonstrate the results from our optimization model is truly the optimum one, we will use the first group of FC values and results from Table 1 as an example. The FC values for the two routing paths are 1.4 and 1.8 respectively and the Total FC obtained is 73 based on the FC and its bandwidth allocation results: 48.3 Kbps for the first routing path and 11.7 Kbps for the second routing path. Therefore, we will give some other random bandwidth allocation schemes to see what their Total FC will be.

Table 2 shows that the Total FC from the other random allocation schemes are all bigger than our optimum Total FC value of 73. Therefore, we can demonstrate that the result we get from our optimization model is the minimum.

5 Conclusion

We have provided in this paper a multipath routing optimization for the allocation of limited bandwidth along multiple paths to a destination. The 3 steps of the multipath routing, path discovery, path selection and load distribution are discussed in details. We have integrated interference into the FC in both path selection and load distribution stages in addition to other three factors of end-to-end delay, power consumption, and hop count. An optimization model was created with consideration of interference by other flows to solve the problem and to obtain the minimum total flow cost. From the investigation of the relationship between the FC and Total FC, FC and Bandwidth allocated to one path, we can show that an optimum result is obtained.

The bandwidth allocation optimization methodology proposed in this paper has the benefit of increasing the reliability of the packet transmission and decreasing network congestion. Future work includes the simulations of our algorithms in a test-bed which will be created in Opnet and the applications of the beamforming directional antenna.

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