End-to-End Bandwidth Allocation for Fairness and Throughput Maximization in Wireless Mesh Network

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Abstract. In this paper, we consider the problems of routing, end-to-end bandwidth demand allocation and throughput maximization for wireless mesh network. The topics are hot issues for this kind of next generation wireless broadband Internet access network. We assume the end-to-end bandwidth allocations are demands of a set of commodities (source-destination pairs) in the network while previous work primarily has focused on bandwidth allocations for nodes. With that objective, we show that routing and end-to-end bandwidth allocation can be formulated under the interference and the well-known max-min fairness model constrains, where the throughput of commodities is to be improved. We propose two alternative algorithms to solve variants of this problem. And we use the numerical results to show the fairness enhancement and throughput improvement after applying our algorithms.

Keywords: Wireless mesh networks, fairness, bandwidth allocation.

1 Introduction

Wireless mesh network (WMN) has attracted increasing interest in recent years. The WMN consists of mesh routers and mesh clients. Mesh routers, stationary nodes, form the infrastructure backbone for clients. Due to the limited wireless channel capacity, the influence of interference, the large number of users and the emergence of real-time multimedia applications, allocating fair bandwidth combining with routing for improving network throughput have become the critical requirements in such networks. In multi-hop wireless networks, it has been shown that wireless interference has a significant impact on network performance [3] [11]. However, through efficiently arranging multiple radios to work on different non-interfering channels, it is expected that higher system throughput [6] [7]. Previous work in this area has largely focused on channel assignment [4] [5] [6]. There are also papers addressing the combination of channel assignment and routing for such a network [7] [9]. However, channel assignment is out of scope in this paper. We assume that the channel assignment is given by [5]. In this paper, we investigate routing, fair bandwidth demand allocation and throughput improvement under the interference constraint in WMN. In this paper, we provide two algorithms: *Centralized and Distributed Max-Min Fairness Routing and Bandwidth Allocation (CMMRBA and DMMRBA)* to solve the problem for routing and bandwidth allocation with the idea based on the remaining available bandwidth of the links can be still provided for the bandwidth demands of commodities in WMN. We also present two different ways to compute the suitable *increasing value* for our algorithms, one based on the characteristics of the possible minimum increase between different links and the other based on a Linear Programming (LP) formulation to maximize the increasing value under a set of interference and traffic constraints. The numerical results also show that the throughput of bandwidth demands is improved after applying our algorithms.

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We summarize some of the related work in Section 2. In Section 3, we describe the problem formulation. Our algorithms are presented in Section 4. Simulation results are showed in Section 5 and we conclude the paper in Section 6.

2 Related work

Recently, multi-channel multi-hop wireless network has become a very attractive topic. In [7] and [9], the authors propose algorithms for channel assignment and routing in multi-channel multi-NIC and single-NIC respectively. The most related works are [4] [5] [6]. The authors develop a set of centralized algorithms for channel assignment, bandwidth allocation and routing in [5]. They also present distributed channel assignment and routing algorithms utilizing only local traffic load information in a later paper [4]. The authors in [1] present a new routing metric, namely Expected Transmission Time/Weighted Cumulative ETT, and a corresponding Multi-Radio Link-Quality Source Routing protocol for multi-radio, multi-hop wireless networks to find a high throughput path between a source node and a destination node.

There are many papers addressing fairness both network layer and MAC layer. The authors in [8] present a polynomial time optimal algorithm to find LMM fractional flow routing solutions. As in [2] [13] [7], Tang's bandwidth allocation problem [13] is implicitly coupled with a flow routing problem as well. However, they address the problem differently by considering Lexicographical Max-Min bandwidth allocation under an interference constraint in a multi-channel multi-hop wireless network to non-gateway mesh routers instead of to the whole set of rate demand in WMN of each commodity as ours.

3 Problem Formulation

3.1 Network Model

We consider the backbone of WMN modeled by a *network graph* $G(V,E)$, where V is the set of nodes (mesh routers) and E is the set of bi-directional links. There are $\mathcal{C}$ orthogonal channels in the network, denoted by the set $OC = 1,2...,\mathcal{C}$. Each node v has $H(v)$ wireless interfaces. Because of local interference at a node, it is not useful to have two radios tuned to the same channel at a given node. Therefore, it is possible that $1 < H(v) < \mathcal{C}$. Each link e has capacity $C(e)$. A flow on link e is denoted by $f(e)$. We assume that the traffic demands are known for the sake of simplicity.

3.2 Interference Model

Due to the shared wireless medium, transmission along a communication link may interfere with other transmissions in the network. Two interfering links cannot engage in successful transmission at the same time if they transmit on the same channel. The interference model defines the set of links that can interfere with any given link in the network. There have been various interference models proposed in the literature, for example, the physical and protocol interference models [5], [8], [15]. We use the *protocol interference* model in [8]. Let e be a link in G, we will use $I(e)$ to denote the set of links in G that interferes with link *e*.

3.3 Problem Definitions

Our assumption is that considering a WMN with demands which can consume any bandwidth assigned to its path between source-destination pairs. This assumption corresponds for instance to a network with demands generating traffic which adapts to the changing bandwidth currently assigned to them. There are K demands in G, denoted by the set $K(G)$ labeled with index *k*, where $K(G) = 1,2,...,K$. Each demand *k* is assigned certain rate (bandwidth) denoted with r_k. Collecting the bandwidth demands, we define the allocation vector as $\mathbf{r} = (r_1, r_2, ..., r_k)$. For a vector $\mathbf{r} = (r_1, r_2, ..., r_k)$, we symbolize $\langle \mathbf{r} \rangle$ to be the elements of $\mathbf{r}$ arranged in a non-decreasing order (i.e., for some permutation θ on the set $\{1,2,...,k\}$, it holds that $\langle r \rangle_i = \langle r \rangle_{\theta(i)}$ for $i = 1,2,...,k$ and $\langle r \rangle_1 \le \langle r \rangle_2 \le ... \langle r \rangle_m$).

Based on those assumptions, our objective is how to assign *feasible* bandwidth demands to the demands' paths in a *fair* way to improve the throughput of WMN. The network throughput of a bandwidth demand allocation vector $\mathbf{r}$ is $B(\mathbf{r}) = \sum_{k=1}^{K} r_k$. A bandwidth demand allocation in WMN is called a *feasible* allocation if all the *interference-aware capacity* constraints are satisfied. So before going to *feasible* bandwidth demand allocation definition, we have the definition of *interference-aware capacity.*

Definition 1.Available Interference-aware Capacity. An *available interference-aware capacity* $A(e)$ is the remaining capacity of a link because of the *link interference* so we have

$$A(e) = C(e) - \sum_{e' \in I(e')} \sum_{k \in K(G)} r_k(e') \ge 0.$$

The *interference-aware capacity* constraint requires that the remaining capacities of links are not exceeded.

Definition 2.Feasible Bandwidth Demand Allocation. A bandwidth demand allocation is a *feasible* allocation if all the *interference-aware capacity* constraints are satisfied. This constraint requires that for every link $e \in E$ the sum of the rates of the demands that share it is at most the *interference-aware capacity* of that link: $\sum_k r_k(e) \le A(e)$.

To allocate bandwidth demand in a *fair* way, we use Max-Min Fairness (MMF) rule, one of the well-known methods to solve this problem [2]. A *feasible* bandwidth demand allocation is MMF, if the rate of a commodity cannot be increased without decreasing the rate of another commodity of equal or lower rate. Now we give the formal definition for the term MMF bandwidth demand allocation (similar definitions appear also in many other works [2], [18]).

Definition 3. MMF Bandwidth Demand Allocation. An bandwidth demand allocation vector $\mathbf{r}$ is called MMF vector if it is a *feasible* allocation and is lexicographically maximum among all feasible allocation vectors, with respect to $\langle \mathbf{r} \rangle \succ \langle \mathbf{r}' \rangle$. A vector $\mathbf{r}^* = (r_1, r_2, ..., r_k)$ is said to be lexicographically greater than vector $\mathbf{r} = (r_1, r_2, ..., r_k)$ if $\exists i, 1 \le i \le k$ such that $r_j = r'_j$, for $j < i$, and $r_i = r'_i$, in which case we denote by $\mathbf{r}^* \succ \mathbf{r}$. The goal of our algorithms is to compute a MMF vector $\mathbf{r}^*$**,** which constitute a *fair* allocation.

4 MMF Routing and Bandwidth Allocation Algorithms

In this section, we will propose two algorithms for the MMF routing and bandwidth demand allocation problem.

We call them Centralized MMF routing and bandwidth allocation (CMMRBA) and Distributed MMF routing and bandwidth allocation (DMMRBA).

Intuitively, the main idea behind our algorithms is that the first lowest value has to be maximized before the second lowest value is maximized. A demand value which has already been maximized to its final rate is called *satisfied*. The algorithms terminate when all demands are *satisfied*. The details of our algorithms are illustrated in Table 1. Our algorithms start at the first state of all demands' rates in G and converge to a final rate allocation. We denote by S the set of *satisfied bandwidth demands* and its complement $\overline{S}$, the set of *unsatisfied bandwidth demand* of the commodities in WMN.

Definition 4.Satisfied bandwidth demand. A demand is called satisfied when it reaches its final rate.We also enote by E' ($\overline{E'}$) the set of *saturated (unsaturated)* links in the network, which is defined below.

Definition 5.Saturated link. A link e is said to be *saturated* if the total of bandwidth demands on it is equal to its available capacity: $A(e) = \sum_k r_k(e)$.

CMMRBA	DMMRBA

1. $S:=\varnothing$; $\mathbf{r}^*:=\varnothing$;
2.**forall** $e\in\overline{E'}$
compute λ ;
3.**forall** $r_k \in \overline{S}$ **do**
$r_k^* := \min_{k\in K}\{r_k\} + \lambda$;
4.**forall** $e \in P_k$
$A(e) := A(e) - \lambda$;
if $(A(e) = 0)$
$S := S \cup \{r_k^*\}$;
$E' := E' \cup \{e\}$;
endif
endforall
5.**if** $\overline{S}=\varnothing$
stop;
else
goto Step_2;
endif
	1. $S:=\varnothing$; $\mathbf{r}^*:=\varnothing$;
	2.**forall** $e\in\overline{E'}$
	compute λ ;
	3.**forall** $e\in\overline{E'}$ **do**
	forall $r_k \in \overline{S}(e)$ **do**
	$r_k^* := \min_{k\in K}\{r_k\} + \lambda$;
	endforall
	$A(e) := A(e) - \lambda$;
	if $(A(e) = 0)$
	$S := S \cup \{r_k^*\}$;
	$E' := E' \cup \{e\}$;
	endif
	endforall
	4.**if** $\overline{S}=\varnothing$
	stop;
	else
	goto Step_2;
	endif

Table.1. CMMRBA and DMMRBA algorithms

4.1 CMMRBA

The idea of CMMRBA is that the algorithm will select the globally smallest unsatisfied demand for an increase. The globally smallest rate demand in the network is marked *satisfied* if it cannot be increased. At first, an *increasing value* λ will be computed basing on the set of unsaturated links $\overline{E'}$. The algorithm will increase the globally smallest unsatisfied demand value by λ. After that, all of the links making a path P_k that the globally smallest rate demand between the source node and sink node of a commodity go through are also decreased by a value λ. If an available bandwidth of any link on path P_k is saturated by a bandwidth demand increase, the algorithm will put that bandwidth demand allocation to satisfied set. The algorithm iteratively operates until all of the links are saturated.

4.2 DMMRBA

In this algorithm an unsatisfied demand is selected to be increased if its rate is smaller than or equal to the rates of all the unsatisfied demands with which it is on the same link. This algorithm is suitable for the distributed environment.

In contrast with CMMRBA, DMMRBA finds the locally smallest bandwidth demand on each link of the set of *unsaturated links* $\overline{E'}$ in WMN and increases it by λ. The algorithm also iteratively operates until all of the links are *saturated*.

In the next step we will present the way how to compute λ, the *increasing value* for a possible demand.

Maximize λ

Subject to

$$\sum_{v:(u,v)\in E} f_{uv} - \sum_{v:(u,v)\in E} f_{vu} = 0\,, k \in K(G)\,,\ \ \forall u \in V \setminus \{s(d), d(d)\} \quad (1)$$

$$\sum_{v:(u,v)\in E} f_{uv} - \sum_{v:(u,v)\in E} f_{vu} = \sum_{\forall e\in u(e)} r_k(e)\,,\ \ k \in K(G)\,,: u = s(d) \quad (2)$$

$$r_k(e) \geq \lambda \ \ \forall e \in E\,, \qquad k \in K(G) \quad (3)$$

$$A_e - \sum_{e'\in I(e)} f(e') \geq 0\,, \qquad \forall e \in E \quad (4)$$

Fig. 1. LP formulation to compute λ

4.3 Computing increasing value λ

In this section, we will present two different ways to compute the λ. One of them is the minimum over all possible increases and the other is based on Linear Programming (LP) formulation.

Intuitively, the available bandwidth of a link can be still fairly divided between the unsatisfied demands. The possible value must be the minimum over all the increases possible by the different links of $K(G)$. So we can compute λ as the *lowest fair share* value between these links in the WMN.

Definition 4.Lowest Fair Share. The value $\lambda = \min_{\forall e\in\overline{E'}} \left(\frac{A(e) - \sum r_k(e)}{\overline{S}(e)} \right)$ is called the *lowest fair share*.

Another way to compute λ that we want to propose is using the LP formulation to maximize the minimum bandwidth demand value λ. Therefore, we can ensure that for any feasible bandwidth demand allocation $\mathbf{r}$, we have $\min\{\mathbf{r}\} \leq \lambda$. We assume that each commodity d has a source node $s(d)$ and a sink node $d(d)$. A flow f_{uv} in

G is the aggregated bandwidth demands of all commodities on the link between node u and node v. We have the LP formulation based on some constraints in Figure 1. Constraint (1) is a general flow conservation constraint. It ensures the flow balance at those nodes which are not source node or sink node. Constraint (2) makes sure that the traffic takes place at source node (at sink node will be similar but negative value). Constraint (4) makes sure that the aggregated link flow allocation is feasible.

5 Performance Analysis

We use ns-2(ver2.28) to evaluate our algorithms. We choose two-ray propagation model and antenna height is $1\,m$. About MAC protocol, 802.11 CSMA/CA is used in all scenarios. Each node has the transmission range of $100\,m$ and carrier sense range of $200\,m$. The simulations are carried out for a 500×500 area in which 50 nodes are placed randomly. We use AODV as the base routing protocol in all scenarios. In our simulation schemes, we present two scenarios corresponding with two ways to compute *increasing value* λ. In the second scenario with computing λ by LP formulation, we use CPLEX Linear Programming [19] solver to solve the LP formulation. We choose IEEE 802.11b (with $\mathcal{C}$ = 3, link capacity = 11 Mbps and number of flows = 20) and 802.11a (with $\mathcal{C}$ = 12, link capacity = 54Mbps and number of flows = 30) standard for each of our scenarios. In each scenario, we initially set the low bandwidth value for every flow and then apply our algorithms for bandwidth demand allocation until bandwidths come to saturation. Each demand is assigned the routing sequence of all simple paths.

For each of those IEEE standards simulation results, we use two figures to show the results. The first one illustrates fairness, in which the x-axis is the sorted bandwidth demand index of the initial allocation and two others allocation by CMMRBA and DMMRBA algorithms, and the y-axis shows the corresponding bandwidth values. The second one shows the network throughput given by these three bandwidth allocation situations. The results are presented in Figures 2-10.

We can see that in both scenarios, both algorithms improve the fairness and also maximize the throughput of WMN. In both scenarios, CMMRBA and DMMRBA almost give the fairness for the system equally. In the first scenario, the throughput of the network after applying our algorithms improves 11.2% for CMMRBA and 11.8% for DMMRBA with IEEE 802.11b standard. With IEEE 802.11a, the network throughput improves 10.1% and 10.7% for CMMRBA and DMMRBA. In the second scenario, the throughput improves 12.7% with CMMRBA and 12.5% DMMRBA for 802.11b standard. With 802.11a standard, it improves 13.2% for CMMRBA and 14.1% for DMMRBA. Based on the numerical results, we can conclude that the *increasing value* λ computed by LP formulation maximizes the throughput more than using *lowest fair share.*

6 Conclusions and Future Work

In the paper we have focused on the problem of routing and bandwidth allocation in multi-channel multi-hop WMN to enhance fairness and increase throughput. We have showed two algorithms CMMRBA and DMMRBA as the solutions for the bandwidth demand allocation of each commodity in the network. We also present two different ways to compute the increasing value for our algorithms. In the future, we will consider problems which are more complex topics such as joint channel assignment and multi-path routing for bandwidth allocation and throughput increase in WMN.

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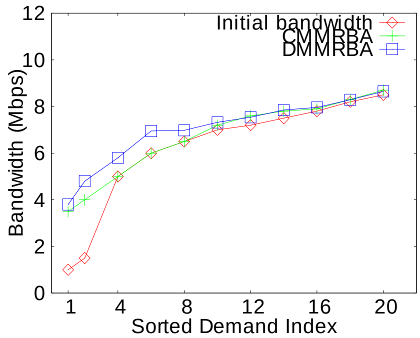

Fig.2. Bandwidth Allocation (802.11b)

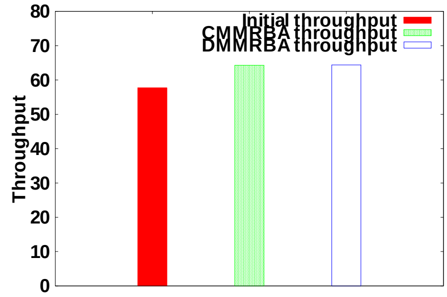

Fig.3. Network throughput (802.11b)

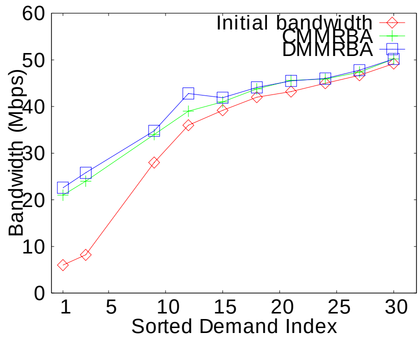

Fig.4. Bandwidth Allocation (802.11a)

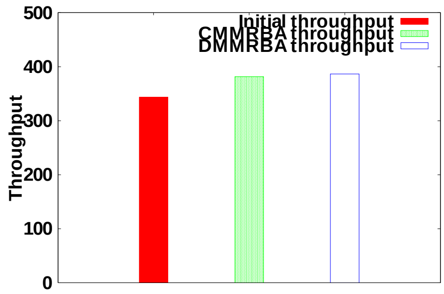

Fig.5. Network throughput (802.11a)

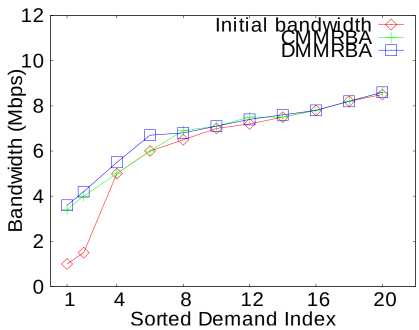

Fig.6. Bandwidth Allocation (802.11b)

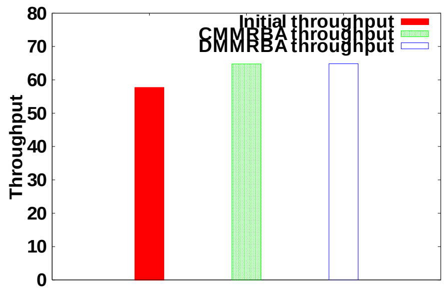

Fig.7. Network throughput (802.11b)

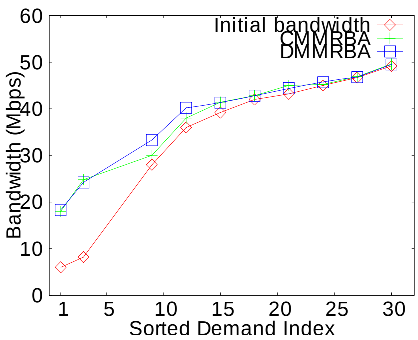

Fig.8. Bandwidth Allocation (802.11a)

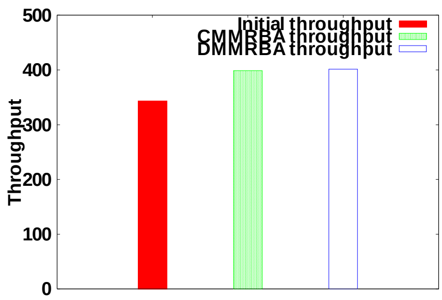

Fig.9. Network throughput (802.11a)