Interference-aware Fair Bandwidth Demand Allocation and Routing 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 multi-channel multi-hop wireless mesh network. We assume the end-to-end bandwidth demands of multi-commodity (a set of source-destination pairs) are satisfied by a set of flows in the network. 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.

1. Introduction

Multi-channel multi-hop wireless mesh networks have 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 [5] [17]. However, in a multi-radio network, more than one network interface card (NIC) designed with a capability of switching over multiple orthogonal channels and performing transmission or reception on any particular channel at a time. In this paper, we investigate routing, fair bandwidth demand allocation and also improving throughput under the interference constraint in multi-channel multi-hop WMN. 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 basing 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 improves 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. One of the first 802.11-based multi-channel multi-hop wireless mesh network architectures is proposed and evaluated in [7]. The authors develop a set of centralized algorithms for channel assignment, bandwidth allocation and routing. There are many papers addressing fairness both network layer and MAC layer. Megiddo in [12] presents a polynomial time optimal algorithm to find LMM fractional flow routing solutions. As in [4] [18] [12], Tang's bandwidth allocation problem [21] 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

We consider a fixed multi-hop wireless network with n nodes. We represent the WMN with a network graph $G(V,E)$ where V represents the set of nodes in the network and E represents the set of links that can carry data. There are C orthogonal channels in the network, denoted by the set $OC = 1, 2..., C$. Each node v has $H(v)$ NICs. 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 $1 < H(v) < C$. Each data link e has capacity $C(e)$. A flow on link e is denoted by $f(e)$. We use the *link 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*.

Our assumption is that there are K demands in G, denoted by the set $K(G)$ labeled with index k, where $K(G) = 1, 2, ..., K$. Each demand represents a commodity (a source-destination pair of nodes) between which some bandwidth is to be allocated. 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. Basing 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 $B(\mathbf{r}) = \sum_{k=1}^{K} r_k$. Below are the definitions for *feasible* bandwidth demand allocation and *fair* bandwidth demand allocation.

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

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: $\sum_k r_k(e) \leq A(e)$.

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]. Now we give the formal definition for the term MMF bandwidth demand allocation (similar definitions appear also in many other works [2], [21]).

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 $\exists i, 1 \leq i \leq k$ 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).

The general idea of our algorithms is increasing each bandwidth demand when the remaining bandwidth of its link is still available. 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 denote 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: $A(e) = \sum_k r_k(e)$.

The algorithm can then be stated as follows:

INPUT: A capacitated WMN $G(V, E)$, a set of commodities $K(G)$ and a initial rate r_k associated with each commodity. OUTPUT: The MMF routing and the associated bandwidth demand allocation vector.

Table.1. Algorithm statement

4.1 CMMRBA

The idea of CMMRBA is that at first, an *increasing value* α will be computed basing on the set of unsaturated links $\overline{E'}$. The algorithm will increase the globally smallest unsatisfied demand value by an *increasing value* α. 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 α. 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 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 α. The algorithm also iteratively operates until all of the links are *saturated*.

CMMRBA	DMMRBA

1. $S{:=}\varnothing$; $\mathbf{r}^{*}{:=}\varnothing$;
2. **forall** $e \in \overline{E}'$
compute α ;
3. **forall** $r_k \in \overline{S}$ **do**
$r_k^{*} := \min_{k \in K}\{r_k\} + \alpha$;
4. **forall** $e \in P_k$
$A(e) := A(e) - \alpha$;
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 α ;
	3. **forall** $e \in \overline{E}'$ **do**
	forall $r_k \in \overline{S}(e)$ **do**
	$r_k^{*} := \min_{k \in K}\{r_k\} + \alpha$;
	endforall
	$A(e) := A(e) - \alpha$;
	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.2. CMMRBA and DMMRBA algorithms

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

4.3 Computing increasing value α

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

Intuitively, the possible value must be the minimum over all the increases possible by the different links of $K(G)$. So we can compute α as the *lowest fair share* value between these link in the WMN.

Definition4.Lowest Fair Share. The value $\alpha = \min_{\forall e \in E}\left(\frac{A(e) - \sum r_k(e)}{\overline{S}(e)}\right)$ is called the *lowest fair share* of ink e. Another way to compute α that we want to propose is using a LP formulation to maximize the minimum bandwidth demand value α. 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 basing on some constraints below:

Maximize α
Subject to

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

$$\sum_{v:(u,v)\in E} f_{uv} - \sum_{v:(u,v)\in E} f_{vu} = \sum_{\forall e \in u(e)} r_k(e) \;\; ; \forall u \in V : u = s(d) \qquad (2)$$

$$r_k(e) \ge \alpha \; ; \forall e \in E \, , k \in K(G) \qquad (3)$$

$$A_e - \sum_{e' \in I(e)} f(e') \ge 0 \; ; \forall e \in E \qquad (4)$$

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 take 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. Numerical Results

In this section, we use numerical results to illustrate the two proposed routing and bandwidth allocation algorithm. We use Qualnet simulator to illustrate the performance of the algorithms by considering a network with V = 8 nodes (which is randomly located), E = 14 links, and k = 10 bandwidth demands. Each demand is assigned the routing sequence of all simple paths.

In our simulation scheme, we present two scenarios corresponding with two ways to compute *increasing value* α. In the second scenario with computing α by LP formulation, we use CPLEX Linear Programming [22] solver to solve the LP formulation. We choose IEEE 802.11b and 802.11a standard for each of our scenario.

Scenario 1: Using *lowest fair share* for *increasing value* α

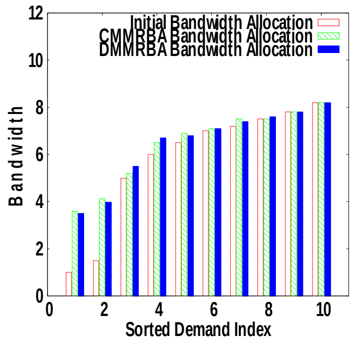

Fig.1. Bandwidth Allocation (802.11b)

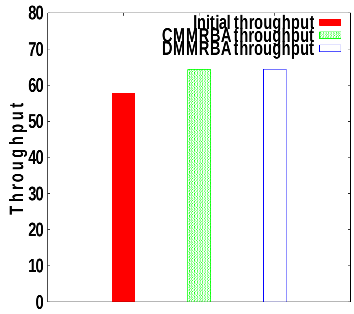

Fig.2. Network throughput (802.11b)

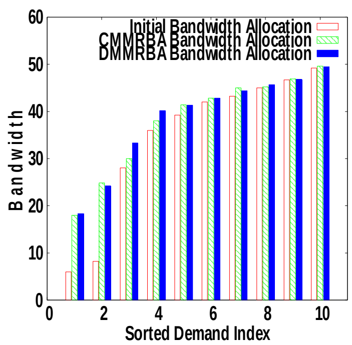

Fig.3. Bandwidth Allocation (802.11a)

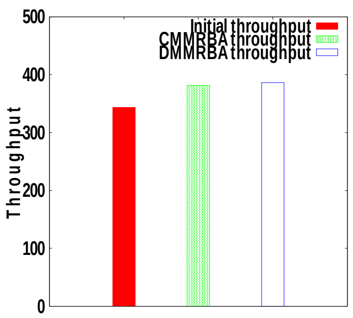

Fig.4. Network throughput (802.11a)

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 11.3% for CMMRBA and 11.6% for DMMRBA with IEEE 802.11b standard. With IEEE 802.11a, the network throughput improves 10.1% and 10.4% 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 13.8% for CMMRBA and 14.1% for DMMRBA. Basing on the numerical results, we can conclude that the *increasing value* α computed by LP formulation maximize the throughput more than using *lowest fair share*.

Scenario 2: Using LP formulation result for *increasing value* α

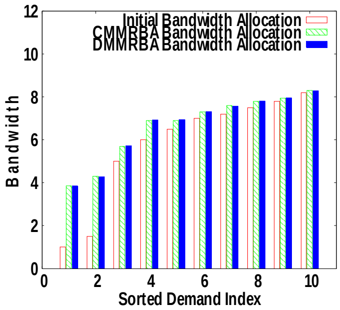

Fig.5. Bandwidth Allocation (802.11b)

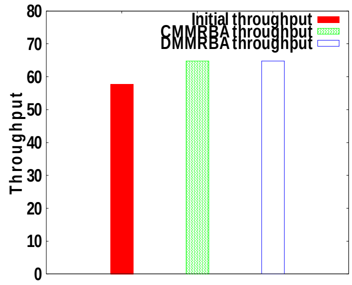

Fig.6. Network throughput (802.11b)

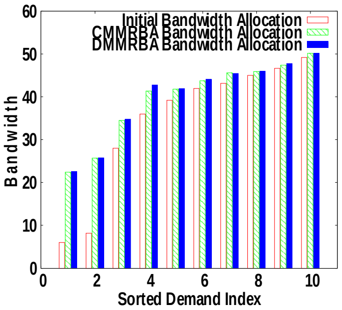

Fig.7. Bandwidth Allocation (802.11a)

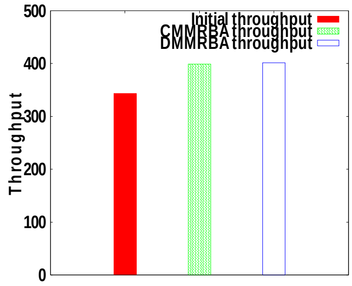

Fig.8. Network throughput (802.11a)

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. One of them is based on LP formulation, which gives the optimized throughput. We demonstrated through simulations that our proposed algorithms not only enhance fairness for routing and bandwidth allocation, but also maximize the network throughput. In the future, we will consider problem which is more complex: joint channel assignment and multi-path routing for bandwidth allocation and throughput increase in WMN.

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