On the Fairness of Frequency Domain Resource Allocation in Wireless Mesh Networks- A Survey

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Abstract—This article presents a concise survey of fairness-aware frequency domain resource allocation techniques in Wireless Mesh Networks (WMNs). Wireless mesh networks have emerged as a key technology for next generation application-specific multi-hop wireless networks. We analyze the state-of-the-art resource allocation schemes for WMNs, providing comprehensive taxonomy of the latest work and the future research trends in this field. In general, the resources that are available for WMNs include, time, frequency, space, relays, and power. An efficient utilization of these resources can make the network more robust, reliable, and fair. In this article we focus the frequency domain resource fairness techniques already presented, and then, provide a suboptimal fair resource allocation scheme that maximizes the sum throughput after guaranteeing the Service-Level-Agreement (SLA) requirements.

I. INTRODUCTION

Wireless mesh networking is a promising communication paradigm for next generation wireless networks. Wireless Mesh Networks (WMNs) consist of Mesh Clients (MCs) and Mesh Routers (MRs), where MRs form a wireless infrastructure/backbone and provide interconnection with the wired networks to extend the Internet connectivity to the MCs. Mesh networks are unplanned multi-hop wireless networks [1]. This type of networks is very attractive in developing countries or in the sparsely populated rural areas where infrastructure is either non-existent or prohibitively expensive. Due to this intrinsic property, WMNs have become the focus of research to increase the coverage range with low cost and easy deployment [2]. A large number of scheduling and resource allocation schemes have been proposed for WMN in literature [3], [4], [5]. Generally, scheduling algorithms prioritize the traffic flows which based on some criteria, including the transmission distance, number of hops, delay and other similar metrics. However, this approach may allow for starvation or reduced Quality of Service (QoS) for flows which do not meet the criteria. The majority of the proposed techniques focus on single objective, which is usually either to maximize throughput, or to optimize fairness amongst contending MRs/MCs. However, it is possible to have high throughput without node starvation at some parts of network. A typical WMN is shown in Fig.1. Fair resource allocation in multi-hop wireless networks (e.g., WMN) is a key research area during the last decade and this paper summarizes the imperative contributions of this era.

II. TAXONOMY OF FAIRNESS FOR RADIO RESOURCE ALLOCATION

Broadly speaking, there are five major categories of radio resource allocation. These categories include: Semi-hard-fairness [6], [7], [8], [9], max-min [10], [11], [12], proportional fairness [6], [7], [13], mixed-bias [13] and maximum throughput [14].

A. Semi-hard fairness

Hard-fairness is also known as Round Robin (RR) resource allocation scheme. It allocates frequency or time equally among the potential candidates regardless of any metric. Simple Time division Multiplexing (TDM) is a good example of RR scheduler, in which, each node is given a time slot to transmit at regular intervals. In networks where some nodes only require a small proportion of resources, hard-fairness causes wastage of available resources. The time division multiplexing scheduling schemes with objective to increase the spatial reuse are categorized as semi-hard-fairness schemes. How to assign the minislots to the different stations in WiMAX is unspecified in IEEE 802.16. A time domain scheduling of minislots in WiMAX mesh networks is described in [7], that defines a fairness model using time division multiplexing, where the notion of fairness is coupled to the actual traffic demands in such a way that the capacity region achieved is higher than...
that of hard fairness due to the multiplexing gain. A flexible and low cost extension of WiFi can be achieved through WMN. By allowing multi-hop communication between access points, it is possible for hundreds of Internet users to share a single broadband connection. But it can lead to severe unfairness and low bandwidth utilization. [8] presented a solution that assigns transmission rights to the links in the WMN and maximizes the spatial reuse (i.e., the possibility for links that do not contend to be activated at the same time). Bidirectional Distributed Coordinated Function (BDCF) [9] solved the unfairness problem between uplink and downlink flows in 802.11 DCF by granting preferential access to access points (APs). This protocol grants fair share of resources to the downlink flows and avoids the monopoly of uplink flows.

B. Max-min fairness

In this fairness scheme, the minimum amount of resources assigned to each node is maximized. In other words, we try to minimize the gap between the minimum and maximum amount of assigned resources to each user. So if there are more than enough resources for each node, every node gets what is needed. Otherwise, the resources are split evenly. This means that the nodes which require fewer resources get a higher proportion of their need satisfied. If a node require more resources, it will starve from resources because more resources are to be allocated to nodes with minimum number of resources and thus the network ends up with quite low packet delivery ratio. This type of fairness works best in networks in which there are no significant differences between the resources requested by each node.

1) Fair End-to-end Bandwidth Allocation (FEBA): Authors in [11] tried to solve the fairness issue in number of hop dependent throughput. In WMN, the end-to-end throughput of traffic flows depends on the path length, i.e., the higher the number of hops, the lower becomes the throughput. FEBA is implemented at the Medium Access Control (MAC) layer of single-radio, multiple channels IEEE 802.16 mesh nodes, operated in a distributed coordinated scheduling mode. FEBA negotiates bandwidth among neighbors to assign a fair share proportional to a specified weight to each end-to-end traffic flow. It provides traffic flows with weighted max-min fair access to the network resources, in terms of throughput, regardless of their spatial bias.

2) Max-Min guaranteed maximum throughput Rate Allocation: (MMERA) scheme [12] provides a solution for joint rate allocation, routing, scheduling, power control and channel assignment problems in multi-radio WMNs. Max-min optimization for a multi-source multi-destination cooperative OFDM-based static mesh network of access points (APs) is done in [10]. Each node is a source as well as a potential relay for other nodes. If the user \( k \) has the sum rate of \( R_k \) over all subcarriers and \( p_{lk}^{(n)} \) be the transmit power of relay \( l \) helping the source \( k \) on subcarrier \( n \), then, in order to achieve the max-min fairness we have to solve the following optimization problem

\[
\max_{(p_{lk}^{(n)})} \min_k R_k
\]

s.t. \( C_1: p_{lk}^{(n)} \cdot x_{lk}^{(n)} = 0, \forall k, n \) and \( l_1 \neq l_2 \)

\( C_2: p_{lk}^{(n)} \geq 0, \forall l, k, n \)

\( C_3: \sum_{k=1}^{K} \sum_{n=0}^{N} p_{lk}^{(n)} \leq P, \forall l \)

Constraint \( C_1 \) ensures selection of only one node to devote power to each subcarrier. Constraints \( C_2 \) and \( C_3 \) enforce non-negative power and power of relay to \( P \) Joule/symbol, respectively.

C. Proportional fairness

Proportional fairness implements time-based fairness and provides a good tradeoff between fairness and network throughput in contrast to max-min fairness where nodes with lower data rate occupy the medium for a larger percentage of time than those with higher data rates, leading to drastically reduced network throughput [15]. In general, proportional fairness allocates resources proportional to some characteristic in the network (throughput, distance, Signal-to-Noise Ratio (SNR), Bit Error Rate (BER) etc). For example, one can select SNR as the priority metric in wireless mesh network. The amount of resource allocated then would be proportional to receive SNR at particular node. The strength of the proportionality can be controlled through the proportionality factor [13] as:

\[
R = \frac{1}{X^\gamma}
\]

where \( R \) is the resource allocation to the source node, \( X \) is the characteristic which priority is given to, \( X > 0, \gamma \) is the proportionality factor, \( \gamma > 0 \).

The algorithm proposed by Qualcomm performs resource sharing by comparing the given rate for each user with its average throughput to date, and selecting the one with the maximum ratio [16]. If there are \( N \) active users in the cell and \( R_i(k) \) is the achievable rate for user \( i \) at the transmission interval \( k \), which depends on the user’s current channel conditions and the maximum block error rate that can be tolerated. The scheduler keeps track of the running average of the achieved rate \( T_i(k) \) for each user. Then, according to the proportional fair scheduling policy, user \( J_k \in 1, \ldots, N \) is chosen for transmission in time-slot \( k \) if [17, eq.(1)]:

\[
J_k = \arg \max_{1 \leq i \leq N} \frac{R_i(k)}{T_i(k)}, \quad k = 1, 2, \ldots
\]

1) Proportional fair End-to-end Rate Allocation (PERA): [12] maximizes the following utility function \( \sum_{k=1}^{K} \log(\alpha_k) \) using proportional fairness, where \( \alpha \) is demand satisfaction factor (DSF). PERA seeks an End-to-End feasible rate allocation vector along with a feasible channel assignment, a feasible flow allocation vector, a feasible transmission schedule, a frame length \( L \), and a feasible power assignment vector.
2) Non-altruistic non-reciprocal node cooperative Resource Allocation Optimization Problem: (NCRAOP) for WMNs with QoS support, subcarrier allocation, power allocation, partner selection/allocation, service differentiation, and packet scheduling, is NP-hard [18]. In general, solving the NP-hard NCRAOP requires exponential time complexity. An efficient and effective resource allocation approach to solve the NCRAOP, is the Lagrangian of the NCRAOP and the KKT conditions. Using the lagrangian and KKT conditions on $U(R(\cdot)) = \ln(R(\cdot)/A)$, ($A$ is a large constant, $A > R$) it is more likely for a mesh node to get an extra subcarrier and/or a partner if its data rate obtained is small, whereas it is less likely to assign an extra subcarrier or a partner to a node whose data rate obtained is already very high. Thus, both criteria match with the notion of proportional fairness.

D. Mixed-bias

The underlying idea behind mixed-bias is to allocate a portion of the total available capacity at a node via a strongly biased policy [13], and allocate the rest employing a fairer policy. Assume that, of the total available node resources $R$, $\beta R$ are allocated via resource allocation policy determined by weight function $w_1(C) = \frac{1}{C^{b_1}}$, and allocate the remaining $(1 - \beta)R$ via weight function $w_2(C) = \frac{1}{C^{b_2}}$, such that

$$R = \frac{\beta}{C^{b_1}} + \frac{(1 - \beta)}{C^{b_2}} \tag{7}$$

where $b_1$ and $b_2$ are the proportionality factors, $b_1, b_2 > 0$, and $\beta \geq 0$. This allows the scheduling algorithm to provide two different biasing levels or “mixed-biasing” against a certain characteristic $C$. It is actually an extension of proportional fairness equation (5).

E. Maximum throughput

Maximum throughput scheduling [19],[20] is only concerned with the allocation of resources to maximize the throughput. A node which can transmit the fastest or most data, gets access to the resources first. This ensures a very high sum-throughput, however, there is a limitation with this approach. Nodes which have less priority, such as those far away from gateways, those with fewer users, fewer flows, or less demanding traffic, are essentially ignored. If enough time passes, all of the packets waiting in the queues at mesh routers are dropped causing some nodes to be starved for traffic. This causes performance problem and should be avoided. Game theoretical approaches can be used to maximize the overall throughput in wireless mesh networks.

III. QoS Guaranteed Frequency Domain Resource Allocation Scheme

We consider a two-hop multiuser multi-relay mesh network with one gateway node. The proposed RB allocation algorithm consists of five steps. In the first step, all sets and RB assignment indicators are initialized. In second step, RB are sorted in descending order (i.e., the RB that gives highest throughput is placed at the top) for each relay-source subchannel. Same procedure has been repeated for every relay with all sources iteratively. Third step provides the RB-pairing between two hops. Since the maximum throughput is achieved when the channel gains of multi-hop links are the same, therefore two RBs are paired for which the differential gain is minimized in forth step. In the final step, one RB-pair which maximizes the instantaneous rate is allocated to each user. Remaining RB-pairs are allocated to the users in order to maximizes the marginal utility of each user while satisfying the some service level agreement (SLA) level ($q\%$) guaranteed throughput. At first, one user with the largest marginal utility is selected. If the selected user does not meet the minimum rate requirement, the RB-pair which maximizes the instantaneous rate of the user is allocated to that user. After every user meets the minimum rate requirement, one of the remaining RB is randomly selected and allocated to the user and relay which maximize the achievable sumrate over all users. This procedure continues until all RB-pairs are allocated. Let $K = \{1, 2, 3, \ldots, K\}$, $M = \{1, 2, 3, \ldots, M\}$, and $N = \{1, 2, 3, \ldots, N\}$ be the set of relays, sources, and subcarriers, respectively. System bandwidth is $B$ Hz and the bandwidth per RB is $B/N$. The transmit power allocated to relay $k$, source $m$, and destination at subcarrier $n$ are $P_{n,k}, P_{n,m},$ and $P_{n,D}$, respectively. $I_{S_m,R_k,D}^{(i,j)}$ denotes source $m$ data rate through relay $R_k$ when RB $i$ is selected between S-R and RB $j$ is selected between R-D. The indicator $x_{m,k}^{(i,j)} \in \{0,1\}$ shows whether or not the RB $i$ and $j$ is used by the link $S_m R_k$ and $R_k D$, respectively. For example, $x_{m,k}^{(0,1)} = 1$ means that the RB $i$ is assigned to link $S_m R_k$ and $j$ to $R_k D$. Each node has constraint on the maximum power denoted by $P_{k}^{max}, P_{m}^{max},$ and $P_{D}^{max}$, respectively. We compare our proposed scheme with simple OFDMA, max-min, simple proportional fairness scheme with same (n-n) RB-pairing.

IV. Conclusion

The wireless mesh network is a unique class of networks. Although there are still many critical problems to be solved,
the WMN has a vast development space in the broadband wireless access systems due to its advantages: flexible networking, easy maintenance, wide coverage, low cost, small risk, and more reliability. Moreover, in the development of WMNs, such technologies as cooperative relaying will play an important role in improving the link performance. In this article we have analyzed the state-of-the-art resource allocation schemes for WMNs with the objective to provide latest work that have been done and the future research trends in this field and proposed a frequency domain resource allocation scheme that maximizes the sum-rate and guarantees the minimum promised quality of service (QoS) as shown in Fig. 2.

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