Channel Assignment and Spatial Reuse Scheduling to Improve Throughput and Enhance Fairness in Wireless Mesh Networks

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Abstract. In wireless mesh network, by equipped mesh router with multiple radios tuned into orthogonal channels, throughput improvement problem can be alleviated. Efficient channel assignment and link scheduling is essential for throughput improvement. Effective channel assignment schemes can greatly relieve the interference effect between nearby transmissions. However, not only the links in wireless mesh network using different channels can be activated at a time, but some links in the same channel also can be activated concurrently if the SNIR (Signal-to-Noise and Interference Ratio) at their receiver endpoints is not lower than the threshold. In this paper, we investigate the problem of how to schedule a set of feasible transmission under physical interference model by using the Spatial TDMA access scheme and channel assignment in wireless mesh networks. We also consider the fairness enhancement to prevent some border nodes of the network from starvation. By using Minimum Spanning Tree as network subgraph constructed from original network graph, we propose centralized algorithms for scheduling and channel assignment to maximize the aggregate throughput and to provide the fairness of the network. We also evaluate the throughput improvement and fairness enhancement of our algorithms through extensive simulations and the results show that our algorithm can achieve significant aggregate throughput and fairness performance.

Keywords: Wireless mesh networks, scheduling, fairness.

1 Introduction

Wireless mesh networks (WMNs) have emerged to be a new, cost-effective for the next generation wireless Internet. In such networks, mesh routers which are stationary or less mobile nodes form the infrastructure backbone for clients whereas the mesh clients are the wireless devices to which the WMN provides connectivity. Only a fraction of nodes have direct access to the Internet and serve as gateways. Based on

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the benefits of multi-radio multi-channel mesh routers, several recent works have focused on many typical problems of WMNs like channel assignment, routing, scheduling [2], [5], [7], [13], [14]. Due to the limited wireless channel capacity, the large number of clients and the emergence of real-time multimedia applications, improving network throughput has become the critical requirements in such networks.

One of the important factors to improve the network capacity is spatial reuse [9], the total number of concurrent transmissions that can be accommodated in the network. Another popular MAC protocol that attracts most of the recent work is CSMA/CA proposed in IEEE 802.11 standard. But, due to its conservative mechanism with carrier sensing and collision avoidance characteristics, when a node transmits, a number of its neighbors must be inactivated. This leads to the fact that high traffic demand can not be satisfied, especially with WMN. In mesh networks, one of the major problems caused by concurrent transmissions is the reduction of capacity due to *interference*. Mesh routers with multiple radios can greatly alleviate this problem. With multiple radios, nodes can transmit and receive simultaneously or can transmit on multiple channels simultaneously. However, due to the limited number of channels available, the interference can not be completely eliminated. So an efficient channel assignment must be done to mitigate the effect of interference. Recently, most of the interest challenges relating to WMN have been investigated under two main interference models: *protocol* and *physical* interference models, which were first proposed in [18]. Until now, the protocol interference model mostly has been used due to the fact of its simplicity. In the physical interference, the transmission between two nodes is successful if the SNIR at the receiver is not lower than a certain threshold. In this way, more than one transmission can take place as long as the condition of SNIR at the receivers satisfied. We see that the characteristic of physical model is suitable with spatial reuse. Moreover, as the majority of traffic is transferred to and from gateways, traffic flows will likely aggregate at the mesh routers close to the gateways. Therefore, without effective channel assignment and scheduling algorithm, there is probably the data starvation of the mesh clients of border mesh routers. So, besides targeting to improve the overall throughput of the system, the transmission scheduling also takes into account the fairness problem to give the communications between border nodes a higher chance for transmission.

Based on discussion above, we present two centralized heuristic algorithms. One of them is for channel assignment problem which efficiently mitigates the interference effect and the other is to address the problem of scheduling using STDMA access scheme under the physical interference model to reach the objective of throughput improvement with fairness for the system. We also present extensive simulation results to evaluate throughput improvement and fairness of our algorithms.

The remainder of our paper is organized as follows. In Section 2, we summarize related work in the literature and highlight the major differences between existing work and our work. We state our models, assumptions and definitions in Section 3. Next, we describe our algorithms for scheduling and channel assignment in Section 4 and section 5. We evaluate the performance of our algorithm in Section 6. Finally, we present our conclusions and discuss the future work in Section 7.

2 Related Work

In literature, there are many works of scheduling mechanisms proposed for STDMA access scheme defined by Nelson and Kleinrock [11] for both protocol and physical interference model. Only a few works have considered physical interference in this context [2], [3], [4], [6], [12]. In [4], Gronkvist and Hasson compare the use of physical interference in STDMA to an approach that considers interference up to a certain distance from a node. Jain et al. [6] consider throughput optimization by formulating the problem of scheduling under both protocol and physical interference model as an LP problem. However, this formulation can be computationally intensive to achieve close to optimal performance. The work of [3] also provides an exponential-time LP formulation. About channel assignment problems, in [23], Ramachandran et al. presents an interference-aware channel assignment algorithm and protocol for multi-radio wireless mesh networks. His proposed solution assigns channels to radios to minimize interference within the mesh network and between the mesh network and co-located wireless networks. In [24], Brzezinski et al. considers the interaction between channel assignment and distributed scheduling in WMNs. Heuristic approaches [14], [15] on channel assignment and load-aware routing are proposed to improve the aggregate throughput of WMNs and balance load among gateways.

About the fairness problem, in [2], Ben Salem et al. propose a scheduling that ensures per-client fairness with solution assigns transmission rights to the links in a STDMA fashion and is collision-free by constructing maximal cliques. However, due to the fact that clique enumeration problem is proven to be NP-hard, her solution just can be used for small size WMNs. In [22], Jian Tang et al. consider the bandwidth allocation problem by using a simple max-min fairness model to achieve the tradeoff between maximizing throughput and enhancing the fairness. They address the problem by considering Lexicographical Max-Min bandwidth allocation under an interference constraint in a multi-channel multi-hop wireless network to non-gateway mesh routers.

3 System Models

3.1 Network Model

We consider the backbone of WMN modeled by a *network graph* $G(V, E)$, where $V = \{1, ..., |V|\}$ is the set of nodes (mesh routers) and $E = \{(i, j) : i, j \in V\}$ is the set of bi-directional links. We assume that time is slotted, denoted by t, and that the packet length is normalized in order to be transmittable in a unit time slot. We denote $Q_e(t)$ the number of packets waiting to be transmitted on link e by the end of time slot t, also known as queue length of link e. In the system, each node is equipped with one or more wireless interface cards, referred to as radios in this paper. We assume there are K orthogonal channels available in the network without any inter-channel interference. By using multiple radios and multiple channels, an interface of a node can transmit the data on one channel while another interface can receive data on a different channel.

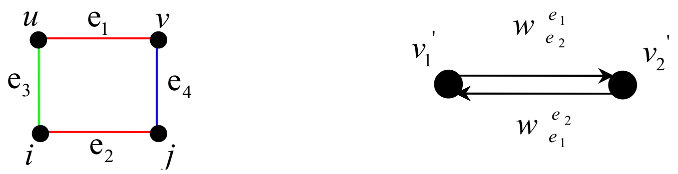
3.2 Interference Model

Physical Interference Mode: To schedule two links at the same time slot, we must ensure that the schedule will avoid the interference. We only consider physical interference model in our work. In this model, a successful transmission from node i to node j depends on the SINR at j. Specifically, denoting RSS_j^i as the signal strength of node j received when node i transmits to node j, and ISS_j^k as interfered signal strength received by j from another node k which is also transmitting, packets along the link (i, j) are correctly received if and only if:

$$\frac{RSS_j^i}{N + \sum_{k \in V_c} ISS_j^k} \geq \alpha \tag{1}$$

where N is the white noise, V_c is the subset of nodes in V that are transmitting concurrently, and the threshold α is the constant. Based on the physical interference model, the set of communication links that interfere with each other can be represented by using *interference graph* [6]. The interference graph will be constructed based on the interference between the links using the same channel.

Interference graph: To define a interference graph $G'(V', E')$, we first create a set of vertices V' corresponding to the communication links in the network. In this interference graph, a node represents for the edge in network graph and the directed edge between two nodes v_1', v_2' (which represents two links e_1, e_2 in network graph) has a weight. The interference graph must be weighted because the more the links on the same channel are active concurrently, the more interference each link will be affected by each other until they become unacceptable for the packet reception at the receivers.



(a) Network graph (b) Weighted interference graph

Fig. 1. Network graph and weighted interference graph

Consider an example in Figure 1, the communications between node u and v, i and j are on the same channel (the same red color in the figure), for example channel 1. The communications between u and i, v and j are on channel 2 and 3 respectively. So there is interference between e_1 and e_2. Therefore, we can construct the interference graph based on the network graph as Figure 2(b). From the above definition of weighted interference graph, we can have the weight value $w_{e_2}^{e_1}$ represents for the interference contributed by e_1 to e_2 (we can calculate $w_{e_1}^{e_2}$ as this way similarly):

$$w_{e_2}^{e_1} = \frac{\max(ISS_j^v, ISS_j^u)}{\frac{RSS_j^i}{\alpha} - N} \tag{2}$$

3.3 Conditions

We find the conditions to determine whether a certain set of concurrent transmissions on the same channel is feasible. 1) A necessary condition*:* The set $E_M = \{e_1, ..., e_k\} \subseteq E$ is feasible only if none of its edges is incident with each other on the same node. 2) A sufficient condition: Every receiver of all links in E_M must have $SINR \geq \alpha$. So, we can state the following corollary:

Corollary 1. *A set* $G_T^{'} \in E$ *of concurrent transmission on the same channel in a given network graph* $G(V, E)$ *is feasible under physical interference model if every vertex of the corresponding interference graph* $G^{'}(V^{'}, E^{'})$ *satisfies:*

$$\sum_{v_k^{'} \in V^{'} - \{v^{'}\}} w_e^{e_k} \leq 1 \tag{3}$$

Proof: We have the set of links $\{e_k = (i_k, j_k), k = 1, 2, ...\}$ transmitting concurrently with link $e = (i, j)$. Therefore, in respective interference graph, we will have of all edges incident on $v^{'}$ represents all interfering signals of all links $e_1, ..., e_k$ to link e. From Eq.(1), packets are received correctly at receiver of link e when:

$$\frac{RSS_j^i}{N + \sum_{(i_k, j_k) \in G_T^{'}} ISS_j^{i_k}} \geq \alpha \Rightarrow \frac{\sum_{(i_k, j_k) \in G_T^{'}} ISS_j^{i_k}}{\frac{RSS_j^i}{\alpha} - N} \leq 1 \Leftrightarrow \sum_{v_k^{'} \in V^{'} - \{v^{'}\}} w_e^{e_k} \leq 1. \qquad \square$$

4 Scheduling Algorithm

In this section, we present a greedy algorithm to construct a feasible schedule for a set of transmissions under physical interference model. Instead of considering for the whole network, proposed algorithm just investigates in a subgraph. The reason is to improve the fairness characteristic. If we consider the feasible schedule for whole network, the links close to management nodes have higher priority will take over the right to be scheduled first. It leads to some links at the border of system may not have a chance to transmit the data. When setting feasible schedule for a subgraph in each period, the number of high priority links has been reduced, so the border links can transmit with higher probability.

Consequently, we decide to choose Minimum Spanning Tree (MST) as the subgraph of the network graph $G(V,E)$ in our algorithm because MST has all characteristics appropriate for the purpose of our algorithm. First, MST is a spanning subgraph that contains all vertices of $G(V,E)$ so it gives an equal chance for all links incident with all nodes to be considered in each period of the schedule. Second, MST of a graph defines the cheapest subset of edges that keeps the graph in one connected component. So each link in a MST will have the higher priority than the others incident on the same node with it. It satisfies the condition that links with higher priority will be considered to be scheduled first. Finally, it can be computed quickly and easily, e.g. Kruskal's minimum spanning tree algorithm [21] can have the running time $O(|E|\log|V|)$. It's an important factor to reduce time complexity of our algorithm. Figure 2 is an example of MST (the bold lines) constructed from a WMN. There are total 7 links operating on channel 1 contend to be scheduled for whole network while in this MST, there are just 4 links. So with the priority criterion, links of border nodes will have higher chance to be in a schedule.

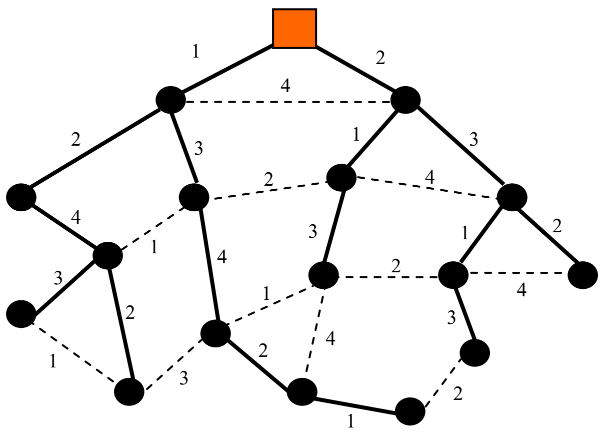


Fig. 2. A Minimum Spanning Tree of a WMN with 4 different channels

The pseudo code of scheduling algorithm is given in Figure 3. First, a MST $T(V_T, E_T)$ is constructed from the network graph. The cost of each link is computed by value $c(e)=\dfrac{1}{Q_e(t)}$ where $Q_e(t)$ is the queue size of link e by the time the algorithm starts to operate. With those edges of this MST, at least one edge of a vertex in $T(V_T, E_T)$ has the minimum cost. At first, the set of links on the same channel to be scheduled are ordered according to the decreasing order of queue lengths (step 2). After that, in step 3, Algorithm 1 finds the maximal feasible set of transmissions (E_M). Beginning with the highest queue length link, the algorithm adds next ordering links into the interference graph until there is a link making the interference graph unsatisfied with corollary 1. After having maximal feasible set of transmission, each link e in E_M will be scheduled in the first available slots beginning from slot 0 to slot $Q_e(t)$ (step 5). The period of this feasible transmission set is the maximum queue length of a link in E_M .

Algorithm 1. Scheduling Algorithm

Input: a network graph $G(V, E)$

Output: a feasible schedule with spatial reuse.

1. Creating MST $T(V_T, E_T)$ from $G(V, E)$

for $i = 1, ..., K$

2. initialize $G_T^{'}(i)$ with $V_T^{'}(i) = 0, E_T(i) \supseteq E_M(i) = 0$;
3. order links in $E_T(i)$ with decreasing number of queue length. Let $e_1(i), ..., e_m(i)$ be the resulting ordering;
4. **for** $j = 1, ..., m$

    $V_T^{'}(i) = V_T^{'}(i) + \{\{v^{'}(i)\} \leftrightarrow \{e^j(i) \in E_T(i)\}\}$;

    construct $G_T^{'}(i)$ with new vertex $v^{'}(i)$ added;

    if $G_T^{'}(i)$ satisfies corollary 1

        $E_M(i) = E_M(i) + e^j(i)$;

        $j = j + 1$;

    else exit;

    endif

    endfor

5. set available slots to $1, ..., T = \max_{e \in E_M(i)} Q_e(t)$
6. **for** $k = 1, ..., l = |E_M(i)|$

    schedule link $e^k(i) \in E_M(i)$ in the first $Q_{e^k(i)}(t)$ slots;

    endfor

endfor

Fig. 3. Scheduling Algorithm

5 Channel Assignment Algorithm

5.1 Overview

The channel assignment problem for mesh networks is similar to the *list coloring* problem. The list coloring problem is NP-complete [21]. Therefore, we rely on an approximate algorithm for channel assignment. Our channel assignment algorithm is also based on the MST subgraph of network graph. The rationale behind the use of MST subgraph is intuitive: we still satisfy our goal described in previous section of giving channel assignment priority to links starting from the gateway and then in decreasing levels of priority to links fanning outward towards the edge of the network. Before using the channel assignment algorithm, the gateway uses the neighbor information collected from all routers to get the link delay information. Neighbor information sent by a router can contain the identity of its neighbors delay to each neighbor. The channel assignment algorithm is summarized in Figure 4. The algorithm starts with all links emanating from the gateway which we called the first-hop level links. These links are sorted by increasing delay values (step 1). The link delay can be calculated using the Expected Transmission Time (ETT) metric [19]. ETT of a link is derived from the link's bandwidth and loss rate. A more detailed description of the metric can be found in [19]. This sort is performed in order to give higher priority to the better links emanating from the gateway. After that, it will assign the channel having better capacity to the link having higher priority that will not conflict with channel assignments of its neighbors to mitigate the effect of interference (step 2). If a non-conflicting channel is not available, a channel will be chosen randomly to be assigned (Step 3). The algorithm continues with links of second-hop level until the last-hop level, gradually fan-out from the gateway to border mesh routers.

Algorithm 2. Channel Assignment Algorithm

```
for  i = first-hop level to last-hop level from the gateway
    for all links in i -hop level
1.      sort links by increasing delay value
2.      assign higher capacity channels in K orthogonal channels to higher priority
        links that does not conflict with their neighbors
3.      if notfound channels in Step 2
            assign random channels
        endif
    endfor
endfor
```

Fig. 4. Channel Assignment Algorithm

6 Performance Evaluation

In this section, through simulation, we evaluate the performance of our scheduling algorithm by comparing with the algorithm of Alicherry, et al. [5], which uses IEEE 802.11 CSMA/CA whose behavior is similar to protocol interference model. We

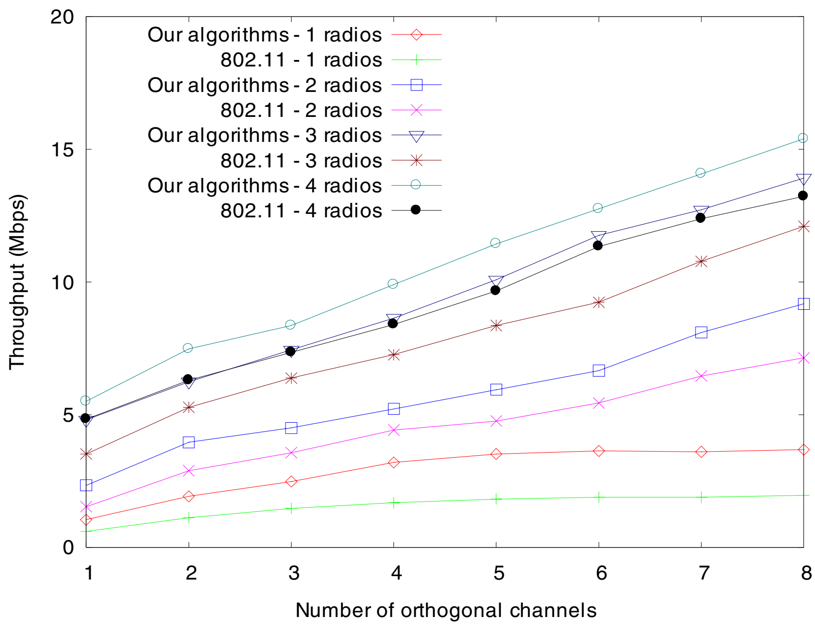


Fig. 5. Throughput Improvement Evaluation

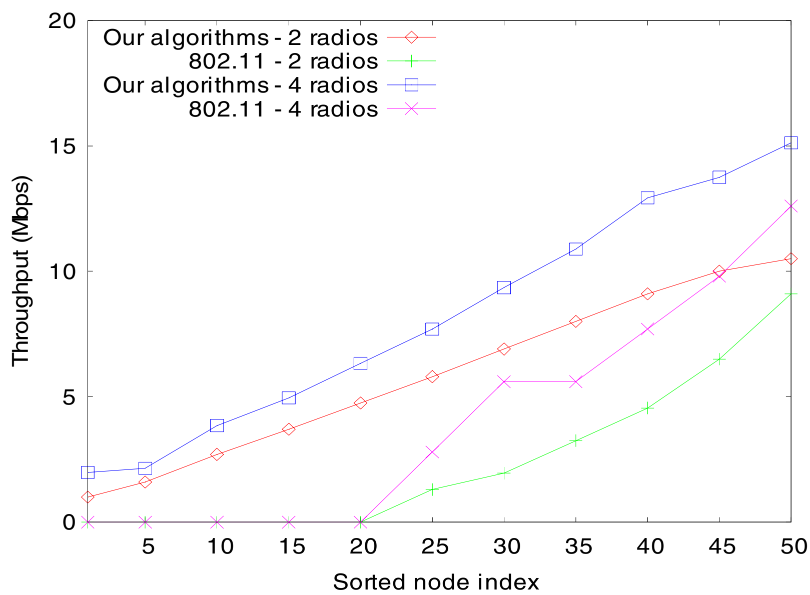


Fig. 6. Fairness Evaluation

present two sets of simulation results. The first set evaluates throughput improvement and the second set evaluates the fairness. We have implemented our algorithm in ns-2 (ver2.28). In particular, we have modified in ns-2 such that the interference perceived at a receiver is the collective aggregate interference from all the concurrent transmissions. We use two-ray propagation model. In case of 802.11, each node has the transmission range of $150\,m$, carrier sense range of $300\,m$. The simulations are carried out for a $800 \times 800\,m^2$ area in which 50 nodes are placed randomly. We use the default transmission rates 11 Mbps to reflect realistic 802.11b data rates. We also use constant bit rate (CBR) over UDP and use Adhoc On-demand Distance Vector (AODV) as the base routing protocol. We choose Kruskal's algorithm [21] to construct the MST from the network for our algorithms.

Throughput Improvements Evaluation: We compare our algorithms and Alicherry's algorithm using 802.11 based on the effect number of channels and number of radios. We vary the number of orthogonal channels available from 1 to 8 and the number of radios is from 1 to 4 respectively. From Figure 5, we see that our algorithm can exploit effectively the increasing number of channels with different number of radios. For example, as the number of channels goes from 1 to 8, the network throughput goes from 1.3 Mbps to 4.6 Mbps, from 2.9 Mbps to 11.7 Mbps, from 5.8 Mbps to 16.86 Mbps and from 6.75 Mbps to 18.9 Mbps in case of 1, 2, 3 and 4 radios respectively. Compared with 802.11, we can see the average increase of our algorithms is respectively 45%, 36%, 30% and 25%.

Fairness Evaluation: To evaluate the fairness of our algorithm and Alicherry's algorithm using 802.11, we compare the aggregate throughput of nodes starting from the border of network towards the nodes which are near the management node. Therefore, the nodes are sorted with the order of increasing queue length. We also vary number of radios (2 and 4 radios) to show their effects on fairness evaluation. We choose the fixed number of orthogonal channels in the network $K = 8$. From Figure 6, it can be observed that the border nodes throughput of our algorithm is higher than that of 802.11. The number of nodes which are starved in case of 802.11 is significant (nearly 20 nodes). With our algorithm, the fairness has been improved much when the border nodes still can transmit the data.

7 Conclusions and Future Work

In this paper, we have investigated how to assign channels and how to schedule links in WMNs by using STDMA access scheme under physical interference model. We proposed heuristic algorithms to solve this problem. Our algorithms not only improves system throughput but also guarantees the fairness for all nodes in the system, which are proven through extensive simulations.

We have identified several future research avenues. One of them is the possibility to joint our fair scheduling and channel assignment algorithm with routing to give the better performance. Another interesting problem to be addressed is developing distributed algorithms to reduce the overhead of exchanging interference measurement information between gateway and mesh routers.

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