On the Fair-Scheduling for Throughput Improvement in Wireless Mesh Networks

Nguyen H. Tran, Choong Seon Hong

Department of Computer Engineering, Kyung Hee University
Giheung, Yongin, Gyeonggi, 449-701 Korea
nguyenth@networking.khu.ac.kr, cshong@khu.ac.kr

Abstract. 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 for multi-radio multi-channel wireless mesh network. We also consider the fairness enhancement in scheduling to prevent some border nodes of the network from starvation. In this work, we propose a greedy algorithm for scheduling to maximize the aggregate throughput and to provide the fairness of the network. Moreover, we also evaluate the throughput improvement and fairness enhancement of our algorithm 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

Multi-radio multi-channel wireless mesh networks (WMNs) have emerged to be a new, cost-effective for the next generation wireless Internet. The main design concern of WMN is increasing the traffic carrying capacity of mesh routers. Consequently, spatial reuse TDMA which was introduced in [6] is an access scheme that provides the concurrent transmissions as long as they do not interfere too much with each other. However, in mesh networks, one of the major problems caused by concurrent transmissions is the reduction of capacity due to *interference*, which is a consequence of using a shared wireless medium. Recently, most of the interest challenges relating to WMN have been investigated under two main interference models: *protocol* and *physical* interference models [7]. 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. So by constructing a transmission schedule carefully using STDMA under the physical interference model, we can achieve the goal of improving the throughput of mesh networks. Based on discussion above, we present an algorithm called *Greedy Fair Scheduling* to address the problem of scheduling using STDMA access scheme under the physical interference model to reach the objective of throughput improvement with fairness to prevent border nodes from starvation. We also present extensive simulation results to evaluate throughput improvement and fairness of our algorithm.

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2006-521-D00394). Dr. CS Hong is corresponding author.

In Section 2, we summarize related work in the literature. We state our models in Section 3. Next, we describe our algorithm in Section 4. We evaluate the performance of our algorithm in Section 5. Finally, we present our conclusions and discuss the future work in Section 6.

2 Related work

In literature, there are many works of scheduling mechanisms proposed for STDMA access scheme defined by Nelson and Kleinrock [6] for both protocol and physical interference model. Only a few works have considered physical interference in this context [2], [3], [4], [6]. In [3], 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. In [11], Brar et al. also address the scheduling problem by using STDMA under physical interference model but they didn't take advantage the multi-radio multi-channel characteristic of WMN into their algorithm. About the fairness problem, in [1], 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. In [9], 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.

3 System Models

3.1 Network Model

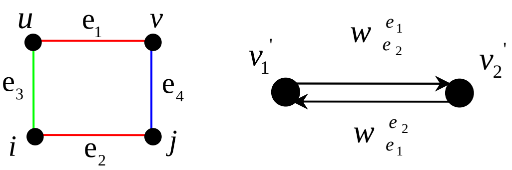
We consider the backbone of WMN modeled by a *network graph* $G(V,E)$, where V is the set of nodes (mesh routers) and E is the set of bi-directional links. Depending on the context, we can denote a link either by (i,j) or by e. We assume that time is slotted, denoted by t, and that the packet length 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. We assume there are K orthogonal channels available in the network without any inter-channel interference.

3.2 Interference Model

Physical Interference Mode: 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:

$$\frac{RSS_j^i}{N + \sum_{k \in V_C} ISS_j^k} \geq \alpha \qquad (1)$$

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 on the same channel that interfere with each other can be represented by using *interference graph* [6].



(a) Network (b) Weighted interference graph

Fig. 1. Network graph and weighted interference graph

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. $V^{'} = \{v' \mid \{v' \in V'\} \leftrightarrow \{e \in E\}\}$. In this interference graph, a vertex represents for the edge in network graph and the directed edge between two nodes $v_1^{'}$, $v_2^{'}$ has a weight. This weight represents the ratio of maximum permissible noise and interference level at the receiver of link e_2 (or e_1) contributed by transmission on link e_1 (or e_2), denoted by $w_{e_1}^{e_2}$ (or $w_{e_1}^{e_2}$) (2). Consider an example in Figure 1, the communications between node u and v, i and j are on the same channel 1 and 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 1(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:

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

3.3 Definitions

Given the network graph $G(V,E)$ and the interference graph $G^{'}(V^{'},E^{'})$ of a specific channel, we can find the conditions to determine whether a certain set of transmissions on the same channel $E_F = \{e_1,...,e_k\} \subseteq E$ is feasible.

DEFINITION 1. *A set $E_F \subseteq E$ of concurrent transmissions on the same channel in a given network graph $G(V,E)$ is feasible under physical interference model if none of the edges in E_F is incident with the others on the same node and all of their receivers have $SNIR \geq \alpha$.*

Given the network graph $G(V,E)$ and the interference graph $G^{'}(V^{'},E^{'})$ of a specific channel, we can state the following corollary.

COROLLARY 1. *A set $E_F \in E$ 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:*

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

Proof: From Eq. (1) and (2), we can easily derive the result.

4 Scheduling Algorithm

4.1 Problem Formulations and Notations

We assume an aperiodic time slotted schedule in which the set of links scheduled for transmissions satisfy corollary 1 in every slot. The length of a period depends on the link which has the maximum queue length in a set of feasible transmissions $E_F \in E$. So the number of time slots of each set of transmissions is equal to the maximum queue length of this set at that time, $T = \max_{e \in E_F} Q_e(t)$, and the algorithm schedule each edge e in $Q_e(t)$ time slots.

4.2 Greedy FAir Scheduling (GFAS) Algorithm

Instead of considering the feasible schedule in the whole network, GFAS just investigates the scheduling problem in a subgraph. The reason to find a subgraph for building a feasible schedule is to improve the fairness characteristic. Consequently, we decide to choose Minimum Spanning Tree (MST) as the subgraph of the network graph $G(V,E)$ in our algorithm because MST is a subgraph that has all characteristics appropriate for the purpose of our algorithm. Firstly, MST is a spanning subgraph that contains all vertices of $G(V,E)$. Secondly, MST of a graph defines the cheapest subset of edges that keeps the graph in one connected component. Finally, they can be computed quickly and easily [10]. Figure 2 is an example of MST constructed from a WMN. There are total 7 links operating on channel 1 contends to be scheduled for whole network while in this MST, there are just 4 links. The pseudo code of GFAS 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. So at first, the set of K 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, GFAS finds the maximal set of transmissions (E_M). Beginning with the highest queue length link, the algorithm adds next order 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 Greedy Fair Scheduling (GFAS)

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 $i = 1, \dots, K$

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 $e_1(i), \dots, e_m(i)$ be the resulting ordering;
4. **for** $j = 1, \dots, m$

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

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

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

    endfor

endfor

Fig. 3. Greedy Fair Scheduling Algorithm

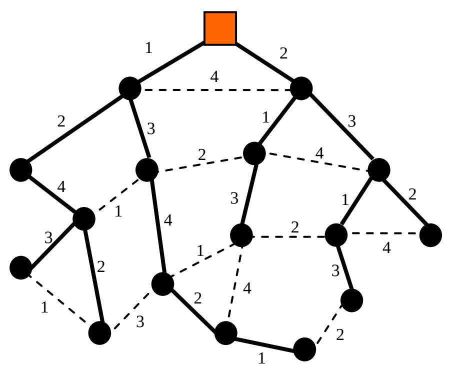


Fig. 2. A Minimum Spanning Tree of a WMN with 4 different channels.

5 Performance Evaluation

In this section, we carry out a simulation study to evaluate the performance of our algorithm by comparing with GreedyPhysical algorithm of Brar et al. [11], which also consider scheduling under STDMA access scheme and IEEE 802.11 using CSMA/CA access scheme whose behavior is similar with protocol interference model.

5.1 Simulation Setup

We have implement GFAS in ns-2 (ver2.30). In particular, we have modified ns-2 such that the interference perceived at a receiver is the collective aggregate interference from all the concurrent transmissions. The simulations are carried out for a 800×800 area in which nodes are placed randomly. We vary the number of orthogonal channels available from 1 to 8 and the number of radios is 4 by default. We use 3 different transmission rates namely 2, 10, 54 Mbps to reflect realistic 802.11 a/b/g data rates. By default we use a 2 Mbps channel. We use AODV as the base routing protocol in all scenarios. We choose Kruskal's algorithm [10] to construct the MST from the network for GFAS.

5.2 Simulation Results Evaluation

Throughput Improvements Evaluation: We compare GFAS, GreedyPhysical and 802.11 to give the throughput improvement results based on the effect of network density, data rates. Figure 4 shows the effect of network density. We vary the number of nodes in simulation area in three cases with 50, 100 and 150 nodes, which represent, respectively, for sparsely, moderately and densely populated networks. From the figure, it can be observed that the relative performance improvement of GreedyPhysical and GFAS are respectively 100% and 50% significantly better than 802.11 in moderate network density. In case of moderate and dense network, the average throughput of GreedyPhysical and GFAS improves 70% higher than that of 802.11. It can be explained that in sparse network, there are more links can transmit simultaneously in the whole network than just in a MST. Figure 5 shows the effect of data rates to throughput improvement evaluation in case of moderate network density with 100 nodes. It can be observed that the performance of GreedyPhysical and GFAS increases with increasing channel data rates. In this case, the relative throughput improvement of GreedyPhysical and GFAS is nearly 150% higher than 802.11.

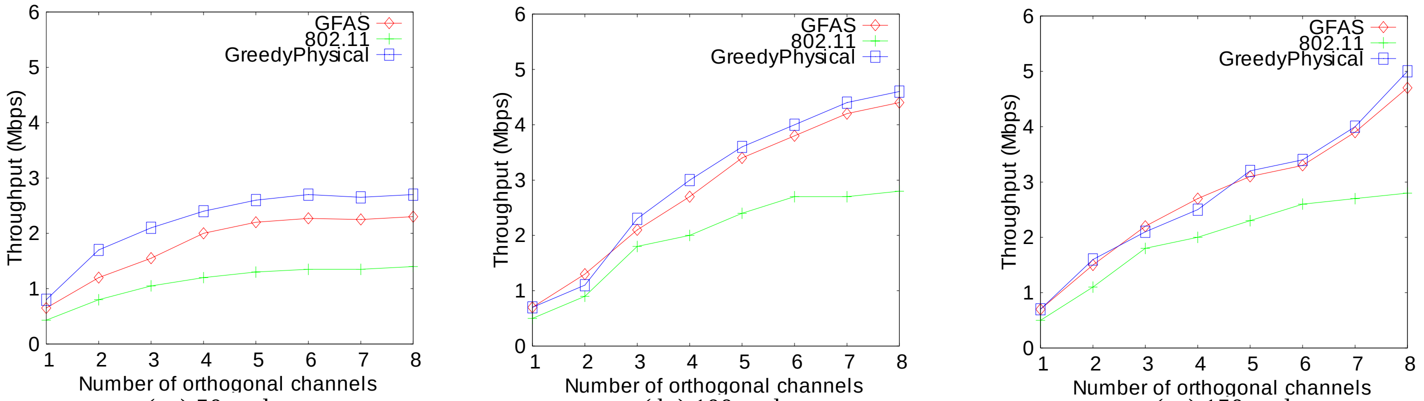
Fairness Evaluation: To evaluate the fairness of GreedyPhysical, GFAS and 802.11, we compare the aggregate throughput of nodes starting from the border of network towards the nodes which are near the gateway. Therefore, the nodes are sorted with the order of increasing queue length. In this scenario, we choose the fixed number of orthogonal channels in the network $K = 8$. From Figure 6, it can be observed that in three cases, the border nodes throughput of GreedyPhysical and GFAS is higher than that of 802.11. The number of nodes which are starved in case of 802.11 is significant. Furthermore, in moderate and dense network, the results show that GFAS has the fairest aggregate throughput at border gateways among three approaches. The effect of data rates to fairness evaluation is reported in Figure 7. We also choose moderate network with 100 nodes for each data rate. We can observe that GFAS also shows the fairest performance. The number of border nodes are starved of GFAS is significantly reduced when comparing with GreedyPhysical and especially 802.11.

6 Conclusions and Future Work

In this paper, we have investigated how to schedule links in WMNs by using STDMA access scheme under physical interference model. We proposed a greedy algorithm, GFAS, to solve this problem. GFAS not only improves system throughput but also guarantees the fairness for all nodes in the system, which are proven through extensive simulations. We have also identified the future research in jointing fair scheduling with channel assignment to give the better performance.

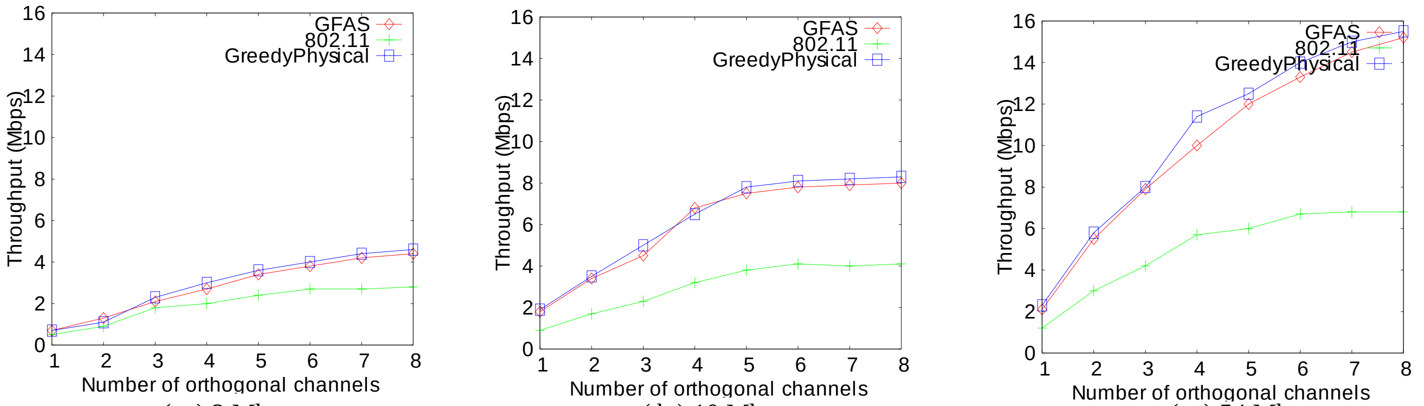
References

1. N. Ben Salem, J.P. Hubaux, A Fair Scheduling for Wireless Mesh Networks, Proc. IEEE Workshop on Wireless Mesh Networks (WiMesh), 2005.
2. J. Gronkvist and A. Hansson, Comparison Between Scheduling, Proc. MobiHoc 2001, pp. 255–258.
3. J. Gronkvist, J. Nilsson, and D. Yuan, Throughput of Optimal Spatial Reuse TDMA for Wireless Ad-Hoc Networks, Proc. IEEE Vehicular Technology, pp. 2156–2160, 2004.
4. M. Alicherry, L. Li, Joint Channel Assignment and Routing for Throughput Optimization in Multi-Radio Wireless Mesh Networks, Proc. ACM Mobicom, pp. 58–72, 2005.
5. K. Jain, J. Padhye, V. Padmanabhan, L. Qiu, Impact of Interference on Multi-Hop Wireless Network Performance, Proc. ACM Mobicom, pp. 66–80, 2003.
6. R. Nelson and L. Kleinrock, Spatial-TDMA: A Collison-free Multihop Channel Access Protocol, IEEE Trans. on Communication, Vol. 33, pp. 934–944, Sept. 1985.
7. P. Gupta, P. R. Kumar, The capacity of wireless networks, IEEE Transactions on Information Theory, Vol. 46(2), 2000, pp. 388–404.
8. R. Draves, J. Padhye, and B. Zill, Routing in multi-radio, multi-hop wireless mesh networks, Proceedings of ACM MobiCom'2004, pp. 114– 128.
9. J. Tang, G. Xue, W. Zhang, Maximum throughput and fair bandwidth allocation in multi- channel wireless mesh networks, Proceedings of IEEE INFOCOM'2006.
10. Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, Clifford Stein, Introduction to Algorithms (2nd Edition), MIT Press, September 2001.
11. G. Brar, D. Blough, P. Santi., Computationally Efficient Scheduling with the Physical Interference Model for Throughput Improvement in Wireless Mesh Networks.



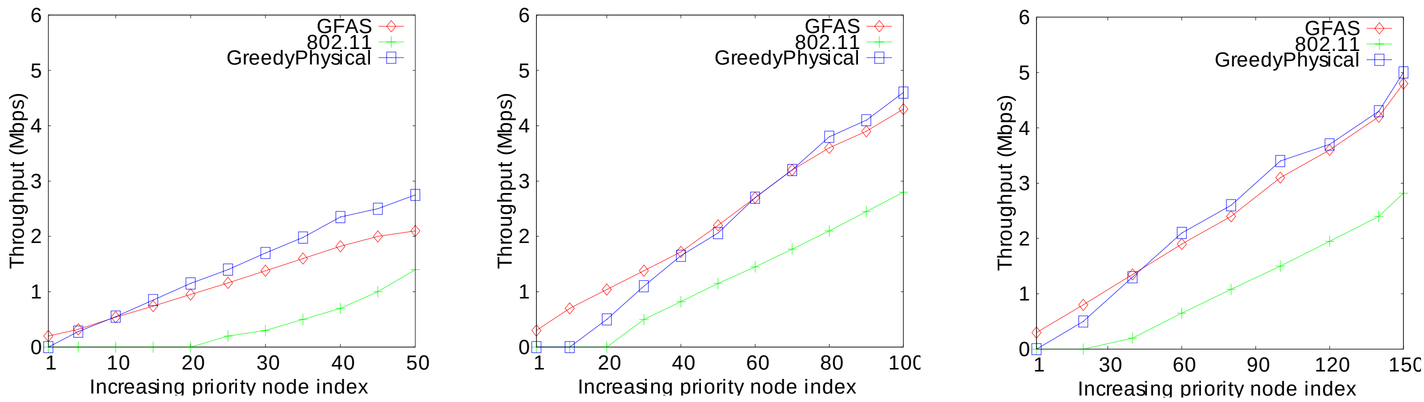
(a) 50 nodes (b) 100 nodes (c) 150 nodes

Fig. 4. Effect of Network Density to Throughput Improvement



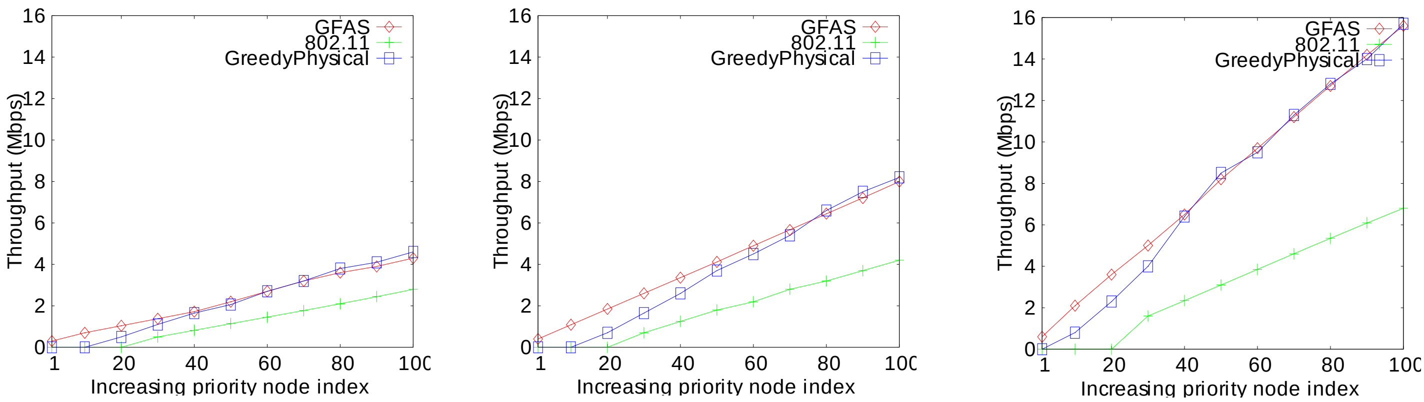
(a) 2 Mbps (b) 10 Mbps (c) 54 Mbps

Fig. 5. Effect of Data Rate to Throughput Improvement



(a) 50 nodes (b) 100 nodes (c) 150 nodes

Fig. 6. Effect of Network Density to Fairness Enhancement



(a) 2 Mbps (b) 10 Mbps (c) 54 Mbps

Fig. 7. Effect of Data Rate to Fairness Enhancement