Exploring the Design Space of Greedy Link Scheduling Algorithms for Wireless Multihop Networks

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***Abstract*—It is known that using a spatial TDMA (STDMA) access scheme can increase the capacity of a wireless network over CSMA/CD access scheme. Modern wireless devices are capable of transmitting at different data rates depending on the current network condition. However, little attention has been paid to how best is to use the multiple data rates capability. In this report, we focus on greedy link scheduling algorithms that work with variable rates, where devices can transmit at lower data rates to accommodate lower quality links. We propose criteria that can be used in the scheduling algorithms and investigate performances of different scheduling algorithms that employ these different criteria. We use the more realistic physical interference model, where packet reception rate depends on signal-to-interference-plus-noise ratio. Our investigation shows that by using the variable rate approach, we can increase the overall capacity of the network over traditional single-threshold-based algorithms.**

I. Network and Interference Model

We consider the physical interference model in this work. In the physical interference model, interference from all concurrent transmitters in the network, no matter how distant, is factored into the SINR value at a receiver. We consider a graded SINR-based rate model. By contrast, in a threshold rate model, a wireless transmission is successful if and only if the SINR at the receiver is larger than a single threshold SINR value. Under a graded rate model, a wireless node is not limited to a single SINR threshold, but the data rate is determined by the received SINR. We do assume a minimum SINR value is necessary for successful reception (at the lowest dara rate) but data rate gets higher as SINR increases from this minimum up to the SINR that produces the maximum possible data rate of a link. We assume that all nodes are capable of changing their transmission rate to fit the SINR at the receiver. All nodes transmit at the same transmission power, P_{TX}. The uniform power assignment scheme was chosen due to its simplicity while it also has the worst-case performance bounded to the non-uniform scheme. [1]

We consider a network with spatial-reuse TDMA (STDMA) access scheme as defined in [9]. All nodes have loosely synchronized clocks in that their deviations from the real clock are bounded at any point in time. The length of the time slot is large enough for a node to transmit one data packet at the lowest data rate.

Define a network graph $G_N = (V, E)$, where V is the set of all wireless nodes. A directed-edge $(u, v) \in E$ if and only if the transmission from u to v can be established at all data rates in absence of interference from other nodes. This means that the SNR value at v when u transmits is at least as high as the SINR value necessary for reception at the maximum data rate. Each edge has a corresponding traffic demand, ω, which is a real number ranging from 1 to ω_{max}. We define one unit of demand as follows.

Definition 1: One unit of traffic demand is the amount of data a transmitter sends to a receiver at the maximum data rate in one time slot.

We assume link-layer reliability in this work. Thus, an ACK packet from v to u is required. We assume that the ACK packet is always sent at the lowest data rate at the end of the slot.

We consider the problem of scheduling all demands on all links in a minimum number of slots, which is called the link scheduling problem. [5] [6] [3] [10]

II. Scheduling Algorithms

In this section, we present all algorithms we used to schedule a network. We start with an overview of all algorithms, and then we present a design space that we considered. Finally, we provide a discussion about selected interesting algorithms.

A. Algorithm Overview

All algorithms have the same basic structure as shown on Figure 1.

The algorithm first calls *MoreLinkToSchedule(E)*, which checks if there is any link with remaining demand. If there exists a link to schedule, the algorithm then orders links in E according to a certain metric. Next, the algorithm checks if the first link (u, v) can be activated in the current slot by calling *IsActivatableAtSlot((u, v),current_slot)*. The algorithm then activates link (u, v) if *IsActivatableAtSlot((u, v),current_slot)* returns *true*. This process continues until all links in E are considered, for the slot. Then, the algorithm advances to the next slot and repeats the procedure. The algorithm terminates once the demand on all links has been satisfied.

SCHEDULE (V, E)

1: $current\_slot = 0$
2: **while** MoreLinkToSchedule(E) **do**
3: SORT(E,*metric*)
4: **for all** $(u, v) \in E$ **do**
5: **if** IsActivatableAtSlot($(u, v), current\_slot$) **then**
6: ActivateAtSlot($(u, v), current\_slot$)
7: **end if**
8: **end for**
9: $current\_slot = current\_slot + 1$
10: **end while**

Fig. 1. Basic structure of scheduling algorithm

B. Design Space Considered

Given the structure of this scheduling algorithm, we note that it is possible to define different scheduling algorithms by changing the underlying implementations of SORT(E, *metric*) at line 3 and IsActivatableAtSlot($(u, v), current\_slot$) at line 5. Next, we present our modifications to each implementation.

1) Link Ordering: There are two aspects of link ordering - the metric used and the direction of ordering. For direction of ordering, we consider both increasing ordering and decreasing ordering. For the ordering metric, we consider two metrics in this report; traffic demand and interference value. Link ordering by traffic demand was used by [2], [8] while the motivation behind the notion of the interference value is the interference number from [4]. The interference number of a link (u, v) is the number of links that have SINR at the receivers lower than the threshold SINR if the link (u, v) is activated, i.e. the number of links that are prohibited from being active if (u, v) is active. Since we are working in a graded interference model, we need to generalize the notion of interference number.

Definition 2: The interference value *(IV)* of a link (u, v) on a link $(w, x) \neq (u, v)$ is the difference between the data rate of the link (w, x) if the link (u, v) is active and if the link (u, v) is inactive. The interference value of the link (u, v) is the summation of all interference values of (u, v) on all other links.

The idea behind the notion of the interference value is the same as that of the interference number - to measure the amount of interference generated by a certain link.

2) Activating Criteria: The activating criteria are used to determine if a link should be activated, given the current network configuration. We consider two activating criteria in this report - an aggregated throughput and a weighted throughput.

The motivation behind the notion of aggregated throughput is the notion of expected throughput from [8]. The greedy scheduling algorithm in [8] uses expected throughput to determine if a new link should be activated, where all links are activated at the same data rate. Since the SINR at the receiver can be less than the threshold SINR, the authors used the notion of expected throughput, which can be calculated directly from the packet reception rate (PRR). We are working in the graded interference model, so we use aggregated throughput instead of expected throughput. We formally define aggregated throughput as follow.

Definition 3: The aggregated throughput *(AT)* of a network is a summation of data rates of all active links in the network.

A weighted throughput is the modification of an aggregated throughput. Instead of summing data rates of all active links, a weighted throughput multiplies each link's data rate with the remaining traffic demand on that link. A weighted throughput is thus a weighted sum of data rates of all active links with remaining traffic demand as a weight function.

Definition 4: The weighted throughput *(WT)* of a network is a weighted sum of data rates of all active links in the network, with remaining traffic demand on each link as a weight function.

For example, a link with two units of demand activated at 54 Mbps has weighted throughput of 108, unlike a link with one unit of demand activated at the same data rate.

Since all activating criteria are based on throughput metric, we only consider that a new link should be activated if it does not decrease the current throughput of a network. Moreover, we also consider a difference between *strictly* higher throughput ($>$) and *not* lower throughput ($\geq$).

From the choices of activating criteria and link ordering, we have a total number of 16 different algorithms in our design space. There are two choices for link ordering metric, two choices for link ordering direction, two choices for activating criteria, and two variations of $>$ and $\geq$.

For convenience, we shall name all algorithms with the following naming convention.

activating_criteria-ordering_metric-direction.

activating_criteria consists of two parts; the criteria and a small variation of *GEQ/GT*. The criteria can be *AT* for aggregated throughput-based algorithms, or *WT* for weighted throughput-based algorithms. *ordering_metric* can be *TD* for link ordering with traffic demand, or *IV* for link ordering with interference value. *direction* indicates ordering direction, it can be either *I* for increasing order or *D* for decreasing order.

Finally, we discuss about some interesting algorithm variations.

C. AT-GEQ-TD-D Algorithm

This algorithm resembles the *expected-throughput* greedy scheduling algorithm from [8]. The *expected-throughput* greedy scheduling algorithm orders links by traffic demand in decreasing order and uses expected throughput as activating criteria. The algorithm activates a new link if it does not decrease the expected throughput of the current slot. The difference between *AT-GEQ-TD-D* algorithm and *expected-throughput* algorithm is that *AT-GEQ-TD-D* algorithm uses aggregated throughput instead of expected throughput.

D. WT-GT-TD-D Algorithm

The idea behind this algorithm is from the following observation. A possible problem with greedy algorithms is that they can leave links with high demand to the end, which can result in inefficient use of later slots, thereby, lengthening the schedule. The *Weighted Throughput* algorithm attempts to avoid this problem by giving higher priority to links with higher demands. The algorithm gives higher priority to high demand links by trying to schedule them first; it also uses a weighted throughput, which puts more emphasis to high demand links.

E. AT-GT-IV-D Algorithm

We call this algorithm *GradedGreedyPhysical* algorithm since it resembles the *GreedyPhysical* algorithm from [4]. Both algorithms order links in decreasing ordering with their respective ordering metric. The difference between *GradedGreedyPhysical* algorithm and *GreedyPhysical* algorithm is that *GradedGreedyPhysical* algorithm works on a slot-by-slot basis instead of a link-by-link basis.

III. Simulation

To compare different scheduling algorithms, we modified the packet-level simulator *ns-3* [11]. We modified WiFi device in *ns-3* to support STDMA and modified Node to incorporate local clock. We used the modified *ns-3* to generate network topologies and run different scheduling algorithms. *ns-3* supports the physical interference model, so we did not need to modify that aspect.

In this experiment, we consider WiFi 802.11a compatible wireless nodes only. The supported data rates are 54 Mbps, 48 Mbps, 36 Mbps, 24 Mbps, 18 Mbps, 9 Mbps and 6 Mbps. Different data rates have different minimum SINR requirements as shown on Table I [7]. The ACK packet is always sent at 6 Mbps. For the single threshold algorithm, we use the data rate at 54 Mbps.

We present two simulation scenarios - simple matching and mesh network.

A. Simple Matching

The network consists of $|V|$ wireless nodes. Every wireless node is acting as a source or a destination for exactly one link. Thus, there are $|E| = \frac{|V|}{2}$ links in the network. The initial demand of each link is an integer randomly selected from 1 to ω_{max}. The network topologies were created as followed. For an edge $(u, v) \in E$, first uniformly place a source node u, then place the corresponding destination node v within the maximum distance d_{max} from u. The value of d_{max} was chosen such that two nodes separated by d_{max} must be able to transmit at maximum data rate, which is 54 Mbps in our settings. The number of links in the simulations range from 50 to 500 links. All nodes are placed in an area of 1000 m by 1000 m.

Data Rate	Minimum SNR (dBm)
54 Mbps	24.56
48 Mbps	24.05
36 Mbps	18.80
24 Mbps	17.04
18 Mbps	10.79
12 Mbps	9.03
9 Mbps	7.78
6 Mbps	6.02

TABLE I
MINIMUM SINR FOR DIFFERENT WIFI 802.11A DATA RATE

B. Mesh Network

The network consists of $|V|$ wireless nodes. All nodes are placed randomly in an area of 1000 m by 1000 m. Ten randomly chosen nodes are assigned as gateway nodes. For every non-gateway node, a shortest path to the closest gateway by hop count is found. It is possible that a non-gateway node has to route its packets through other non-gateway nodes to reach its closest gateway. Thus, this scenario creates a graph consisting of ten trees where each tree has one gateway node as its root.

The demand on each link consists of two parts - the demand of the source node itself, which is an integer randomly selected from 1 to ω_{max}, and the sum of the demands of the sub-tree that has the source node as its root. This scenario is similar to the set-up in [4].

IV. Simulation Results

We ran simulation ten times for each number of links/nodes. We also included results from the *GreedyPhysical* algorithm (called *THRESHOLD*), which is a strict threshold-based algorithm, as a baseline. Figure 2 and Figure 3 show the main results obtained from the simple matching and mesh network scenarios for varying number of links/nodes. We present the results as percentage improvement over *THRESHOLD* algorithm.

A. Overview

For simple matching scenario, the percentage improvements of each algorithm stabilized at about 150 links. The best performing algorithm is *AT-GT-TD-I* algorithm, which provides about 12.02% improvement over *THRESHOLD* algorithm on average. The second best performing algorithm is *AT-GEQ-TD-I* algorithm with roughly 11.23% improvement. *AT-GT-IV-I* algorithm and *AT-GEQ-IV-I* algorithm provide improvement of 10.71% and 10.60% respectively. *WT-GT-TD-D* algorithm and *WT-GEQ-TD-D* algorithm have percentage improvement of 10.35% and 9.93% respectively. Not all algorithms provide improvement over *THRESHOLD* algorithm. For example, schedule lengths produced by *WT-GEQ/GT-TD-I* algorithms have about -2.76% improvements on average.

For mesh network scenario, the results are slightly different from the simple matching scenario. First, the percentage improvements of each algorithm are quite stable for all number of nodes. This is due to the fact that mesh network scenario

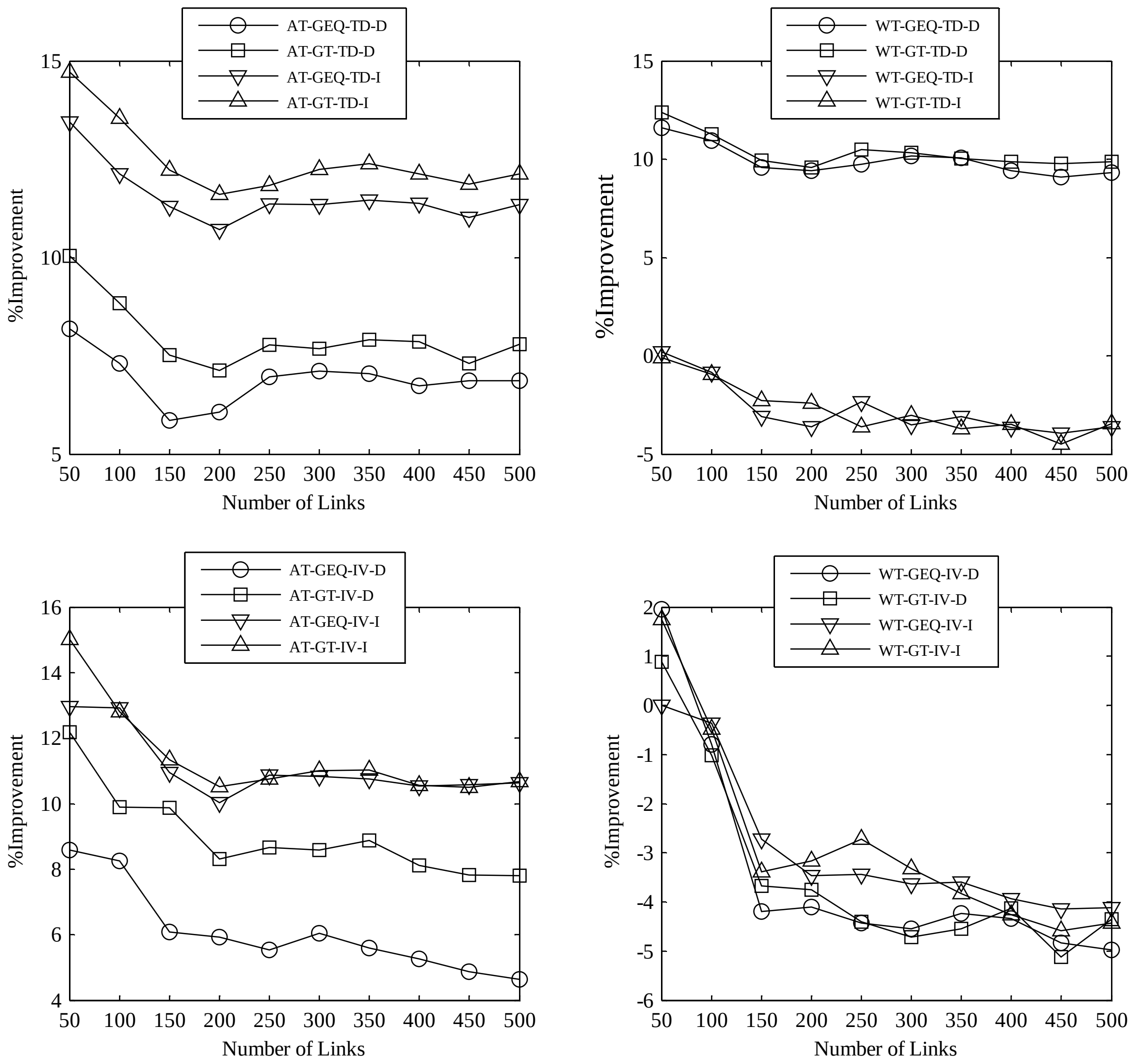

Fig. 2. Percentage Improvement over *THRESHOLD* Algorithm - Simple Matching

has links with higher traffic demands. The best performing algorithm in mesh network scenario is *WT-GT-TD-D* algorithm with about 9.76% improvement on average. The second is *AT-GT-IV-I* algorithm at roughly 9.44% improvement and the third is *AT-GT-TD-I* algorithm with about 9.03% improvement.

Although the schedule lengths produced from different scheduling algorithms are in the same order on average, there are some interesting observations for each algorithm. Next, we present some observations from the simulation results.

B. Aggregated Throughput Algorithm with Traffic Demand Ordering

The first thing to observed is that, *AT-GEQ/GT-TD-D* algorithms, which use decreasing link ordering, produce longer schedule length than *AT-GEQ/GT-TD-I* algorithms, which use increasing link ordering. This ordering may seem counterintuitive since the algorithms considered in the literature usually employ a decreasing ordering [2], [4], [8]. The difference arises from the distinct natures of *graded*- and *threshold*-scheduling algorithms. A *graded*-scheduling algorithm has the ability to accommodate links that would not be possible using a *threshold*-scheduling algorithm. By scheduling low demand links first, the algorithm has a better chance to satisfy low demand links while also accommodating higher demand links as the algorithm proceeds.

It is important to point out that this behavior is observed only when using the *graded*-scheduling algorithm. For the *threshold*-scheduling algorithms, algorithms that use an increasing ordering produce longer scheduling lengths than those that use decreasing ordering.

The next observation is the difference between *GEQ* and *GT* activating criteria. Algorithms that employ *GT* as activating criteria produce shorter schedule lengths than algorithms that

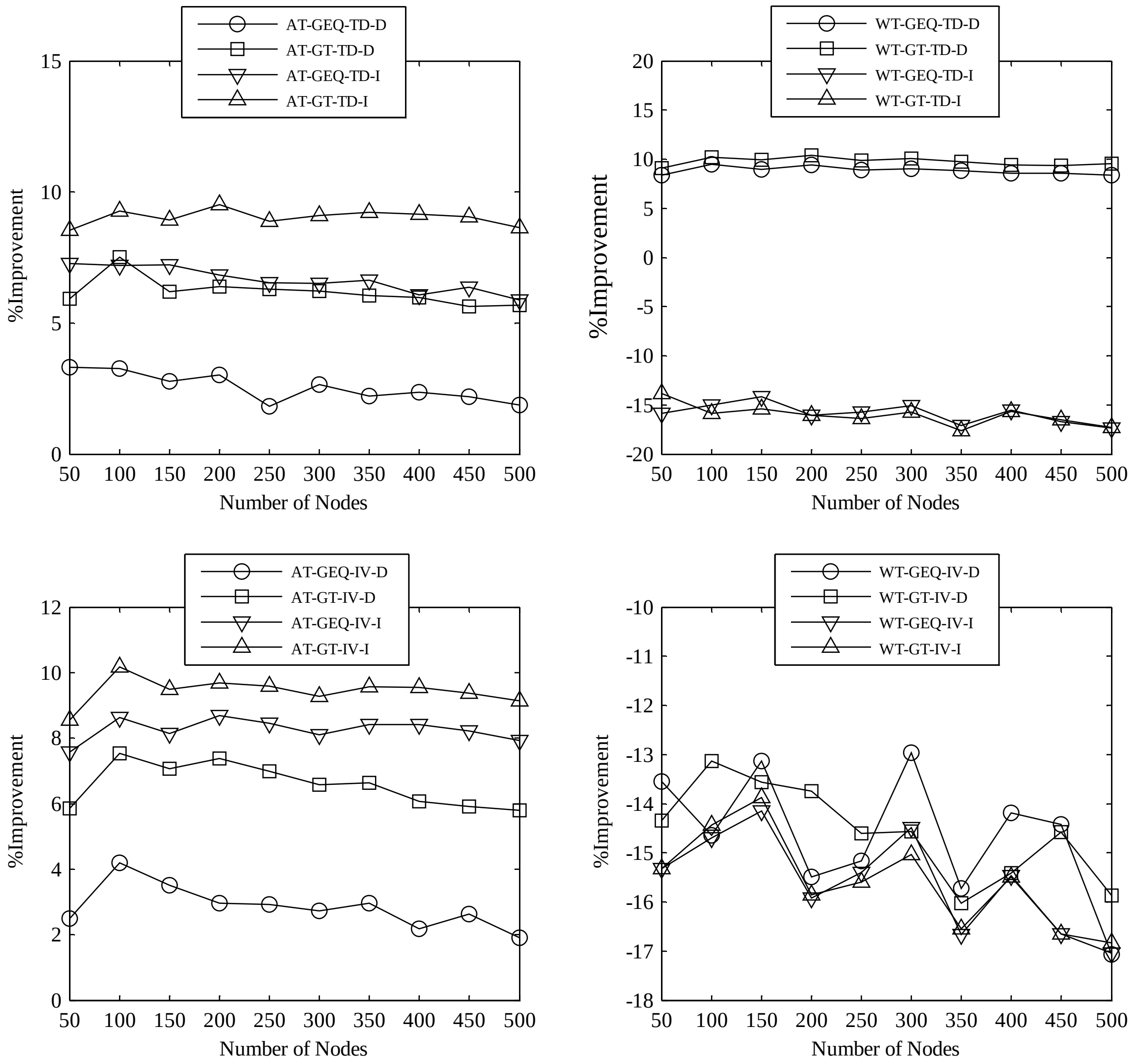

Fig. 3. Percentage Improvement over *THRESHOLD* Algorithm - Mesh Network

use *GEQ*. This can be explained as follows. The aggregated throughput is the sum of all active links' data rates, which are all integers. It is possible that activating a new link will result in the identical aggregated throughput in that slot. For example, say a network currently has link (u, v) activate at 54 Mbps, the new link (x, y) reduces the data rate of (u, v) to 36 Mbps while (x, y) itself can be activated at 18 Mbps, Activating link (x, y) gives the same aggregated throughput in that slot; algorithm using *GEQ* then activates (x, y).

The example shows that *GEQ*-based algorithm favors activating a larger number of links when the aggregated throughputs are equal. The problem is that the network performs the same amount of work (aggregated throughput) but introduces more active links. Activating new links adds more interference to all other nodes and might prohibit other links from being activated as the algorithm proceeds.

We note that the difference between *AT-GEQ-TD-I* algorithm and *AT-GT-TD-I* algorithm; and between *AT-GEQ-TD-D* algorithm and *AT-GT-TD-D* algorithm are larger in mesh network scenario than in simple matching scenario. The reason behind this bigger difference is that links in mesh network scenario can have higher traffic demands than links in simple matching scenario. Thus, a situation where two activation sets with the same aggregated throughput arises can last across more slots than in the simple matching scenario.

It is worth noting that the greedy scheduling algorithm in [8] does not suffer from the same problem of two activation sets with the same aggregated throughput. The greedy scheduling algorithm in [8] uses expected throughput, which is calculated directly from the packet reception rate (PRR) curve. Since the PRR curve is a continuous function, it is unlikely for two activation sets to have the same expected throughput. Also, for the *threshold*-scheduling algorithm, the only case when equal aggregated throughputs can occur is when the new link deactivates exactly one link. In this case, if the algorithm decides to activate the new link, the effect on other nodes is arbitrary, depending on the positions of the new link and the link to be deactivated. Thus, an important observation from our results is that, unlike a *threshold*-scheduling algorithm, the goal of a *graded*-scheduling algorithm should *not* be to maximize the number of active links. This situation can also be observed in the Aggregated Throughput algorithm with Interference Value ordering.

C. Weighted Throughput Algorithm with Traffic Demand Ordering

WT-GT-TD-D and *WT-GEQ-TD-D* algorithms provide roughly the same improvement over *THRESHOLD* algorithm. The difference between *GEQ* and *GT* is very small, and almost negligible. We also note that the variations that employ increasing link ordering do not provide any improvement over *THRESHOLD* algorithm.

By weighting the throughput with the remaining traffic demand on each link, the Weighted Throughput algorithm favors links with high demand. Thus, ordering links by traffic demand in decreasing order is appropriate for the Weighted Throughput algorithm. The schedule lengths produced by *WT-GEQ/GT-TD-D* algorithm are shorter than those produced by *WT-GEQ/GT-TD-I* algorithms due to this reason. We note that by ordering links in increasing order, the Weighted Throughput algorithm is unable to fully achieve its goal of scheduling links with high demands. The Weighted Throughput algorithm tries to focus on high demand links but the increasing link ordering does not support this goal. As a result, the algorithm does not perform well by ordering links in increasing order.

The difference between *GEQ* and *GT* is very small for the Weighted Throughput algorithm. This can be explained as follows. The weighted throughput is the product of link's data rate and link's remaining demand. It is unlikely for two activation sets to produce the same weighted throughputs. Thus, there are only a few cases that the two variations work differently. This is not the case for the *Aggregated Throughput*-based algorithm that simply uses the sum of all links' data rates. It is more likely for two activation sets to have the same aggregated throughput than the same weighted throughput.

D. Aggregated Throughput Algorithm with Interference Value Ordering

The schedule length produced by the *AT-GT-IV-I* algorithm is the shortest among the four variations. Like aggregated throughput algorithm with traffic demand ordering, the variation that employs *GT* activating criteria performs better than the variation that uses *GEQ*. All variations provide improvement over *THRESHOLD* algorithm.

The first thing we note is that, the *AT-GEQ/GT-IV-I* algorithms perform better than *AT-GEQ/GT-IV-D* algorithm. Since the links with smaller interference values are less likely to prohibit other links from being active, it is expected that *AT-GEQ/GT-IV-I* algorithms would activate a larger number of links than *AT-GEQ/GT-IV-D* algorithms. We noticed that this is not the case. Since the activation criteria are aggregated throughput, the numbers of active links for both decreasing and increasing link ordering are roughly the same. However, the increasing link ordering performs better than decreasing link ordering since links with smaller interference values got scheduled first. The links with small interference values do not decrease data rates on other links as much as links with higher interference values. Thus, the *AT-GEQ/GT-IV-I* algorithms produce schedules that have higher average throughput in each slot.

Also, we note that the difference between *AT-GEQ-IV-D* algorithm and *AT-GT-IV-D* algorithm is larger compared to the differences between *AT-GEQ-IV-I* algorithm and *AT-GT-IV-I* algorithm. The reason for this larger difference is the problem of two activation sets with the same aggregated throughput. But, for *AT-GEQ/GT-IV-D* algorithms, activating a new link has higher impact on other nodes since the new link has high interference value. Thus, it is highly likely that activating a new link will prohibit other links from being active at high data rate. This effect, combined with the problem of two activation sets with equal aggregated throughputs, make the *AT-GEQ-IV-D* algorithm performs badly.

E. Weighted Throughput Algorithm with Interference Value Ordering

The Weighted Throughput algorithm with Interference Value ordering algorithms can be viewed as a mixed between weighted throughput and interference value ordering. The link ordering does not have any relation to the activating criteria. If we view this algorithm in terms of Weighted Throughput algorithm with Traffic Demand ordering, these variations are the same as Weighted Throughput with no link ordering, i.e. random link ordering. All links are ordered by interference value but not the traffic demand, thus, they appear random to the algorithm. The results in both simple matching scenario and mesh network scenario are in the same order as *WT-GEQ/GT-TD-I* algorithms, where the algorithms fail to fully achieve their goals of focusing on high demand links.

V. Summary of Results

We have presented a comparison between different scheduling algorithms. We noted some crucial differences between *threshold*-scheduling algorithms and *graded*-scheduling algorithms. While the goal of *threshold*-scheduling algorithms is to activate as many links as possible, the goal of *graded*-scheduling algorithms should not be the same. For *graded*-scheduling algorithms, a larger number of links does not necessarily equal higher throughput, while this statement is true for *threshold*-scheduling algorithms. Instead, the goal of *graded*-scheduling algorithms should be to work on a few links at a time. This goal can be achieved by either favoring low demand links or concentrating on a few high demand links. This behavior is not observed for *threshold*-scheduling algorithms.

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