Fast Randomized STDMA Link Scheduling

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Abstract. In this paper a fast randomized parallel link swap based packing (RSP) algorithm for timeslot allocation in a spatial time division multiple access (STDMA) wireless mesh network is presented. The proposed randomized algorithm extends several greedy scheduling algorithms that utilize the physical interference model by applying a local search that leads to a substantial improvement in the spatial timeslot reuse. Numerical simulations reveal that compared to previously scheduling schemes the proposed randomized algorithm can achieve a performance gain of up to 11%. A significant benefit of the proposed scheme is that the computations can be parallelized and therefore can efficiently utilize commoditized and emerging multi-core and/or multi-CPU processors.

Keywords: Spatial-TDMA, Wireless Mesh Networks, Scheduling, Routing, Wireless Multi-Hop.

1 Introduction

Wireless Mesh Networks (WMNs) have recently emerged as a key technology to fulfil a diverse set of applications. The envisioned applications for WMNs range from being a viable alternative to wire line last mile broadband Internet service delivery at home or offices to backhaul support for wireless local area networks to different cellular networks such as for example LTE [1], [2]. One of the most important building blocks of wireless mesh networks is how to perform efficient scheduling so that high levels of throughput can be attained. For collision-free WMNs that support Spatial Time Division Multiple Access (STDMA) the critical aims is to increase the spectral efficiency by minimizing the frame length (i.e., number of timeslots) that a predefined number of transmitting and receiving pairs of nodes can successfully transmit [3]. Finding the optimal reuse of timeslots, i.e., the shortest frame length, has been shown to be an *NP*-complete optimization problem [4]. To provide a feasible STDMA timeslot allocation a number of sub-optimal algorithms with polynomial time complexity have been previously proposed [5], [6], [7].

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In this paper, a very fast randomized link scheduling algorithm for STDMA wireless mesh networks that is build upon previously proposed greedy scheduling schemes is proposed. As will become evident in the sequel, in the numerical investigations (section 4), the proposed scheme can significantly decrease the frame length by up to 11%, providing in that respect better spatial reuse of timeslots in the mesh network compared to previous well known greedy scheduling algorithms. Another key benefit of the proposed scheduling scheme is that the computations can be parallelized. Clearly, among the applications that can significantly gain from multi-core and multi-CPU enabled network elements are the scheduling algorithms. To this end, the proposed fast scheduling algorithm falls within the family of the so-called "embarrassingly" parallel problems [17] since different iterations of the algorithm can be executed without requiring any communication between them.

The rest of the paper is organized as follows. In section 2, closely related previous research works are discussed and the main contributions of the paper are lined up. Section 3 specifies the system model that has been adopted in the analysis, describes the STDMA link scheduling problem and details the proposed randomized scheduling algorithm. Numerical investigations are reported in section 4 and finally the paper concludes in section 5.

2 Previous Work

The concept of Spatial-TDMA has first been presented in the seminal work of Kleinrock [10]. A significant part of previous research in the area of STDMA scheduling has been concentrating on graph based representation of the STDMA scheduling problem and associated graph theoretic tools; conceiving in that respect the STDMA scheduling as a graph colouring problem [11], [12], [13]. Despite their attractiveness, graph colouring based algorithms can resolve only the problems of *primary* and *secondary* conflicts between the links that need to be scheduled [6]. Hence, their drawback is that they do not consider the effect of aggregate interference, as reflected at the Signal to Interference Noise Ratio($SINR$) constraint for successful packet transmission and, therefore they may lead to schedules which are infeasible [6], [14]. To resolve this issue a number of previous works have explicitly taken into consideration the $SINR$ constraints (the so-called *physical interference* model) together with power control for constructing minimum frame length schedules [7], [8], [15]. In [16] a randomized distributed STDMA scheduling algorithm (DRAND) is presented. The difference with our proposed scheme is that DRAND does not take the $SINR$ constraints into account. Also the randomization has a different rational compared to the proposed RSP algorithm. In DRAND the randomization is on how neighbour nodes are selecting timeslots, whereas in RSP the randomization is on how to deviate from an already feasible allocation and search alternative feasible (hopefully better) solutions.

Recently, the problem of scheduling has also been considered jointly with the routing decisions. The rational being that due to the broadcast nature of the wireless transmission medium, it is possible that better spatial reuse of timeslots can be achieved by considering the problem of routing and scheduling jointly [9].

3 Problem Description and STDMA Link Scheduling

3.1 Preliminaries

We consider a WMN, which can be modelled by a network graph$G(V, E)$, where V is the set of nodes (mesh routers and clients) and E expresses the set of wireless links. Each node is equipped with one wireless interface card, and hereafter the terms radios and nodes are used interchangeably since they coincide. We further assume that all nodes in the mesh network operate at the same frequency band (frequency reuse factor is one) and we do not consider spurious or other inter channel interference. The packet length is normalized and occupies a single timeslot. For a single transmission bit-rate, each link $(i, j)\epsilon\ L$ needs to satisfy a signal to interference noise-ratio threshold (γ) for successful packet decoding; this constraint can be written as follows,

$$\frac{g_{ij}p_{ij}}{\sum_{(m,n)\epsilon L\{i,j\}} g_{mj}p_{mn}+W} \geq \gamma \tag{1}$$

where p_{ij}denotes the transmission power for link(i, j), g_{ij} is the link gain for link (i, j) and W expresses the lump sum power of background and thermal noise.

3.2 Greedy STDMA Link Scheduling

The strategy followed by several scheduling algorithms that utilize the physical interference model consists in firstly sorting the links based on a pre-defined criterion and then greedily packing the links into timeslots to generate feasible schedules. We detail in the sequel two well known heuristic scheduling algorithms, namely the Greedy Physical [8] and the Packing Heuristic [9] algorithms. These algorithms will be the basis upon where the proposed RSP algorithm is developed.

Note that these algorithms do not perform power control. As will be explained, each link transmits above the minimum power needed to transmit on its own, i.e., when there is no interference to allow concurrent transmissions to take place. Furthermore, both algorithms assume that is implicit that a node neither transmit and receive at the same timeslot nor transmit/receive to/from more than one node at the same timeslot. This can be accomplished binding the following two constraints: the *indegree* constraint ensures that only one node can send traffic to the same receiving node in each timeslot; the *outdegree* constraint ensures that a transmitting node can only send traffic to one receiving node per timeslot [18].

3.2.1 Greedy Physical (GP)

Greedy physical starts sorting the links to be scheduled according to the interference number, which is detailed next. The interference number of a link $E_i \epsilon\ E$ is the number of links $E_j \epsilon\ E \setminus \{E_i\}$ that cannot establish a communication at the same time such the set E_i and E_j does not share an endpoint and is infeasible. A set of two links is considered infeasible when the receiver nodes do not satisfy the SINR restriction described in (1). Thereafter, a list is created sorting the links with higher interference number first and then links are packed according to the scheduling algorithm stated in Table 1.

Table 1. Pseudo-code of the GP algorithm

Input	L	A list containing all links sorted by its interference number
Output	S	A feasible schedule
	TS	Frame length found for S

1: $TS \leftarrow 0$
2: for each Link in L **do**
3: Schedule link L_i in the first available slot such that the resulting set of scheduled transmission is feasible with the physical interference model.
4: If currently available slots are not sufficient to schedule L_i, add a new slot at the end of the schedule S and schedule link L_i in this slot.
5: Let $TS \leftarrow TS + 1$
6: endif
7: end

3.2.2 Packing Heuristic (PH)

The Packing Heuristic presented in this paper is the same algorithm used in [9] and it is also a variation of the heuristic used in [19] and [20], where different weights are utilized to sort the links. This algorithm tries to pack as many links as possible in each timeslot, having as a starting point a list where the links are sorted with the links that require higher transmitted power first. The pseudo-code of the algorithm is shown in Table 2 below.

Table 2. Pseudo-code of the PH algorithm

Input	A	A list containing all links sorted by its power levels (highest power first)
Output	B	A feasible schedule
	TS	Frame length found for S

1: $t \leftarrow 1$
2: $B \leftarrow$ Empty List
3: At timeslot t schedule the first link in list A for transmission and shift it from list A to list B.
4: repeat
5: Proceed down the current list A scheduling links for transmission in timeslot t, if feasible, and shifting them to list B if they transmit.
6: Let $t \leftarrow t + 1$
7: until A is empty
8: Let $TS \leftarrow t - 1$

It has to be noticed that there is only one difference between the Packing Heuristic and the Greedy Physical that results in different schedules. The difference is the way the links are sorted in the initial list. In the Packing Heuristic the first links to be scheduled are the ones that have the highest transmitted power, whereas in the Greedy Physical the priority is given to the links that cause more interference. There is another difference between the GP and the PH though, in this case, does not lead to any different schedule. This difference lies in the way the algorithm proceeds to pack the links. In the Packing Heuristic we fix a timeslot and we try to pack in it all the links that have not yet transmitted, whereas in the Greedy Physical we fix a link and we try to pack it in the first timeslot available.

3.3 Randomized Link Swap Packing (RSP) Algorithm

The RSP algorithm is based on altering the interference number list by swapping N_S (number of swaps) times the order of two elements selected randomly from the list. The number of swaps applied to the list characterizes the degree to which the original list is distorted. After the swapped list is generated, the links are scheduled according to the GP or PH algorithms as described in the previous sections. Hence, a new feasible schedule is obtained. Different criteria can be applied in order to determine the best schedule when schedules with the same frame length as the best one found so far are generated. For instance, to improve the interference robustness of the network, possible criteria are (i) to choose the schedule with the best averaged SINR or (ii) the schedule with the maximum average min-SINR across all timeslots. This process is repeated for a pre-defined number of iterations (M_{ITER}). The pseudo-code of the proposed RSP algorithm is shown in Table 3 below.

Table 3. Pseudo-code of the RSP algorithm

Input	L	A list containing all links sorted by its interference number, or power levels
	N_S	Number of swaps
	M_{ITER}	Maximum number of iterations
	P	Number of Processors
Output	$S_{BEST,p}$	A feasible schedule with the minimum frame length found so far at processor p
	$T_{BEST,p}$	The minimum frame length found so far at processor p

1: $S_{BEST}, T_{BEST} \leftarrow$ Schedule(L)
2: **for** each processor **do** in parallel
3: **for** i=1: $\lceil M_{ITER}/P \rceil$ **do**
4: $L_{SWAP} \leftarrow L$
5: **for** j=1: N_S **do**
6: $L_{SWAP} \leftarrow$ Swap two elements from L_{SWAP}
7: **end**
8: $S, T_S \leftarrow$ Schedule(L_{SWAP})
9: **If** $T_S \leq < T_{BEST}$ **then**
10: $T_{BEST,p} \leftarrow T_S$
11: $S_{BEST,p} \leftarrow$ BestSchedule $(S, S_{BEST,p})$

12: endif
13: end
14: $T_{BEST} \leftarrow \min\{T_{BEST,p}\}$
15: $S_{BEST} \leftarrow$ BestSchedule $\{S_{BEST,\forall p}\}$
16: end

As can be observed from the Table 2 above, the proposed RSP algorithm can be easily parallelized and run in P processors. In fact, the RSP algorithm can run without requiring any communication between the different processors, therefore there is no communication cost or delay for exchanging information between the different processors. Hence, the RSP algorithm enables embarrassingly parallel computations since different schedules can be calculated independently, offering a convenient way to use multiple processors concurrently to solve the problem. We note that a brute force enumeration of all possible ways to pack the $\mathrm{N}-1$ links in a predefined number of timeslots would be $(\mathrm{N}-1)!$. But since both the GP and the PH heuristics provide good initial feasible solutions, few iterations of the above proposed approach can provide significant benefits. As shown in the next section, the gains with the number of iterations follow a concave like function, which means that the net benefit of performing higher number of iterations diminishes with the number of iterations.

4 Numerical Investigations

4.1 Setting of the Simulation

The wireless mesh network is deployed in a square area AxA Km^2 containing N wireless nodes that are random uniformly distributed. Two nodes in the mesh network can establish a link if the receiving node satisfies the Signal to Interference Noise Ratio ($SINR$) threshold criterion. A special node in the topology acts as the gateway node for providing Internetworking; throughout the numerical investigations and without loss of generality a single gateway node is considered. Based on all feasible links that can be constructed when no co-channel interference is considered, a shortest path spanning tree is constructed rooted at the gateway node to all other nodes in the network. The spanning tree is based on the minimum power routing (MPR) scheme, as described and analyzed in [9]. The MPR scheme is based on Dijkstra's algorithm and uses the required transmitted power to combat the path loss as the cost of the link. To calculate the required transmission power level for link (i,j) the following simple path loss has been considered hereafter,

$$PL(d(i,j)) = PL(d_0) + 10\eta log\left(\frac{d(i,j)}{d_0}\right) \quad (2)$$

where $d(i,j)$ express the Euclidean distance of link (i,j), $PL(d_0)$ is the close-in reference distance loss, which is assumed to be equal to 78 dB for distance d_0 equal to 50 meters, and η denotes the path loss exponent, which can in general take values between 2 to 5 depending on the environment. Finally, it should be noted that only unidirectional links in the downlink scenario (from the gateway to the nodes) are considered. Similar results are expected to hold also for the uplink scenario but are not considered in this paper. Since a shortest path spanning tree is created that rooted at the designated gateway node, the links that need to be scheduled are always $N-1$. The complete set of the simulation parameters used in the numerical investigations are summarized in Table 4 below.

Table 4. Simulation Parameters Used

Notation	**Explanation**	**Values**
A	Length of the Square Area	850 meters
N	Number of Nodes	20 - 120
L	Number of Links	19 - 119
d_0	Close-in reference distance	50 meters
γ	SINR threshold	8dB
η P_{max}	Path loss exponent	3.5
f_C	Maximum transmitted power	20 Watt
W	Carrier frequency	3.8GHz
	Thermal & background Noise	-132dBW

4.2 Results

We evaluate the performance of our proposed scheduling algorithm by comparing it with two well known and tested greedy STDMA scheduling schemes that utilize the physical interference model, namely the Packing Heuristic [9] and the Greedy Physical [8] algorithms as have been explained in detail in section 3.2. Notice that all results have been averaged over 200 WMNs topologies with randomly distributed nodes.

The quality of the solution provided by the RSP algorithm scheme (T_{RSP}) is compared to the corresponding solutions from the GP (T_{GP}) and the improvement ($\mathbf{I}$) is measured as follows, $\mathbf{I}(\%) = (T_{GP} - T_{RSP})/T_{GP}$. The same measure is used to compare the solution of the RSP with the PH (T_{PH}) algorithm.

Fig. 1 shows the performance gains on the minimum frame length using the proposed randomized scheduling scheme compared to the Greedy Physical algorithm with respect to the number of iterations. Observe that substantial improvements can be achieved with a reduced number of iterations, for instance, with just 15 iterations the schedule allocation is ameliorated above 5 % for topologies with 40 and 60 nodes. This improvement is even better as the number of iterations increases. However, it is becoming less significant as the number of iterations augments. Note that the same behaviour holds when the RSP is applied to the Packing Heuristic, as Fig. 2 shows. In this case, the gain obtained is slightly higher and, in consequence, with less than 10 iterations we achieve an improvement above 5%.

Figure 3 describes the performance improvement on the minimum frame length using RSP (with different number of link swaps) compared to the GP and PH for different number of nodes in the network. As has been mentioned above, the number of swaps applied to the list influences the degree to which the original list is distorted. Observe from figure 3 that after a small number of swaps the performance stops increasing.

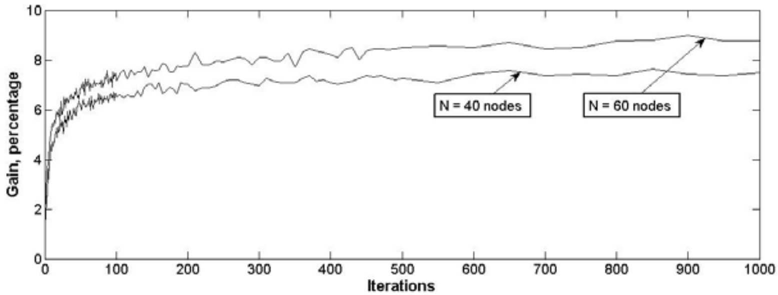

Fig. 1. Performance gains on the minimum frame length using the RSP algorithm compared to the GP algorithm with respect to the number of iterations for topologies with 40 and 60 nodes. These results have been calculated using 3 swaps.

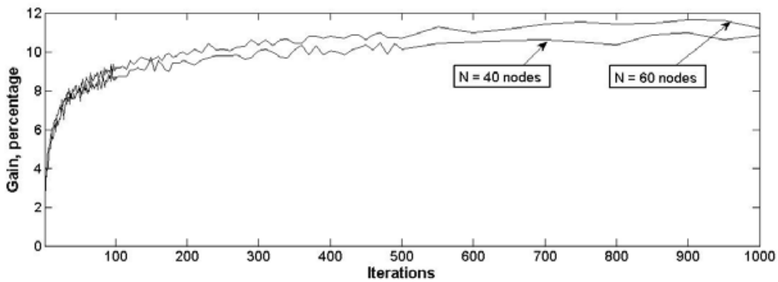

Fig. 2. Performance gains on the minimum frame length using the RSP algorithm compared to the PH algorithm for topologies with 40 and 60 nodes. These results have been calculated using 3 swaps.

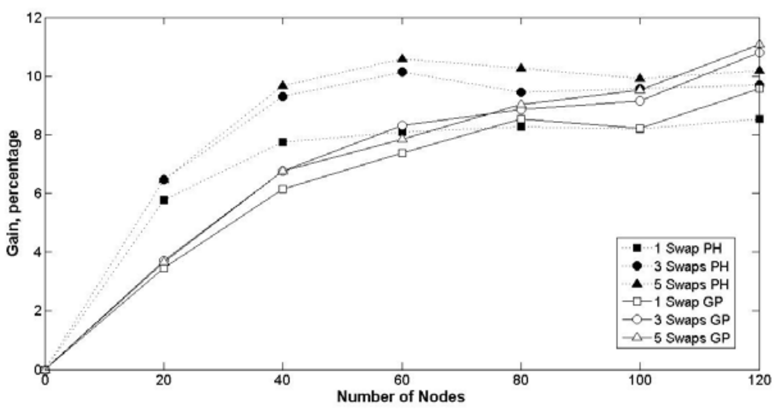

Fig. 3. Performance gains on the minimum frame length using the RSP algorithm (with different number of link swaps) compared to the GP and PH

5 Conclusions

In this paper, a fast randomized link scheduling algorithm for Spatial-TDMA enabled wireless mesh networks is detailed. The randomization is based on swapping links on a list that is created by well known greedy scheduling algorithms such as the Greedy Physical and the Packing Heuristic. In that way, the order of the scheduling is affected and by varying the number of swaps that are performed a larger set of feasible solutions space can be explored. Extensive numerical investigations reveal that the proposed fast scheduling scheme can improve by more than 10% the timeslot reuse compared to the previous mentioned link scheduling algorithms. Another important characteristic of the proposed scheme is that its structure is amenable for parallel processing and therefore, emerging multi-core and multi-CPU enabled network elements can be fully utilized. The simplicity of the algorithm, the achieved gains and the potential of parallel computation clearly demonstrate the potential benefits of the proposed scheme.

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