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Abstract: There is an increasing interest in using Wireless Mesh Networks (WMNs) as broadband backbone for next-generation wireless networking. WMNs is a scalable and cost-effective solution. Industrial standards groups are revisiting the existing protocols and they work enhanced specifications for WMNs.

Wireless Mesh Networks (WMNs) are cost-effective and provide an appealing answer to connectivity issues of ubiquituous computing. One of the key challenges of WMNs is to provide guaranteed quality of service that network operator could claim. In this paper, we address the *Fair Round Weighting Problem - F_RWP* and present mixed integer linear programming models for computing an optimal routing and link scheduling. We have considered two kind of transmissions scenarios, burst transmission and permanent regime, and their specific settings.

Key-words: Wireless Mesh Networks, scheduling, routing, multi-hop, fairness, throughput guarantee

Problèmes du routage et de l'ordonnancement équitable dans les réseaux maillés sans fil

Résumé : Les réseaux maillés sans fil (Wireless Mesh Networks - WMNs) sont peu onéreux et fournissent une solution intéressante aux problèmes de connectivité dans les réseaux ubiquitaires. Un des défis des WMNs est de fournir aux opérateurs les moyens de garantir une qualité de service à leurs clients. Dans ce travail, nous traitons les problèmes du routage et de l'ordonnancement équitable *Fair Round Weighting Problem - F_RWP* et nous présentons un modèle linéaire mixte pour calculer le routage et l'ordonnacement optimaux des liens. Nous considérons deux scénarios de transmission, la transmission par salve et le régime permanent, ainsi que leurs caractéristiques.

Mots-clés : Réseaux maillés sans fil, ordonnancement, routage, multi-saut, équitable, garantie de bande passante

1 Introduction

There is an increasing interest in using Wireless Mesh Networks (WMNs) as next-generation broadband and ubiquituous access network. WMNs is indeed a scalable and cost-effective solution [1]. In such networks, information is routed from source to destination over multiple wireless links, which has potential advantages over traditional single-hop networking, especially for backhaul communication [2]. Industrial standards groups are revisiting the existing protocols and they propose enhanced specifications for WMNs, e.g., IEEE 802.11s and 802.16d.

A WMN is usually composed of wireless mesh routers and mesh clients. Wireless mesh routers form a multihop wireless network that serves as the backbone to provide network access for mesh clients. In such networks, wireless mesh routers are usually stationary and connected with a fixed alternating current power, which makes WMNs quite different from the well-studied wireless ad hoc networks and wireless sensor networks.

In WMNs, a high volume of traffic is expected to be efficiently delivered on the bandwidth-limited wireless channels, and a large number of users must be fairly served [3]. In such networks, an end-to-end throughput guarantee is an important information to the network operator. In this work, we call gateway the mesh routers that interface with other networks. We simply call router each device that is not a gateway. The routers are up to the job of the access point of the mesh clients.

We consider that the traffic goes from all routers to any gateways in the WMN. In wireless networks, the communication channels are shared by the wireless terminals. Thus, one of the major issue is the reduction of capacity due to interference caused by simultaneous transmissions [4]. Multiple channels and multiple radios are just palliatives.

Wireless networks performances study motivates various research works. WMNs deployment in operational situations such as urban areas needs QoS guarantees because of capacity constraints. Indeed it has been prooved under some hypotesis that random network performances degrade with a factor at least $\mathcal{O}(1/\sqrt{n})$ when its size, n, grows [5, 6, 7]. Some capacity evaluation frameworks have been developped to get a network behaviour estimation and a stochastic analysis confirmation [8, 9]. In WMNs, it is known that routers far from the gateways may be starved by routers close to the gateways. Therefore, we consider a max-min model to achieve high throughput but with a good fairness. In this work, we focus on the problem of providing fair throughput guarantees for multi-hop transmissions considering interferences among multiple simultaneous transmissions.

Scheduling only with throughput maximization in mind may cause a severe bias on the bandwidth allocation among the flows. The goal of throughput maximization may force some links to receive very low bandwidth allocation or even to remain silent all the time to prevent interference [3]. We therefore investigate max-min throughput optimization.

In this work, we call a *round* a collection of transmission rates associated with links that can be simultaneously activated in the network. We address the problem *Round Weighting Problem - RWP* that solves the joint routing and scheduling problem in WMNs. The RWP can be defined as follow: Given a graph $G(V_r \cup V_g, E)$ with the set of routers $v \in V_r$ with destination the gateways in V_g and, the size of the time period, the problem is to generate a set of feasible rounds and assign a time slot in $[1, T]$ to each one. Our objective in this work is fairness, therefore we will call the problem *Fair Round Weighting Problem - F_RWP*.

In the following, we provide two MILP formulations for this problem in a context with burst and another context with permanent transmission. In a burst transmission a router send a small quantity of flow and the transmission is finished when the last unit of this flow reaches its destination. In the permanent transmission the units of flow are permanently sent by the routers. In both cases the time interval repeats periodically, therefore in the burst transmission we may have a idle period in each time interval. We observed that in the burst case each route should have its links activated in an increasing order over the time to make faster the transmission.

This work is an extension to the work in [10]. The F_RWP with burst transmission is the same problem to the Minimum Time Gathering (MTG) [10], and the F_RWP with permanent transmission is the same problem to the Bandwidth Alocation problem in [10], the difference is only the objective. In [10], the objective is minimize the time (MinTime) and in F_RWP is maximize the minimal routed flow (MaxMinDemand) by router $v \in V_r$. How we change the objective (MinTime) by (MaxMinDemand), we should given the size of the time period instead of the demands because the objective (MaxMinDemand) is to maximize the demands per router being fair in the given time period.

We analyse the differences between both transmission models and validate the analysis with experimental results.

2 Related Work

The Fair Round Weighting Problem is closely related to the the optimal assignment of interference-free broadcasting schedules in multihop packet radio network, which has been shown NP-complete in [11] by proving that the well-known NP-complete problem of finding maximum cardinality independent sets of nodes in a graph reduces to it.

Another related problem is the Minimum Time Gathering (MTG), for which a 4-approximation algorithm has been developed [10]. In this problem information from devices in the network into the gateway in a minimum number of time-steps where interference constraints are present. They present an algorithm working on any graph, with an approximation factor of 4. It was shown that the problem of finding an optimal strategy for gathering (one that uses a minimum number of time-steps) does not admit a Fully Polynomial Time Approximation Scheme if interference range is greater than transmission range.

The Round Weighting Problem was treated in [12] with the objective to minimize the rounds number (time). The authors make dual analysis and propose approximation algorithms for some specific graphs. They showed this problem is NP-hard by proving that the well-known NP-hard problem of finding the *Fractional Coloring* on unit graphs reduces to it.

In this work, one major focus is on fairness and throughput guarantee.

The capacity of radio networks has been extensively investigated. Under specific routing, interference and probabilistic traffic assumptions, it has been shown that a wireless network cannot provide better than a throughput of order $\theta(W/\sqrt{n})$ bps to each node [5, 6, 7].

The work of [5] has shown that, under a *protocol model* of non-interference, the capacity of wireless networks with n randomly located nodes each capable of transmitting at $W bits/sec$ and employing a common range, and each with randomly chosen and therefore likely far away destination, is $\theta(W/\sqrt{n.logn})$. And even the nodes have a optimal placement in a disk of unit area, and optimal range of transmission, a wireless network cannot provide a throughput of more than $\theta(W/\sqrt{n})$ bits/sec to each node for a distance of the order of 1 meter away. Summing over all the bits transported, a wireless network on a disk of unit area in the plane cannot transport a total of more than $\theta(W\sqrt{n})$ bit-meters/sec, irrespective of how the load is distributed. Generic capacity evaluation frameworks have then been proposed using linear programming [9, 8].

The joint routing and scheduling optimization in the WMNs is a recent topic. An algorithm enumerating a tractably large subset of transmission scenarios has been developed [2]. It allows for efficiently solving a LP formulation computing a lower bound on the maximum throughput attainable. Solving the full LP problem means generating an exponential set of scenarios which is intractable even for small networks.

There are very few direct references to the joint routing and scheduling considering interferences in the WMNs. In [2] was proposed an algorithm to enumerate a tractably large subset of transmission scenarios. It must be noted that solving the joint routing and scheduling LP problem over a reduced set of transmission scenarios yields only a lower bound on the maximum throughput attainable, which is obtained by solving the full LP problem.

The notion of *concurrent transmission pattern* models a feasible transmission schedule with multi-radio multi-channel, which is a collection of transmission rates associated with the links that can be simultaneously supported in the network. To avoid the complexity in constructing the whole set of concurrent transmission patterns, a column generation approach has been developed for an efficient generation of such feasible patterns [13]. The CG approach decomposes the original problem into two sub-problems and solves them iteratively.

The problem of determining if a given rate-demand vector can be achieved in the network has then been formulated as a linear program giving an upper bound on the achievable rates in the mesh network [14]. The LP solution is used to assign channels to the links and also to schedule the time slots in which each link and channel is active. Approximate solutions are obtained through variations of the greedy approach.

In this work, we extend this model. We focus on optimal solution for the Fair Round Weighting Problem under network and transmission assumptions that are described as follows.

From all the above assumptions, we then develop an optimization model finding the minimum number of APs deployed in the WMN ensuring some QoS.

3 Fair Round Weighting Problem

We assume that each wireless node has only one radio and a single common channel is shared by all nodes in a TDMA-based WMN. All communications involve bidirectional messages exchanges, at least for packets acknowledge, inducing symmetric interference pattern. We also assume that all routers are stationary and that

the packets can be buffered at intermediate nodes while awaiting transmission. An intermediate router has infinite memory to save datas from all path going through it, these data will be sent when an outgoing link will be active. These paths share the link capacity.

More formally, a transmitting router will enforce all its neighbors to stay silent. Considering symmetric transmissions creates the same pattern for the receiver. We call $E_{\mathcal{I}}(u)$ the set of radio interfering communications if router u sends datas, and we obtain the set of radio interfering links of a transmission (u, v) as $I_{u,v} = \{E_{\mathcal{I}}(u)\} \cup \{E_{\mathcal{I}}(v)\}$.

We deal with the Fair Round Weighting Problem (F_RWP) for WMNs. In this problem, we want to find out the best routing in which the link scheduling gives a fair throughput to each router in the mesh considering the number of time slots and the link capacity. We develop a Mixed Integer Linear Programming (MILP) formulation giving the maximal throughput that can be guaranteed for every routers in the network. It means that each router can transmit at least with this throughput.

The routing problem in a network consists in finding a path or multiple paths for the router-gateways pairs to send traffic through the network without exceeding the link capacity. It is natural to model the traffic problem as a multi-commodity network flow problem [15].

The scheduling problem consists in finding which path links should be active at a given time, that is, it assigns each link a set of time slots $\subset [1, T]$ on which it will be active and can be used to transmit.

We have considered two kinds of transmission: the burst transmission and the permanent transmission. A burst transmission happens at any moment of the time interval. In the burst transmission a router send a small quantity of units of flow that will move from one node to another, and this transmission is finished when the last unit of this flow reaches its destination. It should be possible have two or more burst transmissions, from different routers, in the same time interval. In the permanent transmission the units of flow are permanently sent by the routers, that is, the routers have always datas to send. In both cases the time interval repeats periodically.

When a router want to send packets there is a initial delay to wait for the next link activation in a path, that is, there are time slots where no transmission exists. In permanent transmissions there will be a moment where all links will have flow, therefore it will not exist time slots whitout transmissions. We observed that this initial delay has a large influence in burst transmissions but in permanent transmission it can be negligible.

To reduce this delay penalty in the burst case, each generated path should have its links activated in an increasing order over the time as the figure 1 shows. In this example, the time period is T=5 in both cases. We can observe 2 different link schedules for the paths from the routers going to node gateway 5. Only the first case is ordered, that is, each path has its links activated in an increasing order over the time.

The worst case to a router node in the ordered sequence happens when the necessity to send a burst arrives one slot after the first slot of the path schedule. In the best case, the necessity to send arrives at the first slot of the path schedule.

We can see in the first scheduling, the best case happens to the source router 1, for instance, when it starts to send at the first slot $t = 2$, therefore it gets two time slots to finish the transmission. In the worst case, this router starts at the time slot $t = 3$, therefore it should to wait the time slots $3, 4, 5, 1$ to start to transmit in $t = 2$.

Ordered Case

Node	Min. time	Max. Time
0	slot **1,2,3**=3	slot 2,3,4,5,**1,2,3**=7
1	slot **2,3**=2	slot 3,4,5,1,**2,3**=6
2	slot **3**=1	slot 4,5,1,2,**3**=5
3	slot **4,5**=2	slot 5,1,2,3,**4,5**=6
4	slot **5**=1	slot 1,2,3,4,**5**=5
6	slot **3,4,5**=3	slot 4,5,1,2,**3,4,5**=7
7	slot **2,3,4,5**=4	slot 3,4,5,1,**2,3,4,5**=8
8	slot **1**=1	slot 2,3,4,5,**1**=5

Not Ordered Case

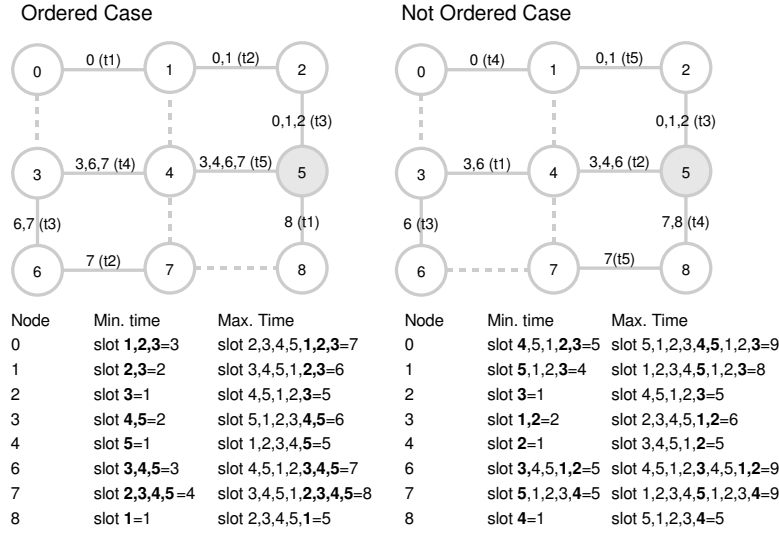| Node	Min. time	Max. Time
0	slot **4,5**,1,**2,3**=5	slot 5,1,2,3,**4,5**,1,2,3=9
1	slot **5**,1,**2,3**=4	slot 1,2,3,4,**5**,1,2,3=8
2	slot **3**=1	slot 4,5,1,2,**3**=5
3	slot **1,2**=2	slot 2,3,4,5,**1,2**=6
4	slot **2**=1	slot 3,4,5,1,**2**=5
6	slot **3,4,5**,1,**2**=5	slot 4,5,1,2,**3,4,5**,1,2=9
7	slot **5**,1,2,3,**4**=5	slot 1,2,3,4,**5**,1,2,3,4=9
8	slot **4**=1	slot 5,1,2,3,**4**=5

Figure 1: Initial delay penalty.

Recall that the number of time slots in one time period is T and that this time interval repeats periodically. Consider that each generated path is represented by sequences c_i of time slots organized in an increasing order, that we call components. These time slots represent the scheduling of the links in this path. Let $t1_{c_i}$ be the first time in the sequence c_i. Let bs represent the size of a burst that is the number of packets to send. Each packet need one time slot to be tranfered from a node to the other. Let ts be the time when the source router of this path is ready to start to transfer its burst and let tr the amount of time depensed to the datas being totaly received.

To the ordered case, we have only one component because all times respect the same order. Therefore, if when the source is ready to send coincides with the begin of the component $ts = t1_{c_1}$ $(x < T)$, we will have the best case and the transmission time $tr = T * bs$. Otherwise, if $ts = t1_{c_1} + x$, we have the worst case and $tr = (T - x) + T * bs$ because it needs wait for a complete period T to reach the first time of the component $t1_{c_1}$ when the time period T repeats. To the nonordered case, we will have more than one sequence, otherwise we will be in an ordered case. We call ns the number of different sequences that exists in a path. In the best case $ts = t1_{c_i}$ and we can send in the sequence i but we should wait the next period T to restart the transmission in the next sequence. Therefore, if $bs = 1$, we should wait $tr = T * ns$. If $bs \neq 1$ it may get more time in the ordered sequence because in a not ordered sequence can have simultaneous transmissions in a same period. That is why the Gathering problem consider only one unit of flow.

3.1   Linear formulation

We consider a simplified max-min fairness model : the objective is that minimum throughput assigned to a router is maximum among all feasible routing and schedules. The network is modelled as a directed graph, where each edge e has a capacity c_e.

In this work we focus on router-gateway traffic pattern, naturaly modelled by a multi-commodity flow problem. The commodities are going from the set of routers V_r to the set of gateways V_g $(V_r \cup V_g = V)$. For every commodity, all links that are within the interference range of either the router or the gateway cannot be used.

Only the neighbors are within the transmission range of a node, and the interference range can be defined in the input of the problem. In our tests we use a symmetric interference model witn interference range equals 2.

Given a network digraph G = (V, E) with routers and gateways nodes, the set E_v of adjacent links to each node, the links capacity $c_e \geqslant 0$ and the number of time slots T, in the Fair Round Weighting Problem (F_RWP)

we want to assign the router throughputs in such a way that the minimum throughput assigned is maximum among all feasible link schedules from the all possible set of routes to each commodity.

The flow over the generated path between router node v and a gateway node is represented by the integer variable p_v. The integer variable $x_e^{v,t}$ represents the flow from the router node v over link e during time slot t. Let the binary variable a_e^t be 1 if link e is active in time slot t, and 0 otherwise.

Problem Definition: Given a network digraph G = (V, E) with routers and gateways nodes, the set E_v of adjacent links to each node, the links capacity $c[i, j] > 0$ and the number of time slots T, in the Fair Round Weighting Problem (F_RWP) we want to assign the router throughputs in such a way that the minimum throughput assigned is maximum among all feasible link schedules from the all possible set of routes to each commodity.

The objective 1 is to maximize the flow in the paths p_v with fairness (to share the network capacity equally).

- Definition of Sets

  - V: Set of nodes. $V = V_r \cup V_g$, $V_r \cap V_g = \emptyset$.
  - V_r: Set of router nodes.
  - V_g: Set of gateway nodes.
  - E: Set of links.
  - E_v: Set of adjacent links of the node v.
  - $I_{u,v}$: Set of interference links of the link (u, v).

- Definition of Constants

  - c_e: Link capacity.
  - T: Quantity of time slots.

- Definition of Decision Variables

  - a_e^t: (binary value) 1 = if link e is active in time slot t. 0 = otherwise.
  - p_v: Flow over the generated path between router node v and a gateway node.
  - $x_e^{v,t}$: Flow from the router node v over link e during time slot t.

- Definition of Objective Function

  - The objective 1 is to maximize the flow in the paths p_v with fairness (to share the network capacity equally).

Objective: $\quad \max(\min_{v \in V_r}(p_v))$ $\hspace{8cm}$ (1)

$$\sum_{e \in I_{u,v}} a_e^t \leqslant 1, \; \forall (u, v) \in E, t \in T \tag{2}$$

$$\sum_{v \in V_r} x_e^{v,t} \leqslant c_e \cdot a_e^t, \; \forall e \in E, t \in T \tag{3}$$

$$\sum_{t \in T} \sum_{i \in V: e=(v,i) \in E} x_e^{v,t} = p_v, \; \forall v \in V_r \tag{4}$$

$$\sum_{t \in T} \sum_{j \in V_g} \sum_{i \in V_r: e=(i,j) \in E} x_e^{v,t} = p_v, \; \forall v \in V_r \tag{5}$$

$$\sum_{t \in T} \sum_{\substack{i \in V_r \\ e=(i,j) \in E}} x_e^{v,t} \geqslant \sum_{t \in T} \sum_{\substack{k \in V \\ e=(j,k) \in E}} x_e^{v,t}, \; \forall j \in V_r, v \in V_r \tag{6}$$

Eq.2: The interference constraint in terms of a link (i, j). Eq.(3): Only active links can have flow. Eq.(4-7): Flow conservation constraints over the time. The model gives more priority to the routers far from the gateways, that is, the links from the longer paths are activated more times.

When considering burst transmission, the order of the links matters. The best case happens when the route have its links activated in an increasing order over the time. Oppositely, the worst case happens if the links are activated in a decreasing order, inducing a delay of $T.l$ where l is the length of the path.

In order to tackle burst transmission, constraint 6 has therefore to be replaced by constraint 7, which activates the links of a path in an increasing order.

$$\sum_{\substack{t1 \in T \\ t1 < t}} \sum_{\substack{i \in V_r \\ e = (i,j) \in E}} x_e^{v,t1} \geqslant \sum_{\substack{t2 \in T \\ t2 \leqslant t}} \sum_{\substack{k \in V \\ e = (j,k) \in E}} x_e^{v,t2}, \, \forall j \in V_r, v \in V_r, t \in T \tag{7}$$

The number of time slots is an input of our model. There is a time when all the throughputs will be almost equal because during this time the model gives more priority to the routers far from the gateways, that is, the links from the longer paths are activated more times. In our experiments, the number of time slots is set such that all routers achieve a non-null throughput.

The figure 2(a) shows a simple example of the relation between the number of time slots and the throughput. The gateway nodes are colored grey. The scenario in d get the minimal time for all routers to have a throughput not null. The scenarios in a and b have a throughput higher than the throughput in c and d. The scenario in a (with T=10) is two repetitions of the scenario in b (with T=5), as we can see in 2(b).

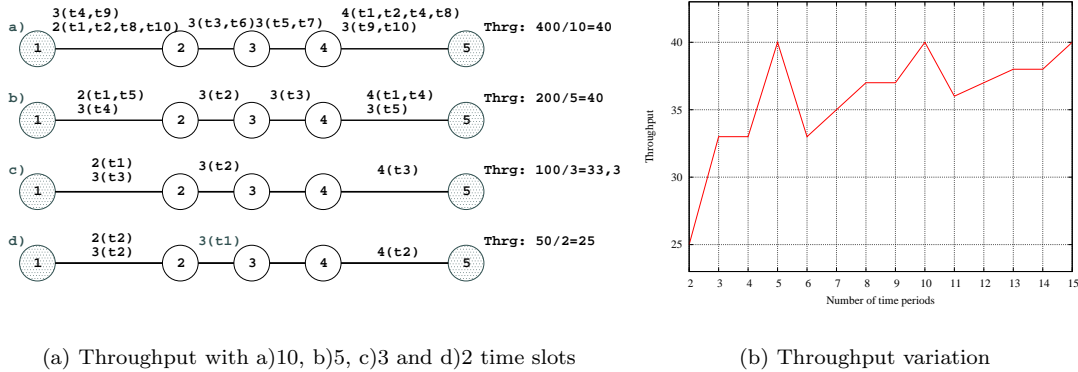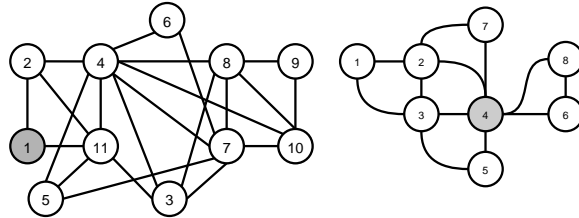(a) Throughput with a)10, b)5, c)3 and d)2 time slots   (b) Throughput variation

Figure 2: Throughput x time

Figure 3: Mesh networks.

Table 1: Results

| Topology | time slots | Permanent Transmission | | | Burst Transmission | | |
		run time(s)	Gap(%)	throughput	run time(s)	Gap(%)	throughput
line7Vg0	10	4.39	0	60	4.75	0	60
grid3Vg4	5	286.31	0	25	26	0	25
grid3Vg5	5	67.98	0	33	4.87	0	25
grid3Vg2	6	130.67	0	40	11.03	0	33
grid3Vg4	6	98.22	0	50	14.9	0	50
grid3Vg5	6	775.31	0	40	30.5	0	37
grid5Vg12	10	1705.20	20	29	1630.47	20	29
grid5Vg4	10	1068.41	20	25	1049.36	20	25
grid5Vg12	20	16362.83	20	62	16411.11	20	62
grid7Vg24	15	40998.59	20	21	43539.55	20	21
mesh6Vg1	5	1.50	0	50	0.21	0	50
mesh8Vg4	5	110.57	0	66	11.75	0	66
mesh11Vg1	10	9444.22	3	33	29827.77	20	40

Let the integer variable $f_{e,v}$ denote the fraction of time link e is active by the router node v over a period of time $[0, T]$.

$$f_{e,v} = \sum_{t \in T} x_e^{v,t}, \ \forall e \in E, v \in V_r \tag{8}$$

We can rewrite the model as follows.

Objective: $\max(\min_{v \in V_r}(p_v))$ (1)

$$\sum_{e \in I_{u,v}} a_e^t \leqslant 1, \ \forall (u,v) \in E, t \in T \tag{2}$$

$$\sum_{v \in V_r} f_{e,v} \leqslant c_e \cdot \sum_{t \leqslant T} a_e^t, \ \forall e \in E \tag{3}$$

$$\sum_{i \in V : e=(v,i) \in E} f_{e,v} = p_v, \ \forall v \in V_r \tag{4}$$

$$\sum_{j \in V_g} \sum_{i \in V_r : e=(i,j) \in E} f_{e,v} = p_v, \ \forall v \in V_r \tag{5}$$

$$\sum_{\substack{i \in V_r \\ e=(i,j) \in E}} f_{e,v} \geqslant \sum_{\substack{k \in V \\ e=(j,k) \in E}} f_{e,v}, \ \forall j \in V_r, v \in V_r \tag{6}$$

4 Results

The MILP model is coded using the GMPL modeling language and it is solved using the commercial software Cplex version 7, on a desktop PC with one gigabyte of RAM.

Table 1 shows some of the results obtained by our model on various size grids or randomly generated mesh.

The topology *grid3Vg4* is a 3 by 3 grid with the gateway located in position 4 (the center). We can see, for instance, that the reached throughput with this topology is 25 units with a time period of 5 time slots. If we put the gateway in the position 5, it now reaches a throughput of 33. We observe that when we increase the time period to 6 we get a better throughput with the gateway located in 4 than the gateway in 5, respectively 50 and 40 units by time period.

Even for small networks and considering small time periods, the program generates MILPs with thousands of constraints and integer variables. Therefore, large problem instances cannot be solved to optimality and only approximate solution can be obtained. The approximation factor is denoted "Gap" in table 1.

We can observe in figure 4 that the model dealing with the burst traffic gives a lower bound to the F_RWP with permanent transmission because the ordering leads to a more restricted scheduling.
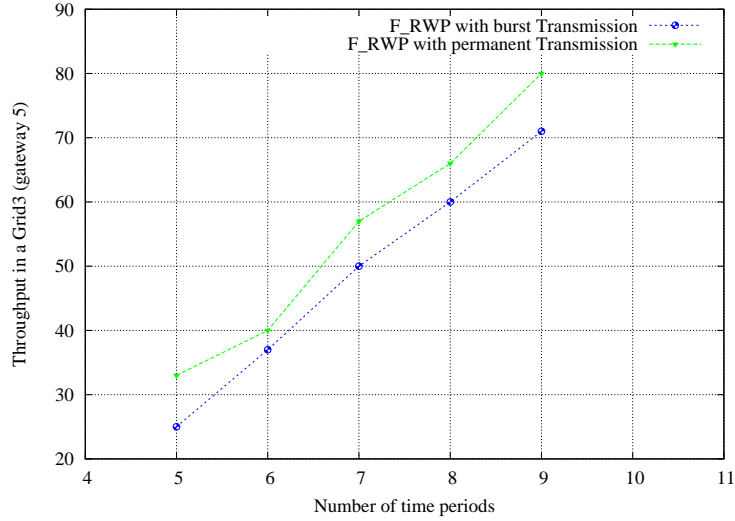
Figure 4: Permanent transmission X Burst transmission.
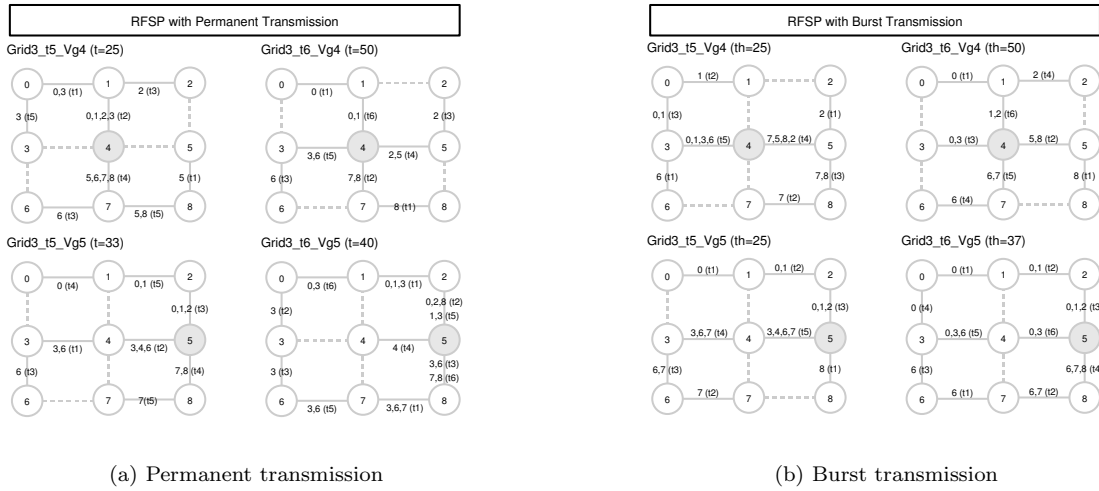
Some grid results are given in figure 5(a) and 5(b).

(a) Permanent transmission   (b) Burst transmission

Figure 5: Grid 3x3 results.

5   Conclusion

We deal with the Fair Round Weighting Problem (F_RWP) for WMNs where our major concerns is fairness and throughput guarantee. We develop a Mixed Integer Linear Programming (MILP) formulation that gives the maximal throughput that can be guaranteed for every routers in the network.

We have considered two kinds of transmission: the burst and the permanent transmission. To reduce the delay penalty in the burst case, each route should have its links activated in an increasing order over the time. Using a MILP model allows to find near optimal solutions for small and medium instances. The difficult task is to prove the optimality of the solution found.

In order to tackle larger network, more sophisticated approaches are under investigation. The call scheduling for permanent transmission is closely related to arc-list coloring with specific constraints, a graph theoretic study should give results or bounds decreasing the complexity of the problem. Moreover, a linear formulation based on more complex combinatorial objects is being designed in order to develop efficient column or line generation algorithms.

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