Joint Per-Flow Scheduling and Routing in Wireless Multihop Networks

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Abstract—**Multihop networks are used in a variety of ways, that include ad-hoc networks, wireless sensor networks, and mesh networks. These networks consist of nodes that connect over a wireless channel, and communicate over multiple links by forwarding each other's messages. The throughput is determined by the contention among the nodes for the wireless resources. Thus routing algorithms, influence the level of contention at each location of the network, and play an important role in the network throughput. Additionally, the sequence of transmission opportunities of each node, which is determined by the scheduling algorithm, should also be carefully designed, since it affects the available resources of each node. In this paper we study the effect of routing and scheduling algorithms on the throughput of multihop networks. We propose a per-flow joint routing/scheduling algorithm that has the property of routing the flows in a way that avoids congested areas with limited availability, and also schedules links, in a way that a) slots are assigned to flows, instead of links or nodes, b) the assignment is fair c) fairness does not lead to underutilization. Simulation results showed that the proposed algorithm increases the average throughput, and the degree of satisfaction of each node, while at the same time it decreases the average delay.**

Keywords-TDMA; Flow; Scheduling; Routing;Throughput; Wireless Multihop Network; Fairness

I. INTRODUCTION

Wireless multihop networks are formed by a set of nodes, where communication between two-end nodes is carried out by hopping over multiple short wireless links. In such a network, each node has to send/receive packets to/from adjacent nodes, and to forward packets on behalf of other nodes, acting as routers.

Multihop networks present a challenge in congestion control, since the nodes don't only have to transmit their own traffic but also the relayed traffic from other nodes. Thus, unless special attention is given, some connections will be starved out, while other will use the entire bandwidth [1]. We argue that in general, the utility of the network, i.e. the total amount of user "satisfaction", will be maximized only when most of the connections transmit at a reasonable rate.

Several cross-layer scheduling algorithms can be found into the literature [1]-[14]. Most of these algorithms create a static schedule, which does not consider the traffic requirements of

the active flows of the multihop network. In this paper, we propose a per-flow joint routing/scheduling algorithm that has the following characteristics: 1) the routing algorithm avoids congested areas, that have limited availability, and 2) the scheduling algorithm assigns slots to flows, instead of links or nodes, and fairness is considered to the extent that it does not cause underutilization.

The paper is organized as follows: Section II overviews joint scheduling TDMA routing algorithms. Section III provides details about the network topology while Section IV presents the proposed per-flow scheduling and routing algorithm. Section V provides details about the simulation parameters and presents the obtained results from the proposed per-flow scheduling and routing algorithm; whereas Section VI concludes the paper.

II. RELATED WORK

Several cross-layer TDMA scheduling algorithms can be found in the literature that combine the TDMA scheduling problem with other issues, including route selection, load balancing and power consumption.

Carello *et al.* [2] proposed a joint routing and interference-based TDMA link scheduling algorithm. The authors formulated the joint routing-TDMA link assignment problem as a mathematical optimization problem and proposed a constraint programming solution method to this problem. Computational results showed that by optimizing the routing algorithm, the number of allocated slots also is reduced, in the cases that scheduling with optimal power control and with optimal rate and power control are required.

Also, Vergados *et al.* [1] proposed a joint routing and TDMA broadcast scheduling algorithm that schedules the transmissions in a fair manner taking into consideration the communication requirements of the active flows of the network. Simulation results showed that when applying load-balancing policy in the proposed scheduling algorithm, the performance of the scheduling algorithm can be further improved in terms of throughput and frame length.

Wolf *et al.* [3] proposed a distributed load-balanced node TDMA scheduling algorithm for wireless ad-hoc networks, which allows nodes to alter their existing transmission schedules so that those nodes which are required to forward

more traffic can reserve additional transmission slots, and thereby alleviating traffic bottlenecks. This is achieved by assigning additional slots to congested nodes. Simulations results showed that the proposed algorithm greatly improves end-to-end packet delay, throughput, and completion rate when compared to a transmission schedule which does not account for traffic load.

Wang *et al.* [4] proposed a joint routing and TDMA link scheduling algorithm for static wireless networks. The authors presented a linear programming formulation in order to find a flow routing, in which the throughput is at least a constant fraction of the optimum, and then they applied weighted link coloring (both distributed and centralized) in order to resolve the scheduling problem. In addition the authors proved that the simple link coloring has the drawback that it cannot achieve good throughput.

ElBatt and Ephremides [5] proposed a two stage joint link scheduling and power control algorithm for wireless ad-hoc networks in order to minimize the power consumption. During the first phase, based on the scheduling algorithm coordinating independent users' transmissions that eliminate strong levels of interference inherent to wireless ad hoc networks are selected. During the second stage power control is executed in a distributed fashion, to determine the "admissible" set of powers that could be used by the scheduled nodes, if one exists. In case that no set of positive powers can be found, control is transferred again to the first phase in order to reduce interference via deferring the transmissions of one or more users participating in this scenario.

Li and Ephremides [6] proposed a two-stage centralized joint power control, TDMA link scheduling, routing algorithm for ad hoc networks. In the first stage, the scheduling algorithm is responsible for coordinating independent users' transmissions to eliminate primary interference. In the second stage, power control is executed to determine the admissible set of power levels that could be used by the scheduled nodes, if one exists. If no such set of positive power levels can be found, control is transferred back to the scheduling phase to reduce interference via deferring the transmissions of one or more users participating in this scenario.

Tang *et al.* [7] proposed a joint link scheduling and power control TDMA algorithm for multihop wireless network with the objective of maximizing network throughput. To achieve this goal the authors use a Mixed Integer Linear Programming (MILP) formulation in order to describe the problem and then either find optimal solutions or apply a polynomial-time heuristic algorithm, the Serial Linear Programming Rounding (SLPR) heuristic, to solve the problem. Numerical results showed that the bandwidth can be fairly allocated among all links by solving the MILP formulation or by using the heuristic algorithm at the cost of a minor reduction of network throughput.

Mao et al. [8] proposed a joint link scheduling and power control algorithm for many-to-one communications in wireless sensor networks, with objective to minimize the energy consumption and the TDMA frame length. To obtain this goal a hybrid genetic and particle swarm optimization algorithm is applied in order to enhance the searching ability. Simulation results showed that the proposed algorithm outperforms the classical node Max Degree First coloring algorithm [9].

Wang *et al.* [10] proposed a joint distributed interference–based TDMA link scheduling and power control algorithm for ad hoc network supporting multicast traffic. The proposed algorithm eliminates links which cause most interference in order to allow the remaining links to reach an acceptable Signal to Interference-plus-Noise Ratio (SINR) level.

III. NETWORK MODEL

We consider a wireless multihop network with a set of N nodes, a set of L logical links, and a set of F flows. We represent the network as a graph, $G = (V, E)$ where V denotes the number of nodes ($|V| = N$), and E the set of the wireless links ($|E| = L$). Links are assumed to be directed and are presented as l_{ij} where i and j denote the source and destination nodes respectively.

The interference model that is used is the protocol interference model [11], [15] where a transmission by a node $u_i \in V$ is successfully received by a node $u_j \in V$, if the distance between the intended destination u_j and the source of any other simultaneous transmission is larger than a threshold.

We also assume that the receiving nodes can only receive one transmission at a time without errors, and nodes cannot transmit and receive packets at the same time.

The information transmitted through the network is grouped in connections. Each connection is an ordered set $[u_i, u_j, m]$, where u_i is the source node, u_j is the destination node, and *m* is the amount of data it contains. The connection is established through the network, by a routing algorithm. The routing algorithm generates a flow for a connection, where a flow is a sequence of hops. Specifically, for the connection c=$[u_i, u_j, m]$, a flow f_c with k hops $f_c = [h_1, h_2, ..., h_k]$ is created, where a hop $h_l = [u_{l,s}, u_{l,d}]$, and for every link *l*, $u_{l-1,d} = u_{l,s}$ and $u_l = u_{l+1,d}$.

We assume that all transmissions are carried out at a fixed bitrate C that is assumed equal for each link (no mixed physical rates are considered). Additionally, a scheduling algorithm assigns a number slots s_i to each hop h_i, with the limitation that hops in each flow are assigned the same number of slots. The rate of each flow r_f is calculated as the number of slots assigned to its hops, divided by the total number of slots, multiplied by the channel transmission rate R. Thus

$$r_{f=} \min\{ s_i, \text{with } h_i \in f_c \} / S * R \qquad (1)$$

We assume that the Medium Access Control (MAC) scheme in the wireless channel is the Time Division Multiple Access (TDMA). The algorithms may be generalized for other MAC schemes, as well. All nodes in the wireless multihop

network must have at least as many transmission opportunities as the number of packets that has to transmit on behalf of the flows that traverse them within each TDMA frame. The TDMA frame (denoted as M in the following of the paper) consists of a number of TDMA timeslots. More than one wireless multihop nodes may transmit in every TDMA timeslot without collision, if they do not have any common neighbors.

The utility u_f of each connection is modeled as the logarithm of its rate, i.e. $u_f=\log(r_f)$. This definition is common in traffic engineering, the captures the fact that the "satisfaction of a user increases less quickly than his throughput. The total utility of the network is modeled as the sum of all utilities in the network.

IV. THE JOINT PER FLOW-SCHEDULING ROUTING ALGORITHM

The main goal of the algorithm is to increase the network utilization by assigning as many slots as possible to the network flows. This is achieved using a joint per- flow scheduling algorithm whose its operation is described in following.

When a flow is created, an information discovery phase is initiated, similarly to any on-demand routing algorithm, which helps the source node to retrieve information concerning the network topology. Then, a routing algorithm is applied in order to determine the optimal path for the specific network flow. We consider two policies for the path selection:

1. the shortest path policy where always the shortest path (in terms of hops) from source to destination is selected.
2. the available throughput policy. In this policy, we consider a metric, denoted as d_l, that represents the available throughput for each link, i.e the quotient of the division of the the network capacity by the currently used throughput of the all the flows that pass through the 1-hop neighbors of the source and the destination nodes. Therefore, the cost of link l is given by

$$d_l = \frac{C}{AV+1} \qquad (2)$$

where C denotes the network capacity and AV the

available throughput of link l.

Then the total cost of a flow is computed as

$$d_f = \sum_{f \text{ uses } l_{ij}} d_{l_{ij}} \qquad (3)$$

The flow that is selected for a connection is the one that has the minimum cost.

It should be noted that each time a flow is created or finished the network metrics are recomputed.

After the routing algorithm has been executed, a scheduling algorithm takes place. The purpose of the scheduling algorithm is to assign slots to hops (and consequently to paths, with the following objectives:

- There are no conflicting transmissions,
- The rate of each path is maximized
- The least amount of slots are unallocated
- The allocation is as fair as possible.

In order to meet these objectives, the scheduling algorithm initially is applied, as described in the following pseudocode:

```
Input:
Priority Queue of Flows (ordered by the number of slots allocated
                        at each flow)

Output:
Frame

Algorithm:
Frame=∅
For every flow f of the Priority Queue{
        Check if on the all links used by flow f slots have been
        assigned
        If succeed {
                Increase the # of slots assigned to flow f by 1
                Insert flow f into the Priority Queue
        }
        else
                Remove flow from Queue
        }
}
```

More specifically, we consider a priority queue where the flows are ordered according to the number of slots that are allocated to each flow. Each time we pop the flow with the fewest allocated number of slots (for fairness).

For all the links that the flow uses a check is done in order to determine if in all the links of the flows slots have been assigned without conflicts (this ensures the first requirement, and that the number of slots allocated to each link in a flow are same).

If this check is succeed, one extra slot for every link of the flow is assigned, since the additional transmission "fits" in the schedule. Then, the flow is inserted into the priority queue by increasing the number of required slots for the flow by one. If this addition it is not feasible, the flow is removed by the priority queue, since no additional slots can be allocated to the flow.

In the length of the frame is assigned a value that is sufficiently large so that the allocation is fair, but not very large. If the frame is too small, then the initial ordering of the

flows plays a significant role in the allocations. A large frame minimizes this effect. On the other hand, if the frame is too large, then its duration will be comparable to the flow lifetime, and thus the schedule will not follow the changing dynamics of the network.

This process is repeated until the priority queue is empty. The construction of the mechanism results in fair allocations where these are feasible, with more slots allocated to flows that use less congested areas.

V. SIMULATION RESULTS

In order to evaluate the proposed algorithms a simulation tool has been created. The simulation tool has the ability of emulating the TDMA scheduling and routing functions in a wireless multihop network topology. It was designed in a way that permits multiple runs to be repeatedly executed and the performance metrics to be gathered.

In addition the following simulation parameters where used for generating the simulation results:

- Channel transmission rate: 1Mbps
- # of connections per iteration: 50
- Transmission Range: 11 m
- Average Connection Size: 1 Mbit
- Number of nodes: 100
- Topology size: a square area 90 x90 m^2
- Burst inter-arrival time: ranges from 1 to 10 sec
- Number of minislots per frame: 200

Moreover, in order to evaluate the performance of the proposed algorithm the following performance metrics are considered:

- The average delay, i.e. the average amount of time needed by each connection for transmitting its data.
- The average throughput per connection
- The network capacity, defined as the total amount of bits transferred through the network, divided by the simulation duration.
- The total utility, defined as the sum of all satisfaction utilities in the network, as described in Section III.
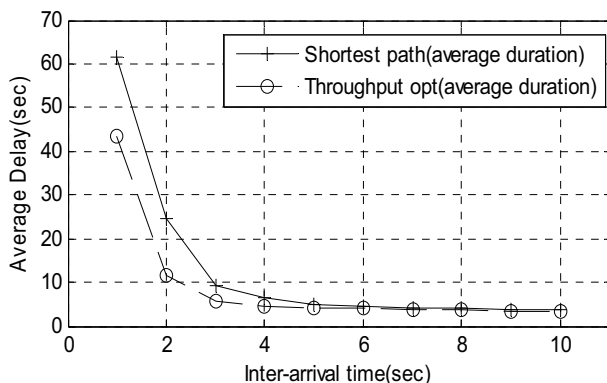

Figure 1 The average delay versus the inter-arrival time

As Fig. 1 depicts the average amount of time needed by each connection for transmitting its data decreases as the inter-arrival time between connections is increased. This is expected, since large inter-arrival times result in lower number of concurrent active flows. Thus, more slots can be allocated to each flow, and the throughput for each flow increases. Moreover the time needed to complete the transmission is smaller. Also, the shortest path routing algorithm causes larger delays than the proposed algorithm. This is expected, since the proposed algorithm routes every flow through paths with less traffic. Thus the throughput is larger, and delays are lower.
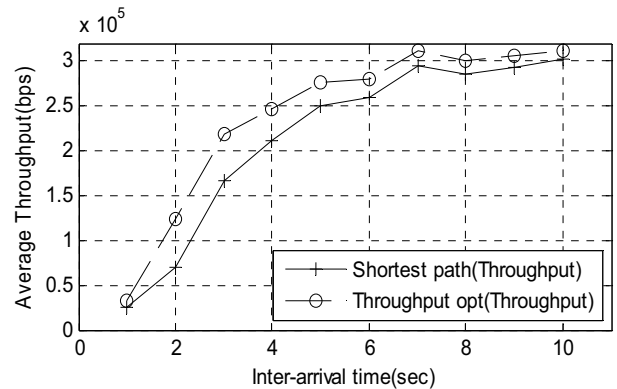

Figure 2 The average throughput versus the inter-arrival time

The previous results are validated by the results in Fig. 2 that depicts the inter-arrival time versus the average throughput from all the connections. As Fig. 2 depicts the proposed algorithm achieves larger throughput than the shorted path algorithm. The improvement is minimized for large inter-arrival times, since at these points there is only limited congestion, and therefore there is no room for optimization.
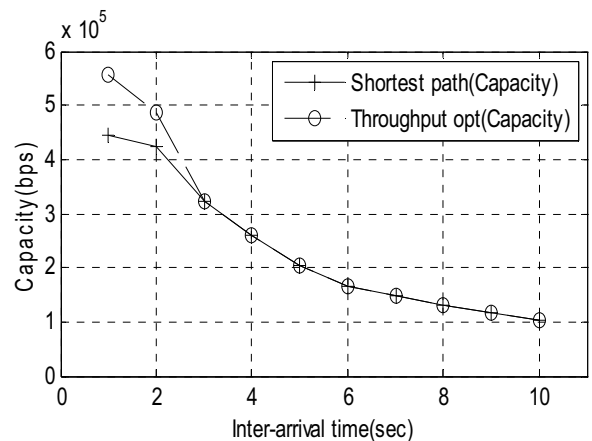

Figure 3 The network capacity versus the inter-arrival time

In Fig. 3 we illustrate the total capacity of the network, for various inter-arrival times. The difference is more obvious in lower inter-arrival times, where there is more traffic to be routed, and thus more room for optimization. When there is less traffic, then the shortest path routing algorithm and the proposed one converge.

Finally, Fig.4 illustrates the total utility for various inter-arrival times. Again, the proposed algorithm is most advantageous when there is more traffic. The improvement in terms of utility is greater than in terms of throughput, due to the logarithmic scale that the utility is measured. The proposed algorithm achieved fairness to greater a extent than the shortest path algorithm, and thus fewer connections are starved. Therefore, their utility affects the total utility positively.
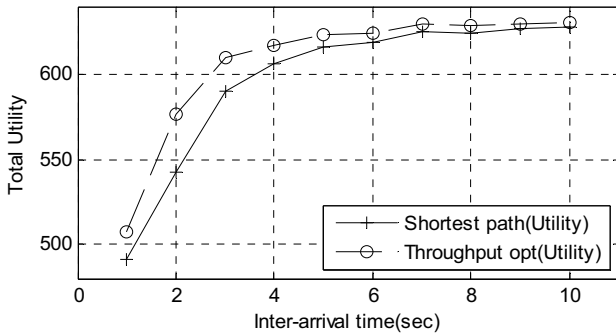

Figure 4 The total utility versus the inter-arrival time

In conclusion, the proposed routing metric achieves significant gains over the shortest path algorithm, for all the aforementioned metrics, especially when the network is more congested.

VI. CONCLUSIONS

In this paper we study the effect of routing and scheduling algorithms on the throughput of multihop networks. More specifically, we proposed a per-flow joint routing/scheduling algorithm, that has the property of routing the flows in a way that avoids congested areas, that have limited availability, and also schedules links, in a way that a) slots are assigned to flows, b) flows are assigned slots in a fair way, and c) the fairness does not lead to underutilization.

Simulation results showed that the joint per-flow scheduling routing policy increases the average throughput, and the total utility while at the same it decreases the average delay. Especially, when the network is congested the gain achieved from the proposed algorithm in comparison with the shortest path algorithm is increased.

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