Improving Fairness in Wireless Mesh Networks

Jorge L S Peixoto
Serv. Federal Process. Dados (SERPRO)
Fortaleza - CE - Brazil
jorge.peixoto@serpro.gov.br

Marcial P Fernandez
Univer. Estadual Ceará (UECE)
Fortaleza - CE - Brazil
marcial@larces.uece.br

Luis F de Moraes
Univer. Federal Rio de Janeiro (UFRJ)
Rio de Janeiro - RJ - Brazil
moraes@ravel.ufrj.br

***Abstract*—Wireless Mesh Networks (WMNs) are networks that aim to establish hybrid wireless communications in areas with little or no telecommunication infrastructure available. The main motivation of these networks in Brazil and other developing countries, particularly in remote areas, is providing Internet access in places without commercial infrastructure and where the telecom operators have no economic interest due to its low demand. The idea is that a user in the network can forward the packets of distant users to the wired network connection point. Currently, wireless mesh networks use the IEEE 802.11 (WLAN) protocol due its availability and low-cost. However, IEEE 802.11 protocol favors the near users at expenses of a very low performance for distant users from the gateway node, connected to the wired network. The goal of this paper is to propose a mechanism using the IEEE 802.11e and QoS extension to provide a fairness network resource distribution for all participating WMN nodes, independent of their distance. The prototype was tested in simulation and the results demonstrated the proposal effectiveness in resource allocation in a wireless mesh network.**

***Keywords*-Wireless Mesh Networks; Fairness; IEEE 802.11e.**

I. INTRODUCTION

The use of wireless networks as an alternative to wired networks has fostered a large number of studies whose focus is improving the behavior of autonomous devices. Due to the lack of an infrastructure network, the communications' management is the responsibility of the nodes themselves.

Wireless Mesh Networks (WMNs) are cooperatives and self-configurable networks, that interconnect a set of fixed nodes that can route packets to each other through multi-hop [1]. They have the advantage to be a low-cost, easy to deploy and a highly fault tolerant network.

The main application of Wireless Mesh Networks is to provide access in areas with fair telecommunications infrastructure where Internet access is given only by Plain Old Telephone Service (POTS). A mesh infrastructure allows to bring Internet access to low-income places where telecom operators don't have interest to offer broadband services. The mesh networks thus become a viable alternative to promote digital inclusion in under developed areas.

Wireless Mesh Networks can be classified into three classes based on nodes' functionality: flat, hierarchical and hybrid[1]. The *flat* WMN are composed of routers (nodes) with gateway functions that provides additional functions to support the mesh network routing. The *hierarchical* WMN are created by users but with functions of routing packets in the mesh. The *hybrid* network are made of mesh routers and clients that provides mesh routing (or not) and wired network gateway. The hybrid network provides connections with different types of networks. This work will be based on this approach.

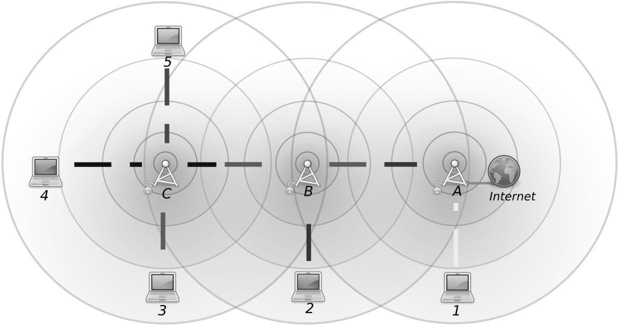


Figure 1. Unfairness forward in Mesh Networks.

In multi-hop wireless networks based on IEEE 802.11 [2], the performance is low, and in some cases, resources starvation, for client nodes far from the gateway node. This occurs due to some characteristics in such networks, such as: hidden and exposed terminal problem; IEEE 802.11 Binary Exponential Backoff [3]; the fact that DCF provides to stations equal access opportunity to the shared environment; and, data streams from distant stations (in number of hops) to the gateway, has more dispute on medium access that increases the packet loss and collision, reducing the throughput.

Figure 1 shows these problems. Suppose A, B and C are part of the wireless back-haul. Only A is connected to the wired network (Internet). Nodes A, B and C are configured with static routes and do not generate traffic, just forward the data from client nodes 1, 2, 3, 4 and 5. Now, suppose 1, 2, 3, 4 and 5 start (each one) a data flow to the Internet. The flow that starts at the node 4, before arriving at A, must pass through C and then B. The flow from node 2, before arriving at A, passes through B. Node 1 communicates directly with A, and then, to the Internet.

Through simulation experiments, we observed that the gradual increase in data rate from client nodes (1, 2, 3, 4 and 5), cause the increase of node 1 flow at the expense of the reduction of flow from other client nodes (2, 3, 4 and 5). Node A divide equally the opportunity for node 1 and B that consolidate the traffic from other nodes. In the Figure 1, while the client nodes forward only one stream each, node A forwards 5 streams (from 1, 2, 3, 4 and 5), B forwards 4 streams (from 2, 3, 4 and 5) and C forwards 3 streams (from a 3, 4 and 5).

This paper proposes a mechanism to share the *medium access time* among wireless back-haul routers and clients. The resource sharing should be proportional to the number of users connected to each wireless router. And also, it should maximize the network resource use in order to avoid resource waste.

The rest of the paper is structured as follows. In Section II, we present some related works and in section III we present the proposed mechanism. Section IV shows the validation methodology and Section V shows the results. Finally, Section VI shows the conclusions and some suggestions to future works.

II. RELATED WORKS

The medium access fairness in IEEE 802.11 wireless networks has been discussed in many papers. However, little work has been done about fairness on mesh networks. Some related works are presented below.

Bensaou [4] and Wang [5] proposed a new algorithm for quantitative back-off instead the DCF Binary Exponential Back-off. In their proposal, each station continuously estimates its own throughput and the throughput from other stations, which competes to the medium access. Then, each one calculates a fairness index used to adjust the contention window. The simulation shows that this algorithm achieves a better fairness than the IEEE 802.11 original algorithm.

Xu et al. [3] shows that, although the IEEE 802.11 MAC protocol support *Ad hoc* networks, it was not designed for it, i.e., the connectivity is basically multi-hop. It presents several problems, such as medium access unfairness and TCP instability, and proposes some solutions. Finally, they show that IEEE 802.11 MAC protocol does not work well in multi-hop networks.

Wang [6] proposed a mechanism to guarantee applications end-to-end delay in multi-hop wireless LANs. Due to node mobility and the distributed medium access, these networks suffer from severe delay and jitter variations. Thus, the perceived fairness on delay is essential to provide all nodes the same delays guarantees in a multi-hop WLAN network. They propose a new framework to guarantee delays using three modules: one is responsible for provisioning the delay information in the class of service, another for the adaptive selection among the available class of services and the last is responsible for monitoring the average delay of each network node and select the MAC priority.

Gambiroza et al. [7] proposed the IFA algorithm (Inter-transit access points Fairness Algorithm) to improve fairness in multi-hop networks. In IFA, each node calculates the amount of time it can use to transmit its data, improving overall fairness. The evaluation requires exchange of information control messages about the state of each link. The nodes send to their neighbors the amount of network resources they need to forward incoming traffic. After an exchange of control information, each node runs the algorithm to calculate its maximum rate allowed.

III. A PRIORITIZATION MECHANISM TO IMPROVE FAIRNESS IN MESH NETWORKS

The mechanism proposed in this paper aims to share *medium access time* in a fair manner among nodes in a wireless back-haul. The mechanism functionality is to define a certain limited amount of shared resources for each wireless router from WMN back-haul. Then, it needs to know the number of client nodes connected in this router and its child nodes. The algorithm calculates the amount of necessary resource and it allocates for each connection.

It is important to know that the algorithm should run only in router nodes, but not in the client nodes. Then, the user does not need to update any software or hardware, they should use the normal WLAN protocol.

When we progressively increase the client nodes transmission rate, the rate of nodes close to the gateway router continues to grow at the expense of reduction on rate of distant nodes. By simulation experiments, we notice that when the network reaches saturation, the client nodes farther from the gateway router suffer starvation. The mechanism proposed aims to minimize this problem.

Another important factor is associated with WMN topology. Most of WMN has only one *path* between two nodes, as data preferentially flows from an external network to client nodes, then more flows are forwarded to the nodes near the gateway router. This gives a disproportion in traffic flows to the router nodes (Figure1), then, it should be given more medium access time to router nodes to minimize this disparity.

The prioritization mechanism allocates the resource *media access time* to the nodes of the WMN back-haul using a parameter that limits the maximum transmission time for each node. This parameter is defined as the Transmission Opportunity (TXOP) by IEEE 802.11e amendment. The resource allocation calculation is done as follows: each client node will receive a fixed amount of resource and the routers nodes receive an amount of resource proportional to the number of upward client nodes connected.

Figure 2 shows a WMN example and how the resource allocation works. Suppose, initially, that the TXOP value is configured to 1 for each client node (1, 2, 3, 4 and 5). Router C is configured with TXOP equal to 3, because there are three clients connected (5, 4 and 3). Router B receives a

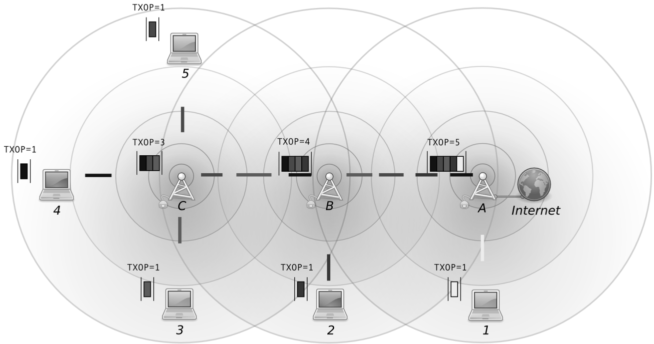


Figure 2. Resource allocation.

TXOP equal to 4, because there are four clients downward (5, 4, 3 and 2). Finally, A receives a TXOP equal to 5 because there are five clients downward (5, 4, 3, 2 and 1).

During the mechanism evaluation, it was noticed that the resources allocated to routers were underused. This was because all packets from the queue of the router were transmitted before the end of the time allocated, thus, on every transmission opportunity time a considerable amount of resource was wasted. To minimize this, it was added some intelligence in mechanism to dynamically adjust the router IEEE 802.11e AIFS parameter according the queue length. When it is near zero, the AIFS is increased and then: decreases the medium access probability for the node; increase the numbers of packets in the queue, and finally; maximizes the resource use because the allocated resource ends before the queue length reaches zero. When the queue length exceeds the threshold, the AIFS value is restored.

IV. PROPOSAL VALIDATION

This section describes the validation methodology and the implementation of proposed mechanism in Network Simulator version 2 (ns-2) platform. Only DCF functions are implemented in the IEEE 802.11 MAC layer of ns-2 core. We chose the TKN (Telecommunication Networks Group) [8] model, that supports an EDCA based on the latest version of IEEE 802.11e draft, which presents an improved binary exponential back-off algorithm that was adopted in the final version. The platform used was the Network Simulator (ns-2) version 2.28 patched with TKN EDCA from Vivek [9]. The operation system was GNU/Linux Ubuntu Hardy 8.04 and compiler was GNU C/C++ Compiler version 3.33 or 2.95.

A. Scenario

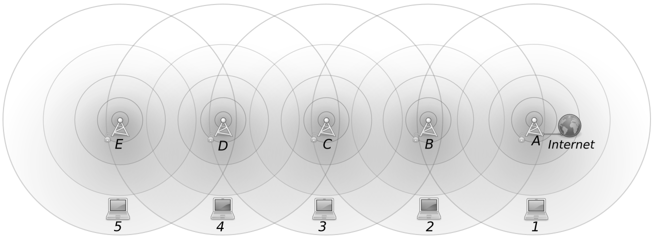


Figure 3. Line WMN scenario: nodes 1, 2, 3, 4 and 5 are clients, nodes B, C, D and E are routers and node A is the gateway.

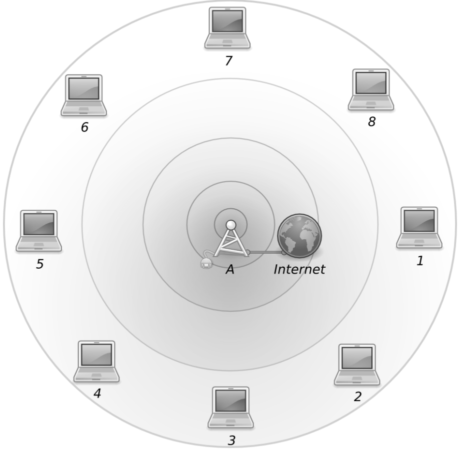


Figure 4. Star WMN scenario: nodes 1, 2, 3, 4, 5, 6, 7 and 8 are clients and node A is the gateway.

To validate the proposal, we performed simulations in three different scenarios. The first scenario, showed in Figure 2, is a **Typical Scenario** of a WMN where the mechanism was evaluated. To validate the proposed mechanism we evaluated in two other scenarios: the **Line Scenario** topology, showed in Figure 3, which represents the worst case for WMN (largest number of hops) and the **Star Scenario** topology, showed in Figure 4, which represents the best case for WMN, i.e., all stations are equidistant from the gateway node (one hop).

In Figure 2, nodes 1, 2, 3, 4 and 5 generate traffic Constant Bit Rate (CBR) using the UDP (User Datagram Protocol) transport protocol. These flows had 500 bytes packets to node A. TCP (Transmission Control Protocol) was not used because its congestion control mechanism would affect the measurement results [10]. Nodes A, B and C are fixed router nodes configured with static routes [9] that make the wireless back-haul. The node A is 100 meters from B and B is 100 meters from C. Nodes 5, 4 and 3 are within 100 meters of C, node 2 is within 100 meters of B and node 1 is within 100 meters of A.

The simulations were performed with and without the mechanism enabled. Each experiment consisted of 10 simulations of 240 seconds and the average with a 95% confidence interval was calculated. Each experiment used a random generated seed. In each round, the traffic rate generated by nodes varies from 0 to the maximum rate that cause the network congestion.

In the first test, we used the IEEE 802.11b DCF at 11 Mbps data and 1 Mbps for RTS/CTS/ACK, while in the second test we used the IEEE 802.11b EDCA at the same rates. All the nodes have omni-directional antennas with the same transmission power, providing 100 m as transmission radius and 150 meters as carrier detection radius. In both tests, the nodes were configured with $\mathrm{CW}_{min} = 31$ and $\mathrm{CW}_{max} = 1023$. In the second test, the $AIFS = 1$ was used. The amount of reserved resource (TXOPLimit) for nodes C is $3t$ and for node B is $4t$, where $t = 0.915ms$, the time in milliseconds to transmit a 500 bytes frame and receiving a frame acknowledgment (ACK). The minimum queue length threshold at nodes C and B is 2 times the number of child nodes, i.e., the threshold of $C = 6$ and $B = 8$.

The number of nodes connected to each router in the prototype were assigned manually since it was not a goal of our work to perform node discovery. However, this function could be implemented using resource discovery protocols, such as Link Layer Discovery Protocol (LLDP).

V. RESULTS

The proposed mechanism was evaluated using the following performance metrics:

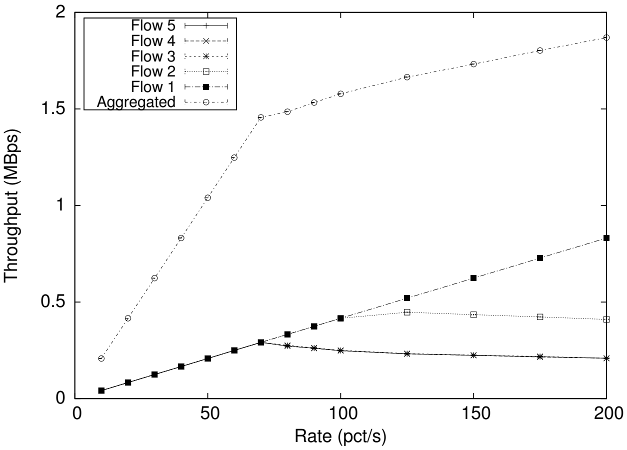
- Throughput in MBps: measuring the number of bytes per second of a specific flow received by the destination application;
- Number of transmission opportunities (TXOP): number of transmission opportunities obtained by each node per second;
- Packet Drops rate in pkts/s due full queue: the number of packets dropped per second for each node due full queue.

We plotted two graphs for each metric: one with standard IEEE 802.11 DCF (no mechanism) and another with proposed prioritization mechanism enabled. In all graphs, the x-axis represents the traffic load generated by the client node at the application layer.

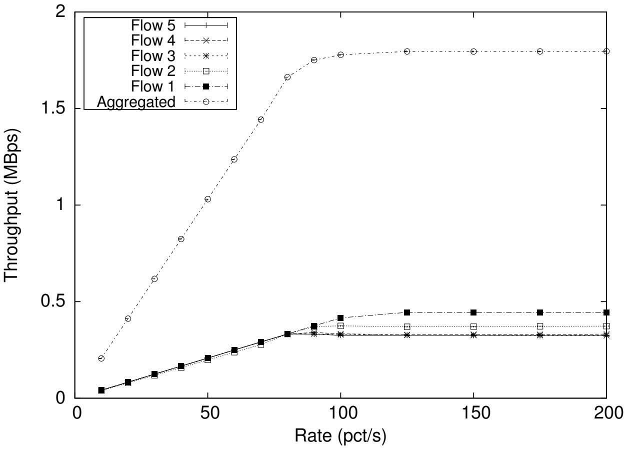
A. Results for Typical Scenario

Figure 5(a) shows what was written in the last paragraph of Section I, about increasing the flow rate in node 1 against other flows. The throughput reaches the maximum rate at 400 pkts/s, when the network becomes saturated. But we can note signs of saturation at 70 pkts/s, when the flow coming from the farthest nodes begins to decrease. The flow from node 2, one hop less than nodes 3, 4 and 5, begins to decrease the throughput at 125 pkts/s.

Figure 5(b) shows the behavior of throughput with the proposed mechanism enabled. We can see a better fairness among throughput from different nodes. When the system is saturated, the flow from node 1 no longer monopolizes the bandwidth. But even with the mechanism enabled, there is a little difference among the flows coming from nodes with different number of hops: node 1 was a little better than node 2 and better than flows from nodes 3, 4 and 5. We can also see a reduction on global throughput because the mechanism gives more bandwidth for distant nodes that have a longer delay to gateway node reducing the overall throughput.



(a) Without mechanism.

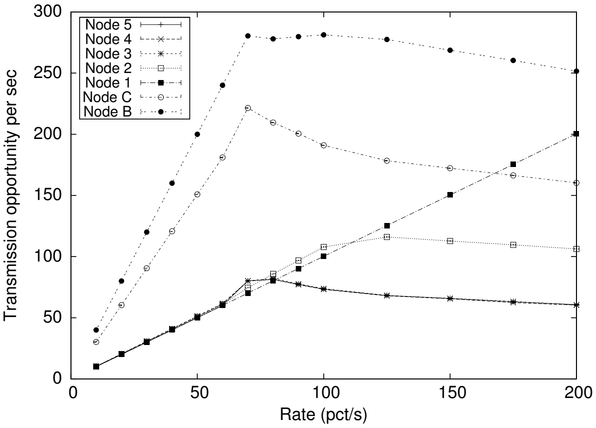


(b) Proposed mechanism enabled.

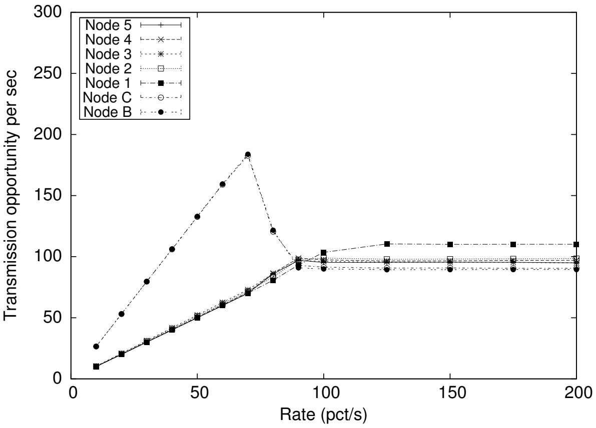
Figure 5. Typical Scenario: Throughput in MBps per flow

In Figure 6, the y-axis shows the number of transmission opportunities per second by node. The client nodes can only send one packet at every opportunity, so we can also consider that y-axis represents the number of packets sent per second (throughput in pkts/s). However, router nodes can send multiple packets at each transmission opportunity period. For example, on the simulation scenario showed in Figure 2, the node C was assigned a value of 2.745 ms, this means that every transmission opportunity given to C, the channel will be reserved for C for a maximum time of 2.745 ms (time enough to forward up to 3 packets of 500 bytes). With the mechanism off, all nodes send one frame every transmission opportunity period.

Figure 6(a) also demonstrates that the network becomes saturated above 70 pkts/s. After that, the graph shows the node 1 bandwidth monopolization.



(a) Without mechanism.

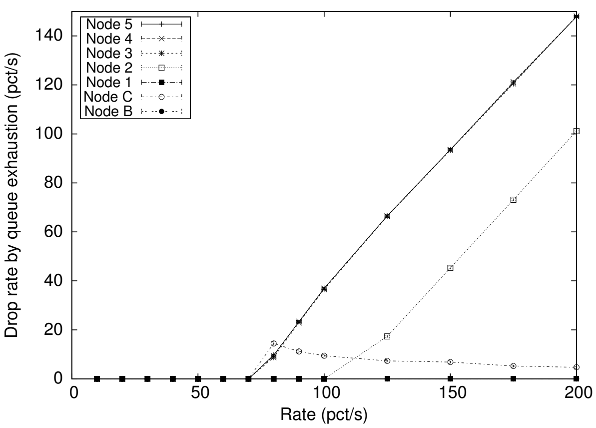


(b) Proposed mechanism enabled.

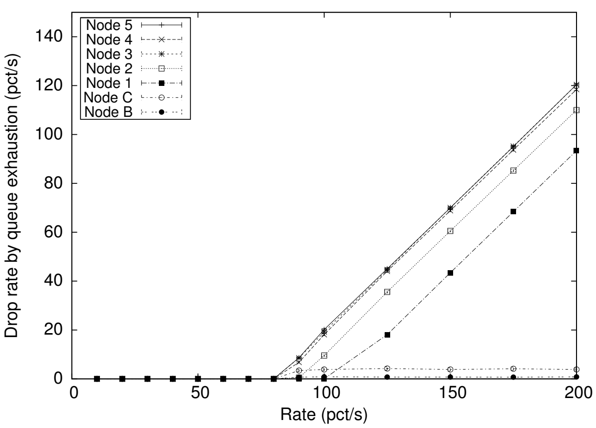
Figure 6. Typical Scenario: Transmission Opportunity per node

In Figure 6(b) we can see the router resource use yield. Yield is defined as the ratio of the number of packets transmitted by the number of transmission opportunities. When the system has low demand (until 70 pkts/s), the yield is low because there are no sufficient packets to fill the queue. When the system is near saturation (at 70 pkts/s), the yield increases, reaching 41% in node C. The maximum yield for the router C occurs when it always transmit 3 frames every transmission opportunity, reaching yield of 93% at 90 pkts/s rate.

After analyzing the results, we could notice that the reasons for dropping packets are full queue (Figure 7) and collision. Client nodes almost drop packets only due full queue. Since the routers only forward packets, not generate them, there is less queue use and hence less full queue drops. We can see in Figure 7 that drop rate is similar with and without the mechanism, but it is clear the improvement on drop fairness, now more distributed among nodes.



(a) Without mechanism.



(b) Proposed mechanism enabled.

Figure 7. Typical Scenario: Drops rate due full queue.

B. *Results for Line Scenario (worst case)*

The mechanism evaluation in a line scenario, worst case for WMN, shows that it was very efficient because in this topology the fairness is clearly evident.

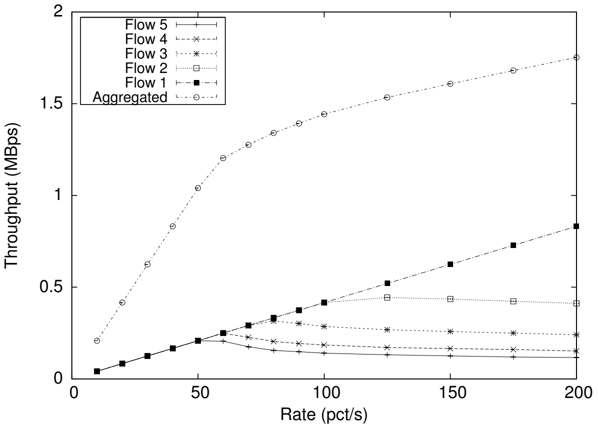
In Figure 8(a), the maximum network throughput occurs at 375 pkt/s rate. But at 50 pkt/s rate there was a reduction on flow 5 throughput. Figure 8(b) shows the better fairness among flows after the mechanism was enabled. When the mechanism is enabled, we see an equalization of TXOP among client nodes and routers.

C. *Results for Star Scenario (best case)*

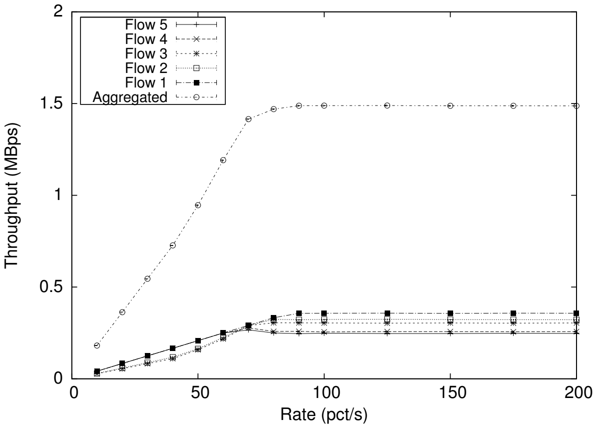
The third scenario evaluated a star topology, the best case of WMN. In this simulation we note that there is no improvement when the proposed mechanism is used, because all client nodes are equidistant (1 hop) from gateway node.

VI. CONCLUSION AND FUTURE WORK

The WMN networks based on IEEE 802.11 are being used to provide Internet access in under-developed areas. Aiming



(a) Without mechanism.



(b) Proposed mechanism enabled.

Figure 8. Line Scenario: Throughput per flow in MBps

to extend the coverage of such networks in an economically viable manner, network designs have been studying platforms characterized by low-cost equipment, ease of configuration, installation and maintenance. When progressively increasing the transmission rate in client nodes, the throughput of the nodes near gateway router continues to increase against the throughput reduction from distant nodes. When the network reaches the bandwidth saturation, we observed that the farther client nodes from the gateway router suffer starvation.

This paper presented a new mechanism to improve the fairness at WMN back-haul. The mechanism changes the prioritization of medium access time of routers nodes to reach fair share of network resource. The basic operation is giving out to back-haul router nodes an amount of medium access time based on the number of client nodes connected.

The simulation experiments showed that the mechanism is effective, since it allocated the resource proportion to the numbers of flows routed by router node, minimizing the problem of unbalanced resource distribution among the WMN nodes. The efficiency was assessed by comparisons of the WMN performance with prioritization mechanism disabled and enabled.

Based on work presented in this paper we can suggest some future work: Dynamic allocation resource: as showed in Section III, the prioritization mechanism allocates an amount of resource based on the number of descendants clients. If the number of client nodes vary dynamically, it is necessary to adjust the resource allocation dynamically. Protocol to exchange information among routers: this protocol would be necessary to implement dynamic allocation resource mechanism to update status information (number of client nodes).

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