Persistence of Routing Tables in Wireless Mesh Networks with Duty Cycling

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Abstract—**Currently, clean energy sources, such as solar and wind power, are more and more used in Wireless Mesh Networks (WMNs). Such power sources, however, are intermittent and require these networks to save energy. Duty cycling is a common approach employed by WMNs to save energy by cyclically turning on and off the wireless radios. When the radios are turned off, the node's routing table eventually expires and, when the radios turn back on, it is necessary to wait for routes to be discovered before sending data. In order to eliminate this need, this work proposes a mechanism to ensure the persistence of the routing tables in wireless mesh networks. PORT (Persistence of Routing Tables) keeps track of routing entries while nodes are in the energy saving mode and thus allows nodes to exchange packets as soon as the radio turns on. Experiments show that PORT increases the route availability and consequently it increases up to 100% the network throughput.**

I. INTRODUCTION

Green Computing has become a very important area to the academic community due to worries about global warming and sustainability. In this context, the energy efficiency of communication networks is a challenge. In 2008, the energy consumed by data centers, computers, and network equipments represented 3% of the energy consumed in the world. In 2020, it is expected that the energy consumed by these equipments achieves 10% of the whole energy consumed in the world [1]. Two facts explain this growth in the energy consumption: the increase of both data transmission rates and the increase capacity of computing devices, mainly in terms of processing power.

The energy efficiency of wireless networks is also challenging. Nodes are usually powered by batteries because they are mobile or because the network operates in hostile environments where it is hard to adopt conventional energy sources or even to replace batteries. Batteries are usually expensive, heavy, and potentially toxic components. Thus, the energy consumption must be reduced in order to increase the network lifetime and to avoid toxic waste.

Research projects, such as ReMoTe [2], [3], [4] and SolarMesh [5], have developed wireless mesh networks to provide Internet access in which network nodes are powered by solar energy. Although the environmental impact is reduced, problems related to reliability, performance, and availability rise due to the intermittency of the energy source adopted. For example, the solar energy is not effective on cloudy days and at night. Experiments performed by the ReMoTe Project team show that several nodes stay off for up to 40% of the observation time particularly during winter months. Thus, the energy must be saved to maintain nodes in operation during these adverse conditions.

Wireless nodes spend more energy to transmit and receive packets than to process them. Thus, radio devices are the main energy consumers of a node. To prove that, we have performed some preliminary experiments with Linksys WRT54G routers. Tests reveal that the radio consumes approximately 40% of the router energy. An efficient method to save energy is the use of duty cycling on the radios.

The IEEE 802.11 standard [6] defines a power saving mechanism(PSM) in which the network nodes turn off their radios periodically during small intervals. However, this technique is not suitable for wireless networks that are multihop in nature, such as mesh networks, because it significantly increases the packet delivery time [7]. Zheng *et al.* [8] define a method to save energy in which the nodes have a schedule that determines when the radios must be on or off. Thus, nodes switch between the active mode, with the radio on, and the energy saving mode, with the radio off.

The aim of this paper is to evaluate proactive routing protocols, such as OLSR [9] and DSDV [10], in wireless mesh networks that employs duty cycling mechanisms to save energy. The main challenge faced by the proactive protocols in this scenario is to maintain the persistence of routing tables after energy saving modes. With proactive protocols, routing tables are updated based on control messages exchanged periodically among nodes. If a node does not receive control messages of a specific node during a given interval, the route to this node expires and it is deleted from the table. When the radios are turned off, these control messages are not transmitted and routes are eventually deleted from the routing tables. On the other hand, if nodes stay in the energy saving mode for a period longer than the expiration time of routes, these routes are deleted from its table. We have conducted some practical experiments to illustrate this problem. We consider an experimental mesh network with 13

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nodes where the maximum number of hops is 7. Network nodes synchronously turn off its radios for 5 minutes. By using this interval, all the routes are deleted from routing tables. When nodes turn radios on, nodes on network edge need 16 s to exchange the first packet successfully.

To avoid this problem, this paper proposes the mechanism referred to as PORT (Persistence of Routing Tables). Basically, our mechanism keeps track of routing table entries while nodes are in the energy saving mode. When an energy save period starts, PORT verifies the expiration time of each routing entry and after that timers configured to do not count the time while the radio of wireless nodes are turned off. In such way, when the radio turns on, nodes have its routing table untouched, i.e., the same table observed at the beginning of the energy saving mode. Thus, PORT allows nodes to exchange packets as soon as the active mode begins.

In order to evaluate PORT, we have performed simulation in different scenarios by varying the number of hops, the duty cycling intervals, and the mobility pattern. For the analyzed scenarios, PORT increases up to 100% the network throughput and decreases the delivery time experienced by the first packet sent just after the radio turns on.

The rest of this paper is organized as follows. In Section II, the main techniques related to duty cycling in wireless mesh networks are presented. In Section III, the PORT mechanism is introduced. In Section IV, simulation scenarios are described. In Section V, simulation results are discussed. Finally, in Section VI, conclusions are presented.

II. RELATED WORK

Several studies are focused on reducing energy consumption of wireless networks. In particular, recent studies argue in favor of duty cycling mechanisms [6], [8], [11].

One of them is introduced by the IEEE 802.11 standard and it is called Power Save Mechanism (PSM) [6]. This mechanism works in the link layer and allows wireless nodes to get in the energy saving mode when they have no packets to transmit. In this mode, PSM defines that radios must be turned off. The way PSM works depends on the wireless network operation mode. In the infrastructured mode, wireless nodes are connected through an access point. In this case, the access point maintains a list of all nodes connect to it. Thus, the access point knows if a given node is in the active or in the energy saving mode. The access point has also a buffer that stores packets that are waiting for transmission, i.e., packets whose destination is a node in the energy saving mode. After one beacon interval, all nodes must turn on its radios, leaving the energy saving mode. At this time, the access point announces the nodes that must be active to receive packets and thus packets that are in the buffer are sent to its destination nodes. On the other hand, there is no access point in the ad hoc mode and thus beacons are sent in regular intervals. Each beacon interval is followed by a time window called Ad Hoc Traffic Indication Message (ATIM) and a data transmission phase. The ATIM window is a period of time where all nodes must be active. During this period, ATIM messages are exchanged and nodes can announce that have packets to transmit, specifying the destination nodes. At the end of the ATIM window, nodes that do not need to send or receive packets enter in the energy saving mode. Then, packets are exchanged during the data transmission phase.

The energy saving mechanism proposed by the IEEE 802.11 standard is designed to single hop networks. Thus, the mechanism is not efficient in wireless mesh networks with multiple hops. Therefore, the use of this mechanism in multihop networks results in higher packet delivery time delay [7], [12].

Zheng *et al.* use the block design concept to define the duty cycling schedules of nodes [8]. These schedules are defined and followed by all nodes of a given network. Even if nodes are not synchronized, two nodes will be active at the same time for a period of time in every cycle of the schedule. Christmann *et al.* propose a mechanism based in the MACZ link layer protocol [11]. This protocol has a different CSMA/CA scheme and uses a network synchronization method in which the network is synchronized by timestamps. These timestamps are recorded in regular intervals. The interval among timestamps is divided in subintervals where nodes are active or inactive.

Several duty cycling mechanisms suffer with the routing table expiration problem when nodes turn off its radios to save energy. This problem occurs because the inactivity time is longer than the route expiration time or because the link layer does not take into account that nodes can be in the energy saving mode. This paper does not aim at introducing a new duty cycling mechanism. Our goal is to propose a mechanism to keep track of the routing tables when a proactive routing protocol is used with a duty cycling mechanism simultaneously.

III. THE PORT MECHANISM

This paper proposes PORT, a mechanism designed to solve the problem of the expiration of entries in the routing tables of wireless mesh nodes, when these node are duty cycling their radio interface. The majority of wireless mesh networks (production and experimental) use proactive routing protocols [13], [14], [15]. Among them, OLSR is one of the most used and will be the object of study of this paper. The two main control messages used by OLSR are the HELLO and the TC (*Topology Control*) messages. The HELLO messages are sent periodically to every one-hop neighbor. The nodes use these messages to detect and monitor the communication state between neighbors. The TC messages flood the network with topology information. The information is collected from received control messages and is used to build the routing tables. Each control message has a validity time and its data is forgotten by the routing protocol when the validity time expires. The routing protocol stores the routing information and the validity time together. This way, the protocol knows when the information expires.

The routing protocol also has two classes of timers that go off periodically: control timers and dispatch timers. A control timer is associated with information collected from a control message and it goes off when the validity time expires. In such way, when a control timer goes off, the topology information is updated and the routing tables are recalculated without the expired information. The control messages are sent when a specific type of timer goes off. This type of timer defines the interval among the dispatch of control messages. Each type of control message has its dispatch timer and each type of control message can be sent at different intervals.

The use of proactive routing protocols in wireless mesh networks with duty cycling is challenging because of the difficulty to keep the routing tables during the duty cycling alternations. In the case of OLSR, the routing tables are updated using the information collected from control messages. When the node radio is turned off, this node stops sending the control messages. As a consequence, the route to this node may be removed by the other nodes. Conversely, when the radio is off for long, the node stops receiving control messages from the other nodes and, eventually, all routes will be removed from its routing table.

The PORT mechanism solves the problem of route loss by avoiding the expiration of the timers and persisting the routes when the nodes are in the energy saving mode.

IV. SIMULATIONS

We have conducted experimental tests to illustrate the problem of route losses after changing radio modes. We consider an operational wireless mesh network with 13 nodes and a mesh topology with paths up to 7 hops. This network is operating at the Computer Institute of the Universidade Federal Fluminense and is configured and maintained by the MidiaCom Laboratory team. Figure 1 shows the topology of the experimental network. All nodes have its clocks synchronized through NTP [16] and are configured to simultaneously turn off its radios by 5 minutes. This time is long enough for every route to be removed from the routing tables. After this time, radios are turned on and edge nodes immediately try to send packets. Edge nodes experience an average time of 16 s to exchange packets successfully.

We evaluate PORT by simulations using NS-2 [17]. We consider three different configuration sets. In Set I, we consider a wireless mesh network with the same topology of the operational network, illustrated by Figure 1, installed in the Computing Institute at Universidade Federal Fluminense. Our goal is to observe the behavior of our mechanism in a real network. Each simulation run has 2000 s. Simulations are divided in two subgroups. In the first subgroup, radios are turned on and off synchronously in intervals of 2, 3, 5, 10, 25, 50 and 100 s. In such way, the mechanism performance can be evaluated for different intervals. These intervals are used because they are shorter, similar and longer than the expiration timer of routing entries. Values of timers are received by control messages and when these timers expire some routes can be lost.

In the second subgroup of simulations, radios are turned off in a desynchronized fashion. The goal of these experiments is to evaluate the impact of the desynchronization in the mechanism performance. Simulations are made with a desynchronization level of 1%, 5% and 10% of the duty cycling interval. In this subgroup, all the simulations have the duty cycling interval of 25 s.

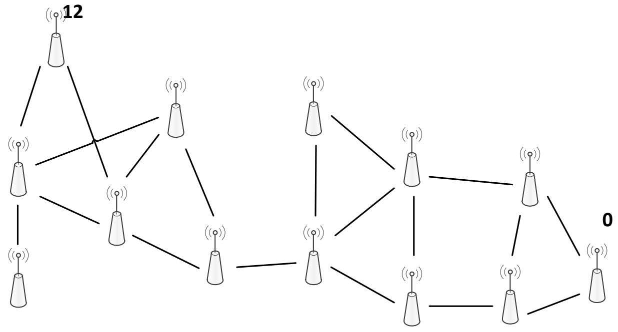


Fig. 1. Set I topology - Operational WMN at Fluminense Federal University.

In Set II, a scenario with 5 mobile nodes is considered. Mobile nodes follow a movement trace called ZebraNet [18]. This trace was collected from a real-world experiment with zebras in a natural reserve in Kenya and the nodes have a herd behavior. A tool provided by [18] is used to create the NS-2 formatted trace of the nodes. The area of the experiment is 1000 m long and 1000 m wide. The PORT performance is evaluated by varying the speed of the nodes and the duty cycling intervals. Besides the normal speed, tests with doubled and half speeds are done. The duty cycling interval is 40 s. The simulations last 2000s with normal speed, 1000 s with double speed and 4000 s with half speed. Using the normal speed, the mechanism is evaluated with the duty cycling interval equals to 20, 40 and 80 s. In this scenario, if nodes are 100 m away, the packets are delivered successfully 50% of the times and if nodes are 300 m away, packets are delivered successfully 0.9% of the times.

In Set III, a different kind of mobility scenario is tested. The nodes in these scenarios use the configuration presented in the VanLAN [19]. These scenarios have 11 base stations spread across five office buildings on the Microsoft campus in Redmond and 2 moving vans that operate around the campus during the day. Performance is evaluated varying the speed of the nodes. While the speed changes, the duty cycling interval is 40 s. The simulations last 20500s with normal speed, 10250 s with double speed and 41000 s with half speed. In this scenario, if nodes are 100 m away, the packets are delivered successfully 50% of times and if nodes are 300 m away, the packets are delivered successfully 0.02% of times.

The NS-2 was configured to use the propagation model Shadowing, which has two parts: path loss model and shadowing model. With these parts, this propagation model predicts the received power accounting for fading effects. The maximum transfer rate at link layer is 1 Mb/s. Each scenario was simulated five times with different seeds. The results are presented with error bars for a confidence interval of 90%.

Fig. 2. Set III topology - Base stations spread across buildings on a Microsoft campus.

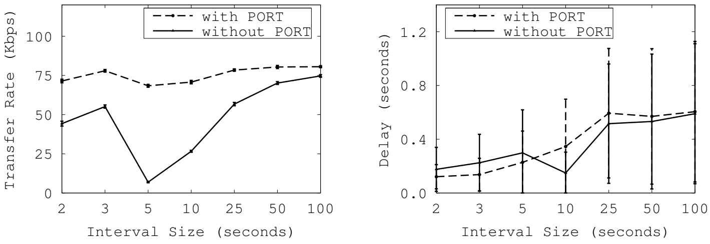
The routing protocol OLSR is used with the link quality metric Expected Transmission Count (ETX). The HELLO messages are set to be dispatched in intervals of 2 s with validity time equals to 6 s. The TC messages are set to be dispatched in intervals of 5 s with validity time equals to 15 s. These values are suggested by RFC 3626, which is a standard proposal of the OLSR protocol[9]. The standard also suggests the dispatch of control messages in a way that the nodes do not send control messages at the same time. To avoid the collision of control messages and then the loss of these messages, the synchronization is prevented with the insertion of a jitter in the dispatch timers. According to the standard, the jitter must fluctuate between 0 and a quarter of the dispatch interval of HELLO messages. Therefore, in the simulations this value is between 0 and 0.5 s.

Every scenario is simulated with and without the PORT mechanism. The intervals with radio on and off have the same duration but the mechanism allows the use of different intervals. The simulations of Set I are done with a data flow among the nodes in the edge of the network. As observed the Figure 1, the source is the node **0** and the destination is the node **12**. In Set II, each node has a data flow to every other node in the network. In Set III, there is a data flow between one base station (source) and the van(destination). The data traffic is simulated using constant bit rate (CBR) with the UDP protocol. In Sets I and III, the data flow has the transfer rate equals to the Link Layer rate and the packets have the size of 1000 bytes. In Set II, each data flow has the transfer rate of 100 Kb/s and the same packet size.

V. RESULTS

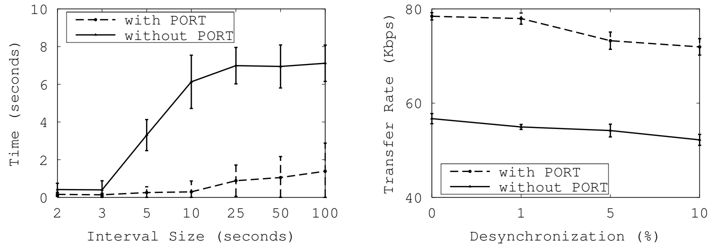
The evaluation is done with three metrics: transfer rate, delay and delivery time of the first packet after the radio restart. The transfer rate is calculated only when the network is not in the energy saving mode. The delivery time of the first packet includes the route discovery time and the delay.

A. Set I - Real World Scenario Simulations



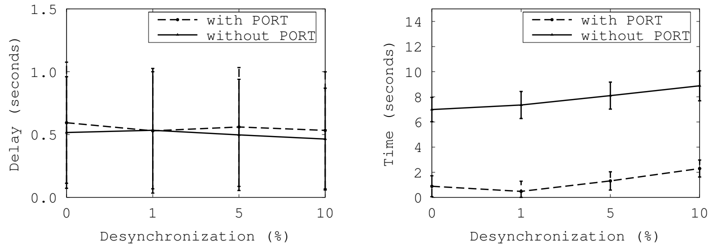
(a) Transfer Rate

(b) Delay



(c) First Packet

(d) Transfer Rate - no sync



(e) Delay - no sync

(f) First Packet - no sync

Fig. 3. Set I Results

The Figure 3 presents six results for the Set I scenarios. The first three figures are graphs of the first subgroup with different intervals. The results are presented to each interval configuration. The last three figures are graphs of the second subgroup with time desynchronization and the results are presented to every tested desynchronization. Graphs with the transfer rate, delay and delivery time of the first packet with and without the PORT mechanism are presented.

In the Figures 3a and 3d the transfer rate is bigger when the PORT mechanism is used. When the PORT mechanism is used, the routes are saved and are available as soon as the radio restarts. As a result, the nodes are available for a longer period of time and are able to send more packets.

As demonstrated in Figures 3c and 3f the delivery time of the first packets after the radios restart is shorter when the PORT mechanism is used. This explains the bigger transfer rate when the PORT is used because the nodes start to send packets quicker in these conditions. In Figures 3b and 3e the delay has statistically equivalent values with and without PORT. So, the mechanism PORT does not alter the network delay.

The results of the first subgroup show that some stations do not have route to the destination when the radio restarts. The control messages must traverse on the network to create the routes. The delivery time of the first packet is the delay time plus the time to create the route to the destination. When the PORT mechanism is not used, the curve is similar to the curve of the time to create the route to the destination. In this situation, the routes are not persisted and when the radio restarts, the nodes need to create the route to the destination before sending data packets. When the PORT mechanism is used, the routes are persisted and the delivery time of the first packet curve is similar to the delay graphic curve.

The routing protocol is set to send the HELLO control packets at 2 s intervals with validity time equals to 6 s. The TC control packets are set to be dispatched in 5 s intervals with validity time equals to 15 s. In this scenario, it is expected that the PORT does not work very well, since the interval is less than 6 s, and this time is not enough to cause the loosing of the routes. The results show that this hypothesis is not true. The control packets are dispatched in a broadcast way and do not have any failure control in the routing protocol or in the link layer. The time to send these control packets is the configured dispatch interval plus the jitter. In this way, too many packets are lost because they are dispatched in the radio off intervals. The loss of these packets reduces the route availability, what makes the PORT mechanism efficient in this situation.

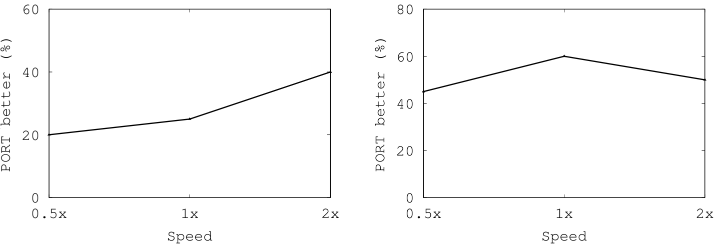
TABLE I
SET I - TC RECEIVED IN THE DATA SOURCE STATION.

Interval Size (seconds)	TC with PORT (packets)	TC without PORT (packets)
2	7384 ±24	3972 ±118
3	4638 ±60	4078 ±56
5	4651 ±45	2588 ±56
10	4164 ±40	3087 ±25
25	3674 ±44	3944 ±69
50	3651 ±39	4194 ±44
100	3805 ±43	4374 ±54

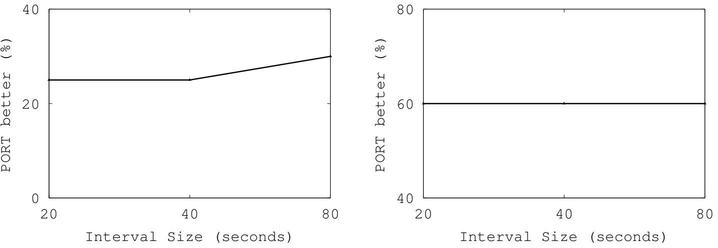
In the Figures 3a and 3d the value of the transfer rate metric is not good when the PORT mechanism is not used and the interval size is 5 s. In this situation, too many TC control packets are lost. The Table I shows the loss of TC control packets. The TC control packets are dispatched in 5 s intervals plus jitter. When the size of the interval is 5 s, too many TC packets can be dispatched in the radio off interval. The destination is more than one hop away from the source and the source needs to receive TC control messages to create the route to the destination. However, these messages are lost, reducing the transfer rate metric.

In the second subgroup, the end of the intervals are desynchronized, but the metrics are calculated as if the intervals are synchronized. With the desynchronization, the 25 s duty cycling interval can be longer or shorter, but the metrics are calculated as if the duty cycling interval is always 25 s. The authors of this paper do not expect a desynchronization longer than 2.5 s with a well configured NTP implementation. So, the simulations are done with the maximum desynchronization of 10% of the duty cycling interval, that is 2.5 s. The desynchronization do not disturb the operation of the mechanism and the mechanism continues to persist the routes. In the Figures 3d and 3f the transfer rate decreases as the desynchronization increases. This happens because the *first packet delivery time* increases with the increase in desynchronization.

B. Set II - ZebraNet scenarios



(a) Speed - Transfer Rate (b) Speed - First Packet



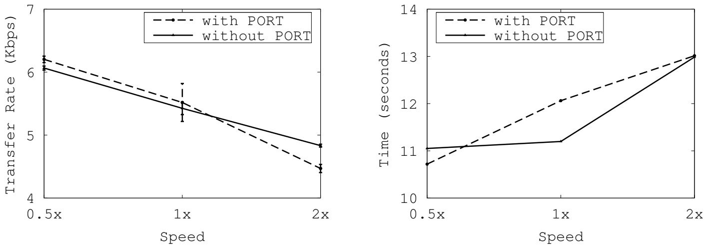
(c) Intervals - Transfer Rate (d) Intervals - First Packet

Fig. 4. Set II Results

The graphics of delay are not presented in the Set II and III results, since the results of delay is always the same with or without the use of the mechanism. In Set II, each scenario has 20 data flows because each node has a data flow with every other nodes. So, in Set II, the results are presented as the percentage of times the metrics transfer rate and *first packet delivery* is better with the use of the mechanism.

The mechanism performance is random in these scenarios. The results of *first packet delivery* in the Figures 4b and 4d show improvements between 40% and 60% of times. The transfer rate in Figures 4a and 4c should have the same percentage of improvements, but this is not observed. This happens because PORT persists a route that is no longer efficient when the node restarts.

In the scenarios of the Set II, the change of the duty cycling intervals does not change the performance of the mechanism. In the scenarios with speed change, the performance of the *first packet delivery time* appears to be random but the transfer rate appears to increase the performance with PORT while the speed increases too.



(a) Transfer Rate

(b) First Packet

Fig. 5. Set III Results

C. Set III - VanLan scenarios

In these scenarios the performance of PORT also varies significantly. In the scenario of original speed, the *first packet metric* takes longer to get to the destination, when PORT is used. It is presented in Figure 5b and happens because the persisted route is not valid when the radio restarts and the time to fix the route is longer than the time to create a new route. Even with bigger *first packet delivery time*, the original speed scenario presents bigger transfer rate with PORT, which is not deterministic. In the half and double speed scenarios, the transfer rate metric does not present the same gain of performance observed with the *first packet delivery metric*.

In the scenarios of the Set III, while the speed increases, the transfer rate tends to decrease and the first packet metric tends to increase. The first packet metric increases because the time to get the routes increases. Differently from the previous set of scenarios from ZebraNet, when nodes were put to move in the patterns described by animal herds, in the other scenarios where mobile nodes move among base stations, the metrics tends to have these behaviors.

VI. CONCLUSION

In this paper, the problems caused by the expiration of routes during the duty cycling of the radios are analyzed. The PORT mechanism was proposed to allow the persistence of routing tables in these conditions. To ensure the persistence of the routing tables, PORT controls the timers that manage route expiration.

The mechanism effectiveness is demonstrated with simulations of different scenarios, different topologies and different duty cycles. The metrics data transfer rate, delay and time of *first packet delivery* after the radio restart are analyzed. PORT increases route availability and data transfer rate while the network delay was not significantly increased by the mechanism. In most scenarios, the use of PORT increases the transfer rate.

Port naturally presents good performance in static wireless mesh networks. In mobile wireless mesh networks the performance improvement is uncertain. The next research step is testing the mechanism in a real experimental wireless network in order to further evaluate its performance.

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