ABI: A Mechanism for Increasing QoS in Multi-Radio Wireless Mesh Networks with Energy Saving

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***Abstract*—Wireless Mesh Networks (WMNs) are becoming increasingly popular mostly due to their ease of deployment. One of the main drawbacks of these networks is that they suffer with respect to Quality of Service (QoS) provisioning to its clients. Equipping wireless mesh nodes with multiple radios for increasing the available bandwidth has become a common practice nowadays due to the low cost of the wireless chipsets. Even though the available bandwidth increases with each radio deployed on the mesh node, the energy consumed for transmission increases accordingly. Thus, efficient usage of the radio interfaces is a key aspect for keeping the energy consumption at low levels while keeping a high QoS level for the mesh network's clients.**

In the light of the above presented aspects concerning WMNs, the contribution of this paper is two-fold: (i) ABI, a mechanism for efficient usage of the available bandwidth for the mesh nodes, and (ii) decreasing the energy consumption by activating the radios only when needed. The solution proposed is throughly evaluated and shows that the two contributions can provide good QoS and decrease the overall energy consumption.

Keywords*—*Networking and QoS, Congestion control

I. INTRODUCTION

In the last years, WMNs have evolved as a cost-efficient solution for providing network connectivity to users and maybe high-quality services. WMNs are characterised by self-configuration and self-organisation, which makes them easy to deploy and maintain by their operators. Nowadays, due to the low-cost of wireless network interface cards, the mesh nodes can be equipped with multiple radios, which can operate on orthogonal channels, thus without interfering with each other. This technique enables the mesh network to achieve a higher throughput and to provide its clients better quality of service, as compared to the single-radio mesh networks.

In this way, one of the main concerns for the WMN's operators to provide their clients with high QoS can be overcome. This, unfortunately, brings another concern to the operators: the energy consumption. GreenTouch [1], a leading communication technology research consortium, aims to increase the network energy efficiency by a factor of 1000 by 2015. Nowadays, when the interest for energy consumption gains more and more attention, it is important to propose methods to create efficient WMNs.

Considering the above two main concerns for WMNs, this paper proposes ABI, **A**vailable **B**andwidth **I**ncrease mechanism for 802.11 based-WMNs, which provides good QoS levels to the mesh network's clients while keeping the energy consumption at low levels. In particular, we focus on the capability of the radios, installed on the wireless mesh nodes, to be turned off or on. Each radio when is not transmitting or receiving data finds itself in the IDLE state. In this state, a wireless radio is overhearing all the traffic and verifies whether there are packets destined to it. This process of overhearing consumes almost as much energy as when actually receiving the packets. Thus, idle radios on mesh nodes, even though useful for increasing the available bandwidth, consume a lot of energy if they are not used efficiently.

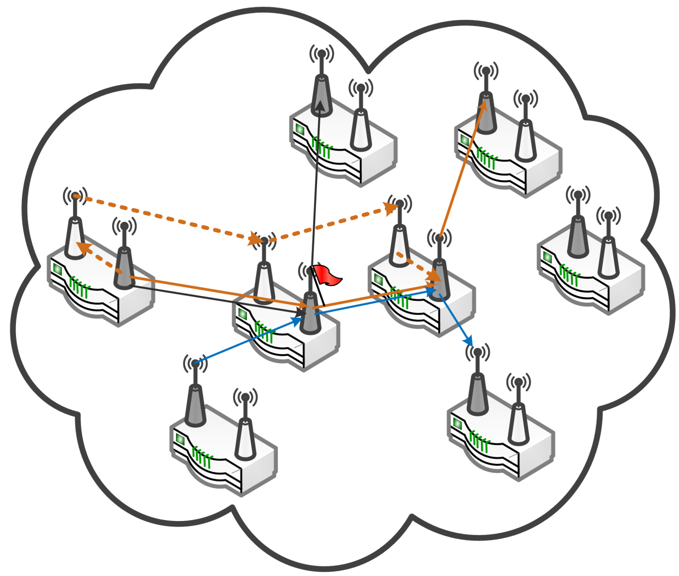

Fig. 1. Multi-Radio Wireless Mesh Network

In this work we assume the mesh network is at its lowest energy consumption level by using only one interface on each mesh node, while the other interfaces are turned off, thus consuming no energy. In this way, all the mesh nodes are always connected, using the first radio and are ready to deliver traffic as it enters the network. ABI runs on each mesh node belonging to the network and constantly monitors the node's load. When a node becomes congested, it activates a second interface and selects a flow, which is then shifted to the second interface. The mechanism, thus uses the available bandwidth only when needed and saves energy. The solution proposed is illustrated in Figure 1, where each mesh node is equipped with two radios. The active radios are represented with darker colour, while the inactive radio with a lighter colour. The congested node (depicted with a flag) triggers the enabling and usage of the second radio interface, hence a flow (e.g. the orange flow) is selected and shifted to the second interface (e.g. the dotted orange line).

This paper focuses on video delivery, which is a sensitive application to sudden changes in the wireless mesh networks. Video streaming is very sensitive to delay variations. Another important factor which affects video delivery to end-users is packet loss which must be kept at low levels. Any delay variation or loss rate over a specific threshold decreases the QoS level and consequently the service quality, as experienced by the users. Thus, providing good video QoS levels in a WMN while lowering the energy consumption is a challenging task.

The rest of the paper is structured as follows: Section II reviews related works in the area, Section III introduces the proposed mechanism and describes it in detail, while Section IV analyses the performance of the mechanism in terms of quality of service and energy consumption. Section V concludes the paper with some final remarks.

II. Related Word

Energy efficiency in WMNs has gain attention in last years due to the increased interest in reducing the communication energy consumption. Many solutions to minimise the energy consumption have been proposed in the past and studies, such as [2], have classified the existing approaches dedicated to energy saving in WMNs at different layers: network layer (performing energy-efficient routing [3]), data-link layer (through power-efficient MAC protocols [4]) and physical layer (controlling the transmission power of a node [5]). However, none of the above mentioned works consider the possibility of switching on and off the radios of a multi-radio node belonging to a wireless network for saving energy and increasing the QoS for the end-users in the same time.

An energy-aware routing protocol extension is proposed in [6]. The authors propose to switch off as many routers as possible in the mesh network and thus save energy, while satisfying the throughput demands. However, this method reduces the coverage area of the mesh network and does not consider the case of switching the nodes back on.

The authors in [7] have shown through measurements that the energy consumed by wireless nodes while being idle is significant and it should be considered when designing energy-efficient solutions. Hence, our work focuses on switching on and use additional radios on a mesh node only when a node becomes congested and needs the extra available bandwidth for keeping the QoS at high levels for its clients.

III. ABI Mechanism

A. Overview

In a wireless mesh network, the mesh nodes can be equipped with multiple antennas, due to the low cost of the wireless cards, in order to increase the available bandwidth and, thus, provide higher QoS for its users. Unfortunately, this usually comes at a cost which is reflected in the increase of energy consumption. Thus, the operators have to balance the users' demand for high QoS with the increase of energy consumption.

ABI, the mechanism proposed in the work, aims at improving the QoS for the end-users while keeping the energy consumption at low levels. This is done by using only one wireless interface active at all times on each mesh node, and the other available interfaces disabled. Keeping one wireless interface active on all mesh nodes ensures that the connections between all nodes are established, active and ready to be used for new flows. When a node becomes congested, it enables an extra interface and shifts on it some traffic flows temporarily.

B. ABI Mechanism Description

In the considered wireless mesh network, each mesh node is equipped with multiple wireless radio cards. An example of a mesh node representation is depicted in Figure 2. A plane represents the channel on which each wireless interface card operates on. The dark coloured plane represents the first wireless network interface card (i.e. WNIC 1), which is always active, on each mesh node, and it operates in this example on channel 1. The lighter coloured planes represent the other wireless interface cards (i.e. WNIC 2 and WNIC 3) operating on orthogonal channels (i.e. channel 6 and channel 11).

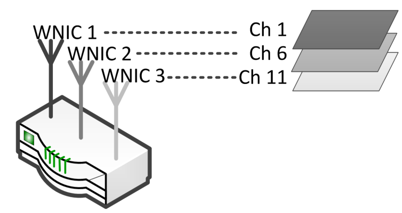

Fig. 2. Multi-Radio Wireless Mesh Node

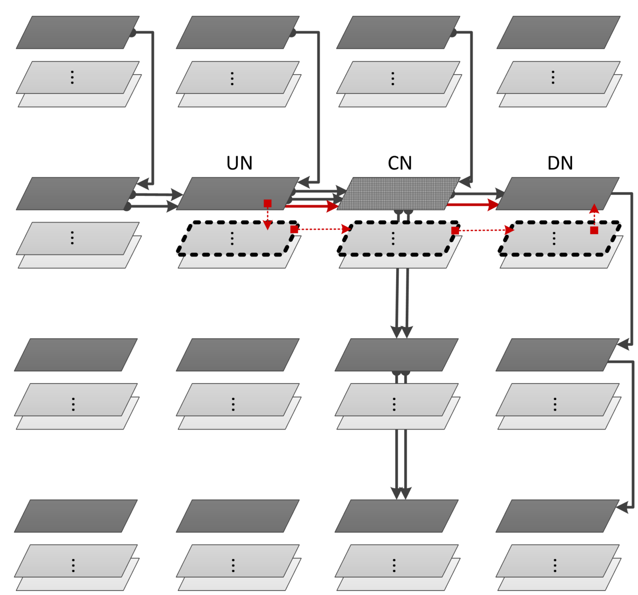

Fig. 3. ABI Mechanism

Initially, only the first interface is active on each mesh node for relaying the traffic. Each mesh node monitors the video traffic load by looking at the IEEE 802.11e video queue occupancy. Once a node signals that its video queue occupancy has reached a certain threshold, the mesh node enables the second interface and selects a flow passing through it to shift it to the second interface. For the selected flow the downstream node (DN) and the upstream node (UN) is identified and a message is sent to them to enable the second interface and to use it for shifting the selected flow on to it.

An example of how the ABI mechanism performs is presented in Figure 3. The video traffic flows running inside the mesh network are represented through lines connecting the nodes the flow passes through. The congested node is represented with a grid texture. A traffic flow (i.e. the red flow) is selected by the congested node to be moved on the second interface. In this case, the flow which occupies the largest share of the video queue in the loaded node is selected to be shifted as it will decongest quicker the interface. The congested node sends a message to the downstream mesh node and the upstream mesh node of the selected flow to send the next packets on the second interface, represented with a dotted border. From the whole flow only a section, corresponding to the congested node, is shifted to the second interface. The proposed mechanism is shown in Algorithm 1 as a pseudocode.

Algorithm 1: ABI Algorithm

Data:
$QO - QueueOccupancy$
$MNi - Mesh\ Node\ i$
$CN - Congested\ Node$
$UN - Upstream\ Node$
$DN - Downstream\ Node$
$NN - Neighbour\ Node$
Result: Flow $\mathcal{F}$ shifted to second interface

while *(1)* **do**
  Monitor QO_{MNi}
if *(($QO_{MNi} \geq \tau$) and ($\mathcal{T}$ elapsed))* **then**
  $CN \leftarrow MNi$;
  $\mathcal{F} \leftarrow$ (Select flow $\in CN$);
  Enable second WNIC on CN;
  Enable second WNIC on DN;
  Enable second WNIC on UN;
  UN : Shift $\mathcal{F}$ on second interface;
  CN : Shift $\mathcal{F}$ on second interface;
  DN : Shift $\mathcal{F}$ on second interface;

This algorithm is executed on the congested node. A $\mathcal{T}$ back-off period of time is considered after the algorithm is applied again on the same congested mesh node in order to avoid the shifting of flows to quickly to the other available interfaces.

IV. Analysis of Results

This section assesses the performance of the ABI mechanism.

A. Simulation Settings

ABI has been developed and assessed using the NS-3 network simulator [8]. The simulation setup considers two mesh topologies: a sixteen-node grid topology and a twenty-five-node grid topology. Our decision for choosing grid topologies is justified by a study [9] which shows the benefit of grid topologies in terms of coverage, connectivity and network throughput, over random topologies. However, this does not affect the benefit of ABI for other topologies.

The inter-node distance is set at 125 meters and, thus, the maximum data rate transmission of a link is set to 6Mbps. Two maximum video queue sizes are considered: 50 and 100 packets. This option is based on the legacy open source MadWifi drivers for Atheros chipsets (present on some wireless network interface cards) which use a driver ring buffer of 200 packets. The ath5k drivers for the same chipset divide these 200 packets equally among the four queues (VI, VO, BE and BK queues) [10]. Thus, we can assume the video queue can store 50 packets if the 200 packets are equally distributed. As well, this distribution can be uneven, by defining a larger video queue, e.g. 100 packets, and smaller queue sizes for the other queues. However, setting a video queue bigger than 100 packets leads to unusually large packet delays, so we decide to avoid such settings. Similarly, a video queue smaller than 50 packets seems to us unrealistic as it may lead to important packet loss rates.

Five video flows, each with a mean bit rate of 160 kbps, are randomly distributed between mesh nodes. The number of video flows is selected such as to keep the overall packet loss around 2%, which is an acceptable loss for video deliveries. The $\mathcal{T}$ back-off period for the ABI mechanism is set to 0.5 seconds. Simulations prove that larger back-off values are not suitable as it leads to high packet losses in the network. Lower back-off values do not allow sufficient time for the node to recover after a congestion and thus all the flows running through the node are shifted to the second interface too quickly.

To ensure the accuracy of the results obtained, five distinct simulation runs are performed for each considered case using different seeds. A summarisation of the network parameters used in our simulations are presented in Table I.

TABLE I. SIMULATION SETUP

Parameter	Value
Simulator	NS-3.10 [8]
Topology	Grid 4x4 & Grid 5x5
Distance between nodes	125 m
Number of interfaces	2
WiFi Mesh Mode	802.11a
Wifi Client Mode	802.11g
WiFi Data Rate	6 Mbps
Network Access Method	CSMA-CA
Propagation Model	LogDistancePropagationLossModel
Error Rate Model	YansErrorRateModel
Remote Station Manager	ConstantRateWifiManager
Video Queue Size	50 / 100 packets
Traffic Type	MPEG4 Video Trace Files
Video Type	Medium Quality
Video Mean Bit Rate	160 kbps
Number of Video Flows	5
Queue Occupancy Threshold	60%
Routing Algorithm	OLSR
Number of simulation epochs	5

ABI's performance is compared against two other mechanisms, 1-WRI and 2-WRI as described below:

- **1-WRI** - a mesh network where the nodes are equipped with only one wireless radio interface card. All the radios are operating on the same channel and every communication link between nodes operates on that channel. A default routing protocol (i.e. OLSR) is establishing the routes for the flows.
- **2-WRI** - a mesh network where the nodes are equipped with two wireless radio interface cards. On every mesh node the channels chosen are orthogonal

(e.g. one radio operates on channel 1 and one radio operates on channel 6). ABI mechanism is not employed and the default routing protocol establishes the routes for the flows and interface selection.

- **ABI** - similar to 2-WRI, but initially only the first radio on each mesh node is active, while the second radio is inactive. The ABI mechanism is enabled on each node and activates only when needed, as presented in Section III. The default routing protocol is used only for the initial setup of routes between all mesh nodes.

B. Performance Metrics

For each simulation performed, five performance metrics are considered:

- **Delay [ms]** - The time needed for the packets to reach their destination;
- **Packet Loss [%]** - The ratio between the amount of packets not received at the destination nodes and the total number of packets sent;
- **Throughput [kbps]** - The average network throughput;
- **PSNR [dB]** - One of the most widespread metric for video quality. The PSNR value is calculated based on the loss and throughput rates using the equation in [11].
- **Energy Consumption [J]** - The amount of energy consumed by a radio is given by the product of the supply voltage and the current consumed consumed during the period of time the radio is in the corresponding state. The values used are selected according to the technical specification for the Atheros AR5416 chipset [12], which can be found in many wireless network cards, and are summarised in Table II.

TABLE II. ATHEROS AR5416 CHIPSET POWER CONSUMPTION

Parameter	Value
Supply Voltage	3.0 V
Tx Current	0.615A
Rx Current	0.433A
Idle Current	0.038A
Switching Current	0.038A

C. Results

This subsection presents the results obtained from the simulation studies conducted on different topologies, namely a 16-node grid topology (Figure 4) and a 25-node grid topology (Figure 5), and different queue sizes of 50 packets and 100 packets. In each of two figures, the top graphs present the results for a 50 packets queue, while the bottom graphs present the results for a 100 packets queue. Each sub-graph compares, for a specific performance metric, the three cases presented in subsection IV-A.

The first column of graphs from each figure shows the overall average delay, the second column of graphs shows the overall packet loss, the third column of graphs presents the overall average throughput of the mesh network and the forth column of graphs presents the overall average PSNR for all the flows running in the network. Peak Signal-to-Noise Ratio (PSNR) is one of the most widespread methods used to measure video quality. The PSNR value was calculated based on the loss and throughput rates using the equation presented in [11]. For each of these four performance metrics, a vertical line spans from the minimum obtained value to the maxim value, while a bar is centred at the average value (represented with a white dot) and its two extremities represent the standard deviation of the values. The right-hand side graphs from each figure depict the energy consumption of the whole mesh network. The lighter grey colour shows the overall energy consumption of the first interface and the darker grey colour shows the overall energy consumption of the second interface on all mesh nodes.

1) 16-node Grid Topology: Figure 4 depicts the results obtained for a 4x4 grid topology. It can be observed that ABI vastly outperforms the other two cases for all the performance metrics considered. In terms of packet loss, ABI achieves lower values than 1-WRI (74% lower) and 2-WRI (38% lower). Compared to 1-WRI the improvement is explained by the fact that ABI uses 2 interfaces, hence a larger bandwidth. Compared to 2-WRI the improvement is explained by the reaction time of ABI to a queue which is prone to overflow and drop packets. This improvement in packet loss is reflected in the higher throughput achieved by ABI. The performance of ABI is good compared to other cases also for nodes with 100 packets queue size. The only difference between the 50 packets queue size scenario and the 100 packets queue size scenario is visible at the overall delay. The overall delay increases slightly compared to the 50 packets queue size scenario, but still ABI gives a smaller delay compared to the other cases.

Regarding the PSNR metric, which estimates the video quality, ABI obtained the highest value, around 32 dB for both scenarios: 50 packets queue size and 100 packets queue size. This value is 56% higher than 1-WRI and 15% higher than 2-WRI.

The simulations conducted also measure the energy consumption caused by the wireless radio cards achieved in each case. For 1-WRI only the grey bar is visible because the nodes are equipped with only one radio card which is the sole energy consumer. 2-WRI case shows a higher energy consumption because each node is equipped with two radio cards, thus consuming more energy. For both scenarios, with 50 packets queue size and 100 packets queue size, ABI consumes nearly the same energy as 1-WRI, but is still almost 10% lower. Compared to 2-WRI, ABI saves almost 40% more energy in both scenarios.

2) 25-node Grid Topology: Figure 5 depicts the results obtained for a 5x5 grid topology. Even for a larger topologies, ABI performs better than the other two considered cases. For the first scenario (i.e. 50 packets queue size), ABI obtains 76% lower packet loss compared to 1-WRI and 75% lower compared to 2-WRI. Packet loss is strongly correlated with the network's average throughput, for which ABI obtains the highest values.

In terms of delay, for the 100 packets queue size scenario the delay is slightly higher than the 50 packets queue size scenario. This is because of the larger queue size which keeps the packets enqued for a longer period of time. However, for both scenarios, ABI obtains lower average delays compared to 1-WRI and 2-WRI. Due to the increased travel times of packets between two nodes, the delays are slightly higher than the values obtained for the 4x4 grid topology.

The PSNR values obtained by ABI are around 31 dB for the 50 packets queue size scenario and 28 dB for the 100

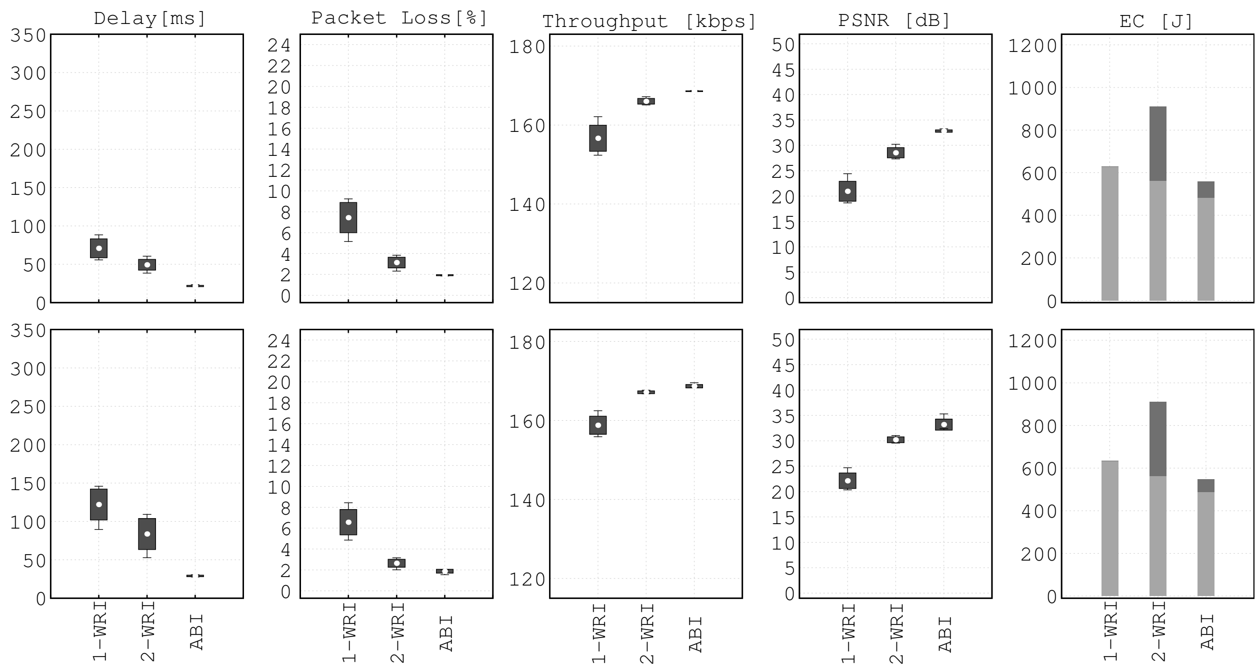

Fig. 4. 16-node grid topology with 50 packets queue (top row) and 100 packets queue (bottom row)

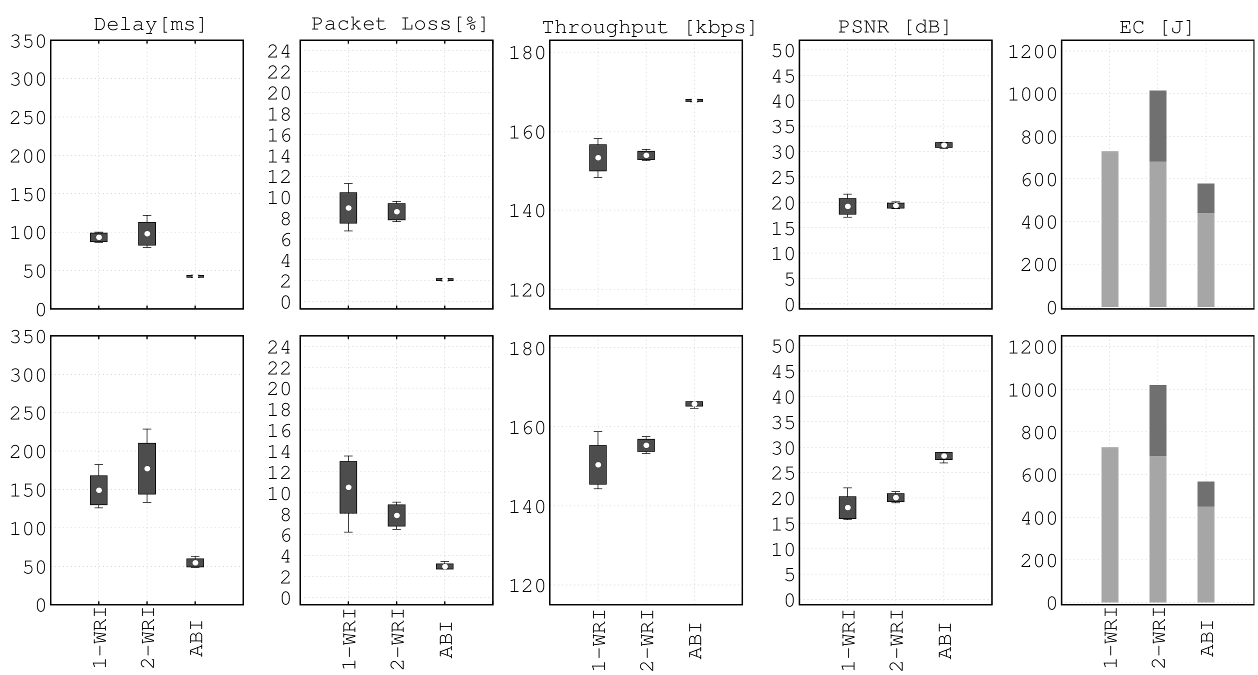

Fig. 5. 25-node grid topology with 50 packets queue (top row) and 100 packets queue (bottom row)

packets queue size. This value is 61% higher than 1-WRI and 2-WRI for the first scenario (i.e. 50 packets queue size) and 56% higher than 1-WRI and 40% higher than 2-WRI for the second scenario (i.e. 100 packets queue size).

For larger network topologies the energy consumption is higher, as compared to the 16-node topology. However, the energy consumption for the network, obtained by ABI is smaller compared to 1-WRI (29% lower) and 2-WRI (43% lower) for both 50 packets queue size scenario and 100 packets queue size scenario.

V. Conclusion

In this paper we addressed the problem of video QoS and energy consumption in wireless mesh networks. The goal of the paper is to increase the video QoS for the wireless mesh network's users and saving energy in the same time. This is achieved by enabling the wireless radios of a mesh node only when the node becomes congested. ABI, the mechanism proposed in this paper, considers wireless interface's queue occupancy of nodes for enabling the additional radios and thus, increasing the available bandwidth only when needed.

Through simulation studies we showed that ABI performs better than single-radio mesh nodes for almost the same energy consumption and better than the traditional two-radio mesh network with large energy savings. ABI saves on average 40% more energy than the two-radio mesh network, while increasing the video quality with 15%.

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