ABI: A Mechanism for Increasing Video Delivery Quality in Multi-Radio Wireless Mesh Networks

Adriana Hava*, Gabriel-Miro Muntean‡ and John Murphy*
*Performance Engineering Laboratory, University College Dublin, Dublin, Ireland
‡Performance Engineering Laboratory, School of Electronic Engineering, Dublin City University, Ireland
adriana.hava@ucdconnect.ie, gabriel.muntean@dcu.ie, j.murphy@ucd.ie

***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 their clients. Equipping wireless mesh nodes with multiple radios in order to increase the available network bandwidth has become a common practice nowadays due to the low cost of the wireless chipsets. As 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 offering high QoS level for video deliveries to the mesh network's clients.**

In WMN context, this paper proposes the Available Bandwidth Increase (ABI), a mesh node-based mechanism for efficient usage of the available bandwidth, which manages the wireless radio interfaces by activating them only when needed such as the energy consumption is maintained low. The proposed ABI is thoroughly evaluated and it is shown that it can provide video deliverie at good QoS level and at low energy consumption.

Keywords*—*Networking and QoS, Congestion control

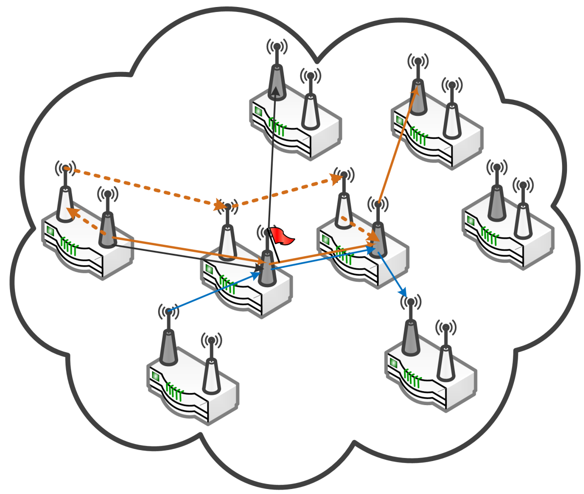

Fig. 1. Multi-Radio Wireless Mesh Network

I. Introduction

In the last years, WMNs have evolved as a cost-efficient solution for providing network connectivity to users and offer support for 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 the **A**vailable **B**andwidth **I**ncrease mechanism for 802.11 based-WMNs (ABI), which provides good QoS levels for video delivery 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 the potential of increasing the available bandwidth, consume a lot of energy if they are not used.

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, (and consume 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, extends the available bandwidth only when needed and saves energy otherwise. 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 an application affected by sudden changes in the wireless mesh networks. In particular, 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

Many research efforts were put into proposing solutions for balancing energy efficiency [2] [3] and quality of video deliveries [4] [5] over various wireless networks. Energy efficiency in WMNs has gained attention in last years due to the increased interest in reducing the communication energy consumption. A comprehensive recent survey [6] has classified the existing approaches dedicated to energy saving in WMNs according to the network layer they operate at: network layer (performing energy-efficient routing [7]), data-link layer (through power-efficient MAC protocols [8]) and physical layer (controlling the transmission power of a node [9]). 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 [10]. 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 [11] 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 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. Thus, the operators have to balance the users demand for high QoS with the energy efficiency.

ABI aims at improving the QoS for the end-users while keeping the energy consumption at low levels. This is done by employing a default policy of 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 the connectivity between all nodes is enabled, active and ready to be used for new flows. When a node becomes congested, ABI activates temporarily an extra interface and shifts on it some of the traffic flows.

ABI is designed to work in multi-radio WMNs, where each mesh node is equipped with multiple wireless network interface cards (WNICs). A representation of a multi-radio wireless mesh node is presented in Figure 2. The node is equipped with Wi-Fi radios working on orthogonal channels without interference. Each channel is represented through a plane. The dark coloured plane represents the first WNIC, which is always active, on each mesh node, and it operates in this figure 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).

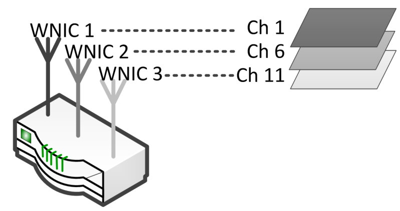

Fig. 2. Multi-Radio Wireless Mesh Node

An example of how ABI performs in a WMN environment is presented in Figure 1. The video traffic flows running inside the mesh network are represented through coloured lines connecting the nodes the flow passes through. Initially, only the first interface (coloured with dark grey) is active on each mesh node for relaying the traffic. Each mesh node monitors the video traffic load by monitoring the IEEE 802.11e video queue (AC_VI) occupancy. Once a node signals that its video queue occupancy has reached a certain threshold, the mesh node is considered congested and triggers the execution of ABI. The congested node is represented with a red flag. A traffic flow (i.e. the orange flow) is selected by the congested node to be moved on the next available interface. The process of flow shifting to another interface involves notifying the upstream and downstream nodes on the path of the flow to enable as well one of their additional interfaces, which matches the channel number of the interface activated by the congested node. Thus, the upstream node will send the following packets belonging to the selected flow through this interface and the downstream node will receive these packets through this interface. As result, the selected flow is shifted on a new channel, which is represented with a dotted orange line

B. ABI Architecture

Figure 3 illustrates the detailed block architecture of ABI based on the TCP/IP protocol stack model. ABI's components are represented in green coloured blocks and reside at the network, data-link and physical layer of every mesh node, respectively, providing a cross-layer framework for enhancing multimedia delivery QoS.

The components that make up the ABI mechanism are: ① **Node Early Congestion Detection** - This block resides at the data-link layer and is responsible for monitoring the occupancy levels of the video queues of every active wireless interface on the mesh node. The node is considered congested once the video queue occupancy level at any active interface reaches a certain threshold.

② **Flow Selector** - Once the queue occupancy threshold triggers ABI, the *Flow Selector* selects a video flow, to be

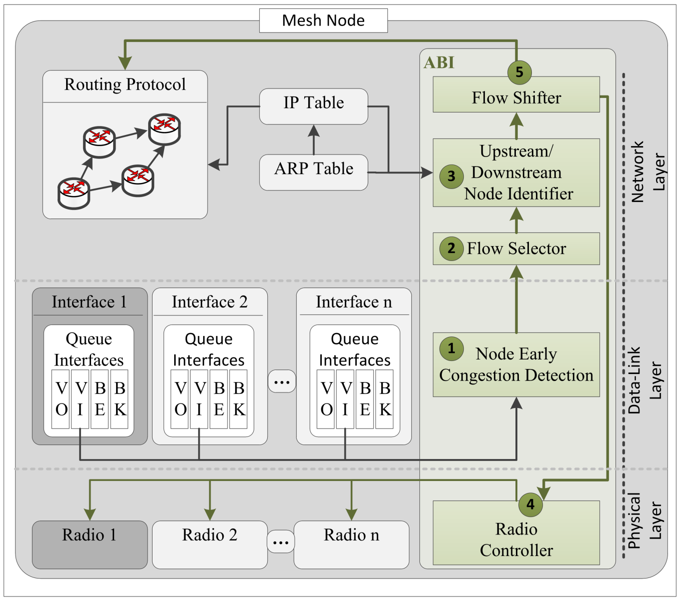

Fig. 3. ABI Node Architecture - Block Diagram

Algorithm 1: ABI Algorithm

Input:
$WI - Wireless\ Interface$
$QO - Queue\ Occupancy$
$MNi - Mesh\ Node\ i$
Output: Flow $\mathcal{F}_{sel}$ shifted to second interface
foreach *(active WI at MN)* **do**
    Compute QO_{AC_VI};
    if *(($QO_{AC\_VI} \geq \tau$) and ($\mathcal{T}$ elapsed))* **then**
        //MN's threshold has been exceeded;
        CN ← MN;
        if *($\Sigma(WI_{active}) < \Sigma(WI_{installed})$)* **then**
            $\mathcal{F}_{sel}$ = Flow_Selector();
            UN ← Upstream_Node_Identifier ($\mathcal{F}_{sel}$);
            DN ← Downstream_Node_Identifier ($\mathcal{F}_{sel}$);
            I ← Next_Available_Interface;
            Flow_Shifter(CN,I,$\mathcal{F}_{sel}$);
            Flow_Shifter(UN,I,$\mathcal{F}_{sel}$);
            Flow_Shifter(DN,I,$\mathcal{F}_{sel}$);
    else
        if *(($QO_{AC\_VI} == 0$) and ($\mathcal{L}_{\mathcal{F}}$==$\emptyset$))* **then**
            Disable corresponding WI on CN;
        else
            //MN is below threshold;

shifted to the next available interface. Each node keeps a list, $\mathcal{L}_F$, with the flows passing through each active interface. The flow which occupies the largest share of the wireless interface of the node, which triggered the execution of ABI, is selected to be shifted to another interface.

③ **Upstream/Downstream Node Identifier** - Once a flow has been selected to be shifted to another interface, the upstream node (UN) and downstream node (DN) on the path of the flow need to be identified. The UN and DN belong to the one-hop neighbour set of the loaded node and they can be identified based on the IP table and ARP table of the loaded node. The *UN* will be informed to send packets belonging to the selected flow using the advertised interface. The *DN* will be informed to enable the selected interface in order to be able to receive the packets belonging to the selected flow.

④ **Radio Controller** is responsible for enabling an inactive radio card or disabling an active one. Besides the first interface, which is always kept active, the other interfaces can be activated or deactivated. The information about the interface which needs to be activated is received from the *Flow Shifter* component.

⑤ **Flow Shifter** resides at the network layer and acts on the routing table of the mesh node and on the radios the node is equipped with. After informing the *Radio Controller* about the interface which needs to be activated at the nodes, the routing table of the nodes are updated to use the new interface. Hence, all the packets belonging to the selected flow will be outputted through the newly activated interface.

C. ABI Algorithm

The aim of ABI is to reduce the congestion at the node level by making use of additional network interfaces a node is equipped with. ABI mechanism is a distributed mechanism and a cross-layer solution, which runs on all the mesh nodes in the network. The proposed mechanism is shown in Algorithm 1 as a pseudo-code.

On every mesh node, the video queue occupancy levels at every interface are monitored. If the occupancy level has reached a certain threshold the mesh node (MN) is called a congested node (CN). The algorithm checks if the node avails of inactive radios on which a flow can be shifted. If this is the case, a video flow is selected for shifting, by calling the *Flow Selector* component.

The UN and the DN in the path of the selected flow are identified by the *Upstream/Downstream Node Identifier* component. Next, the first inactive interface is identified, by execution *Next Available Interface* function, and enabled on the CN. A message is sent by the CN to the UN and to the DN informing them to enable the same interface for the specific flow. Once the UN and the DN enable the inactive interface, using the *Radio Controller* component, their routing tables must be updated to shift the packets belonging to the specified flow on the newly activated interface, by using the *Flow Shifter* component. In case an interface (different from the first interface) is no longer used for relaying traffic, ABI instructs the node to disable its radio and therefore save energy.

ABI mechanism executes itself each time the video queue occupancy threshold has been reached. However, in order to avoid quick shifting of all the flows from the first interface to the other available interfaces, a back-off period, τ, is considered, allowing the node to recover.

IV. Analysis of Results

A. Simulation Settings

ABI has been developed and assessed using the NS-3 network simulator [12]. The simulation setup considers two mesh topologies: a 16-node grid topology and a 25-node grid topology. Our decision for choosing grid topologies is justified by a study [13], 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 divide these 200 packets equally among the four queues (VI, VO, BE and BK queues) [14].

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.

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 [12]
Topology	Grid 4x4 & Grid 5x5
Distance between nodes	125 m
Number of interfaces	2
WiFi Mesh Mode	802.11a
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

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 using the equation in [15].
- **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 [16], 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. Performance Analysis

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.

D. Results

This subsection presents the results obtained from the simulation studies conducted on two different topologies, namely a 16-node grid topology (Figure 4) and a 25-node grid topology (Figure 5). Figure 4-a and Figure 5-a present the results for a 50 packets queue size, while Figure 4-b and Figure 5-b present the results for a 100 packets queue size. Each individual plot presents the overall average results for a specific performance metric, and compares the three cases presented in Subsection IV-C.

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 last plot from Figure 4-a, Figure 4-b, Figure 5-a and Figure 5-b depict the energy consumption of the whole mesh network. The lighter grey coloured bar shows the overall energy consumption of the first interface and the darker grey coloured bar shows the overall energy consumption of the second interface on all mesh nodes.

1) 16-node Grid Topology: Figure 4 presents the results obtained for a 4x4 grid topology. In Figure 4-a 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 (77% lower) and 2-WRI (47% 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

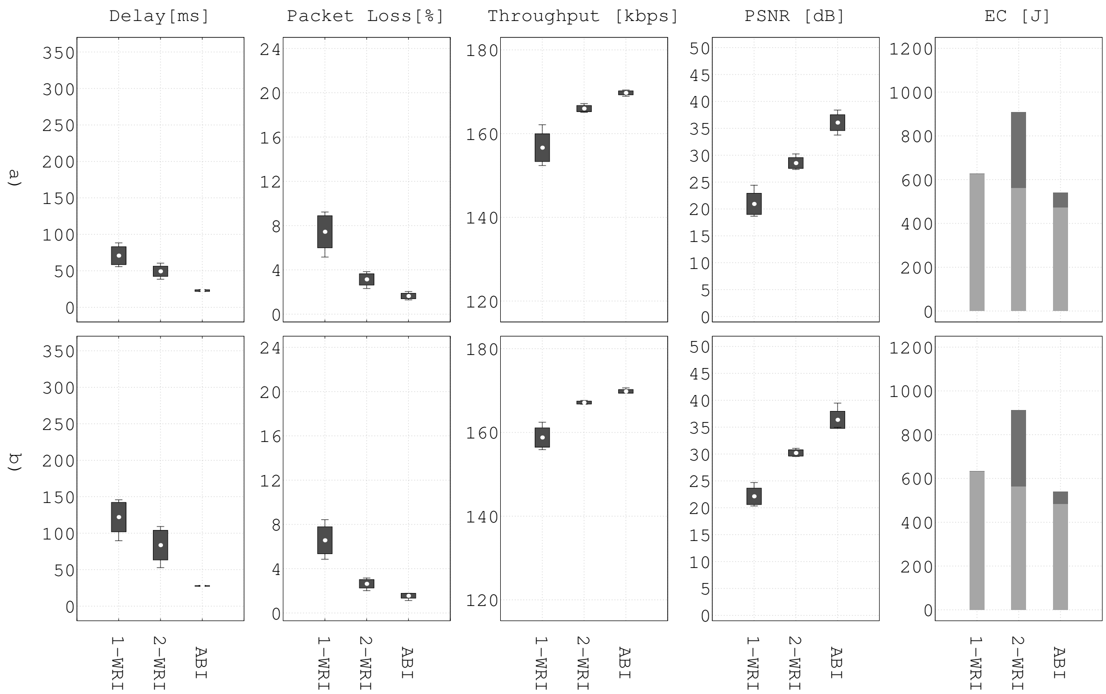

Fig. 4. 16-node grid topology with 50 packets queue (top row) and 100 packets queue (bottom row)

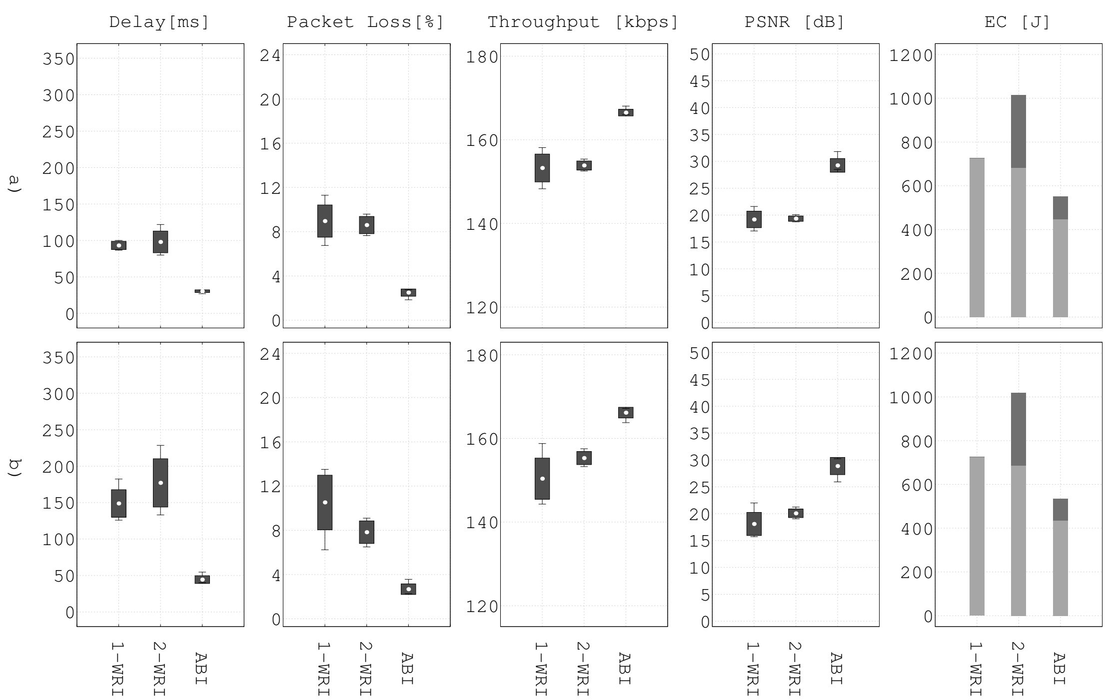

Fig. 5. 25-node grid topology with 50 packets queue (top row) and 100 packets queue (bottom row)

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 PSNR achieved by ABI. ABI achieves a PSNR value 72% higher and 28% than 1-WRI and 2-WRI, respectively. This increase in PSNR and decrease in packet loss is not obtained at the cost of delay. It can be observed in the first plot from Figure 4-a that ABI obtains the lowest delay, 23 ms. ABI's delay is 77% and 67% lower than 1-WRI and 2-WRI case, respectively.

Figure 4-b shows that ABI outperforms the other solutions, as well, when the mesh nodes have a queue size which can store 100 packets. The overall delay increases slightly, to 28 ms, compared to the delay obtained for 50 packets queue size

scenario (Figure 4-a), but still ABI obtains a delay 76% lower compared to 1-WRI and 65% lower compared to 2-WRI. At the expense of an increased delay, the packet loss drops compared to the results presented in Figure 4-a. However, ABI still outperforms 1-WRI and 2-WRI by 76% and 40%, respectively.

Regarding the PSNR metric, which estimates the perceived video quality, ABI obtains the highest value, around 36 dB for both scenarios: 50 packets queue size (Figure 4-a) and 100 packets queue size (Figure 4-b). This value is 70% higher than 1-WRI and 21% higher than 2-WRI.

The simulations conducted are also measuring the energy consumption caused by the wireless radio cards, for each considered case (1-WRI, 2-WRI and ABI). For 1-WRI only the light-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. ABI consumes 15% less energy compared to 1-WRI and 40% less energy compared to 1-WRI. It can be observed that 2-WRI balances the energy consumption between the two interfaces, however the overall energy consumption per node is higher than 1-WRI and ABI.

2) 25-node Grid Topology: Figure 5 depicts the results obtained for a 5x5 grid topology, which prove that even for larger topologies, ABI scales up and performs better than the other two considered mechanisms (1-WRI and 2-WRI). For the first scenario (i.e. 50 packets queue size) depicted in Figure 5-a, ABI obtains an overall packet loss of 2.50% which is 72% lower compared to 1-WRI and 70% lower compared to 2-WRI. Packet loss is strongly correlated with the network's average throughput, for which ABI obtains the highest values.

Besides the fact that ABI has a low packet loss, it also manages to deliver the packets in the shortest time, obtaining an overall delay of 31 ms. The delay obtained by ABI is 63% lower than 1-WRI and 68% lower than 2-WRI. The delay is slightly higher, 44 ms, for the 100 packets queue size scenario (Figure 5-b). However, the delay obtained in this scenario is, as well, lower than the one obtained by 1-WRI and 2-WRI.

The PSNR values, which measures the user perceived quality, obtained by ABI are around 30 dB for the 50 packets queue size scenario (Figure 5-a) and 29 dB for the 100 packets queue size scenario (Figure 5-b). The PSNR obtained by ABI 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 this network topology the energy consumption is higher, as compared to the 16-node mesh topology. Still, the overall energy consumption of the network, when ABI is employed is smaller compared to 1-WRI (29% lower) and 2-WRI (43% lower) for both scenarios (50 packets queue size and 100 packets queue size).

V. Conclusion

This paper proposes ABI an innovative mechanism which considers increasing the available bandwidth only when needed to support increasing video traffic in a wireless mesh network environment. ABI monitors the wireless interface's queue occupancy of nodes in order to detect traffic congestion and manages dynamically the wireless network interfaces, enabling when needed and turning them off otherwise. ABI's goal is to increase the video delivery QoS for the wireless mesh network's users and maintain low energy consumption at the same time.

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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