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An Energy-efficient Mechanism for Increasing Video Quality of Service in Wireless Mesh Networks

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Abstract—The continuous growth in user demand for high-quality rich media services puts pressure on Wireless Mesh Network (WMN) resources. Solutions such as those which increase the capacity of the mesh network by equipping mesh routers with additional wireless interfaces provide better Quality of Service (QoS) for video deliveries, but result in higher overall energy consumption for the network.

This paper presents LBIS, a distributed solution which combines the benefits of both load-balancing and interface-shifting in order to enhance QoS levels for video services delivered over multi-hop WMNs, while maintaining low energy consumption levels within the network. Simulation-based results show very good performance of our proposed mechanism in terms of QoS metrics (delay, packet loss), Peak Signal-to-Noise Ratio (PSNR) and energy consumption in mesh network topologies, and with varying video traffic loads and distributions. The results demonstrate how LBIS can increase the QoS for video deliveries by more than 30% at the cost of an insignificant increase of the overall network energy consumption compared to the WMN with multiple radio interfaces without the LBIS adaptation.

I. INTRODUCTION

WMNs are a very good technological solution for providing Internet connectivity in public spaces. They are being deployed by city authorities in highly populated areas to provide free of charge Internet access to an increasing number of city inhabitants. In particular the EU project Carmesh has addressed the problem of providing network-based services at good quality levels to highly mobile pedestrians or drivers via such WMNs [1], [2].

A typical WMN consists of wirelessly interconnected mesh routers, which forward the traffic in a multi-hop fashion to the mesh network clients. In a city scenario, the mesh nodes can be installed on traffic lights or on lamp posts and communication between these nodes is performed through the IEEE 802.11 technology. This technology is preferred as it provides a cheap and easy to deploy alternative compared to other technologies and it is suitable for best-effort services, such as browsing.

However, an analysis from Cisco shows that mobile video traffic represents nowadays more than half of the overall mobile traffic that is being generated and it is expected to increase up to 69% by 2019 [3]. This means that more than half of the mobile user traffic over the

WMNs provided by city authorities is video traffic, which has special QoS needs as compared to best-effort services.

As most WMNs are 802.11-based, they inherit many of the 802.11 protocol's disadvantages, including lack of support for QoS provisioning. By employing IEEE 802.11e, QoS for multimedia traffic can be enhanced as it makes use of separate queues for different types of traffic classes (i.e. voice, video, best effort and background) [4], [5]. However, for large volumes of video traffic, the video queue will eventually saturate leading to a drop in QoS.

A possible solution for improving network capacity and QoS for services delivered over WMNs is to equip the wireless mesh nodes with additional 802.11 radio interfaces. This has been made possible recently, as the prices for the wireless chipsets has dropped considerably. However, increasing the available bandwidth by adding extra wireless cards comes at the cost of an increased energy consumption, which is an important factor associated with wireless communication. The energy consumption represents an important factor for the city authorities which wish to provide a cheap way to connect to the Internet.

Apart from the flat energy consumption of a powered device, every time the device sends or receives data there is an energy cost for transmission or reception, which is proportional with the amount of data sent or received. The larger the packets the more energy is consumed for the transmission/reception. However, a station typically spends only a small amount of time receiving or sending data. The rest of the time the station finds itself in idle mode. Previous research shows that the amount of energy consumed by a device while in idle mode is significant and it should be considered for enabling significant energy savings [6].

Thus, beside providing high QoS levels for user video services in a wireless environment, the network energy consumption is also a key aspect to be taken into consideration. This motivates us to propose a combined *Load-Balancing/Interface-Shifting (LBIS)* solution, which makes use of both traffic load-balancing [7] and energy-efficient management of the wireless cards a node is equipped with [8]. The aim is to maintain a low overall network energy consumption, while providing high QoS levels to the mesh network users.

The remainder of the paper is organized as follows: Section II discusses the related work. Section III presents in detail the proposed LBIS solution. Section IV describes the simulations carried out and the result analysis. The paper is concluded in Section V.

II. RELATED WORK

The energy saving solutions proposed in the literature consider using a smaller set of nodes, adapting the transmission power of the radio [9] or switching-off the mesh nodes' interfaces when they are not necessary to satisfy traffic demands. The solution proposed in [10] makes use of directional antennas, which limit the applicability into WMNs and does not address the network throughput issue as only energy consumption-related results are presented. Also, the proposed network management framework needs a centralized management of the mesh nodes, in order to switch them back on. Another centralized approach for optimising the energy consumption in WMNs is presented in [11], which aims putting the under-utilised mesh nodes in sleep mode, thus reducing the energy consumption. However, similar to [10] a centralized framework is needed, while the solution proposed in this paper is fully distributed.

An energy efficient channel assignment, E²CARA-TD for WMNs is proposed in [12]. The solution finds routes for a known set of traffic demands such as to keep the total utilization of the collision domains below a certain threshold, saves energy by switching off unused radios and assigns channels to the radios left turned on. Important aspects of the algorithm are missing from the description, such as how the thresholds are set and how the turned-off radios can be switched back on again as they are not reachable any more. As well, a central entity is needed to run the algorithm for identifying the new routes and the new configuration of radios for the given set of traffic demands. To the best of our knowledge this is the only solution which considers saving energy by switching off/on the radios in the nodes. However, in comparison with our solution, E²CARA-TD is not a distributed solution. It has been shown that distributed solutions are preferable to centralized ones [13], [14], as they allow larger networks to quickly adapt to changes in the network dynamics.

III. LBIS SOLUTION

A. Overview

LBIS represents a distributed QoS-enhanced multimedia delivery solution that combines principles of video load balancing (**ViLBaS** [7]) and efficient usage of the available interfaces a node is equipped with (**ABI** [8]).

The LBIS mechanism is designed to operate in WMNs whose nodes are equipped with multiple interfaces. Multi-radio nodes bring, besides increased capacity, an improvement in terms of QoS. However, if the available interfaces a node is equipped with are used inefficiently, the gain in terms of QoS is obtained at the expense of high energy consumption. As well, due to uneven distributions of video

flows some mesh nodes are overloaded and have to carry a large number of video flows, while others are under-utilised. These nodes become congested and their packet queues will eventually overflow and drop packets. The aim of LBIS is to increase the capacity of the WMN and increase QoS levels for video deliveries, while maintaining low network energy consumption.

The proposed LBIS mechanism is a distributed solution, which runs on every mesh node and monitors their video queue occupancy levels. Once the number of packets stored in the video queue of a node has reached a threshold, the node is considered congested and LBIS is employed. LBIS is designed to choose the best action based on the congested node's condition: either to re-route selected flows through another set of less congested mesh nodes (by applying the ViLBaS mechanism [7]), or to use the available interfaces of the node (by applying the ABI solution [8]). It is worth noting that using a second interface has less disruption on the video delivery than employing re-routing.

Figure 1 illustrates the concept behind the LBIS mechanism. In this figure, the congested node is marked with a red flag and the selected flow, on which the LBIS solution is applied, is represented with a continuous orange line. If the red-flagged node decides to apply ViLBaS, the selected flow is re-routed around the congested node and this action is represented with a dotted blue line. If the congested node decides to employ ABI, it will use the additional interfaces among the available ones, to shift the selected flow, action which is represented through a dotted orange line.

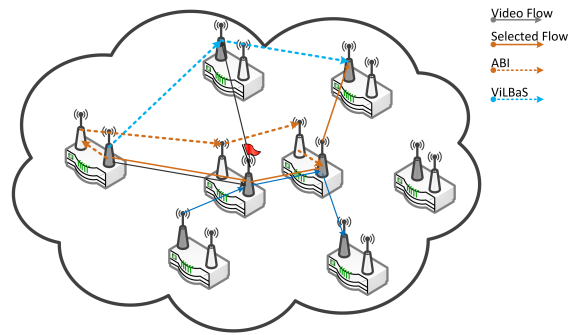


Fig. 1. LBIS Concept

B. LBIS Architecture Description

Figure 2 illustrates the node-level LBIS architecture based on the TCP/IP protocol stack. The LBIS solution resides at the network layer, data-link layer and physical layer, providing a cross-layer framework for enhancing multimedia delivery, by combining the principles of ViLBaS [7] and ABI [8] mechanisms.

The architecture consists of several building blocks, identified in Figure 2. The building blocks that are common to both ABI and ViLBaS mechanisms are coloured in blue in Figure 2 and are briefly described next:

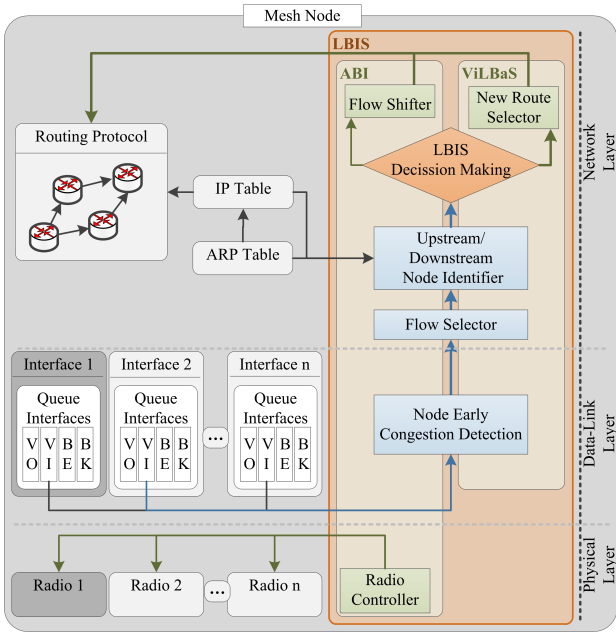


Fig. 2. LBIS Node-level Architecture

- **Node Early Congestion Detection**, is in charge with detecting mesh node's congestion. A node is considered congested when the video queue occupancy has reached a certain threshold;
- **Flow Selector**, is in charge with selecting a flow running through the congested node, on which LBIS is applied;
- **Upstream/Downstream Node Identifier** identifies the upstream node and the downstream node on the path of the selected flow.

The architectural blocks, specific to each mechanism, are green-coloured in Figure 2. These blocks are:

- **Flow Shifter** and **Radio Controller**, are components belonging to ABI. These components shift the selected flows to an additional interface of the congested node and of the upstream and downstream node;
- **New Route Selector**, is part of ViLBaS and is used for identifying a new path for the selected flow such as to bypass the congested node;

The diamond shape block coloured in orange in Figure 2, is specific to the LBIS mechanism. This block represents the decision point at the mesh node's level which chooses between using the ABI mechanism or the ViLBaS mechanism when congestion occurs.

The basic principle behind the LBIS solution and a detailed description of the algorithm are presented in the next sub-section.

C. LBIS Algorithm

The LBIS solution is triggered by a node when the node becomes congested. Once the congested node selects a flow it decides to either re-route the flow such as to

avoid the congestion, using the flow load-balancing solution (ViLBaS) or shift it to another interface on the same node, through the efficient usage of additional interfaces mechanism (ABI) in order to increase video QoS for the end-user.

The decision to select one or the other mechanism is based on the load situation of the congested node. As long as the congested node has inactive interfaces or the queue occupancy of the in-use ones is below a threshold, the node employs ABI, otherwise ViLBaS. The decision to apply first ABI in case of mesh node congestion is justified by the fact that ABI has a lower disruption for the video traffic and the contention for the medium is lowered faster.

The pseudo-code of the decision process handled by the LBIS solution is described in Algorithm 1.

The algorithm is enabled when the video queue occupancy level (QO_{AC_VI}) of a wireless interface reaches the threshold τ (line 3). In this case, the node is called congested (CN) and it triggers the *Flow Selector* component to select a flow to be shifted to another interface of the congested node or to be re-routed around the congested node. In case the mesh node is equipped with additional interfaces, which are inactive (line 8), it will shift the selected flow to one of these interfaces, by executing the ABI mechanism. If the mesh node has all the available interfaces enabled, it searches through each interface (line 14) one which has the queue occupancy level below a threshold τ and applies ABI (line 18). In case none of the available interfaces meets the conditions mentioned before, than the selected flow will be re-routed through another path, by executing ViLBaS (line 20).

If a wireless interface is not used any more (line 23) then the interface is shut down to save energy. This state can be identified when the video queue occupancy of a wireless interface is zero ($QO_{AC_VI} == 0$) and no flows pass through the interface ($\mathcal{L}_F == \emptyset$). This can happen when the flows have been re-routed through other paths or when the flows finished, leaving the wireless interface in an active state, but unused.

In order to avoid considering consecutive complaints from the mesh nodes in a short period of time, \mathcal{P} amount of time must elapse before another complaint from the same node is taken into consideration (line 18).

IV. PERFORMANCE ANALYSIS

The description of the simulation environment used and the performance evaluation carried to assess LBIS are presented in the following subsections.

A. Simulation Setup

The LBIS solution has been modeled, deployed and assessed using the NS-3 network simulator. The emulation-simulation-based test-bed, presented in [7], has demonstrated that the simulation-based results are accurate, so in this work LBIS is assessed via simulations only. The simulation setup considers a sixteen-node grid topology

Algorithm 1: LBIS Algorithm

Input:
 WI - Wireless Interface
 QO_{AC_VI} - Queue Occupancy of the Video Queue
 MN_i - Mesh Node i
 τ - Queue Occupancy Threshold
 \mathcal{P} - Complaint Period

```

1 foreach ( $WI \in MN_i$ ) do
2   Compute  $QO_{AC\_VI}$ ;
3   if ( $(QO_{AC\_VI} \geq \tau)$  and ( $\mathcal{P}$  elapsed)) then
4      $CN \leftarrow MN$ ;
5      $\mathcal{F} \leftarrow$  Flow Selector();
6     if ( $\Sigma(WI_{active}) < \Sigma(WI_{installed})$ ) then
7       Shifting - ABI Decision;
8     else
9        $WI_{ok} = \text{false}$ ;
10      foreach ( $WI_{active}$  at  $MN$ ) do
11        if ( $QO_{AC\_VI} < \tau$ ) then
12           $WI_{ok} = \text{true}$ ;
13      if ( $WI_{ok} == \text{true}$ ) then
14        Shifting - ABI Decision;
15      else
16        Load-Balancing - ViLBaS Decision;
17    else
18      Complaint is dismissed;

```

with the inter-node distance set to 125 meters. Each node has two Network Interface Cards (NICs) and each waiting queue can store a maximum number of 50 packets.

The video traffic has been randomly distributed between mesh nodes. The number of video flows deployed in the network was varied, for each set of simulations, between five and ten in order to analyse how the mechanism performs in different loaded network scenarios.

Regarding the LBIS mechanism's specific parameters, the queue occupancy triggering threshold was set to 60% and the pause interval was set to 0.5 seconds (as identified in [7], [8]). To ensure the accuracy of the results obtained, five distinct simulation runs are performed for each considered case using different seeds. For each seed the origin and destination of the flows are kept constant. A summary of the network parameters used in the simulations is presented in Table I.

B. Performance Analysis

The performance evaluation of LBIS solution (Case D) is compared against a baseline mechanism (Case A), ViLBaS (Case B) and ABI (Case C), as follows:

- **Case A** - Refers to a baseline mechanism which re-routes flows to their destination using the OLSR mechanism;
- **Case B** - Employs the ViLBaS mechanism only, meaning the selected flows are always re-routed around the congested node;
- **Case C** - Employs the ABI mechanism only, meaning the selected flows are shifted to the available interfaces

TABLE I
SIMULATION SETUP

Parameter	Value
Simulator	NS-3.10 [15]
Topology	Grid 4x4
Distance between nodes	125 m
Number of mesh interfaces	2
WiFi Mesh Mode	802.11a
WiFi Data Rate	6 Mbps
Error Rate Model	YansErrorRateModel
Remote Station Manager	ConstantRateWifiManager
Video Queue Size	50 packets
Traffic Type	MPEG4 Video Trace Files
Video Type	Medium Quality
Video Mean Bit Rate	160 kbps
Number of Video Flows	5-10
Queue Occupancy Threshold - τ	60%
Pause Interval - \mathcal{P}	0.5 seconds
Routing Algorithm	OLSR
Number of simulation epochs	5

the congested node is equipped with;

- **Case D** - Employs the proposed LBIS solution, which combines the benefits of ViLBaS and ABI.

Note OLSR is used for neighbour discovery only in this simulation-based comparison study. If used in conjunction with ABI, ViLBaS or LBIS, OLSR would interfere with the route selection of the mechanisms as OLSR updates the routes at specific time intervals. Thus, OLSR would change the routes proposed by the proposed solutions, and this is the main reason why hybrid solutions such as OLSR+ViLBaS or OLSR+ABI are not considered in this study.

The performance metrics considered in the assessment are the overall average delay, the overall average packet loss, the overall average PSNR and the overall energy consumption.

- **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;
- **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 [16].
- **Energy Consumption [J]** - The amount of energy consumed by a radio is given by the product of the supply voltage and the current 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 [17], which can be found in many wireless network cards, and are summarised in Table II.

In each plot the average value obtained for the considered performance metric is represented with a white dot inside a black bar. The extremities of the black bar represent the standard deviation of the values, while the whiskers represent the minimum and the maximum value obtained.

TABLE II
ATHEROS AR5416 CHIPSET POWER CONSUMPTION

Parameter	Value	Parameter	Value
Supply Voltage	3.0 V	Tx Power	1.845 W
Idle Current	0.114 W	Rx Power	1.299 W

C. Analysis of results

The overall average delay in the four cases considered (A, B, C, and D) when varying the traffic load is depicted in Figure 3. In this figure, the trend for all the four cases shows that the average delay increases as the video load increases. This is due to the increased number of packets that are stored in the video queues of the wireless NICs, and take longer time to be transmitted. However, the LBIS solution (Case D), as it combines the benefits of ABI and ViLBaS, obtains the lowest overall delay for every type of traffic load distribution.

The results in Figure 3 show that for a network loaded with five or six videos, the LBIS solution employs ABI only, and consequently Case C and Case D have the same performance in terms of delay. The LBIS solution maintains for these two traffic loads a delay of only 23 milliseconds, almost 66% lower than Case A and Case B. For increased traffic loads the delay increases up to 60 milliseconds for nine video flows, but LBIS results are 68% lower than Case A (OLSR) and Case B (ViLBaS), and 6% lower than Case C (ABI). For the case of a highly loaded network (10 video flows), the lowest delay of 73 milliseconds is obtained in Case D. This value is 22% lower than that in Case C (ABI), 65% lower compared to Case B (ViLBaS) and 68% lower than that in Case A (OLSR).

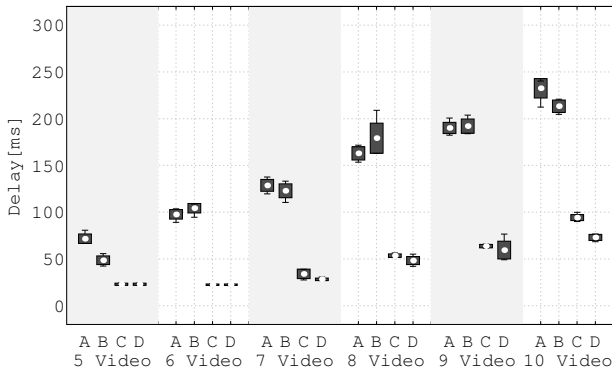


Fig. 3. Overall Average Delay for Varying Traffic Load

Considering that a small delay can be obtained at the expense of a high packet loss, Figure 4 presents the overall packet loss obtained for each of the four cases considered when the traffic load increases. Even though the same trend is observed (the packet loss increases as the number of video applications increases), the increase for LBIS is not as steep as that for OLSR or ViLBaS for the whole range of traffic loads. The LBIS mechanism manages to maintain

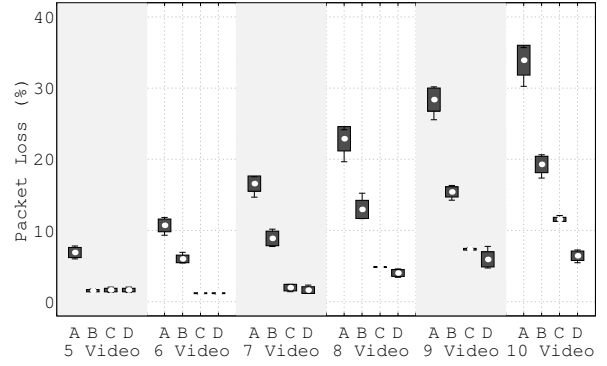


Fig. 4. Overall Average Packet Loss for Varying Traffic Load

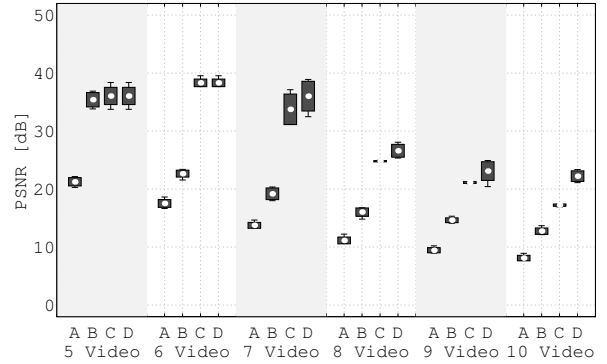


Fig. 5. Overall Average PSNR for Varying Traffic Load

a packet loss below 7%, even when all ten video flows are transmitted inside the mesh network. For a network loaded with ten video flows, the proposed solution decreases the packet loss by 80% compared to OLSR, by 66% compared to ViLBaS and 44% compared to ABI.

The results in terms of PSNR, which estimates the quality of the video transmitted over the mesh network, are presented in Figure 5. The PSNR values are strongly related to the packet loss previously analysed. Again, LBIS is able to deliver higher QoS for the network's clients when increasing the video traffic load in the mesh network. For a low traffic load (five videos) the PSNR value obtained for Case D is almost 37dB, which is 71% higher than Case A and close to the PSNR value obtained by Case B and Case C.

For a higher load (ten video) of the network, the LBIS solution achieves an average PSNR of 22dB, which is 173% higher than Case A (OLSR), 74% higher than Case B (ViLBaS) and 28% higher than Case C (ABI). This results show tremendous improvement of LBIS over the other mechanisms, in terms of video quality delivered to the users.

The overall network energy consumption is presented in Figure 6. Each bar comprises of two parts: a light-grey bar showing the average energy consumption for the first interface of all the mesh nodes, and a dark-grey bar

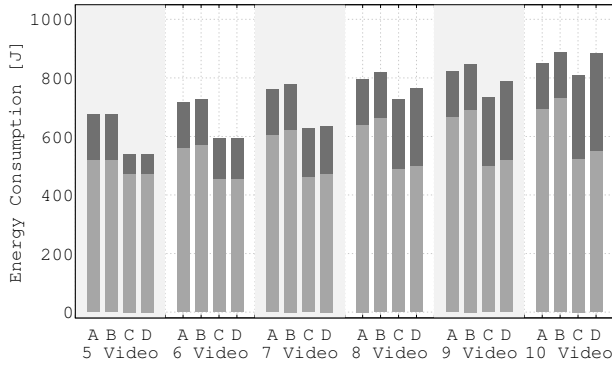


Fig. 6. Overall Average Energy Consumption for Varying Traffic Load

showing the average energy consumption of the second interface. Because the energy consumption of a NIC is proportional with the amount of traffic the card is sending, the energy consumption of the whole network also increases proportional with the traffic load introduced in the network.

It can be observed that ABI (Case C) utilizes the lowest amount of energy, but this is achieved at the expense of a lower video QoS, as shown in Figure 5. Case D consumes slightly more energy than Case C, but manages to provide higher quality for the videos delivered for a difference of 10% in energy consumption for instance, when ten video are delivered over the mesh network. This result should be factored in by a WMN operator, as the 10% margin may sometimes be important, depending on the operators cost targets. From another perspective, these results show that a WMN with LBIS solution deployed can deliver a larger number of good quality video streams for a modest increase in energy costs.

V. CONCLUSIONS

This paper has introduced the Load-Balancing/Interface-Shifting mechanism (LBIS), which combines the benefits of both re-routing and employing additional interfaces in an innovative manner. When a node becomes congested it decides whether it is best for its status to enable additional interfaces or to request to the previous node to re-route flows on new paths avoiding the congestion. The LBIS mechanism was assessed through NS-3 simulations on a 16-node grid topology, under various load conditions and compared against a baseline mechanism (i.e. OLSR) and two state of the art solutions: ViLBaS and ABI. The results demonstrate that the LBIS mechanism obtains better overall performance as compared to the other mechanisms in terms of delay, packet loss, PSNR, at the expense of a slightly higher energy consumption. For a highly loaded network with ten video streams, the LBIS solution provides an excellent improvement in terms of QoS. The quality of the video is increased by almost 30% when compared to when ABI was used and by 74% in comparison with when ViLBaS was employed, for an insignificant increase in the overall network's energy consumption.

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