Increasing User Perceived Quality by Selective Load Balancing of Video Traffic in Wireless Networks

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***Abstract*—Wireless networks are becoming increasingly popular mostly due to their deployment flexibility. Unfortunately in general they offer lower Quality of Service (QoS) levels to their users, especially when they avail from rich media services such as video deliveries. These rich services put additional pressure on the limited wireless network resources, eventually affecting user perecived quality and providing solutions to address this is highly challenging.**

This paper shows how by using ViLBaS, an innovative selective load balancing solution for video deliveries, increased QoS levels of remotely transmitted video are obtained in Wireless Mesh Networks (WMNs). ViLBaS employs distributed monitoring of network traffic, identifies the node most affected by congestion and prevents imminent packet drops by re-routing the video flows around the congested node.

A hybrid simulation-emulation-based test-bed is built and used for assessing ViLBaS performance in comparison with classic solutions employing the best-known routing metrics. Real video traffic was transmitted from a sever to a client over a WMN topology and the received video quality was assessed in different scenarios. The results demonstrate that ViLBaS outperforms all other solutions when delivering various video content with diverse characteristics and at different quality levels.

***Keywords*—Wireless mesh network, load balancing, video, emulation, routing**

I. Introduction

Delivering rich media services over wireless networks has become highly popular mostly due to the deployment flexibility of these networks and their relative reduced costs. Unfortunately the distribution of rich media services in general and video content in particular is associated with increased bandwidth requirements and is affected by wireless delivery-related factors (such as increased loss for instance), lowering the QoS levels to their users.

Among the wireless networks, Wireless Mesh Networks (WMN) are an important step forward towards cost-effective and high-bandwidth network connectivity for a specific geographic area. They operate in the licence-free spectrum which reduces significantly the deployment costs compared to the technologies operating in the licensed spectrum (e.g. LTE). WMNs consist of wireless interconnected routers arranged in a mesh topology, which forward the traffic in a multi-hop fashion. Beside the many characteristics of WMNs, which make this technology a desirable option for an easy and fast deployment, WMNs also face multiple challenges. One of them is their limitations in fulfilling user expectations in terms of high QoS levels. One of the reasons is that WMNs were not designed originally to work in conjunction with any QoS mechanism. Another reason is that most of the times the traffic is not evenly distributed in the network. This means that some nodes carry more traffic than the others and become congested. Congestion will cause the nodes to drop packets which will influence negatively the transmission of any content. In particular loss affects the quality of video transmissions and therefore remote viewer perceived quality or Quality of Experience (QoE) severely decreases.

In this context, the problem of unbalanced traffic distribution in a wireless mesh network is addressed in this paper. The classic routing solutions re-route the traffic in the mesh network without considering the load at the mesh nodes queues, and therefore some mesh nodes may rapidly get overloaded because they carry too much data and/or too many video flows. This causes traffic congestion at those nodes, which results in significant reduction of the overall network capacity and affects the remotely transmitted video quality levels. In order to address this issue, this paper proposes **a queue-occupancy-based selective load-balancing solution, ViLBaS, which identifies congested nodes and increases viewer Quality of Experience (QoE) levels for video deliveries over WMNs by re-routing flows selectively around those nodes [1]**. In this way, the network capacity is improved through a balanced distribution of flows.

ViLBaS employs distributed monitoring of network traffic, identifies the node most affected by congestion and prevents imminent packet drops by re-routing the video flows around the congested node. The mechanism distinguishes itself from other load-balancing mechanisms proposed in the literature through the following:

- The decision to re-route is taken per flow and is event-triggered by a congested node in distributed manner.
- The traffic is split into different classes, where delay-sensitive applications have the highest priority.
- Queue occupancy levels at each network interface are used to detect congestion pro-actively.
- Selective load-balancing is performed such as to increase user QoE levels.

The concept behind ViLBaS usage in a WMN environment is illustrated in Figure 1. In Figure 1 the gray squares represent

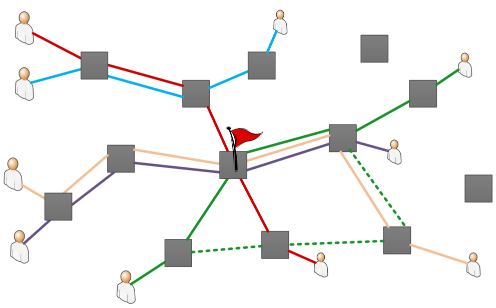


Fig. 1: ViLBaS Concept

the mesh nodes and the different colored lines indicate the various video flows traversing the WMN. When multiple flows are overloading a node inside a mesh network (i.e. the node with a red flag), the node employs a flow selection algorithm to identify a flow (i.e. the green flow) to be re-routed around the congested node along a less congested path (i.e. the green dotted path). This has a positive influence for both the re-routed video flow and the other video streams traversing the congested node in the WMN.

ViLBaS is tested when delivering different video quality levels and various video content and is compared against a static routing solution and existing state of the art routing algorithms employing metrics like hop-count and ETX. ViLBaS's performance assessment is performed using a purposely-built hybrid emulation-simulation-based test-bed and involves real video network delivery.

The remainder of the paper is organized as follows: Section II highlights some of the well-known existing routing metrics in the literature. Section III presents an overview of ViLBaS, the proposed algorithm for selective video load-balancing in WMNs. Section IV presents details regarding testing setup including the emulation concept, test-bed, multimedia content and the methods used for assessing the quality of the video received at the client side. Chapter V presents the results of the video perceived quality assessment, using two well-known metrics: PSNR and SSIM. The conclusions of this work and future plans are presented in Section VI.

II. Related Work

The decision for choosing a route from multiple available paths is driven by routing metrics, which are used by routing protocols. Routing protocols can be classified into reactive protocols and proactive protocols. Reactive protocols are also called on-demand routing protocols because a route between two nodes is discovered only when requested by flooding the whole network. Examples of routing protocols which fall in this category are Ad hoc On Demand Distance Vector (AODV) [2] and Dynamic Source Routing (DSR) [3]. The main criticism of reactive routing protocols is the high latency in discovering a new route and the excessive flooding needed for route discovery.

The proactive routing protocols, also called table-driven routing protocols, maintain on each node an updated list of routes to all the other nodes in the network. Optimized Link State Routing (OLSR) [4] is an example of a proactive routing protocol. The advantage of proactive routing is that no delay is associated to route discovery for a new flow. If a routing combines elements from the proactive and reactive routing protocols is called a hybrid routing protocol and one example is the Hybrid Wireless Mesh Protocol (HWMP) [5].

All the routing protocols are driven by routing metrics for identifying the best route between a source and a destination.

The hop-count metric is the most commonly used in protocols such as OLSR. Using this metric, the routing protocol identifies the shortest route in number of hops between all source and destination pairs. The disadvantage of the hop-count metric is that it does not consider interference or packet loss ratio and thus, it can lead to a poor network performance with increased delays and high packet loss.

The ETX metric is proposed in [6] and it aims to chose a route between two nodes based on the path's quality. The link quality is estimated based on the number of probe packets received by each node. The quality of a route in a multi-hop scenario will be calculated adding all the ETX values of the links belonging to the path. The main criticism of ETX is that it does not consider differences in transmission rates. The transmission rate of the probe packets is low, and so it does not reflect with accuracy the effect on the throughput of the actual traffic. As well, it does not consider the link load, hence it routes the packets through heavily loaded nodes leading to unbalanced traffic inside the mesh network.

The Estimated Transmission Time (ETT) metric [7] is built as an improvement to the ETX metric by considering the link transmission rate and packet size. For evaluating the link quality, two back-to-back probes, one small probe followed by a large one, are sent by each node. The receiving neighbour measures the inter-arrival time between the two packets and reports it back to the sender of the two probes. After a certain number of probes are received, the sender computes the capacity of the link by dividing the size of the larger probe by the smallest delay measured. The route with the lowest sum of ETT values of the links along the path is chosen for routing. As ETT considers the ETX metric into its formula, it inherits many of the ETX disadvantages. One of its drawbacks is that it does not consider link load, thus it cannot avoid routing the traffic through heavily congested nodes.

The Weighted Cumulative ETT (WCETT) [7] is proposed as an enhanced metric over the ETT by taking into consideration interference and the multi-radio nature of the nodes. WCETT tries to reduce the number of nodes that transmit on the same channel along a path. WCETT gives lower weights to the path with more diversified channel assignment on the links, meaning they have a lower intra-flow interference. The main drawback of using WCETT is the non-isotonicity property which makes it unusable for proactive routing [8].

All the above mentioned metrics consider either the link quality or the channel interference. However, they do not consider the load of the nodes on the path of a route. Hence, there is a need for a solution which considers the load of nodes in a wireless mesh infrastructure.

Several notable works exist in the literature on QoS-aware routing and in particular on application-aware solutions for increasing QoS for video delivery. In [9] the authors examine the complexity of finding paths that satisfy multiple constraints and also discuss the selection of suitable metrics for QoS routing. In [10] a resource management scheme, which aims to improve the QoE for YouTube users in a wireless mesh network, is introduced. The mechanism proposed in their paper makes use of a central entity, which periodically collects information about the network and application status and stores it in a database. The scheme makes use of either client-based metrics or network-based metrics. The client-based solution adapts the video resolution of the YouTube movie. The network-based measures include: gateway change, for which the packets are re-routed to a less congested gateway, and buffer-based prioritization, for which defines prioritization policies for each gateway. The test-bed on which the simulations were carried consists of four nodes: one mesh node and three gateways. However, for a realistic mesh topology, which consists of more than four nodes, the overhead introduced by the continuous reporting of the parameters to the central entity can affect the quality of the video traffic being transmitted.

A solution employing a QoE-aware double reinforcement learning strategy, which computes dynamically efficient routes for each flow depending on their service type is presented in [11]. This solution brings together QoE-awareness routing and reinforcement learning in a WMN context. The work focuses on three types of services: audio, video and data transfer, but the video distribution presents the highest benefits when employing the proposed mechanism. A routing solution specific to video transmission is considered in [12], which proposes an electro-static potential inspired routing scheme. However, the performance analysis of the proposed solution considers only two video flows, which might not be enough to evaluate how the proposed mechanism behaves in a loaded network.

Note that most Application layer solutions adapt the content delivery process, reacting to loss and eventually to degradations of other QoS parameters and highly depend on the application type. The solution proposed in this paper works at the Network layer, where packets are exchanged, regardless of the solution employed at application layer. A proactive approach is considered by our proposed network layer solution which reroutes flows around the bottleneck area, improving the delivery performance and increasing the efficiency of the application layer solution.

III. Innovative Selective Load Balancing Solution for Video Deliveries (ViLBaS)

A. Overview

In a WMN, a routing protocol, such as OLSR, distributes the traffic flows on the shortest routes between their source and destination. Often, this results in highly congested nodes along the most common delivery path, nodes which eventually will lose some of the large numbers of packets they deal with, affecting the quality of the transmitted data flows. This is particularly affecting negatively the video flows, as often retransmission is not possible given the time-sensitivity of the video delivery traffic. In order to address these issues, load balancing of the video flows in WMN is performed.

ViLBaS differentiates traffic in four classes as described in the IEEE 802.11e QoS MAC extension [13]. IEEE 802.11e gives higher priority to traffic from time-sensitive applications such as voice and video, and lower priority to other data traffic such as best effort and background. This is achieved by associating different queues to different traffic classes and prioritizing the access of data from different queues to the transmission medium. QoS support is part of most newer standards, such as the IEEE 802.11n [14], requiring that all devices include the enhancements introduced by 802.11e.

As ViLBaS targets the video flows inside a WMN, it focuses on the video queue. It enables identification of the loaded nodes, and re-routes the video traffic around them, balancing the load.

B. Architecture Description

At each node, ViLBaS monitors the video traffic load, identifies the potential for node congestion, and if so selects a flow and reroutes it on a different path by notifying the previous node in that flow's current path. In order for the ViLBaS mechanism to operate, knowledge about flows passing through each node, nodes' load and neighbouring nodes' status is required. In order to enable scalability, ViLBaS is designed as a distributed solution residing on each mesh node.

Figure 2 illustrates the ViLBaS cross-layer architecture based on the TCP/IP network protocol stack model. ViLBaS comprises of components which reside at both network and data-link layers. The figure also illustrates the four major stages of ViLBaS. As presented in Figure 2, ViLBaS mechanism has four major stages:

1 **Node Activity Detector**, which identifies when a node is to become congested based on the video queue occupancy reaching a certain threshold. Hence, each mesh node monitors continuously its own video queue occupancy by measuring the amount of packets enqueued in the AC_VI queue.

2 **Flow Selector**, which selects a flow to be rerouted around the congested node identified at the previous point. The flow which occupies the largest share of the video queue in the loaded node is selected for rerouting. However, the existing packets belonging to the selected flow in the loaded node's queue will still be transmitted to their destination.

3 **Previous Node Identifier**, which identifies the previous node on the path of the selected flow.

4 **New Route Selector**, which selects the new route for the selected flow. The calculation of the route starts at the previous node. This node will select from its neighbours, the next hop based on the utility function $\mathcal{U}_{MN,NN}$, (1) where MN is the current node and NN is the neighbour node.

$$\mathcal{U}_{MN,NN} = \alpha \cdot \mathcal{U}_{VIQO_{NN}} + (1-\alpha) \cdot \mathcal{U}_{\mathcal{DHC}_{NN,DN}} \qquad (1)$$

The utility function (Eq. 1) is computed based on a weighted summation method, which has two components: a utility term

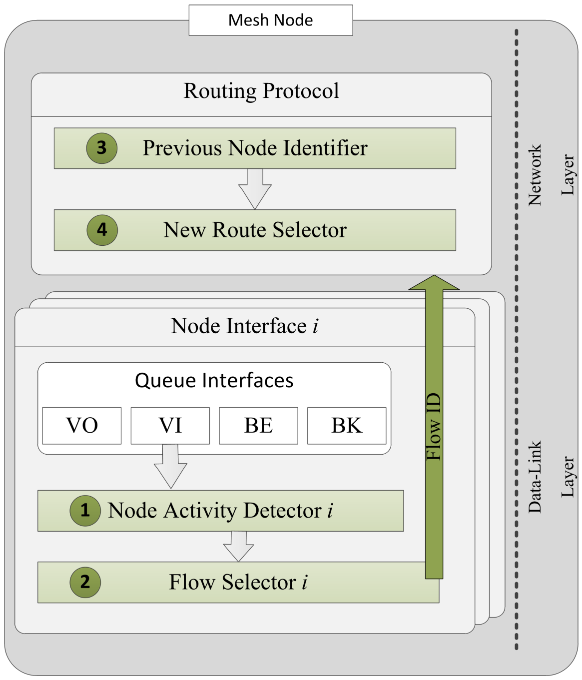


Fig. 2: ViLBaS Cross-layer Architecture and Major Stages

computed based on the traffic load of the neighbour node and a term computed based on the distance to the destination of the flow. The first term of the equation, $\mathcal{U}_{VIQO_{NN}}$ (Eq. 2), is a utility function defined for the video queue occupancy of the neighbour node. The first term is obtained by dividing the number of packets stored in the video queue by the maximum number of packets the queue can store. $\mathcal{U}_{\mathcal{DHC}_{NN,DN}}$ (Eq. 3) is a utility function defined for the distance, in number of hops, to destination from the neighbour node. The second term is obtained by dividing the number of hops to destination to the maximum acceptable number of hops for which the quality of the video does not degrade. In Eq. 1 α represents the weighting factor.

$$\mathcal{U}_{VIQO_{NN}} = \frac{VIQO_{NN}}{Max_{VIQO}} \quad (2)$$

$$\mathcal{U}_{\mathcal{DHC}_{NN,DN}} = \frac{\mathcal{D}_{NN,DN}}{MaxDist} \quad (3)$$

ViLBaS is presented in Algorithm 1 and includes the four stages described above.

The route calculation mechanism starts with the previous node on the path of the selected flow. For each one-hop neighbour of the previous node the $\mathcal{U}_{MN,NN}$ utility function is calculated. The next hop is selected as the neighbour which returns the best $\mathcal{U}_{MN,NN}$ value. This process is repeated until the destination node of the flow is reached.

Unlike the classic approaches, our solution is event-based. The execution of this mechanism is triggered by every node which notices increased load in its video queue occupancy monitoring process, and only after a set up period of time has

Algorithm 1: ViLBaS Mechanism

Data: Mesh Nodes, Video Flows
Result: Load-Balanced Video Traffic

Loaded Node←Queue Occupancy Threshold Reached 1;
Current Node = Loaded Node;
$\mathcal{F} \leftarrow$ Flow Selection On Current Node 2;
Identify previous node for selected $\mathcal{F}$ 3;
while *(1)* **do**
  foreach *Neighbour Node of the Current Node* **do**
    if *$(Neighbour\ Node! = destination)$* **then**
      Calculate $\mathcal{U}_{MN,NN}$ (Eq. 1) ;
    else
      return $\mathcal{R}$;
  Select the neighbour node with the best $\mathcal{U}_{MN,NN}$;
  Current Node = Selected Neighbour;
  $\mathcal{R} \leftarrow Selected\ Neighbour$ 4 ;
Update Routing Table on each mesh node $\in \mathcal{R}$;

elapsed from a previous run of the algorithm (in order to allow for full algorithm convergence). Once the queue occupancy levels for the video buffer reaches a certain threshold τ, the local re-routing mechanism is triggered. As the proposed mechanism will be employed when necessary only, the additional overhead introduced for finding a new path around the congested nodes and for re-routing flows is kept low.

Let Q_i be the video queue at the mesh node i and $\mathcal{O}(Q_i)$ the occupancy level of this queue. μ_i is the transmission (service) rate of the video queue belonging to node i and $\lambda_i^{F_k}$ is the packet arrival rate at the node i's video queue for the video flow Fk. The total arrival rate at queue Q_i can be expressed as $\lambda_i = \sum_k \lambda_i^{F_k}$

If $\lambda_i \leq \mu_i$, the mesh node i can process the data at the rate the video flows are transmitting the data traffic. However, if $\mathcal{O}(Q_i) \geq \tau$, it is likely that any fluctuation in the traffic, (including processing new flows) will result in $\lambda_i > \mu_i$ (the packet arrival rate is higher than the service rate of the queue), determining consequent loss when the queue capacity will be exceeded.

Our mechanism detects when $\mathcal{O}(Q_i) \geq \tau$ and proactively and iteratively selects video flows contributing to Q_i traffic for re-routing until $\mathcal{O}(Q_i) < \tau$ and $\lambda_i < \mu_i$. This prevents packet loss and results in higher video delivery quality. If $\mathcal{O}(Q_i)$ is not taken into consideration as a trigger, the classic routing solutions would re-route the traffic in the network periodically.

IV. Experimental Test-Bed Description

A. Emulation Concept

Emulation enables test-bed creation and use with real devices and real applications. The main advantage of using a hybrid emulation-simulation-based test-bed is that it reduces any possible discontinuity when moving from simulation to real network deployment. In this work, real applications running on real devices are used for sending and receiving real video traffic over a simulated WMN topology.

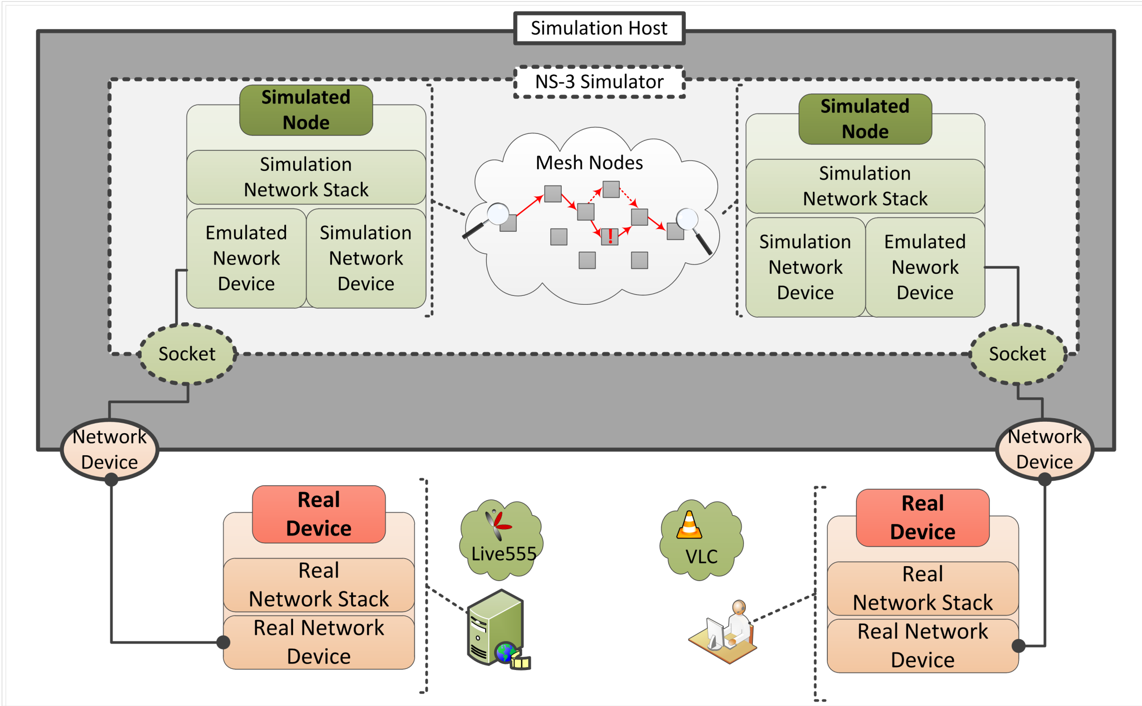


Fig. 3: Emulation Concept and Integration into Test-bed

Although, emulation reduces the gap between simulations and real life deployments, very few works make use of this feature in the validation of their results. In [15] the authors use the emulation feature provided by NS-3 for evaluating various service discovery protocols in mobile ad-hoc networks. Their test-bed consisted of a set of scripts running Linux Containers, providing a way to start the service discovery protocol. NS-3 emulation is also used in [16] for the evaluation of a distributed back pressure routing protocol for WMNs. Emulation is also used in one of our previous work for prototypic telematic services, such as safety applications or location based services, and for evaluating how these services influence the underlying network infrastructure on top of which they operate [17].

Recent works have focused as well on the limitations of using network emulation [18] inside a test-bed. The authors identify some of the issues that might arise while using emulation. However, it is proven that a good parametrization of the simulation model can give very good approximation of a real network behaviour.

Emulation is very important especially when performing research studies in the area of wireless networks with their pseudo-random behaviour. Consequently many well-known network simulators have had emulation capabilities added on, including NS-2 and Qualnet [19, 20, 21, 22], and by having NS-3 [23] natively support it.

Figure 3 presents the general concept of the combined simulation/emulation approach used in our test-bed. The interaction between the simulation environment (i.e. NS-3) and simulation host is done via sockets. The simulation host connects these sockets to the actual networking devices. These devices on the simulation host grant entry points into the simulation for the real hosts. This enables real traffic to flow between real hosts while being backhauled through a complex simulated topology.

B. Test-Bed Description

Figure 3 also illustrates the high-level view of the deployed test-bed used for assessing ViLBaS, which integrates the NS-3 simulation and emulation features. Figure 4 shows the actual test-bed deployed, which makes use of real machines playing the roles of video server, video client and simulation host, respectively.

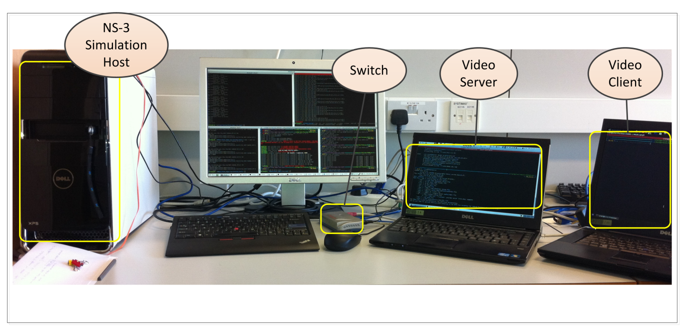


Fig. 4: Test-Bed Deployment

The test-bed presented in Figure 4 comprises of four components:

① one laptop, hosting the video server (e.g. Live555),
② one laptop, hosting the client (e.g. VLC),
③ one desktop computer, hosting the NS-3 simulator,
④ one switch, which enables the communication between the three machines.

The desktop computer, hosting the NS-3 simulation, is a Dell XPS 8300 machine with an Intel Core i7-2600 CPU@3.40 GHz and 8GB RAM memory. The machine has four cores, each with two threads.

The before mentioned components are interconnected via Ethernet cables. The network interface card on the computer hosting the NS-3 simulation is set to promiscuous mode.

Two nodes from the simulation (the most left one and the most right one in Figure 3) are chosen as ingress point and egress point, respectively, for the video traffic. All the mesh nodes in the simulation are equipped with *WifiNetDevice* components, which enable wireless communication between the nodes. As shown in the figure, the two selected nodes are having an additional *EmuNetDevice* component, which allows the node to receive or send packets to real devices outside the simulator.

Before running the tests with real video traffic, the available bandwidth between the selected two nodes is measured using Iperf. Iperf is set in client mode at one node and in server mode at the second selected node. This tool measures the available bandwidth between the two end-points by inserting probe traffic into the network. The available bandwidth between the two selected nodes is thus measured as being around 1.2 Mbps. This value is obtained according to the simulation parameters presented in the next subsection. Based on this measurement, the video load is selected accordingly. Hence, we selected three quality levels for the video in the range of the identified available bandwidth.

In order to provide the appropriate QoS guarantees to video traffic, network devices need to identify such traffic, and therefore all the video packets sent by the server need to be tagged. In this way, every simulated mesh node receiving a packet is able to identify if it belongs to a video flow and enqueue it in the video queue of the wireless network interface, or not. Following the Cisco marking scheme recommendation for multiservice networks, we set the DSCP (DiffServ code point) field in the IPv4 header with value AF41 (Assured Forwarding 41). Figure 5 presents a screen shot of a Wireshark capture of a packet tagged as belonging to a video flow (i.e. the DSCP field has a value AF41).

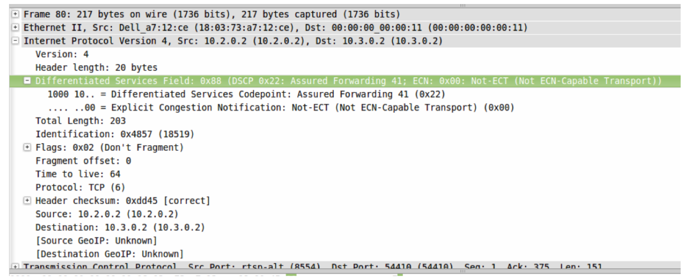


Fig. 5: Wireshark Screen Capture

C. Simulation Setup

The test-bed deployed for assessing ViLBaS with real video traffic also comprises of a simulation-based component. This component models the WMN nodes, which are carrying the video traffic. NS-3 is an event-based simulator and for large number of nodes or for high amount of traffic deployed in the simulated network, the simulation complexity increases very much. This results in simulation times much larger than real time. In a hybrid simulation-emulation environment this situation imposes several limitations, mostly in terms of the size of the topology, which have also been identified and mentioned in [18].

TABLE I: Simulation Setup

Parameter	Value
Simulator	NS-3.10 [23]
Topology	Grid 4x4
Distance between nodes	125 m
Mesh Nodes Communication	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 packets
Traffic Type	MPEG4 Video Trace Files
Video Type	Medium Quality
Video Mean Bit Rate	150 kbps
Routing Algorithm	OLSR
Weight Parameter α	0.5
Queue Occupancy Treshold	60%

The test-bed employed in our experiments uses such a hybrid approach and real video traffic. In order to minimize the effect of these limitations, extra consideration should be given to the above-mentioned situation. If the number of nodes is too high, the simulation is slower than the rate at which the real video packets are injected. This means the simulator is not able to process the packets at the speed they are being sent, leading to incorrect results. To avoid this behavior, a 16-node grid topology was chosen in which any two neighbouring nodes are placed 125 meters apart.

Similar topologies are widely used in the literature [24], [25], while very large topologies are not preferred as it has been demonstrated that the throughput drops significantly, even up to 40% on a large multi-hop path [26]. More specifically, the packets are lost while in transit and this is undesirable, especially for video traffic which is sensitive to packet loss.

A grid topology is chosen in this work as grid topologies are proven to show benefits in terms of both coverage and connectivity [27].

The weighting parameter α and the queue occupancy threshold τ are parameters that belong to the proposed mechanism. In the scenarios considered τ was set to 60%. This value was determined following extensive simulations in which for

TABLE II: Big Buck Bunny - Video frames belonging to different quality levels of the same movie sequence

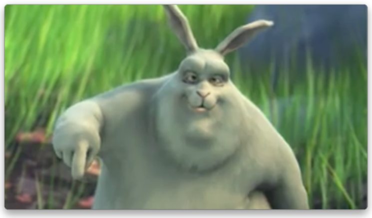
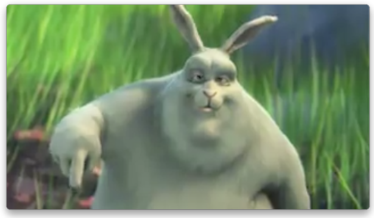
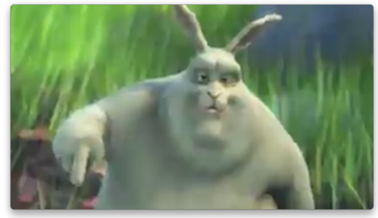
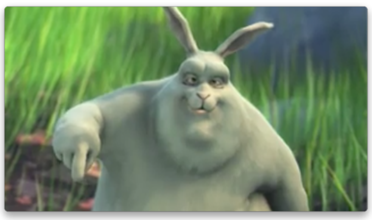
BIG BUCK BUNNY		
QL1	QL2	QL3
		

TABLE III: Video frames belonging to Big Buck Funny, Clay Figures and Tolerantia

Video Sequences Encoded at QL2		
QL2	QL2	QL2
		

diverse topologies and different video queue sizes, the queue occupancy threshold was varied from 30% to 100%. A value of 60% forτ was associated consistently with the best results in terms of packet loss, Peak Signal-to-Noise Ratio (PSNR) and delay. The weighting parameter α gives higher importance to one or the other of the sums components. A higher value for α encourages re-routing of the selected flows through less congested nodes at the cost of increased number of hops and higher delays, and a lower value for α results in re-routing the flows over shorter paths, but very likely more congested, and therefore increasing loss probability. In our test-bed the α parameter was set to 0.5 as this value best balances the two potential avenues of the mechanism and thus enabling it to find less congested and relatively shorter paths to the destination.

Simulated background video flows are used to load the WMN. Video traces of MPEG4 streams [28] are used and are randomly distributed between the mesh nodes. The video traces are extracted from video traffic with an average bit rate of 150 kbps and a peak bit rate of 800 kbps. All the other parameters used for setting up the simulation model are summarised in Table I.

D. Video Content

The real video content which is delivered through the WMN consists of three different movie sequences:

1) Big Buck Bunny [29]
2) Clay Figures [30]
3) Tolerantia [31]

The *Big Buck Bunny* is a 10 minutes long animated clip produced by the Blender Foundation. The movie is transcoded at three different quality levels, based on the encoding settings presented in Table IV and the available bandwidth between the two selected nodes as measured by Iperf. A 50 seconds long movie sequence is selected to be streamed by the server to the client, through the simulated WMN. The selected sequence presents fast changing scenes with dynamic elements and characters, thus having very high levels of spatial and temporal complexity.

Table II illustrates, for a selected frame, the variation in quality between the three selected quality levels for the *Big Buck Bunny* movie sequence. The image encoded at QL1 presents sharp edges and clear details, while the frame for QL3 encoding has blurry aspects due to the lower video bitrate. The image encoded at QL2 does not present sharp edges as QL1 does, but provides a good quality level. These three quality levels will be used later for assessing ViLBaS under different video bitrates.

TABLE IV: Encoding Settings for the Video Sequences

Quality Level	Video Codec	Overall Bitrate	Reso-lution	Frame Rate
QL1	H264/MPEG4 Baseline Profile	575 Kbps	320	25
QL2		324 Kbps	x	25
QL3		197 Kbps	176	25

50 second long sequences from both, *Clay Figures* and *Tolerantia* are extracted and encoded at the QL2 quality level. As we will see it later, the QL2 quality level represents the best choice with regard to the available bandwidth in the WMN. The selected sequence from the *Clay Figures* movie presents changing scenes with low dynamic background (i.e. a clay shaping into different objects), thus having very low levels of spatial and temporal complexity.

The sequence selected from *Tolerantia* movie presents a camera moving slowly over a landscape scene with one character moving very slowly. Table III illustrates frames belonging *Big Buck Bunny*, *Clay Figures* and *Tolerantia* sequences, respectively. All the frames belong to movie sequences encoded at the QL2 quality level.

Note that relative to the three selected movies, *Big Buck Bunny* and *Tolerantia* consist of computer-generated images, while *Clay Figures* represents a real life video clip. This selection of video sequences ensures that the proposed mechanism is tested for both animated and real life videos.

E. Simulation Scenarios and Video Quality Assessment

ViLBaS performance is evaluated by comparing its results with those collected in four other scenarios.

TABLE V: Considered Scenarios

Scenario	Characteristics	Video Flows
SC1	Static Routes	One real video flow
SC2	Static Routes	One real video flow & five simulated video flows
SC3	OSLR + hop-count	
SC4	OLSR + ETX	
SC5	ViLBaS	

In the first scenario (SC1) we evaluate the quality of the transmitted video between the server and the client when no other simulated background video flows are present in the network. The second scenario (SC2) considers one real video flow running between the server and the client and five additional simulated video traces. For this scenario we consider a static routing table, which does not change over time. The third (SC3) and forth (SC4) scenarios are similar to the second scenario, but we considered the OLSR routing protocol [4] employing the hop-count metric and OLSR employing the ETX metric [32], respectively. The fifth scenario (SC5) evaluates the performance of ViLBaS. Table V presents a summary of the selected scenarios for assessing the ViLBaS mechanism against the other routing mechanisms.

In each scenario the quality of the video received at the client side is assessed using the MSU Video Quality Measurement Tool [33]. This tool is a program for objective video quality assessment, which enables the user to compare the quality of two videos considering diverse objective metrics.

Objective metrics are used to estimate the video quality through mathematical models. The objective metrics differentiate between them depending on the computational complexity and the factors they consider for estimating the quality levels. Objective metrics include: Peak Signal-to-Noise Ratio (PSNR), Video Quality Metric (VQM) [34], Structural Similarity Index (SSIM) [35], Multi-Scale Structural Similarity Index (MS-SSIM) [36], and many others. Subjective metrics are also used to assess video quality and among them the best know is Mean Opinion Score (MOS) [37].

In our test-bed we compare the video received at the client side with the original video, which is sent by the server in terms of PSNR and SSIM. PSNR is the most common and most widely used objective method for video quality assessment. Its main advantage is that it has low computational complexity. However, this metric has been criticised for poor correlation with the perceived video quality. SSIM is based on frame-to-frame measuring of three components: luminance similarity, contrast similarity and structural similarity. These three components are combined into a value which reflects the similarity between two frames. The obtained value ranges between 0 and 1, where 0 means no similarity with the original frame, and 1 means the exact same frame as the original. Its main advantage is that it is more consistent with the human perception than PSNR. Additionally, the packet loss and throughput are also considered for assessing the video received at the client side as QoS metrics.

In general PSNR is given in dB, but in order to make comparisons clearer it is simpler to map the PSNR dB scale into the MOS scale. For this purpose, we employ the PSNR dB scale mapping to the MOS ITU 5-point scale, as shown in Table VI. It is considered that acceptable values for wireless transmission quality loss should be about 20 dB to 25 dB for the PSNR metric [38]. The mapping between the SSIM metric to the MOS scale is presented according to the work done in [39] and the mapping between PSNR and MOS is presented according to the work in [38].

TABLE VI: PSNR and SSIM to MOS conversion

PSNR	MOS	SSIM	Meaning
$\geq$27.2	5	>0.99	Excellent
26.9-27.2	4	[0.95,0.99)	Good
26.1-26.9	3	[0.88,0.95)	Fair
16.2-26.1	2	[0.5,0.88)	Poor
$\leq$16.2	1	<0.5	Bad

Although many objective metrics have been proposed in the literature, a general consensus on using a specific metric over another has not been achieved yet. This work has used on one hand PSNR, SSIM and their mapping to the MOS scale, and packet loss and throughout on the other for assessing the video delivery performance and analysing how each scenario impacts the quality of the received video.

V. Analysis of Results

The following tables present the results obtained for video transmissions when considering the different scenarios, as detailed in Table V. In all the tables with results, SC1 is associated with the case when the real video only is transmitted over the simulated WMN (i.e. there is no contention). Because the video bitrate is lower than the maximum bandwidth identified with Iperf, the quality of the received video is the same as the one sent (zero loss). In the results, a value of 50dB was considered as the maximum PSNR value for a video received with no loss at the client side instead of the undefined value that would result when computing PSNR estimation with a packet loss of 0 (i.e. due to division by 0).

For all the results presented in this paper, each experiment was repeated five times in order to verify the consistent behaviour of the proposed mechanism. Different start times within each movie and different simulation seeds were used. Although there is natural variability between these results, they demonstrate that our proposed mechanism consistently outperforms the other solutions for different quality levels of the movies and various video content in all the experimental tests.

A. Performance Assessment for Video Delivery at Different Bitrates

This subsection assesses the delivery performance over the WMN using the *Big Buck Bunny* video sequence encoded at three different quality levels (QL1, QL2, QL3).

Table VII presents the results obtained when the video is encoded at the QL1 quality level. Packet loss, throughput and estimated user perceived quality using PSNR and SSIM are computed on the received video for all five scenarios.

TABLE VII: Big Buck Bunny encoded at QL1

BIG BUCK BUNNY - QL1				
Scenario	Packet Loss [%]	PSNR [dB]	SSIM [0-1]	Throughput [kbps]
SC1	0	50	1	575.00
SC2	22.6	15.16	0.64	445.05
SC3	22.6	14.91	0.71	445.05
SC4	33.3	13.90	0.64	383.53
SC5	13.1	16.69	0.78	499.67

It can be observed that among all five scenarios, SC5 (ViLBaS) gives the best results across the five performance metrics considered with the natural exception of SC1, which is the ideal case.

Because for this case the video bitrate is almost half of the available bandwidth the packet loss obtained is high due to contention with the other simulated video flows. However, ViLBaS obtains 13% packet loss, which is almost 42% lower than the packet loss obtained in SC2 and SC3, and 59% lower than the packet loss obtained in SC4 .

In terms of PSNR, all scenarios suffered a drop in quality for the video received. However, ViLBaS performs better than all other three scenarios considered. ViLBaS obtains a PSNR value 10% higher than SC2, 11% higher than SC3 and 20% higher than SC4. The highest SSIM value (i.e. 0.78) is obtained by ViLBaS, which brings an improvement of 21% compared to SC2, 9% compared to SC3 and 21% compared to SC4.

Considering that the video consumes half of the available bandwidth, the quality of the received video in terms of PSNR and SSIM is relative low. However, this quality is acceptable for users with small screen devices. For users with larger screen devices, for which the received quality is not acceptable in this case, an application-layer adaptive multimedia solution such as QOAS [40], ROIAS [41] or BaSe-AMy [42] could be employed to adapt the video to a lower quality level, such as QL2 or QL3. These quality levels are considered and analyzed in the following tables. Another solution could be to use access control mechanisms. This option should be employed as a last measure, in case the re-routing mechanism does not solve the congestion problem.

TABLE VIII: Big Buck Bunny encoded at QL2

BIG BUCK BUNNY - QL2				
Scenario	Packet Loss [%]	PSNR [dB]	SSIM [0-1]	Throughput [kbps]
SC1	0	50	1	324.00
SC2	7.6	20.66	0.90	299.37
SC3	7.2	20.96	0.92	300.67
SC4	6.4	19.43	0.88	303.26
SC5	1.7	27.46	0.97	318.49

Table VIII summarises the results obtained when the video is encoded at QL2 quality level. The packet loss, throughput, PSNR and SSIM are computed on the received video for all five considered scenarios.

Similar to the previous case, using ViLBaS results in the lowest packet loss of only 1.7%. Compared to the SC2, SC3 and SC4 scenarios the packet loss is with 77%, 76% and 73% lower, respectively. The PSNR value obtained when using ViLBaS for video delivery is 27.46 dB, which is 31% higher than the PSNR value obtained in SC3 scenario (i.e. 20.96 dB), 33% higher than that in SC2 and 41% higher than that resulted in SC4. The highest SSIM value of 0.97 is obtained also when employing ViLBaS, which is 3% only from the ideal.

TABLE IX: Big Buck Bunny encoded at QL3

BIG BUCK BUNNY - QL3				
Scenario	Packet Loss [%]	PSNR [dB]	SSIM [0-1]	Throughput [kbps]
SC1	0	50	1	197.00
SC2	6.4	19.89	0.91	181.58
SC3	11.6	20.29	0.91	174.14
SC4	4.7	23.98	0.94	187.74
SC5	1.7	31.76	0.97	193.65

Table IX includes the results obtained when the video is encoded at QL3 quality level. Although there is no improvement in terms of the packet loss, compared to the previous case (QL2), as the bitrate is higher, the estimated user perceived quality of the video at the client side is higher and reached 31.76 dB in terms of PSNR. Compared to the other scenarios, ViLBaS gives the best PSNR value for the considered video, 60% higher than the PSNR value obtained for SC2, 56% higher than the PSNR obtained in SC3, and 32% higher than the PSNR value obtained in SC4. In this case, as in the previous one, the SSIM value is 3% only from the ideal case.

In this subsection we considered the transmission of the same video encoded at different quality levels. As expected, the video delivery performance correlates with the quality level considered. However, when using ViLBaS the best performance is achieved in terms of QoS parameters such as loss and throughput and estimated user perceived quality, in comparison with other solutions, regardless of the transmitted quality of the video sequences.

B. Assessment of Delivery Performance for Different Video Content

This subsection assesses the performance of ViLBaS when delivering different video content over the simulated WMN. Different video sequences encoded at the same quality level QL2 are considered for transmission. This specific quality level is selected following the results of the previous subsection, as it enables good video delivery quality given the available bandwidth.

We have considered *Big Buck Bunny*, *Clay Figures* and *Tolerantia* video sequences encoded at QL2 in the context of the five scenarios. *Big Buck Bunny* presents fast changing scenes with many dynamic elements; *Clay Figures* has average motion content scenes with average number of dynamic elements and static background, while *Tolerantia* includes a slow moving background and a character with low dynamicity. Tables X, XI and XII present the results obtained for the three video sequences, respectively.

TABLE X: Big Buck Bunny encoded at QL2

BIG BUG BUNNY - QL2				
Scenario	Packet Loss [%]	PSNR [dB]	SSIM [0-1]	Throughput [kbps]
SC1	0	50	1	324.00
SC2	7.6	20.66	0.90	299.37
SC3	7.2	20.96	0.92	300.67
SC4	6.4	19.43	0.88	303.26
SC5	1.7	27.46	0.97	318.49

TABLE XI: Clay Figures encoded at QL2

CLAY FIGURES - QL2				
Scenario	Packet Loss [%]	PSNR [dB]	SSIM [0-1]	Throughput [kbps]
SC1	0	50	1	324.00
SC2	9.2	25.77	0.98	294.19
SC3	7.1	30.90	0.98	300.96
SC4	9.9	26.19	0.98	291.92
SC5	1.0	36.21	0.99	320.76

For all three movie sequences considered, when comparing the five scenarios considered, ViLBaS performs the best in terms of packet loss, throughput and PSNR and SSIM.

TABLE XII: Tolerantia encoded at QL2

TOLERANTIA - QL2				
Scenario	Packet Loss [%]	PSNR [dB]	SSIM [0-1]	Throughput [kbps]
SC1	0	50	1	324.00
SC2	10.6	20.28	0.81	289.65
SC3	15.6	20.27	0.81	273.45
SC4	10.5	18.11	0.74	289.98
SC5	1.2	25.23	0.93	320.11

For the *Clay Figures* sequence (Table XI), ViLBaS (SC5) gives a PSNR value of 36.21 dB, which is 40% higher than when using static routes (SC2), 17% higher than OLSR employing hop-count (SC3), and 38% higher than OLSR employing ETX (SC4). In terms of packet loss, ViLBaS losses only 1% of all packets, which is 89% lower than SC2, 85% lower than SC3 and 89% lower than the packet loss obtained in SC4 . In terms of SSIM, in all scenarios considered ViLBaS gives almost the highest value (i.e. 0.99), which is 1% smaller than the ideal value.

When considering the *Tolerantia* sequence (Table XII), ViLBaS (SC5) gives a PSNR value of 25.23 dB, which is almost 24% higher than OLSR employing hop-count (SC3) and the scenario using static routes (SC2). Compared to SC4, ViLBaS obtains a 39% higher PSNR value. In terms of packet loss, ViLBaS losses only 1.2% of all packets, which is 88% lower than SC2 and SC4, and 92% lower than the value obtained in SC3. In terms of SSIM, ViLBaS obtains the highest value, 0.93, among all the scenarios considered.

When performing the comparison between the three selected movie sequences, when using *Clay Figures* the highest PSNR is obtained because of the reduced area that changes between all frames (i.e. the clay figure changing shapes) on a static background. On the other hand, *Big Buck Bunny* and *Tolerantia* sequences have moving background and moving characters, which in case of lost frames, the impact on the PSNR metric is high, thus the PSNR values obtained by both movies are similar.

C. Overhead Analysis

This section analyses the overhead incurred by ViLBaS compared to the other solutions considered. For simplicity, the overhead analysis considers a 100 second interval. OLSR transmits periodically HELLO and TC messages. HELLO messages are not broadcasted and they can reach only the one-hop neighbours of the nodes sending them. TC messages, on the other hand, are broadcasted and retransmitted by every node in order to diffuse them in the entire network. If we consider the default emission intervals of these messages as recommended in RFC 3626[4], a HELLO message is sent every 2 seconds and a TC message every 5 seconds. Considering the above mentioned assumption, in the considered mesh network:

- 48 HELLO messages are exchanged every 2 seconds (4 corner nodes*2 HELLO messages + 8 edge nodes*3 HELLO messages + 4 nodes*4 HELLO messages)

- 48 TC messages are exchanged every 5 seconds. For simplicity we assume the TC messages are not forwarded. However, in reality these messages are forwarded, thus the number of TC messages exchanged is larger

In a 100 second time interval, 2400 HELLO and 1200 TC messages, which totals 3600 messages are exchanged. This is the case for SC3 and SC4.

SC1 and SC2 considered in our evaluation involve keeping static the routes discovered initially. Thus, no overhead is incurred by this mechanism, but the performance of delivery is poor in dynamic network conditions.

In SC5, the largest number of re-routings ViLBaS performed was seven and the lowest number of re-routings performed was three. These re-routings were performed for the duration of the simulation run which is longer than the interval considered in our assumptions. However for the analysis of the overhead introduced by ViLBaS, we consider the worst-case scenario in which ViLBaS always re-routes seven flows (regardless of the video content and quality level considered) and always operates on the longest path (e.g. six hops). Thus, the following messages are exchanged:

- one message is sent by the congested node to the previous node on the path of the selected flow
- four messages are sent by the previous node to the one-hop neighbour (in a realistic scenario a message would not be sent to the congested node if it belongs to the one-hop neighbours set)
- four reply messages are sent by the one-hop neighbours (if the congested node belongs to the one-hop neighbour set it would not sent a reply)

Thus, eight messages would be exchanged per hop. For a path of six hops (worst case scenario) 49 messages would be exchanged. Considering the worst-case scenario of seven re-routings, 343 messages would be exchanged. Thus, the overhead introduced by ViLBaS represents only 10% of that introduced by the other four scenarios discussed.

VI. Conclusions

This paper addresses the issue of unbalanced traffic distribution in WMNs with focus on video flows. An unbalanced traffic distribution leads to both poor utilisation of network resources by overloading some mesh nodes and, due to the consequent loss, to lower user perceived video quality. The paper describes ViLBaS, a selected load-balancing mechanism, which prevents mesh node congestions by monitoring the video traffic and performing re-routing for selected video flows around the loaded area.

The performance evaluation of ViLBaS was carried out using a hybrid emulated-simulated test-bed in terms of QoS parameters such as loss rate and throughput and QoE metrics including PSNR and SSIM. Video sequences encoded at various quality levels and video sequences with different characteristics are considered for evaluation. ViLBaS was compared with three other representative state of the art solutions and the results demonstrate how ViLBaS outperforms the other solutions in terms of all performance parameters across all the scenarios considered. Noteworthy is that on average the quality of the video delivered when employing ViLBaS was associated with a PSNR value with 30% higher than the second-best solution in all four considered scenarios. This demonstrates the excellent benefit of our proposed solution.

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