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Evaluation of Video Transmission Energy Consumption and Quality

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Abstract The widespread use of wireless enabled devices and the increasing capabilities of wireless technologies has promoted multimedia content access and sharing among users. However, the quality perceived by the users still depends on multiple factors such as video characteristics, device capabilities, and link quality. While video characteristics include the video time and spatial complexity as well as the coding complexity, one of the most important device characteristics is the battery lifetime. There is the need to assess how these aspects interact and how they impact the overall user satisfaction. This paper advances previous works by proposing and validating a flexible framework, named EViTEQ, to be applied in real testbeds to satisfy the requirements of performance assessment. EViTEQ is able to measure network interface energy consumption with high precision, while being completely technology independent and assessing the application level quality of experience. The results obtained in the testbed show the relevance of combined multi-criteria measurement approaches, leading to superior end-user satisfaction perception evaluation.

Keywords Energy efficiency · Video · IEEE 802.11 · Wireless · Quality of experience · Testbed

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1 Introduction

Nowadays many computer applications, especially multimedia applications, are becoming increasingly important in a true technological society. With the widespread deployment of new multimedia systems, applications such as Internet protocol television (IPTV), video conferencing and video on demand (VOD) replace legacy systems very quickly [1]. The growing amount of multimedia traffic raises new challenges for access technologies, since these applications have stronger network requirements. The quality expectations of end-users using multimedia video services over the Internet are also high, since these services are replacing legacy video systems, where the perceived Quality of Experience (QoE) plays a crucial role. Thus, it is imperative for both operators and end-users to employ novel mechanisms and tools to perform accurate QoE assessment in real world scenarios. Besides the concerns about the quality of video traffic, the future Internet must also be able to meet several requirements regarding energy-efficiency [2, 3].

Until now, most research work has focused on each of the issues described above, lacking a combined study of both QoE and energy performance of multimedia applications over wireless access networks. This work extends a methodology for evaluating quality and energy consumption of video transmission [4], aiming at filling the identified gap by carrying out an integrated assessment investigation of video quality and energy consumption. Apart from using distinct evaluation scenarios, where various wireless network conditions were emulated (e.g., delay or packet loss), this paper also investigates the relationship between video sequence characteristics and the quality achieved. Furthermore, the proposed EViTEQ framework was also designed to allow easy configuration procedures, while being able to support fully automatized and integrated batch test processing. The usage of standalone QoE evaluation tools within the proposed framework is possible too.

The empirical analysis performed in the experimental testbed showed the importance of integrated and multi-featured evaluation concerning the end-user perceived quality, where both video QoE and energy consumption are extremely important. By analyzing the performance of videos with different characteristics and heterogeneous wireless medium conditions, the results have shown the relevance of the proposed combined approach within a real demonstrator. Additionally, the achieved results highlight the need to establish a proper trade-off between end-user perceived Quality of Experience and energy required by the network interface to receive a video.

The rest of the paper is structured as follows. Section 2 discusses related work and presents some basics on video quality evaluation and metrics, followed by the introduction of the proposed framework in Sect. 3. The experimental assessment procedure and the obtained results with the proposed framework to evaluate video quality and energy consumption within various heterogeneous IEEE 802.11 access scenarios are described in Sects. 4 and 5, respectively. Finally, Sect. 6 summarizes the results of the work and discusses the main conclusions.

2 Approaches for Assessing Energy Consumption in Wireless Networks

This section discusses the key issues involved in the assessment of video transmission energy consumption and quality over wireless networks. In Sect. 2.1, the most relevant assessment requirements are identified, followed by the related work analysis in Sect. 2.2. Section 2.3 introduces the reader to video quality evaluation basics and metrics.

2.1 Assessment Requirements

The study of energy-efficient video transmission in portable devices assumes an important role in the end-user's usage of those devices, as these multimedia-based applications have strong impact on the devices' battery lifetime. Various related works have addressed this problem by employing an empirical approach, ranging from basic energy assessment testbeds to more complex energy-aware evaluation methodologies. Concerning video assessment, it is important to assess not only network level QoS metrics, but also to have mechanisms able to evaluate the QoE perceived by the end-users. A detailed discussion regarding video quality evaluation concepts and metrics will be provided in Sect. 2.3.

Although there are various approaches in the literature addressing this subject, there is a gap concerning the systematic identification of the core requirements that should be fulfilled to guarantee accurate and realistic assessment of video transmission energy consumption and quality. To simplify the analysis, the identified features were grouped into three distinct main subjects, namely evaluation environment, energy consumption assessment, and quality assessment, as follows:

⇒ Evaluation environment:

- *Testbed assessment*: the assessment should be done in a testbed, to accurately measure the impact in real life systems;
- *Configurable network conditions*: the capability to perform assessments under heterogeneous network conditions (e.g., random losses or varying bandwidth);
- *Batch tests*: batch test processing for systematic repetition of experiments;
- *Easy configuration*: to provide easy configuration of the evaluation environment, namely by using configuration files (e.g., XML).

⇒ Energy consumption assessment:

- *High precision*: it is vital to employ hardware providing high resolution and high accuracy energy measurements;
- *Focused measurement*: measurements should be performed only on the network cards, to accurately study energy consumption in wireless systems;
- *Technology independence*: the assessment approach must be technology independent, which can guarantee its usage and accuracy with distinct wireless access technologies.

⇒ Quality assessment:

- *Quality of Experience (QoE) assessment*: Quality perceived by the end-users is very important to understand the impact of video optimization techniques;
- *Quality of Service (QoS) assessment*: the use of network level metrics is needed to complement QoE assessment and to provide insights on global network performance;
- *Thorough metrics*: evaluation should encompass multiple metrics, to allow the assessment from different perspectives, by using distinct QoE and QoS metrics.

These requirements will drive the analysis of related work presented in the next section towards the identification of open issues about the assessment of energy-efficient video transmission.

2.2 Related Work Analysis and Discussion

This section introduces and discusses the related work regarding the video quality and energy consumption assessment in wireless networks.

Balasubramanian et al. [5] have studied energy consumption in mobile phones with multiple network interfaces. The main goal was to evaluate energy efficiency of 3G, GSM and WiFi. Their main contribution is a protocol that reduces energy consumption of applications by scheduling transmissions. Wang and Manner [6] used an Android-based phone, and tested the energy consumption by means of Enhanced Data rates for Global Evolution(EDGE), High Speed Packet Access (HSPA) and IEEE 802.11 wireless technologies. The effects of packet size and packet rate were addressed in the study, but only the total energy consumed by the device was measured, which is a serious drawback when trying to optimize network protocols or applications.

Rice and Hay [7] proposed a methodology to measure the energy consumption of IEEE 802.11 interfaces in mobile phones, by replacing the battery with a tailored plastic battery holder; this allows an accurate measurement to be made within the telephone "real energy" circuit. The measurement system also employs a high-precision resistor to prevent rapid changes in energy consumption caused by the high-frequency components of the mobile phones. The study encompasses batch test operations with different mobile phones. While this study is able to measure energy consumption of mobile phones accurately, it is not able to carry out a precise evaluation of the impact of IEEE 802.11 interfaces on mobile phones. The reason for this is that the various mobile phones tested have different behaviors, particularly when employing different operating systems or hardware. The energy consumption while receiving a video over UDP and TCP in Android devices has been addressed by Trestian et al. [8]. The authors conducted a study encompassing the analysis of network-related parameters in the device's power consumption when receiving video. Although this study reports both QoS and QoE metrics in the video assessment, it does include neither a high-precision measurement facility, nor a technology independent assessment with easy configuration allowing batch tests.

Shih et al. [9] have developed a technique to increase the battery lifetime when VoIP calls are made. The proposed technique is able to shut down the wireless card/radio when it is not in use. Although this technique was designed to a specific application (i.e., VoIP), it has the potential to allow the network interface states (e.g. idle or sleep) to be analyzed so that other applications can be adapted accordingly. Following the need to better understand the impact of application design in the energy consumption, Vergara and Nadjm-Tehrani have proposed the EnergyBox [10] framework. The main goal of EnergyBox is to enable an accurate energy consumption estimation of data transmission. The application data pattern can be given by capturing the real network traffic or by using a synthetic traffic generation tool. EnergyBox also uses specific information about the wireless network interface in use and allows the configuration of device power levels. The proposed tool was validated with real hardware and showed an accuracy between 93–99 % for WiFi and 94–99 % for 3G. Even though EnergyBox can help developers to improve and validate energy-aware solutions, it cannot provide energy consumption information of the network interface. Furthermore, as the tool relies on information about the power consumption of the distinct states of wireless interfaces, it depends on the wireless technology used, and it does not provide Quality of Experience assessment.

Li et al. [11] have conducted a study of energy-efficient video transmission over a wireless link, by controlling the parameters associated with physical and link layers. The results showed energy savings of around 38 % for a CDMA system supporting six users. However, the assessment was entirely based on simulations, which do not accurately reflect real system behavior. Other simulation studies have proposed energy-efficiency approaches for video transmission based on scalable video coding features, using content-aware rate control techniques [12] and cooperative video transmission with end-to-end statistical Quality of Service provisioning [13]. The mobile video services' energy consumption using both IEEE 802.11 and cellular network access was also studied by Hoque et al. [14]. The assessment was performed in a testbed, and includes the usage of three distinct video streaming services and six distinct mobile phones. The attained results show that energy performance of mobile phones when receiving video streaming is not optimal, and various optimization suggestions are given. In fact, the results show the importance of having a way to measure both quality and energy consumption in a integrated way, regardless of the assess technology.

Yuan el al. [15] have employed cross-layer techniques to improve multimedia application quality, while keeping battery energy consumption at a minimum. The proposed cross-layer solution was validated in a testbed with the aid of a digital oscilloscope for assessment of energy related factors, but did not take into account the impact of the approach on end-user perceived quality. The evolution of video quality metrics has shown the importance of making an accurate assessment of end-user QoE [16]. Many researchers have studied how transmitting video under different network conditions affects the perceptions of end-users, but without focusing on energy consumption [17, 18].

A qualitative assessment study of the reviewed literature, taking into account the requirements already defined in Sect. 2.1, was performed. The main goal was to assess the related works' capability to fulfill the needs of an accurate and realistic assessment approach for video transmission energy consumption and quality. Table 1 summarizes the findings, by qualitatively analyzing the availability of the relevant features in each work. The check mark (✔) means that the work has such feature, while the cross (✗) says that it is not available. Moreover, if the feature is completely out of scope of the work (e.g., a work does not take into account any energy related issue) it is marked with a square symbol (■)

The empirical energy consumption measurements have been addressed in the literature mainly by measuring the total energy consumption of end-user devices. Although these techniques can be a feasible approach to analyze these systems as a whole, they do not focus on the energy consumption of the network interface and consequently they are not able to measure only the energy consumed by the MAC and PHY layers. Accurate energy measurements at the lower layers enable the possibility to establish important relationships between application network design and the energy spent.

Nevertheless, the state-of-the-art analysis also showed that there is a clear gap in the literature concerning unified experimental evaluation of video energy-efficiency assessment, with multiple works considering only energy consumption or quality evaluation as main goal. Therefore, there is the need to propose an integrated empirical framework able to assess video transmission energy consumption and quality, while considering all the core requirements previously identified. Besides being an asset to validate and evaluate novel energy-aware video streaming algorithms and approaches, a framework fulfilling all the identified requirements can also play a key role in the design of realistic simulation models.

Table 1 Related work analysis summary

Work	Evaluation environment				Energy consumption assessment			Quality assessment		
	Testbed	Config. net cond.	Batch tests	Easy config.	High precision	Focused measur.	Tech indep.	QoE	QoS	Thorough metrics
[5]	✔	✗	✗	✗	✔	✗	✔	✗	✗	✗
[6]	✔	✗	✗	✗	✔	✗	✗	✗	✔	✗
[7]	✔	✗	✔	✗	✔	✗	✗	✗	✗	✗
[8]	✔	✗	✗	■	✔	✗	✗	✔	✔	✔
[9]	✔	✗	✗	✗	✔	✔	✔	✗	✗	✗
[10]	✔	✗	✔	■	✔	✗	✗	✗	✗	✗
[11]	✗	✔	✔	■	■	■	■	✗	✔	✗
[12]	✗	✔	✔	■	■	■	■	✗	✔	✗
[13]	✗	✔	✔	■	■	■	■	✗	✔	✗
[14]	✔	✗	✗	■	✔	✗	✗	✗	✔	✗
[15]	✔	✗	✗	✗	✔	✗	✗	✗	✗	✗
[17]	✔	✗	✗	✗	■	■	■	✔	✔	✗
[18]	✔	✗	✗	✗	■	■	■	✔	✔	✗

✔ available feature, ✗ not available feature, ■ out of scope

2.3 Video Transmission Basics and Evaluation Metrics

Video transmission requires high bandwidth, which is reduced through the use of adequate coding mechanisms. Currently, one of the most widely used codecs is H.264 [19], also known as MPEG-4 Part 10 or AVC (Advanced Video Coding), which was developed by the ISO/IEC Moving Picture Experts Group (MPEG) and the ITU-T Video Coding Experts Group (VCEG). H.264 can provide the same quality as legacy MPEG-4 Part 2 but it only uses between one third to one half of the bandwidth.

There are three distinct type of frames, such as I, P and B. I-frames are the only independent frames. P-frames are predicted frames and depend on the previous I-frame. B-frames are bidirectionally predicted frames and depend on both I and P frames. The only optional frames are the B-frames. Moreover, MPEG-4 combines all the frames in a Group of Pictures (GOP). Each GOP consists of a single I-frame, various P-frames and, if required, the corresponding B-frames. Figure 1 illustrates the GOP structure for H.264/MPEG-4 AVC.

H.264 is used in High-Definition TeleVision (HDTV) and Blu-Ray. It is also an optional codec inITU-T H.323, which is recommended for audio-visual communication in packet-based networks. A detailed analysis of the performance and complexity of H.264/MPEG-4 AVC is shown in [21]. Wiegand et al. have analyzed its standard implementation and architecture in detail, and made comparisons with the most popular legacy video compression standards, such as H.263, MPEG-2 and MPEG-4 [19, 22].

HDTV, video on demand, video streaming, and video broadcasting are all non-interactive applications, since the end-users only receive the video and otherwise do not interact. The applications that have these characteristics are less vulnerable to network delays, since buffering mechanisms and error control protocols do not affect the end-user experience. Nonetheless, bandwidth requirements of non-interactive applications are often higher than those of other video systems (e.g., video conferencing). The bandwidth requirement is a serious issue in HDTV transmissions, because each channel requires high bandwidth. As in interactive systems, the loss rate is important, because each packet contains different information about the video.

During the last few years, researchers have deployed new metrics and methods to evaluate video application quality in an attempt to address the accuracy problem in video quality assessment. These new techniques are aimed at mapping the information collected in the network to end-user perceived quality, usually known as Quality of Experience. The following sections outline some of the most important metrics that are employed to address video streaming QoE.

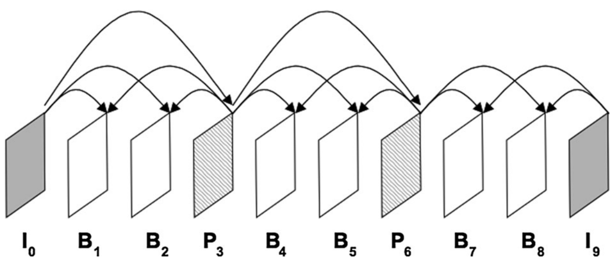


Fig. 1 GOP structure for H.264/MPEG-4 AVC (source [20])

2.3.1 Peak Signal to Noise Ratio

The peak signal to noise ratio (PSNR) is an objective evaluation metric that represents the ratio between signal power and noise power. In the context of video evaluation, the original signal is the original video and the noise is the error caused by compression algorithms/codecs, losses in the network and other problems in video delivery.

The calculation of PSNR, shown in Eq. 2, is based on the mean squared error (MSE) metric (Eq. 1).

$$MSE = \sum_{i=1}^{x}\sum_{j=1}^{y}\frac{(|A_{(i,j)} - B_{(i,j)}|)^2}{x \times y} \tag{1}$$

$$PSNR(dB) = 10 \times \log_{10}\left(\frac{MAX^2}{MSE}\right) \tag{2}$$

where *MAX*—the maximum fluctuation of the input image pixel; *A* and *B*—the images to be compared; x—image width; y—image height; $x \times y$—number of pixels.

This metric is usually converted into a mean opinion score (MOS) scale. However, PSNR raises several problems regarding the quality perceived by end-users. Figure 2 shows two images with the same PSNR; however, it is noticeable that the quality of the image on the right is inferior.

The weak performance of PSNR is due to its inability to assess the different degrees of sensitivity of the human vision. In fact, PSNR is distortion and content agnostic. The distortion-agnostic property is related with the characteristics of distortion. The content-agnostic property is associated with the place where the distortion occurs; for instance, if the distortion is in the sky it will have less impact on the subjective quality than if it is in the tower [16].

2.3.2 Structural Similarity

The Structural Similarity (SSIM) index [23] is an objective and full-referenced image quality metric, which measures the similarity between two images. SSIM is based on three

Fig. 2 Example of a PSNR error: both images have the same PSNR (source [16])

different similarity components, namely contrast, luminance and Structural Similarity. Unlike PSNR, SSIM considers the parameters of human eye perception, making the evaluation more accurate. Equation 3 illustrates the general form of SSIM.

$$SSIM(x, y) = [c(x, y)]^{\alpha} \times [l(x, y)]^{\beta} \times [s(x, y)]^{\gamma} \tag{3}$$

where c—luminance comparison of signals; l—contrast comparison of signals; s—structure comparison of signals; x and y—two non-negative image signals; α, β, γ—weight/importance of each component.

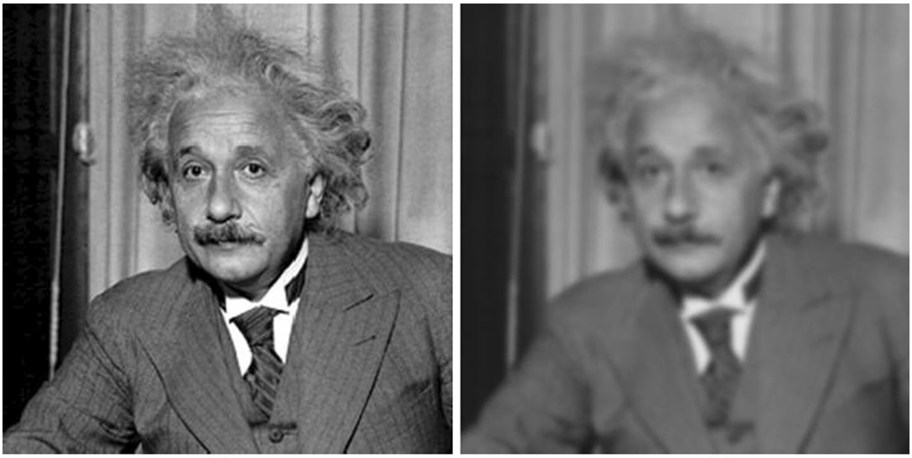
The final SSIM metric is a merging of the three similarity components in a unique value between 0 and 1, where 0 indicates there is no correlation with the source image, and 1 indicates the image is completely equal. Figure 3 illustrates two images with the same PSNR. It is possible to observe that Fig. 3a is clearly better than Fig. 3b.

SSIM is able to distinguish the quality of the images; in Fig. 3a SSIM = 0.988 (almost equal to the original), while in Fig. 3b SSIM is only 0.694. This is a considerable improvement in accuracy compared to PSNR. In addition, SSIM not only detects problems arising from the compression algorithm, but it is also able to detect problems caused by artifacts [25].

2.3.3 Video Quality Metric

The video quality metric (VQM) [26] is a standardized objective video evaluation method developed by the National Telecommunications and Information Administration (NTIA). Figure 4 illustrates the general model proposed by NTIA as a standard for video quality measurement. One of the key elements in the model is the calibration process, which includes spatial and temporal alignments, valid regional estimates, and gain/level offset calculation in both original and processed video streams. Apart from the calibration process, VQM is also able to estimate the desired video quality parameters.

The video quality experts gVQEG) is an independent group of video experts that have devised various data sets to perform the evaluation of video quality techniques. The VQM



(a) **(b)**

Fig. 3 A comparison of accuracy between SSIM and PSNR (source [24])

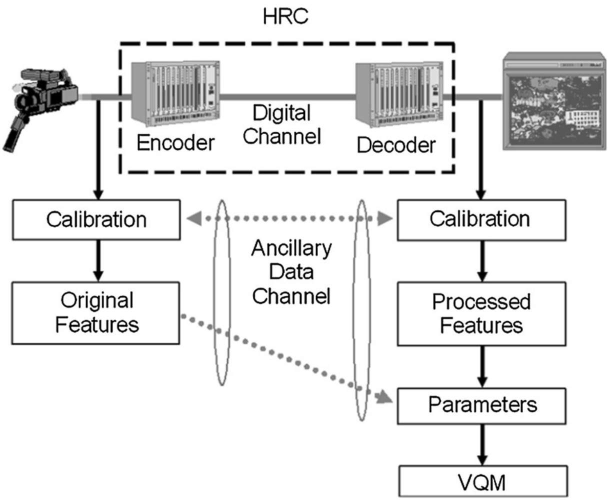


Fig. 4 General model for VQM (source [26])

general model uses reduced-reference technology [27], which enables a good evaluation to be conducted in near real-time video. It also has a very good performance in the VQEG Phase II Full Reference Television tests [28], and was accepted as a standard by the American National Standards Institute (ANSI) (ANSI T1.801.03-2003) and later approved by ITU (ITU-T J.144 and ITU-R BT.1683 recommendations).

3 EViTEQ: Evaluation Framework to Assess Video Transmission Energy Consumption and Quality

This section describes the developed framework to assess video quality and energy consumption, based on the methodology defined in [4].

The framework aims to address the end-user perceived Quality of Experience and the energy consumption of video traffic. The framework must be able to assess QoE and to establish the relationship with energy consumption. High precision energy consumption measurement must be carried out for each transmitted video. Since accuracy is of crucial importance, the used hardware must be able to support multiple samples per second, since energy in small devices (i.e. network interfaces) tends to undergo slight variations. Moreover, an independent technology evaluation is required to allow comparison between different wireless technologies (e.g. IEEE 802.11 vs Long Term Evolution (LTE)). The framework must also enable video streaming and energy consumption measurements under variable, but controlled and repeatable, network conditions. The proposed framework has three main components: video traffic generation, energy measurement and network configurator, as depicted in Fig. 5.

Section 3.1 describes the framework's video traffic generation component, followed by the presentation of the energy measurement approach in Sect. 3.2. The network configurator scheme is outlined in Sect. 3.3, and the assessment metrics are discussed in Sect. 3.4.

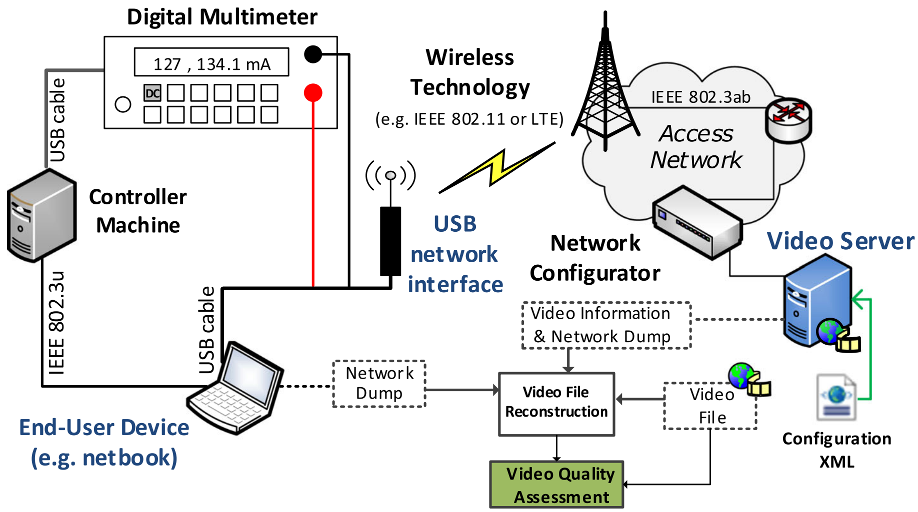


Fig. 5 Architecture of the framework

3.1 Video Traffic Generation

The video traffic generation, depicted in Fig. 5, is performed using a server/client logic, where there is a "Video Server" entity transmitting video streaming to a certain "End-user Device". First, the raw video data compression must be performed, where a raw lossless YUV video is compressed so that it can be sent to the end-user. The codec that will be used and all the compression tools should be selected in accordance with the specific requirements of the assessment goals. In addition supplying a set of scripts to prepare the video compression, the proposed framework also provides the tools and scripts required to start all the procedures for video streaming. Each configuration can be saved in an Extensible Markup Language (XML) format, which allows configuration reuse and rapid parameter changes. Additionally, the proposed framework makes it possible to configure the number of repetitions to be performed.

When the sender (i.e., "Video Server") starts the transmission it will simultaneously begin to gather information about the transmitted video. The same network capture is repeated at the receiver side until the video transmission ends. The network information about the transmitted packets is collected using the tcpdump tool [29].

The specific features of video streaming, such as frame types and transmission times, are collected with the aid of the Evalvid [30] tool. Moreover, even when various frames got lost, Evalvid can still reconstruct the received video. The proposed framework is designed to work together with Evalvid, but is not restricted to it. For instance, other similar video transmission and reconstruction tools such as Video Tester [31] can also be used.

When all the video and network information has been collected from both the sender and receiver, the video is reconstructed frame by frame by using the collected information and the source video file. Thus, the reconstructed coded video is transformed back into a raw YUV format, so that it can be compared with the original *lossless* raw YUV video. The tools and metrics used to perform video quality assessment will be discussed in Sect. 3.4.

3.2 Energy Measurement

The energy measurement setup was designed to meet all the requirements mentioned earlier, with special focus on accuracy. It also provided an opportunity to automatize all the tests and to allow an assessment of different wireless network technologies by making only essential changes to the real-time hardware systems.

The first choice was using an external Universal Serial Bus (USB) network interface, since it can accurately measure the energy consumed by the interface solely. One of the main requirements identified in earlier related work is a system with stable and continuous voltage [6, 7]. The impact on the voltage by connecting the USB network interface directly to an end-user device was rather small in the preliminary tests. Thus, the USB network interface was connected to an external USB hub, which was externally powered by AC and which could stabilize the system. When connecting the USB hub, the voltage dropped by less than 1 %, which is rather negligible for the overall system analysis. Figure 6 shows the equipment used in energy measurement.

The measurement configuration consists of a “Controller machine” and a high-precision Rigol DM3061 digital multimeter with a maximum sampling rate of 50,000 samples/s and a test resolution of 6 1/2 digits, cf. Figure 5. The multimeter can receive Standard Commands for Programmable Instruments (SCPI) as defined by IEEE 488.2 [32]). It implements the Universal Serial Bus Test and Measurement Class Specification (USBTMC) standard interface.

The “Controller Machine” can control and manage the digital multimeter by using SCPI commands and USBTMC. This allows to perform accurate and repeatable tests. The “Controller Machine” is also connected to the end-user device. It is a fast and reliable entity to control experiments and to collect measurement results from the digital multimeter. The energy measurements were calculated by collecting current values and by considering stable voltage values. As illustrated in Fig. 6, the common-collector voltage (VCC) conductor of the USB cable was intercepted to allow such measurements.

3.3 Network Configurator

The challenges involved in assessing both video streaming quality and energy consumption are not restricted to the measurement techniques themselves, since network configuration

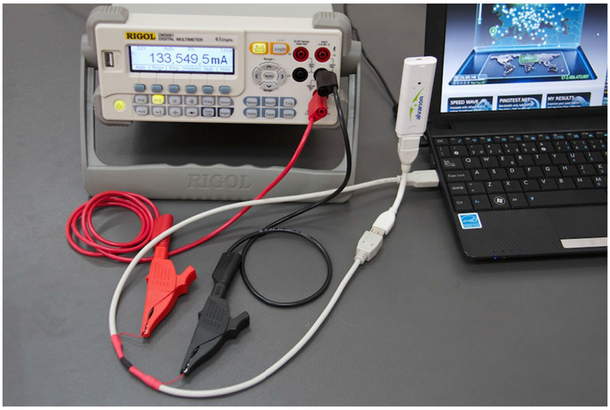


Fig. 6 Energy measurement hardware setup

and conditions also play an important role in the process. Many studies in the literature only consider nearly perfect network conditions, which may not correspond to the real conditions faced by an end-user.

The proposed framework for video quality and energy consumption allows several network conditions to be emulated, depending on the evaluation goals and needs.

The “Network configurator” was developed using a Dummynet [33] enabled transparent bridge together with the KauNet extension [34], depicted in Fig. 5 as “Network configurator”. Dummynet works by intercepting the defined traffic and, by using a set queues, it applies the defined rules (e.g., extra delay) to the filtered data. KauNet extends Dummynet by providing pattern-oriented emulation.

By using this kind of deterministic network emulation tool, the proposed EViTEQ framework provides a fully configurable environment, enabling the study of several network conditions. This solution does not require changes in the other components, since it acts as a transparent bridge between the “Video Server” and the access network. Using the “Network configurator” component allows testing of real environment conditions within perfect laboratory conditions, where otherwise no packet loss or delay would be noticeable.

Therefore, it is possible to emulate scenarios with controlled packet loss or delay where the environment is stable, and the experiments can be repeated within the same conditions. For example, the following network-related parameters can be configured through Dummynet/KauNeT:

- *Bandwidth*: makes it possible to limit the bandwidth used, by adopting static and dynamic approaches;
- *Packet Loss*: allows a deterministic packet loss percentage or configuration;
- *Bit-Error*: similar as the “Packet Loss” but at a bit level for packet transmission, it allows errors to be introduced in specific bits;
- *Delay*: allows changes in end-to-end delay, for instance, by introducing extra delays or using a certain delay pattern depending on the number or type of packets;
- *Trigger patterns*: allows emulation of cross-layer mechanisms by reacting to certain applications or triggers at a lower level.

3.4 Assessment

The proposed framework can report information about both video streaming quality and energy consumption, as described in the following subsections.

3.4.1 Video Quality Assessment

The video quality can be assessed by both Quality of Service and Quality of Experience metrics. QoS metrics allow the network behavior to be understood through the assessment of packet loss, end-to-end delay, delay variation and bitrate information.

The report of QoS metrics is always given by the tool used to perform video traffic generation (Sect. 3.1), while QoE can be assessed by using any external tool that is able to compare two raw movies. The “Video Quality Assessment” procedure requires raw formats of both original video file and video file reconstructed using network information, as illustrated in Fig. 5.

Even though some video traffic generation tools can also be used to obtain QoE-related information, the available QoE metrics are usually limited. Therefore, this framework enables different tools to be employed in the video QoE assessment, with minor modifications required (e.g., syntax issues) in the projected *scripts*.

As an example, Evalvid can give information like peak signal noise to ratio (PSNR), mean option score (MOS) or Structural Similarity Index (SSIM), but not video quality metric (VQM). By using the same input information, the MSU video quality measurement tool [35] can provide around twenty QoE-related metrics, including all those mentioned previously. The MSU video quality measurement tool is a software designed exclusively to perform objective video assessment.

3.4.2 Energy Consumption

Energy is assessed by measuring both power and energy consumption for the reception of a video. Moreover, power can be analyzed as a function of time, so that the video characteristics can be correlated with the power consumption. The energy consumption for a desired period (which is different from the total video playing time) can also be obtained.

Equation 5 depicts the energy consumption, where "Time" represents the time needed to receive the video and "Power" is defined as work done at the rate of one Joule per second. The relationship between the "Power" and both "Voltage" and "Current" is depicted in Eq. 4.

$$Power(Watt) = Voltage(Volt) \times Current(Ampere) \tag{4}$$

$$Energy(Joule) = Power(Watt) \times Time(seconds) \tag{5}$$

All the units showed in the equations are the ones defined by the International System of Units. When employing the EViTEQ framework energy monitor facility, the energy consumption assessment can be performed by collecting only the current values, as the voltage is stable. Using these values it is possible to obtain the total energy consumption by applying Eqs. 4 and 5.

4 Experimental Assessment Procedure

This section outlines the assessment procedure to perform the combined evaluation of video QoE and network energy consumption using the developed framework.

The assessment procedure was developed to fulfill the two main goals of the experimental evaluation. The evaluation aims at assessing the impact of video categories and network conditions on QoE and energy consumption. Furthermore, the evaluation also wants to demonstrate the capability of the proposed framework to achieve accurate results.

The following sections are structured as follows. Section 4.1 presents the employed video sequences, followed by the network conditions and scenarios presentation in Sect. 4.2. The experimental testbed and metrics are described in Sects. 4.3 and 4.4, respectively.

4.1 Video Sequences

Four distinct sequences from the SVT High Definition Multi-Format Test Set [36] were selected, as illustrated in Fig. 7. The movies—"CrowdRun", "InToTree", "OldTownCross" and "ParkJoy"—were selected since they represent a good set of varied "coding complexity" movies. "CrowdRun" and "ParkJoy" sequences have a high level of

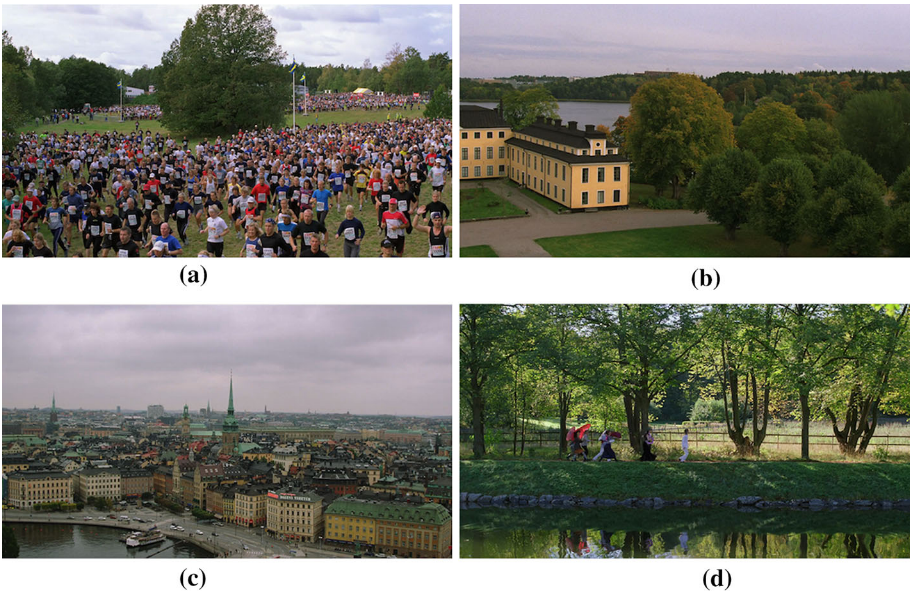


Fig. 7 Selected video sequences. **a** CrowdRun. **b** InToTree. **c** OldTownCross. **d** ParkJoy

"coding complexity", while "InToTree", "OldTownCross" have low "coding complexity" [37].

All sequences have a resolution of 1920 × 1080 pixels, a frame rate of 25 frames per second, and contain 250 frames (i.e., 10 seconds). The videos used in this evaluation were compressed by H.264/MPEG-4 AVC codec. All the video-related operations were performed using *ffmpeg* [38]. Additionally, all the movies were codified, using a GOP of 30 frames with 25 Frames Per Second (FPS).

Several examples of video assessment in the literature attempt to study video streaming performance by only using distinct *bitrates*, which does not guarantee a consistent degree of quality assessment since the video quality and "coding complexity" have a strong impact on the process. Hence, this study seeks to control the video quality by using the constant rate factor (CRF) with the aim of achieving a certain quality for the complete sequence, without directly controlling the file size. Therefore, the distinct video qualities used have been undertaken by selecting three different CRFs (27, 36 and 45), which were mapped into three different video qualities, *High*, *Medium* and *Low*, respectively. The CRF scale ranges from 0 to 51, where 0 is lossless, 23 is the default compression and 51 represents the worst quality. Table 2 depicts the most relevant parameters for each compressed sequence.

4.2 Network Conditions and Scenarios

The network configurator entity, introduced in Sect. 3.3, allows distinct network configurations to be designed that make use of single parameters (i.e. they only introduce extra delay) or combined parameters (e.g. random packet loss and extra delay).

In this assessment, three different scenarios and configurations were selected. First of all, a scenario without restrictions was defined. This configuration allows the study of a

Table 2 Parameters of compressed video sequences

Name: sequence and quality	CRF	Average bitrate (kb/s)	Ref. PSNR	Ref. SSIM	Ref. VQM
CrowdRun-*Low*	45	1285	22.75	0.56	6.81
InToTree-*Low*	45	491	27.54	0.60	4.43
OldTownCross-*Low*	45	449	27.88	0.71	3.83
ParkJoy-*Low*	45	1044	21.42	0.52	7.53
CrowdRun-*Medium*	36	4149	26.71	0.74	4.13
InToTree-*Medium*	36	1510	30.81	0.73	2.92
OldTownCross-*Medium*	36	1078	32.12	0.82	2.33
ParkJoy-*Medium*	36	4224	25.17	0.74	4.66
CrowdRun-*High*	27	13,721	31.97	0.89	2.25
InToTree-*High*	27	6581	34.47	0.85	1.83
OldTownCross-*High*	27	3689	35.01	0.87	1.58
ParkJoy-*High*	27	17,067	30.86	0.90	2.46

Table 3 Configured scenarios for the assessment

Scenario name	Parameters	Value	Expected behavior
No restrictions	–	–	–
Delay-20	Delay	20 ms	Extra delay of 20 ms in all packets
Delay-40	Delay	40 ms	Extra delay of 40 ms in all packets
Delay-80	Delay	80 ms	Extra delay of 80 ms in all packets
Delay-160	Delay	160 ms	Extra delay of 160 ms in all packets
Delay-320	Delay	320 ms	Extra delay of 320 ms in all packets
PL-05	Packet loss	0.5 %	0.5 % of all packet are lost randomly
PL-1	Packet loss	1 %	1 % of all packet are lost randomly
PL-2	Packet loss	2 %	2 % of all packet are lost randomly
PL-4	Packet loss	4 %	4 % of all packet are lost randomly

scenario with nearly ideal network conditions (no packet loss), where all the traffic is routed through the Kaunet/Dummynet bridge without changes. The other two scenarios were defined with the aim of studying the video streaming perceived quality and energy consumption in scenarios where the network is, for some reason, experiencing delay or packet loss. Extra delay was introduced in the network by means of the defined network configurator component. The purpose of this was to emulate the delay in the transmission, which can be caused by the communication distance or even by MAC layer retransmissions. The configuration includes scenarios with 20, 40, 80, 160 and 320 ms extra delay. A similar process was carried out to emulate scenarios with packet loss, where various packet loss probabilities were introduced in the network (0.5, 1, 2 and 4 %). The evaluation scenarios are summarized in Table 3.

4.3 Testbed

This subsection outlines the University of Coimbra IEEE 802.11 testbed, depicted in Fig. 8. The IEEE 802.11 access network is composed of a IEEE 802.11n router (Cisco

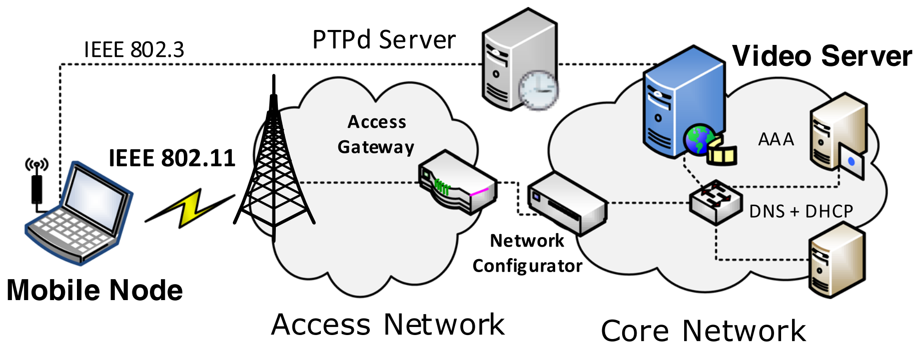


Fig. 8 IEEE 802.11 testbed architecture

Linksys E4200) and USB network interface (Cisco Linksys AE1000) at the end system, both operating in the 2.4 GHz band.

The testbed was configured to support the proposed framework for video quality and energy consumption (Fig. 5). The system clocks of the end-hosts were synchronized with an open-source implementation of the IEEE 1588 Precision Time Protocol (PTP), the PTPd [39], to measure one-way end-to-end delay. PTPd provides synchronization accuracy in the magnitude of sub-milliseconds, in the order of 10 μs [40]. All the hosts use a dedicated network card for the exchange of PTP messages, and to ensure that the synchronization traffic does not introduce overhead into the wireless link.

The "Mobile Node" was configured in an Asus EEE 1001PX-H netbook equipment, running Ubuntu Linux kernel version 2.6.32-21-generic. The netbook includes the USB stick and all the energy-related measurement facilities, as it was discussed in the description of the framework. The "Video Server" machine, is a HP ProLiant DL320 G5p server running Debian Linux kernel version 2.6.32-5-amd64. The Dummynet/Kaunet bridge runs over FreeBSD 7.4, since this is the system recommended for it.

All the video streaming traffic referred to in the rest of the paper is generated by the "Video Server" machine in the core network using Evalvid and received by the "Mobile Node" in each scenario. The transmissions were performed using the Real-time Transport Protocol (RTP), but the framework is fully independent of the transmission protocol.

All the results analyzed in the following sections are measured in accordance with the proposed procedure, and include 30 runs for each test setup with a confidence interval of 95 %. The energy consumption was calculated by measuring the electric power consumption using a rate of 50 K samples.

4.4 Metrics

The proposed assessment procedure uses different metrics to evaluate both video quality and energy consumption. In addition the metrics used for analyzing the typical packet loss, with end-to-end delay and frame loss, two distinct video quality metrics were also employed. The video Quality of Experience metrics selected were the Structural Similarity (SSIM) and the Video Quality Metric (VQM). Mean Opinion Score (MOS) metric was not selected, as it is a sensorial metric, which requires humans to evaluate the quality in a scale from 1 (bad quality) to 5 (excellent quality). In fact, MOS is replaced by computational based evaluations such as SSIM and VQM, as it is based on human perception of the system and it is hard to maintain a system with such characteristics.

Both QoE metrics employed in this study were obtained using the MSU Video Quality Measurement Tool, since Evalvid is not able to report the Video Quality Metric. Therefore, in this setup, Evalvid was used only to reconstruct the video and to assess the network-related metrics previously described.

Energy efficiency is assessed by measuring energy consumption used by the end-user device's wireless interface for the reception of a complete video.

5 Results

This section discusses the results obtained with the developed EViTEQ framework, employing the assessment procedure and conditions described in the Sect. 4.

First, the IEEE 802.11 scenario without restrictions (i.e., no packet loss or delay are introduced) is outlined in Sect. 5.1, followed by the study of scenarios with extra delay introduced via the network configurator in Sect. 5.2. Finally, Sect. 5.3 shows the results for the scenarios with packet loss, also introduced using the network configurator.

5.1 IEEE 802.11 Scenario Without Restrictions

This section discusses the results obtained from the video quality and energy consumption assessment performed in the IEEE 802.11 testbed without using the Dummynet bridge/link emulator (i.e. it was disabled).

The Structural Similarity (SSIM) values for all the tested sequences/qualities (see Table 2) are depicted in Fig. 9. The x-axis shows the video quality, while the SSIM metric is represented in the y-axis.

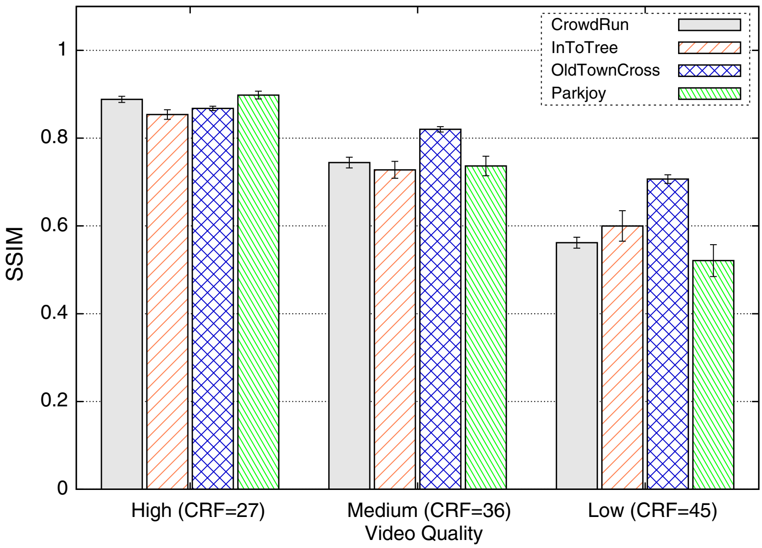


Fig. 9 IEEE 802.11 native scenario: Structural Similarity (SSIM)

The results for "High Quality" sequences always show an SSIM $\geq$ 0.85, which means that the similarity is high when compared with the original video. Although the network conditions in the IEEE 802.11 testbed are very good, the SSIM values were not the maximum (i.e. SSIM = 1). The reason for this is that the maximum possible SSIM for each sequence is directly related to the employed video data compression. The SSIM values illustrate their similarity compared with the corresponding *lossless* movies. This means that, when analyzing the results, the maximum possible SSIM values for each video must be those shown in Table 2. The obtained values for a 95 % confidence interval, represented by the vertical lines over each bar, show the accuracy of the empirical framework proposed, where the uncertainty was always below 3 %.

The relationship between the defined quality levels (*High*, *Medium* and *Low*) and the respective SSIM is clear. However, the type of movie used in this study has also impact on the quality assessment. The "CrowdRun" and "ParkJoy" sequences have a hard coding complexity and this can be noticed in the quality perceived by the end-user. For instance, when the "CrowdRun-Low" sequence is used, the decline in quality, in terms of SSIM, when compared with the "CrowdRun-High" is around 37 %, while the decline for the equivalent qualities using an "easy coding video", (the "OldTownCross"), is only around 18 %.

The VQM results are depicted in Fig. 10. The x-axis shows the video quality and the VQM is plotted in the y-axis. In the VQM metric, higher values represent a worse quality.

The VQM results highlight the gap between "High" and "Low" quality in the complex videos (i.e., "CrowdRun" and "ParkJoy"). For instance, the "ParkJoy-Low" sequence has VQM = 2.46, while the "ParkJoy-Medium" and "ParkJoy-High" have VQM = 4.66 and VQM = 7.53 respectively. The results for the "InToTree" sequence range from VQM = 1.83 for "Low" quality sequence and VQM = 4.43 for the "High". This means that the "InToTree-Low" movie has a slightly better quality than "Parkjoy-Medium". SSIM and VQM result in different video assessments, as shown in Table 4.

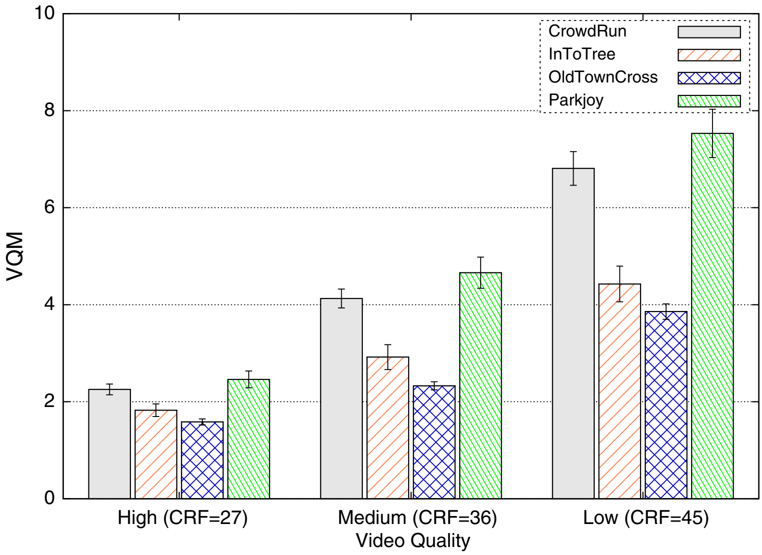


Fig. 10 IEEE 802.11 native scenario: VQM

Table 4 Quality ranking of sequences when employing SSIM and VQM metrics

Quality ranking	High quality	Medium quality	Low quality
Structural Similarity (SSIM)			
1st	ParkJoy	OldTownCross	OldTownCross
2nd	CrowdRun	CrowdRun	InToThree
3rd	OldTownCross	ParkJoy	CrowdRun
4th	InToThree	InToThree	ParkJoy
Video quality metric (VQM)			
1st	ParkJoy	ParkJoy	ParkJoy
2nd	CrowdRun	CrowdRun	CrowdRun
3rd	OldTownCross	OldTownCross	OldTownCross
4th	InToThree	InToThree	InToThree

VQM always keeps the same ranking for each tested sequence, regardless of the employed compression quality (i.e. distinct constant rate factor). SSIM only follows the same pattern for "High" quality sequences. Although this study does not seek to compare the performance of the video quality metrics, this different behavior of the two metrics should be highlighted, since the metric selection plays an important role in the assessment of video streaming QoE. Such behavior might be explained by the metrics definition. SSIM measures the similarity between two images in the video, while VQM also includes valid regional estimators and analysis of spatial and temporal alignments.

Apart from the quality of experience perceived by the end-user, the energy consumption is also becomes an important assessment parameter. In fact, both video quality and energy consumption affect end-user satisfaction, since the battery lifetime can be more important than the streaming quality.

By employing the proposed testing procedure, it was possible to measure the energy consumed during each sequence. Figure 11 shows the total energy consumed in Joule (y-axis) when receiving each distinct sequence.

Since in this study the IEEE 802.11 interface does not have any enabled power saving mode, which allows the network interface to enter in a state of lower energy consumption (e.g., *idle mode*) when no communication with the network is required, the energy consumption mainly depends on the video quality. Thus, the energy needed to transmit the "High" quality videos is slightly higher than both "Medium" and "Low" video qualities. However, the difference shown between the two lower qualities is not significant.

The results highlight the need to establish a proper relationship between end-user perceived Quality of Experience and energy spent to receive a streamed video over the network. Moreover, when using cellular network environments, where the traffic costs are usually higher than in IEEE 802.11, the cost/benefit tradeoff between the achieved overall end-user satisfaction and the billing costs should also be taken into account [41].

5.2 IEEE 802.11 Scenario with Extra Delay

This section examines the results obtained in the scenario where extra delay was introduced through the network configurator component.

The extra delay configurations encompass four situations with distinct delay values. Figure 12 shows the real delay (in milliseconds) measured in the testbed, in accordance

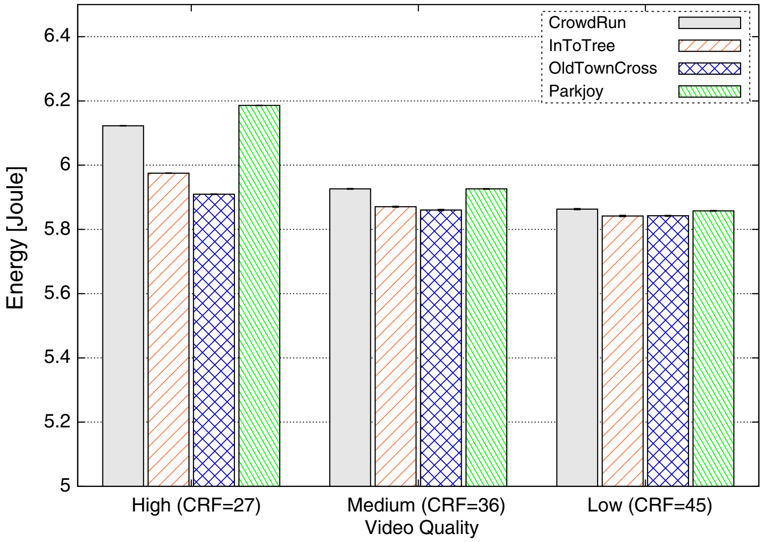


Fig. 11 IEEE 802.11 native scenario: total energy consumption

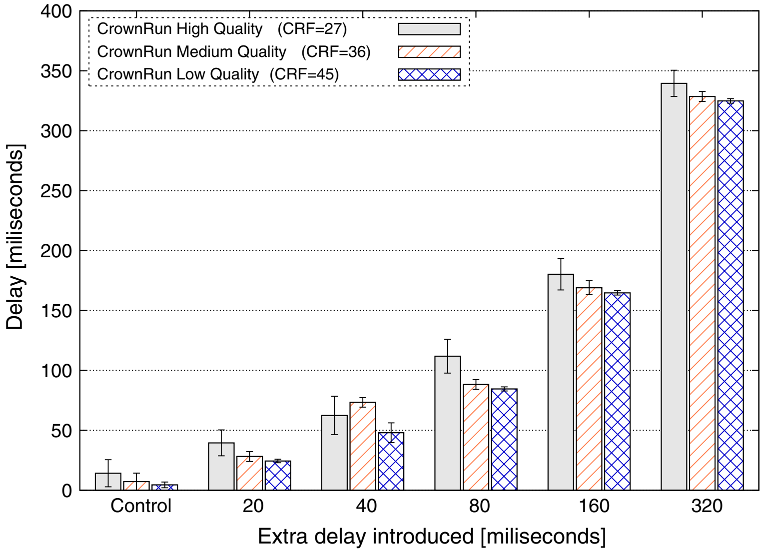


Fig. 12 Delay for extra delay Crowdrun video sequences

with each of the extra delay values that are configured (x-axis). The x-axis also shows the "Control" delay, which is the delay when no restrictions were introduced.

The "CrownRun" sequence was selected as an example. The level of accuracy in the results is similar for all the sequences. It is clear that, by using the network configurator entity, this study can achieve a good level of accuracy in terms of the extra delay that is introduced. The confidence interval limits are represented by the lines on the top of each

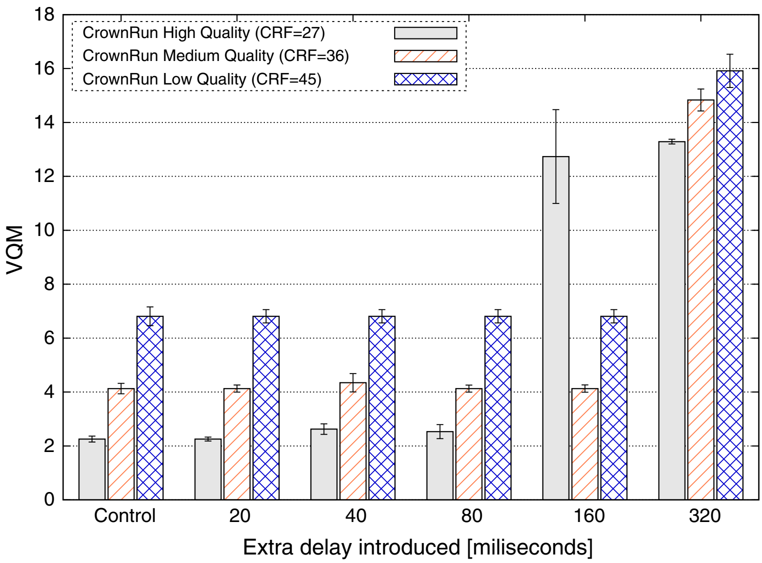


Fig. 13 VQM for extra delay scenarios of Crowdrun sequences

bar. By observing the confidence interval bars, it is possible to notice the higher uncertainty for the greater quality videos. Such behavior is due to the higher *bitrate* used by the best quality sequences, which results in more packets being transmitted and queued in the network and, consequently, in a more variable extra delay.

The QoE that is perceived by the end-user is illustrated in Fig. 13. The VQM metric is shown in the y-axis, while the extra delay scenarios for the whole "CrownRun" scenario are represented in the x-axis. The control bars show the values corresponding to the scenario without restrictions.

In all the tests performed, the *playout time* was always defined as 150 ms. The results highlight the importance of this buffer, since it is closely linked to the maximum tolerable delay during the video streaming transmission. As a result, the effects of the extra delay introduced in the first three scenarios (total delay always below 150 ms) on the QoE is negligible. When the extra delay introduced equals 160 ms, there is already some quality degradation for higher quality videos. In this case, both "Low" and "Medium" quality are able to achieve better VQM than the "High" quality sequence. This is caused by the impact of the extra delay, which is introduced in the "Higher" quality sequence, where more video frames are affected by the delay. There is a direct impact of delay on the VQM, since the delayed frames cannot be shown in time to the end-users. For instance, in the scenario with an extra delay of 320 ms, the impact of delay is clearly noticeable in all the sequences.

The same VQM analysis was also conducted for the low complexity movie "Old-TownCross" and shown in Fig. 14, where a similar QoE degradation pattern can be observed.

Although the degradation pattern is identical, the absolute quality of *'OldTownCross"* sequence is higher when compared with "CrownRun" for this scenario. However, in the scenario without restrictions both video sequences have similar absolute quality. This behavior is related to the lower coding complexity of *'OldTownCross"*, since it needs

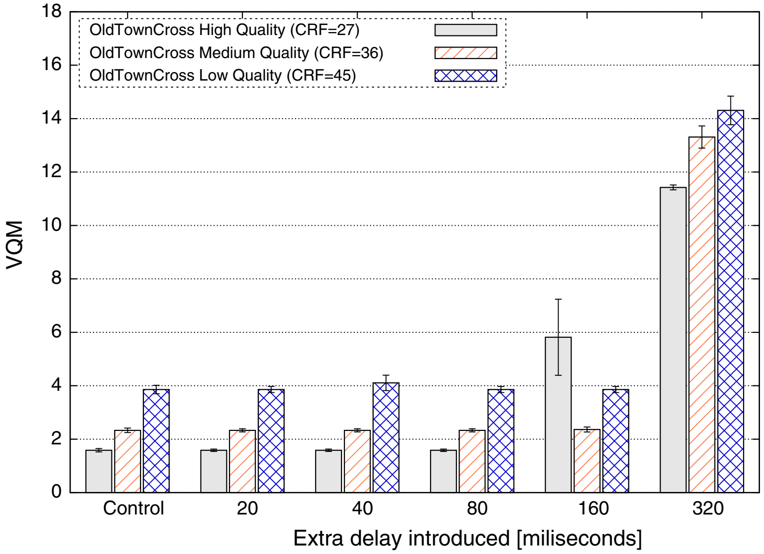


Fig. 14 VQM for extra delay scenarios of OldTownCross sequences

lower bitrate to be transmitted and, consequently, it is less affected by quality degradation introduced by the extra delay present in the link.

The energy consumption information is not depicted for this scenario, since apart from the extra delay introduced, all the information will be received by the end-users, leading to similar results as the ones presented in the previous section.

5.3 IEEE 802.11 Scenario with Packet Loss

This section examines the scenarios where packet loss is introduced via the network configurator component.

Figure 15a shows the real packet loss (y-axis) measured for each of the scenarios with configured packet loss, as depicted in the x-axis. The results demonstrate that the relationship between the configured packet loss rate and the real packet loss measured in the tests is aligned. Since the packet loss probability is random, more fluctuations occur in the video frame losses, as depicted in Fig. 15b.

A comparison between the frame and packet loss rate (Fig. 15) highlights the need to have accurate QoE metrics to correctly evaluate the perceived end-user quality.

The QoE assessment based on the VQM metric is illustrated in Fig. 16a. Figure 16b illustrates energy consumption where the total amount of energy consumed during the transmission (in Joule) is represented in the y-axis.

The results depict the direct impact of packet loss on the quality, since quality degradation increases with higher packet losses. However, with lower packet loss rates, the quality is not significantly affected, since the codec is able to deal with a certain amount of packet loss without affecting the quality perceived by the end-user. It can be observed that, for scenarios with similar packet loss introduced, when “High” quality sequences are transmitted, the impact on the perceived QoE is slightly higher. Such correlation can be

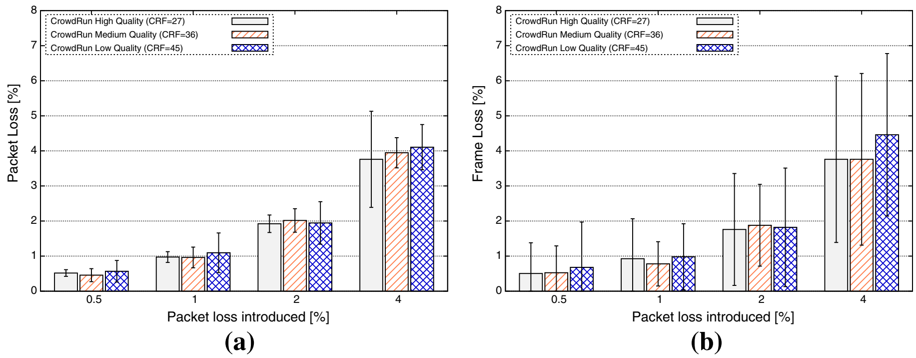


Fig. 15 Packet and frame loss for Crowdrun scenarios with configured packet loss. **a** Packet loss. **b** Frame loss

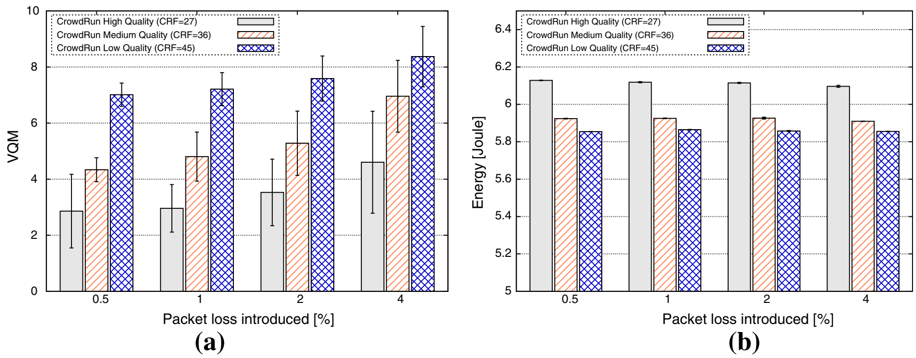


Fig. 16 VQM and energy consumption for Crowdrun scenarios with configured packet loss. **a** VQM. **b** Total energy consumption

explained by the "High" quality sequences superior bandwidth requirements, leading more video information to be lost when compared with lower qualities sequences.

The energy consumption for the scenarios with a higher packet loss is slightly lower, as there are fewer packets being received by the end-user. These results show the proposed framework capability to allow a proper and controlled study regarding the impact of packet loss rate in both video energy consumption and perceived quality.

6 Conclusions

This paper has introduced EViTEQ, an integrated framework to assess video energy consumption and quality in heterogeneous networks with variable conditions. Extensive experimentations have shown the importance of video sequences and compression parameters in the performance of video streaming, especially when assessing QoE metrics. With regard to energy consumption, the experimental results showed that the energy costs of transmitting video sequences are closely related with the video quality.

The establishment of an appropriate relationship between the QoE perceived by the end-users and the energy spent to receive a video was clearly depicted in the obtained results. The scenarios with bad network conditions, namely with introduction of delay or packet loss, showed also that network conditions should always be considered when aiming at maximizing the cost/benefit trade-off between the video quality and energy consumption.

The systematic characterization of energy consumption profiles within real systems can be used for multiple purposes. On one hand, an accurate characterization of the energy consumption can help in the development of optimized mechanisms that dynamically adapt video coding and transmission parameters, taking into account the desired quality level and available energy or expected battery lifetime. On the other hand, this information can be used to develop enhanced energy saving mechanisms that use information about the video characteristics and perceived quality of experience to perform aggregation or dynamic adaptation of sleep periods. The experimental data about Quality of Experience and energy consumption can also be used to create or improve simulation models, which fills an important gap in the literature.

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