End-to-End Performance Evaluation in High-Speed Wireless Networks

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***Abstract*—When dealing with lossy networks, performance management through conventional Quality of Service (QoS) based methods becomes difficult and is often ineffective. We find, in fact, that in this case quality emerges as an end-to-end factor, for it is particularly sensitive to the end-user perception of the overall service. To better explore the value of assessing Quality of Experience (QoE) alongside QoS in high-speed, lossy networks, this paper investigates the case of video streaming services in Radio-over-Fiber (RoF) networks, a prominent example in which network performance is critically related to the application. By means of a pilot RoF test-environment, we study the sensitivity of QoE to the most critical network parameters for different test case scenarios. The outcome is a QoE-based method to assess networks performance, which allows to underpin the network criticalities and non-linear relationships between service and network planes.**

I. Introduction

With the exponential increase of mobile devices, wireless networks are growing in complexity and management turns out to be a difficult task. Thus analysing the network performance and taking improvement measures becomes fundamental. Traditionally, Quality-of-Service (QoS) based evaluations have been used for this purpose, whereby network quality is assessed through bandwidth, latency or packet loss ratio. However, when dealing with wireless networks where interference and other contextual factors affect network services even if there is sufficient nominal capacity, QoS assessment is insufficient and mostly inadequate [1]. QoS metrics reflect the status of individual networks but do not capture the quality delivered and perceived by the end user, namely the Quality of Experience (QoE) [2] [3]. Thus, the performance evaluation of a lossy wireless network needs to take into account not only the physical network characteristics (QoS) but also how these affect the end-user application (QoE) [4], which is not linearly dependent upon QoS [5].

Herein we introduce a network performance assessment method that complements QoS with QoE considerations and gives further insights, particularly for high-speed, lossy networks. We consider the case of a pilot Radio-over-Fiber (RoF) network, assessing the QoE of a high-definition video streaming service (Figure 1). The Fiber-To-The-Home (FTTH) access network is terminated at the residential gateway (RG) where the service is distributed to the cells of the building over graded-index multimode fiber (GI-MMF). Inside each cell a remote antenna unit (RAU) distributes the WLAN service to the users within.

We have chosen a RoF testbed as a prominent, state-of-the-art network which can deliver high throughput wirelessly but has strong sensitivity to the distance between source and sink nodes. However our method is generic and may be used in other cases. We consider both QoS and QoE quality metrics, showing how the latter considerably enhances our understanding of how network conditions affect the quality that is actually delivered. Looking at the relationship between network and end-users service helps pinpointing the most critical parameters and, in turn, dimensioning and operating networks and services in an integrated fashion.

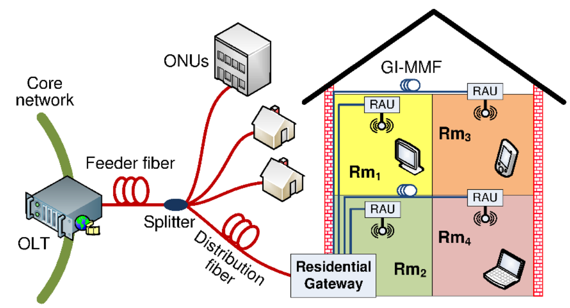


Fig. 1: Scenario of the in-door optical network terminating the Fiber-To-The-Home (FTTH) networks

II. Fiber-Wireless networks

Due to a booming need for indoor wireless connectivity as well as throughput, conventional standards such as Bluetooth and WiFi are already congested in the wireless spectrum. In order to meet the raising demand, one promising solution is to create an indoor optically-fed network consisting of many wireless picocells [6]. By means of such a RoF technique, each picocell is a simple antenna site which only converts the radio signals between optical and electrical domain and all the signal processing functions are centralized via the fiber backbone [7]. The backbone is transparent to various wireless services, because it does not require any additional interfacing like up- or down-conversion [8]. Since the radio frequency can be reused among these non-overlapping picocells, the total network capacity is hence increased. However, when stressed to the limits of its resources, losses increase and the quality can be affected. Furthermore, its set-up characteristics and possible external interference can have a negative influence on the network performance. These conditions make RoF perfect to demonstrate QoS-QoE evaluations.

III. Assessing Quality of Experience

QoE is defined as the degree of delight or annoyance of the user of an application or service [9]. Due its subjective essence, QoE methods based on human interaction analysis are the most appropriate ones, i.e. subjective QoE (sQoE) [10]. However, subjective tests are time consuming and not always suited for real time monitoring. Thus, objective metrics (oQoE) that mimic human perception are also used [11] [12].

We adopt the well-known oQoE algorithm of Structural Similarity (SSIM) [13] , which was originally developed to assess still images, but was later adapted to video. SSIM is based on the observation that a natural image or frame in a video is highly structured [14]. Structural information is defined as the attributes that represent the structure of objects in the scene, independent of the average luminance and contrast. Hence SSIM combines comparisons in terms of luminance, contrast and structure. As the Human Visual System (HVS) is highly adapted to structural information [15], SSIM performance is better correlated with sQoE than other oQoE metrics as PSNR.

IV. Integrated QoS-QoE Performance Evaluation Method

On assessing the performance of a network, no matter whether wireless or wired, there are certain physical conditions, characteristics and limitations that a service provider must address. These physical situations can affect the end-user received quality in ways not easily detectable by a mere QoS assessment. Our method proposes to enhance the performance evaluation by means of QoE analysis at application level (specifically video streaming is considered for illustration purposes) (Figure 2). A video streaming application is used

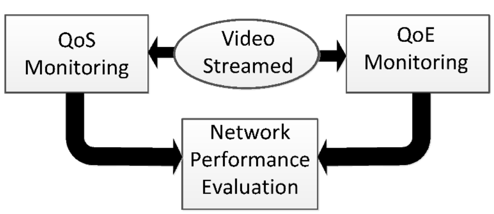


Fig. 2: QoE-QoS Network Performance Evaluation block diagram

to transmit videos to the client. The received videos are then evaluated both on terms of QoS, instantanous throughputs, and QoE, SSIM indexes. The combined result of both analyses is used to evaluate the overall network service.

V. RoF Test-bed

Figure 3 shows the set-up based on the proposed concept. A computer server is used to generate IP packets and video streams. To emulate a simplified FTTH access network, we use a pair of commercial small-form factor (SFP) transceivers distributing the signal to the residential gateway (RG) over 25 km duplex standard singlemode fiber (SSMF). The wavelengths of downlink and uplink are 1490 nm and 1310 nm, respectively. A Hurricane II PacketStorm IP network emulator is included to emulate IP layer impairments. The RG provides the interfacing between the FTTH network and the in-building network. A conventional wireless router translates the gigabit Ethernet signal to the IEEE 802.11n signal, which is modulated by a direct modulation laser (DML) at 1310 nm. After transmission over GI-MMF , the signal is detected by a photodetector (PD) and amplified by a bi-directional power booster (PB) at RAU. The signal is finally radiated to the air via an omni-antenna. A multimode vertical-cavity surface-emitting laser (VCSEL) source operating at 850 nm and PD are used for the uplink stream. The mobile device (MD) uses the Integrated QoS-QoE method to evaluate the network performance.

The 10 seconds, 25fps, 1080HD video Shields from the Live Video Database [16] is used for the evaluation. Its average characteristics in terms of both temporal motion and spatial complexity [17] make this video suitable for a general analysis in a wide range of conditions. Due to the RoF network's time variable conditions, the original video streamed over the network consist of a 6-times repetition of Shields in raw format, thus having a total duration of 1 minute. During the streaming session, the target video is first encoded to MP4 at a desired bitrate and then streamed to the client using the Real-Time Protocol (RTP) over UDP. Further details of the streaming procedure can be found in [18].

VI. Experiments and results

Evaluating the influence of the RoF physical characteristics on the received video QoE and comparing it with the physical QoS in an ideal single-user scenario became our first objective (section VI-A). Furthermore, sharing the link could induce a drop on the individual quality received (section VI-B). Finally, the effect of additional impairments from the access network is considered in section VI-C.

A. Case 1: Single-user, RoF optimization and Bandwidth-Distance relationship

Since multimode fiber can support more than one propagation mode, due to the larger core-size, the bandwidth-distance product is severely limited by modal dispersion. For this reason, in our first experiment we studied how this relationship affects the performance, evaluating the set-up using fiber lenghts of 200 m, 1.3 km and 2.4 km.

On the first stage of the tests, we aimed to estimate the optimal throughput for each of the three lengths. Optimal throughput is defined as the maximum bitrate possible with low or close to no packet losses and stable jitter. In this direction we carried out a cross-layer UDP packet analysis. The optimal throughputs for the studied cases can be seeing in Figures 4a, 4c and 4e; respectively: 25 Mbps for 200 m, 20 Mbps for 1.3 km and 14 Mbps for 2.4 km. The jitter gradually increases from approximately 0.5 ms in the case of 200 m to a maximum of 1.3 ms for 2.4 km. The average packet loss is below 2% in all three cases.

This QoS analysis made clear that the bandwidth-distance factor limits the maximum throughput available. This means that within the bandwidth limits the quality received is guaranteed. In order to validate this statement, we applied our QoS-QoE method. Encoding the target video for the optimal

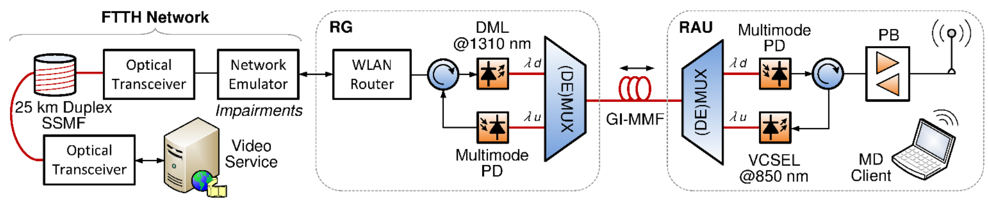
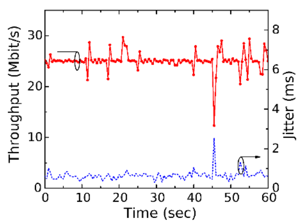
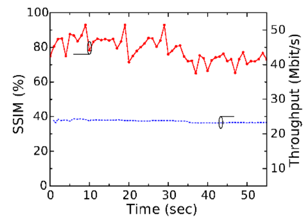


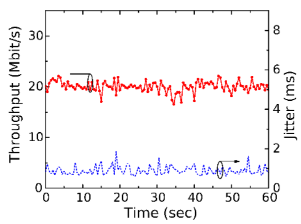
Fig. 3: Experimental setup



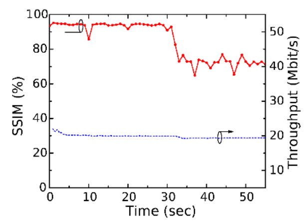
(a) Throughput-Jitter 200 m



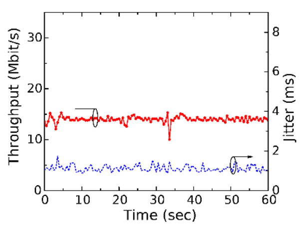
(b) SSIM-Throughput 200 m



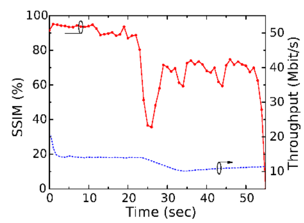
(c) Throughput-Jitter 1.3 km



(d) SSIM-Throughput 1.3 km



(e) Throughput-Jitter 2.4 km



(f) SSIM-Throughput 2.4 km

Fig. 4: RoF: Single-user case results

throughputs, we streamed using the procedure explained in section V. Figures 4b, 4d and 4f show the received SSIM values against the instantaneous throughputs, respectively for 200 m, 1.3 km and 2.4 km. In the three cases the SSIM index starts at a level between 80% and 90% and is maintained between these limits until a throughput drop occurs. The less stable behaviour on the 200 m result can be explained due to the influence of external WLANs in the building. Having a closer look at the point when the throughput drops and comparing it with the SSIM degradation for each of the cases, we find some unexpected results. In the 200 m case, figure 4b, a throughput drop of around 4% can be depreciated in the overall SSIM index. On the other hand, a similar 4% drop in the 1.3 km case, figure 4d, causes a drop of close to 20% on the overall SSIM index. This behaviour becomes more evident for the case of the 2.4 km. In it, a throughput drop of nearly 12% induces an instantaneous drop of 60% in the SSIM index. The stabilization of the throughput and video buffering help the SSIM index to increase to a definite 65%, nearly 30% less than at the beginning of the session.

These results make us conclude that the bandwidth-distance factor not only limits the throughput but, as the fiber distance increases, the QoE gets degraded faster. A combined QoS-QoE analysis brought us further on the network performance assessment.

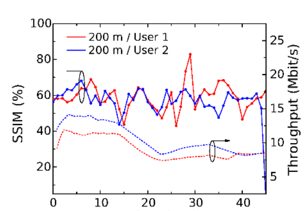
B. Case 2: Multi-user

In a real life situation it is highly unlikely that just a single user is allowed to use the whole network bandwidth, hence this second round of experiments.

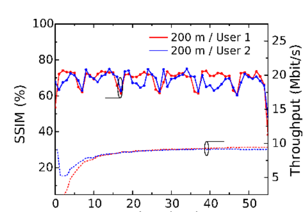
Two users were connected inside the same optimized cell (200 m RoF). A video was then streamed simultaneously to both users and the QoS-QoE method was applied.

We aimed to assess if and how the network performs the task of sharing its limited resources. Using our integrated QoS-QoE method, the video was streamed with the previously optimized bandwidth set-up (25 Mbps). Figure 5a provides the comparison of SSIM indexes and instantaneous throughput. It can be seen that the effective bitrates for both users were reduced to about 12.5 Mbps, because both users had to share the bandwidth within the same cell.

Having proven that the network set-up is able to split the resources to provide service to multiple users, we decided to study what the consequences on the end-user quality received would be, when the aggregated throughput of the streamed videos was within the bandwidth limits. Setting the streaming rate at 10 Mbps per user, i.e. 80% of the optimal bandwidth, we proceeded again as before with the QoS-QoE performance evaluation method (figure 5b). The results show that even if both users are provided the expected 10 Mbps of bandwidth, the SSIM index didn't go higher than 70%. The reason for this behaviour is the mutual interference between the different signals, which causes corruption in the video data received.



(a) SSIM-Throughput 25Mbps



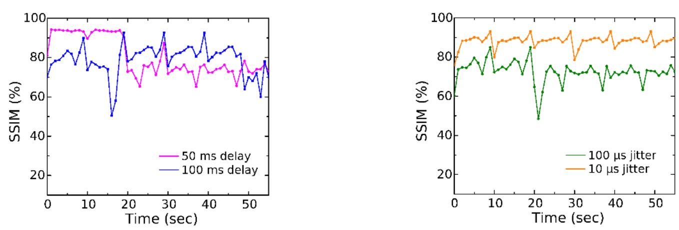
(b) SSIM-Throughput 10Mbps

Fig. 5: RoF: Multi-user case results

If only a bandwidth evaluation were to be performed, the network performance would have been considered to be satisfactory. The inclusion of a QoE analysis brought us crucial information about the real limitations of the network.

C. Case 3: Access network impairments

Packet delays and jitters could affect the data transmission [19] [20], even impairing the videos to such an extent that they become unrecoverable. Thus, in our last experiment we tried to understand how and in which ways the end-user quality was affected by these additional impairments.



(a) SSIM with packet delays (b) SSIM with time jitter

Fig. 6: RoF: Access network impairments case results

Using the Network Emulator introduced in section V and the optimized RoF set-up (200 m RoF), we streamed the targeted video at 25 Mbps in different tests. Four streaming sessions took place: 50 ms delay, 100 ms delay, 0.01 ms jitter and 0.1ms jitter. The SSIM indexes results provide some interesting results (Figure 6). Increasing the packet delay (a) does not cause a substantial decrease on the quality. Furthermore, from the twentieth second on the quality received with higher delay is nearly the same and in some points higher than with lower delay. On the other hand, increasing the jitter by just 10 % (b) is the main cause of a degradation on the SSIM index of nearly 20%, correlated all over the transmission.

VII. Conclussions

We proposed a new network performance evaluation method based on integrated QoS-QoE metrics, particularly useful in lossy networks, to show how a combined QoS-QoE analysis provides further insights into the criticalities, limitations and characteristics of wireless networks Our claim was that the combined action of a QoS and QoE analyses For the single-user case we demonstrated that not only the distance-bandwidth factor is limiting the maximum bandwidth available for the user, but also that as the distance is increased the end-user QoE is more difficult to maintain and eventually starts to decrease. On the multi-user case we discovered that even within the bandwidth limits, sharing the resources could provoke a drop in the individual experienced quality, even with appropriate transmitted throughput. Finally, for the impairment study a QoE analysis provided with the interesting correlation between jitters. These results reinforce our claim and give us new ideas on further test case scenarios on where to further apply the integrated QoS-QoE approach.

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