Cross-layer Multimedia quality enforcement through user aware information in wireless networks

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Abstract—**Quality assessment of multimedia traffic is a hot topic. In this paper we present a Multimedia Management System, which can be used on-line to assess and guarantee the quality of multimedia traffic in a wired and wireless network. The proposed platform uses both network and application layer metrics to build up a scalable quality assessment framework. The core of this framework provides means for traffic provisioning capabilities by coordinating the network access and usage both from the wireless node and from the network access point. These two combined features permit our platform to guarantee a satisfactory multimedia user experience. We evaluate our proposal by issuing an experimental deployment in a testbed and performing a series of tests under different network situations to demonstrate the Quality of Experience guaranties of our system. The results show that the quality of video perceived by end-users is considerably improved compared to the typical wireless network.**

Index Terms—**QoE, Wireless Network Management, Multi-layer**

I. INTRODUCTION

The massive market penetration of new mobile devices such as laptops, mobile phones, and netbooks, all with different Internet connection capabilities, encouraged the broad deployment and adoption of wireless technologies such as GPRS, Bluetooth, or Wireless LAN (WLAN) everywhere. In addition, the good performance/cost tradeoff of the latter favored the apparition of a vast number of hotspots offering Internet connectivity, e.g., at the city's airport, at the university campus, or even at the coffee shop next door, contributing to increase the user's effective on-line periods [1].

This "always connected" attitude acquired by the users has greatly affected the network usage patterns. Indeed, watching on-line TV programs, video-chatting with family or friends, or visiting video-streaming sites are now common practices. As a consequence, all this new multimedia traffic has introduced a series of network constraints in terms of latency and data transmission reliability, that network technologies must comply with in order to offer a competitive network connection. Despite of this, WLAN and other mobile technologies using a shared medium access, do not have mechanisms to guarantee such reliability.

To overcome this limitation, in this paper we present a Multimedia Wireless Management System (MWMS), offering

an on-line multimedia traffic quality monitoring and enforcing platform for wireless environments. Hence the contribution of this work is twofold:

1) First, we propose a multi-layer approach to on-line multimedia traffic quality assessment and enforcement, which combines application and networking data in order to guarantee higher priority for the multimedia flows in the wireless network.
2) And second, our solution uses a two-way approach, i.e., traffic control both from the network access point and from the end-node, to overcome the inherent unreliability of the wireless medium, hence guaranteeing the proper quality of multimedia flows.

Our system uses both network metrics such as used bandwidth and packet losses; and application metrics, namely, the Mean Opinion Score (MOS), in order to make informed management decisions. The main difference of our approach compared to other existing solutions [2] is that we use information from different layers, and combine them at both edges of the wireless network to provide a complete resource management platform.

We experimentally evaluate our proposal in our testbed by comparing the perceived user experience, i.e., Quality of Experience (QoE), between our platform and the generic case of unmanaged network resources. To do this comparison, we generate a video stream using a well-known multimedia streaming application under different network service degradation scenarios. The results show that the quality of the flows is properly maintained during the streaming when the network is managed by our MWMS, while the user perception is clearly degraded in the same conditions with an unmanaged network.

The rest of the paper is structured as follows, the next section details some related work about the requirements in order to design a QoE assessment and enforcement platform. In Sections III and IV we describe our MWMS, and the policies used to perform the resource management. In Section V, we detail the experimental testbed used and evaluate our platform, and finally in Section VI, we conclude and outline our future lines of research in this topic.

II. RELATED WORK

A full-fledged Multimedia Wireless Management System must consider three important aspects in its design, *i)* it needs mechanisms to compute the QoE, *ii)* then it must consider the medium reliability, specially in wireless links, and finally *iii)* it requires mechanisms for resource reservation.

QoE sets the umbrella of techniques used for the subjective analysis of the end-user perception of a given service. This *subjectiveness*, can be made objective by means of well-known techniques, such as the MOS (defined in ITU-T G.113), combined with the E-Model (defined in ITU-T G.107) for voice transmission, or techniques such as [3] for video streams. This paper does not intend to propose a new method for computing the QoE, but rather to exploit existing techniques to receive feedback about the quality delivered to the user, so that we can dynamically manage the resources on the wireless network. In particular, in this work we compute the multimedia flow's QoE by using the technique detailed in [4], a solution which is able to estimate the perceived QoE from a single point of analysis by using frame loss and frame type information at the application layer.

Regarding the reliability of the wireless environment, in the case of WLAN, there are some efforts to provide Quality of Service (QoS) in the Wireless MultiMedia extensions (WMM), which in conjunction with the standardized medium access algorithm defined in 802.11e [5] can prioritize certain packets on the network. However, this standard even if based on a powerful medium access control, is insufficient to have higher level guaranties of proper multimedia quality, specially from the end-user perspective. Most of the contributions in quality assessment in wireless environments are based on low level mechanisms to provide QoS [2], [6], but neither considering user's perception nor application's specific constraints. Our MWMS, specifically uses QoE metrics as the control axis for the resource management.

Similarly to our approach, in [7] the authors propose a cross-layer QoE framework for HSDPA networks, the main difference with our approach is that they center the quality improvements by re-adapting the requirements of the applications for improving the MOS, while we improve the user perceived quality by prioritizing the Multimedia traffic.

Finally, the last identified challenge in our platform is the definition of the mechanisms to prioritize the traffic in the network. In this regard, there are several existing techniques both in commercial routers as in commodity operating systems (ACLs, firewalls, etc.), which permit to limit and control the up and downstream load of the wireless network. More specifically, in our work we use Linux Advanced Routing and Traffic Control as a solution that provides a very versatile mechanism, namely Traffic Control, to enable fine control of the upstream by priority queuing the packets matching a specific criteria, and the downstream, e.g., by delaying TCP's ACK packets.

III. MULTIMEDIA WIRELESS MANAGEMENT SYSTEM

The Multimedia Wireless Management System (MWMS) presented in this paper is a multi-layer approach to on-line assessing and enforcing of the QoE in multimedia flows. MWMS proposes an efficient platform that combines information from different layers and provides a very fast and reliable traffic provisioning mechanism for multimedia flows in wireless environments.

The complete framework is presented in Figure 1. The MWMS is mainly composed of three different parts, first
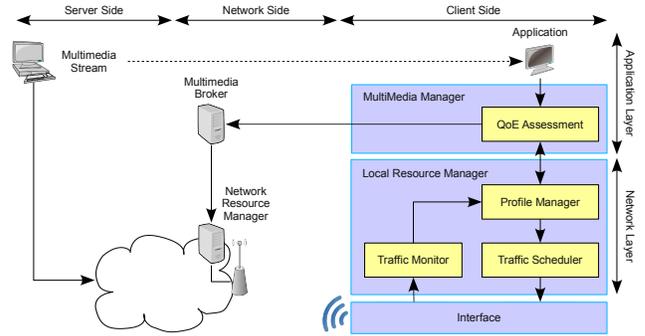

Fig. 1. The Multimedia Wireless Management System (MWMS).

the Client Side, with two different tasks, to assess the user perceived QoE, and to manage the wireless link usage of the end-node, by locally detecting possible causes of service degradation. Second, the Network Side, which controls the access to the whole wireless network by relying on the multimedia flows' QoE as a metric. And third, the Server Side, which streams the media over the network. In this work we focus on the management system on the client and network sides, leaving the end-to-end QoE assessment and provisioning as an important part of our future work.

A. Client Side Resource Management

QoE assessing of multimedia flows is not a trivial task, as it involves comparison of the original and received video frames using PSNR [3], which means that this mechanism cannot be used in a real-time assessment platform. However, this approach can be simplified by using approximations such as [4]. In this case, the best location to perform the user satisfaction assessment is within the destination multimedia application, where the most accurate information about the data delivered to the user can be gathered. To this end, we propose to directly adapt the end-user application in order to infer the delivered QoE, while giving feedback both to the Local Resource Manager (cross-layer vertical signaling) and to the Multimedia Broker (horizontal signaling). It is worth noticing that the application's adaptation only involves to inform the MWMS about the lost frames and their type in the video stream [4].

1) Local Resource Manager: The Local Resource Manager (LRM) performs the low level monitoring and measurement tasks of the wireless link in the local node. LRM is composed by three different entities, i.e., the Traffic Monitor, the Profile Manager and the Traffic Scheduler.

The *Traffic Monitor* monitors in real-time the bandwidth and resource usage of the wireless node, periodically reporting its status to the Profile Manager. Then the *Profile Manager* computes the amount of raw resources required in terms of bandwidth, delay, jitter, and packet losses in order to optimize the resource reservation performed by the Traffic Scheduler. Such parameters are inferred from the effective requirements imposed by the Multimedia Manager. Finally, the *Traffic Scheduler* prioritizes the multimedia traffic over the rest of the wireless node traffic in case of service degradation.

2) MultiMedia Manager: The MultiMedia Manager (MMM) gathers quality information directly from the client

application, it issues periodic queries about the experienced QoE, and receives information about the resource availability in the wireless node from the lower layers. The task of the MMM is twofold. On the one hand, if the service degradation is caused by other applications within the wireless node, the Multimedia Manager instructs the LRM to increase the priority of the multimedia flows. On the other hand, if the degradation is due to the wireless network, the MMM requests more resources to the Multimedia Broker on the Network Side.

B. Network Side Resource Management

Given the shared medium nature of wireless links, in order to provide service guaranties and a reliable resource allocation mechanism, the network must be controlled from both sides of the link. The Network Side Resource Management manages the resources in the downstream to the wireless node, and it is composed of two different parts, i.e., the *Multimedia Broker* and the *Network Resource Manager.*

1) Multimedia Broker: The Multimedia Broker (MB) is the entity within the network that receives the feedback from all the subscribed multimedia applications about the experienced user satisfaction in real-time. The MB interfaces with the Network Resource Manager in order to instruct whether more resources are needed, and as we detail in the next section, it bases the resource reservation decision depending on a preset acceptable QoE boundary. By design, the MB is independent of the underlying network, consequently it does not consider specific network metrics, but it only triggers resource reservations to the Network Resource Manager.

2) Network Resource Manager: The Network Resource Manager (NRM), analogously to the LRM, is responsible of guaranteeing that the multimedia traffic is received properly by the end-user. To this end, the NRM defines the different traffic profiles recognized by the system, and maps the input received by the MB to actual network parameters. Then, at the lower layer, it also controls the overall access to the wireless environment by scheduling the traffic within the wireless access point. With this two-way approach (i.e., client and network sides), the system can effectively guarantee the offered service to the user from both sides of the wireless network.

One important task of the network side resource management left as future work is the connection management and prioritization among the multimedia flows. This can be accomplished by a Connection Access Control (CAC) system, by introducing a business model with billing and accounting processes to define user categories, or by a combination of both alternatives.

IV. QUALITY OF EXPERIENCE ASSESSMENT AND ENFORCEMENT

After the introduction of the MWMS building blocks, this section is devoted to the description of the specific criteria used for reserving and releasing the mentioned resources. As outlined previously, MWMS defines two modes of resource allocation, local node resource management and network resource management.

A. Local resource management

The local resource management is driven by two different layers, first the low level resource allocation and second the high level QoE assessment.

The low level local resource allocation policy is based on the local's node resource usage monitoring and reservation as follows:

Definition 1: Let $\mathcal{U}_t \in [0,1]$ be the used resources at time t in the input queue for the wireless node. Then $\mathcal{U}_t$:

$$\mathcal{U}_t = R_t + \mathcal{B}_t \tag{1}$$

Where $R_t = \sum_{j=1}^{n} r_j$, with $R_t \in [0,1]$, are the ratio of resources needed for all the flows $r_{1..n}$ under surveillance by the system, and $\mathcal{B}_t$ is the usage of the rest of the incoming background traffic toward the node at time t. Then, if $\mathcal{U}_t > \Theta$, where Θ is the upper bound for a reliable wireless link usage, the system issues a reservation as instructed by the Profile Manager for the R_t resources. It is important to notice that R_t is easy to compute because the resource usage of multimedia flows is rather constant over time.

Similarly to the resource reservation, the resources are released when the link usage drops below θ, i.e., $\mathcal{U}_t < \theta$, where θ is the lower safety bound in the link usage to trigger the resource release, or when the multimedia flow finishes, as advertized by MMM. The pseudo-code to implement the whole LRM can be found in Algorithm 1. It is worth noticing, that measuring the link usage is a straight-forward task because it only involves to query the queue status of the interface, as provided by kernel data structures.

Algorithm 1 *LRM*

   Input: resources, $\mathcal{U}$*, forced* {*resources* : Amount of resources to manage by the system,
        $\mathcal{U}$: resource usage ratio, *forced* : whether to force the resource reservation}
   Output: success or failure
   if $\mathcal{U} > \Theta$ **then**
      trigger *resourceReservation(resources)*
5:    currentReservation ← *resources* {global status update}

      return success
   end if
   if *forced* **then**
      if *resources* > currentReservation **then**
10:     trigger *resourceReservation(resources)*
        currentReservation ← *resources*
        return success
      end if
      return failure
15: **end if**
   if $\mathcal{U} < \theta$ **then**
      trigger *resourceRelease(currentReservation)*
      currentReservation ← 0
   end if
20: **return** success

To complement the LRM, both allocation and release of resources can also be triggered by the higher MMM layer.

Hence, besides the strict low level resource usage, the system must also consider the user perception of the delivered multimedia traffic. Therefore, the MMM assesses the QoE of the received multimedia streams as described below (we refer interested readers to [4] for a throughout description of the MMM QoE assessment).

Let $\sigma \in [1,5]$ be the lower tolerable MOS threshold for a multimedia flow. Then, for any multimedia flow j under surveillance present on the system, if the quality of experience $q(t)$ at time t of any flow j is $q_j(t) \leq \sigma$, MMM will trigger a *local resource reservation* request (vertical multi-layer signaling) to the LRM. If the reservation is not successful, or if the quality continues below σ, despite the reservation, MMM will trigger a *network resource reservation* request (horizontal signaling).

As it can be noted, the LRM keeps track of the current status of the reservation and reports whether the reservation is successful or not. This process can be invoked in two different ways, periodically, as a traffic monitor, or it can be invoked by the MMM in case the QoE is below σ.

B. Network resource management

Analogously to the local resource management, the network resource management is composed of two different parts, the low level resource reservation, performed by the NRM and the high level management performed by the MB. The interfaces between these two levels are similar to the one detailed in the LRM and the MMM. However, a key difference is the fact that the MB needs to consider all the reservation requests of all the nodes in the wireless network, opposed to the single node approach of the local resource management. Analogously the NRM will prioritize the multimedia flows subscribed into the system towards all the wireless nodes.

The flow subscription is issued by the MMM, which gathers the properties of the flow and informs the MB about specific application constraints, in terms of frame losses and required bandwidth.

V. EXPERIMENTAL EVALUATION

This section details the tests, the testbed used, and the evaluations performed to validate the MWMS. All the evaluations are focused on comparing the end-user's MOS obtained by running MWMS against a typical unmanaged network.

A. Tests and testbed

The testbed used to perform the MWMS validation is composed by the Multimedia Streaming Server (MSS), the Network Access Point (NAP) and the Wireless Node (WN). All three components are standard PC using the Linux Debian Operating system with traffic control capabilities to manage the resources. In the testbed the MB and the NRM are embedded within the NAP, while in the WN we set up the MMM and the LRM, together with the video streaming client. On its side, the video server is configured to stream using the RealTime Protocol (RTP), a high quality video[1] of 1024x576

[1]The Elephant's Dream – http://www.elephantsdream.org

pixels with a bit rate of 5.5Mbps for both audio and video. The streaming application used is VideoLan Client (VLC).

In order to test the MWMS we deployed our system as follows. We set up a high delay variation queue with limited capacity in order to produce a random amount of packet losses in the wireless network. In the WN we monitored the MOS of the traffic as described in Section IV, with a $\sigma = 3$ as advised in [3], $\Theta = 0.8$ and $\theta = 0.5$, and with an update interval of 1 second. Once the violation of QoE is assessed, the NRM configures a priority queue for the multimedia flows.

With the above methodology we simulate three different service degradation levels: *low*, *medium* and *high*. Finally, we run the same set of tests disabling our management system to compare the results in the same conditions.

B. MWMS evaluation

The experimental evaluation of the proposed system is performed by running the tests specified previously. In our first study, we verify that the MWMS is able to provide better QoE during the whole test than the case with unmanaged network resources. To this end, in Figure 2 we show the Cumulative Density Function (CDF) of the obtained MOS over time, in the left we show the results for MWMS and in the right the case without any network management. For the sake of clarity, we transposed the CDFs, this way the X-Axis shows the normalized fraction of time where the quality of the video stream is below $q_j(t)$ (for all t in the test), while in the Y-Axis shows the instantaneous MOS for each test.

The figure highlights that MWMS easily outperforms the unmanaged case for all the tests, and independently of the level of service degradation the quality is very good most of the time. In particular we can see that in the case of MWMS only $\sim 6\%$ of the time the obtained MOS is below 3, while in the case of an unmanaged network it ranges from $\sim 35\%$ to $\sim 65\%$ of the time, i.e., around half of the streaming duration. Moreover, when MWMS is not present, between 30 and 50% of the time the quality reaches the lowest possible MOS value, i.e., 1, meaning that the video and audio are completely disrupted. Opposed to this, in the case of MWMS this value is around 1%, which roughly corresponds to the assessment and QoE enforcement setup time of the system.

It is worth noticing that the results for high and medium service degradation levels, the unmanaged network obtain similar results. The reason for that is the exponential degradation of the service in the presence of frame losses.

In order to analyze in more detail these results, in Table I we detail the numeric values in terms of quality. In the first column, we show the average MOS obtained for each one of the tests. As it can be noted, the quality is constant, around 4.75, when using MWMS, while it degrades in the case of an unmanaged network. In the second column we computed the 5th Percentile, which identifies the lower bounds in quality for the tests. As before, managing the system mostly avoids having low quality periods given the relatively high value of the percentile. The third and fourth columns in the table complement the above information by indicating the amount of service degradation periods, and the percentage of time
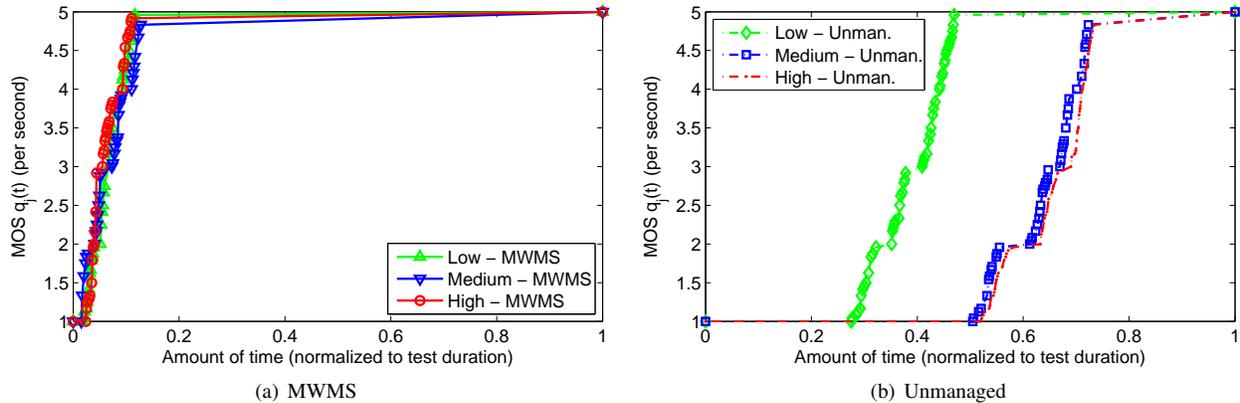
(a) MWMS

(b) Unmanaged

Fig. 2. Transposed Cumulative Density Function of the MOS per degradation level

	Average	5th Prc.	# Degr	% Degr.
Low MWMS	4.74	2	38	5.9%
Low Unmanaged	3.45	1	243	37.8%
Medium MWMS	4.73	2.78	35	5.4%
Medium Unmanaged	2.44	1	409	64.7%
High MWMS	4.76	3	28	4.4%
High Unmanaged	2.38	1	427	66.5%

TABLE I

EVALUATION RESULTS: COLUMNS 1 AND 2 SHOW MOS VALUES FOR THE DIFFERENT TESTS, COLUMNS 3 AND 4 THE DEGRADATION PERIODS

with a degraded system, respectively. In particular, we can see that the degradation periods are fairly constant over the tests for the managed system, while they are much bigger when disabling the management. Since each period is equivalent to 1 second of streaming, we can notice that the amount of service degradation intervals are between ~ 8 and ~ 11 times higher when not using MWMS. Analogously, we can observe that in the worst case the percentage of time with service degradation with high degradation level is kept at 4.4% with MWMS, while it is ~ 15 times worse without our management solution.

In the results it can be noted that the MOS of the high degradation level with MWMS is better than the rest. This is caused by the fact that with high service degradation MWMS is able to react faster as the MOS decreases in less time and the degradation is more noticeable, activating the resource provisioning faster.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a Multimedia Wireless Management System (MWMS) which performs two different tasks. On the one hand, it is able to accurately assess the QoE of multimedia flows directly from application's data, and on the other hand, it guarantees the multimedia traffic quality by using low level resource management mechanisms. In addition, by directly acting over the access point of the network, the system is allowed to have a very tight control over the incoming traffic to the wireless network. This together with the QoE based feedback given from the wireless node, makes our MWMS a competitive solution for wireless network resource provisioning.

Given the versatility of our solution, we were able to evaluate its performance in a real environment under a dif-

ferent set of conditions, which prove that MWMS provides an effective QoE assessment and enforcement mechanism for multimedia streaming over wireless networks. Moreover, given the distributed and lightweight design of MWMS, the system can easily scale for managing a wireless network environment.

As an important part of our future work, one complementary part to complete the platform is the implementation of an admission control system in the wireless network in order to make a more fair use of the resources for all the nodes. This is to avoid the potential starvation of non-multimedia flows or the excess of resource reservation by some nodes in the wireless network,.

Another line open for further research, is to develop an end-to-end mechanism, which combined with this local approach can guarantee the multimedia quality even in the case that the cause of the service degradation is not in the end-user network.

Finally, we plan to upgrade our platform by integrating support for the Wireless Multimedia extensions present in 802.11e, which can further improve the quality of multimedia flows.

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