QUALITY OF EXPERIENCE OPTIMIZED SCHEDULING IN MULTI-SERVICE WIRELESS MESH NETWORKS

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ABSTRACT

A growing trend has emerged in network architecture research to switch focus from Quality of Service (QoS) to Quality of Experience (QoE) optimization. In this paper, we first present QoE models that characterize user satisfaction of video, audio, and data services over wireless networks. We then develop a novel packet scheduling algorithm for multi-hop wireless networks that jointly optimizes the delivery of multiple video, audio, and data flows according to the QoE metrics. We formulate a multidimensional optimization problem that minimizes the overall distortion across all flows for the given network resources on wireless links. Fairness constraints over the flows are also considered as part of the optimization. Our experimental results, obtained with the NS-2 IEEE 802.16 MESH-mode simulator, show that distortion-aware scheduling can significantly increase the perceived quality of different wireless services under bandwidth constraints. Additionally, improved fairness across the competing flows is demonstrated relative to conventional scheduling techniques.

1. INTRODUCTION

With QoS-based traffic engineering, research in network performance has generally aimed to provide improvements in objective traffic parameters such as throughput, delay, link utilization, and packet loss. The optimization of objective network parameters does not, however, translate linearly to optimal satisfaction for the end-user, and the impact of resource constraints on the perceivable quality varies from service to service.

Specific characteristics and traffic patterns of services such as audio and video streaming show that common network metrics are hardly indicative of the end-users' perception of the quality of the service being provided [1]. Likewise, network mechanisms for obtaining the best objective-quality parameters (i.e., throughput, delay) may be unsuitable for the next-generation content-centric, multimedia-oriented networks. Instead, traffic engineering centered on QoE metrics, with a focus on the end-user's perception of quality, is expected to yield better results in terms of user satisfaction.

To address these concerns, we present a novel approach for maximizing the QoE of multiple network flows associated with different wireless services over mesh networks. In particular, we first present QoE models that describe the user's satisfaction of video, audio, and data wireless services, respectively. Then, we develop a model capable of unifying QoE models for video, audio, and data services under the notion of user utility functions, suitable for integration as part of multi-service capable frameworks. Based on the QoE models, we design a constrained optimization algorithm that maximizes the overall QoE of the flows for the given network resources. As part of the optimization, we also consider fairness constraints among the competing flows.

We exploit the QoE and optimization models by designing a packet scheduler that operates at every network node and maximizes the user perceived QoE of multiple different flows being delivered over the multi-hop wireless network. Packet drop decisions are not made on a per-packet basis, but are considered as combinations of drops, thus permitting balanced impacts on different flows and services, and all-around improved QoE performance. The complexities inherent to such a method are analyzed in terms of computational cost, leading to insights in its potential realization in actual systems. A performance evaluation on the NS-2 simulator shows that our approach significantly increases the QoE of the different flows, while preserving fairness between them.

To the best of our knowledge, most of the related work considers resource allocation in single service or single-hop networks without taking into account subjective quality. For instance, a rate-distortion optimized frame dropping technique for video streaming is presented in [2]. The proposed approach accounts for the impact of packet drops on the transmission rate. Additional related works that focus on single service video streaming networks are [3] that explores rate allocation across multiple wireless networks, [4] that presents a cross-layer approach for video delivery over multi-hop wireless networks, and [5] which proposes multipath transport of video over ad-hoc networks. Finally, the work in [6] optimizes audio streams over WiMAX networks.

The rest of the paper is organized as follows. In Section 2 we describe the QoE models that are adopted for the different services. Section 3 describes the design of the packet scheduler and the related optimization of multi-service QoE-based mesh scheduling. The actual implementation of the scheduler in *ns2mesh* and its performance evaluation are presented in Section 4. Finally, we summarize our research in Section 5.

2. QUALITY OF EXPERIENCE MODELS

In this section we present an overview of mathematical models that relate certain network and/or content properties to values which express user satisfaction. In our system model, multiple coexisting users have various sessions, each consisting of different types of flows: audio, video and file transfer. As a result, we need to consider three different quality models to reflect the impact of resource constraints on user perceivable quality. Such models will provide the metrics for our framework's packet scheduling optimization problem.

In order to simplify the design process, we will consider user utility functions that can be defined under a single metric to optimize user perceivable quality. Such utility functions need to be accurate in their operation and be applicable in real-time processing, as our goal is to apply them to packet scheduling algorithms. We will use the Mean Opinion Score (MOS) as a unifying metric. While MOS was

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originally proposed for estimating voice quality, it can be used as a general-purpose quality score, ranging from 1 (poor) to 5 (excellent). Quality models for video and file transfer will require mappings in order to derive MOS scores from their outputs.

We adopt the model proposed in [7] to determine user satisfaction based on video quality. This model evaluates the impact of packet losses on video quality while accounting for parameters such as video codec, bit rate, packetization, and content characteristics. Its algorithm is suitable for real-time monitoring, with support for H.264, the current *de facto* standard for encoding video. Quality is given in terms of the average Peak Signal-to-Noise Ratio (PSNR) of the video signal; we apply a non-linear curve mapping PSNR to MOS that de-emphasizes the impact of small losses when video quality is at extreme values, as proposed in [8]. To determine audio distortion, we make use of ITU-T's E-Model [9], which provides a parametric estimation based on loss and delays of audio packets, and defines an R-factor that accounts for the various impairments on voice quality. Finally, for the user perception of a file transfer service quality, we consider a logarithmic relation between the achievable data rate and MOS, as proposed in [10].

3. MULTI-SERVICE PACKET SCHEDULER

The goal of our packet scheduler is to maximize the overall user perceived quality and fairness among competing flows under resource constraints, in a distributed multi-hop network. To this end, we formulate a minimization problem of a cost function which denotes the impact of packet drop decisions on the user perceived quality of individual flows. Such packet drop decisions will be triggered by an active queue management algorithm in case resource limitations are discovered, e.g., once the buffer utilization reaches a definable threshold. The scheduler then determines, based on the outgoing data rate and buffer fill rate, how much data it needs to drop from the buffer so as to keep it from overflowing.

3.1. Scheduling process

In our work, we redefine the use of MOS as a measure of user satisfaction to other services such as video streaming or downloading. This enables us to develop an optimization framework based on such MOS metrics that is capable of maximizing overall MOS subject to fairness constraints, or average MOS for all flows subject to resource constraints.

Fig. 1 illustrates the scheduling process. The scheduler locates sets of packet combinations across all active flows of all users that pass the node that would satisfy a given buffer reduction. For each of these combinations, an estimation of the user satisfaction expressed in MOS decrease for each flow is calculated. The scheduler then drops the packets whose combination results in the smallest decrease in QoE satisfaction.

One issue in mesh networks is that the nodes on a network path are unaware of what packets were dropped at upstream nodes, which is important for accurate estimation of a flow's quality. To this end, we propose to keep track of dropped packets at a node, and then broadcast this information to its neighbors. For audio and data flows, the impact of packet loss can be inferred by tracking sequence numbers. For video flows, each node must attach a header to the packets it is forwarding, containing information on the distortion of the frames it has dropped.

3.2. Rate-distortion cost function

The optimal packet drop combination can be found by minimizing a cost function, $Q(p)$, calculated for each packet drop combination p. Our $Q(p)$ is not guaranteed to be the fairest resource allocator – other cost functions, such as *minmax*, can be focused more towards fairness than towards raw MOS increase.

For n flows, $Q(p)$ is given by:

$$Q(p) = \sum_{i=1}^{n} k_i \cdot \Delta MOS_p^i - \lambda \cdot \sum_{i=1}^{n} \Delta R_p^i + \mu \cdot n \cdot \sigma(\Delta MOS) \, , \quad (1)$$

where ΔMOS_p^i is the MOS reduction for flow i due to the dropping of p, and k_i is a weighting coefficient for preferential packet dropping from specific flows. Through k_i, the scheduler can be configured to drop more packets from certain classes of traffic. Furthermore, ΔR_p^i is the rate reduction of flow i due to the dropping of p, while λ is a weighting factor that controls how aggressively the scheduler drops packets. Finally, $\sigma(\Delta MOS)$ is the standard deviation of the MOS reduction over all flows, while μ determines the weight of the standard deviation in (1).

The generic model in (1) can be applied directly to all packets present in the buffer. However, to reduce the processing time, a pre-selection of packet combinations can be done based on a target buffer size. The rate reduction component $\lambda \sum_{i=1}^{n} \Delta R_p^i$ is thus unnecessary, and can be removed. To obtain a set of suitable packet combinations, we first determine the amount L of bits to be dropped from the queue based on the buffer fill rate R_{buff}, the outgoing data rate R_{tx}, and the buffer fullness μ_{buff}:

$$L = (R_{buff} - R_{tx}) \cdot \mu_{buff} \quad (2)$$

Then, a range of $[C_{min} \cdot L, C_{max} \cdot L]$ bits is chosen and a set S of n_S packets is selected so that

$$C_{min} \cdot L < \sum_{i \in S} size(S_i) < C_{max} \cdot L, \quad (3)$$

i.e., the total size of the combination must be in a range of C_{min} and C_{max} around L.

4. PERFORMANCE EVALUATION

We implemented the proposed QoE scheduler and QoE models in the *ns2mesh* simulator [11], an extension to the standard NS-2 simulator that adds support for IEEE 802.16 mesh topologies. This allows us to evaluate the proposed framework and determine the extent of the QoE improvements it can bring to a mesh network. Video traffic was simulated with video traces found at [12]. Further information on the structure of the employed video traces and how to process and packetize their frame information can be found in [13].

4.1. Implementation

The implemented architecture acts on top of the existing packet scheduler in *ns2mesh*, which is responsible for pushing packets from the buffers to bandwidth reservation slots. The queue management algorithm is triggered when the inbound buffer exceeds a user-defined threshold; it begins by profiling the packets in the buffer for size and distortion information, updating the MOS statistics of all flows going through the node, and then determining which packet combinations satisfy (3).

The number of possible combinations is 2^n, where n is the number of packets in the buffer. We identify each combination with a

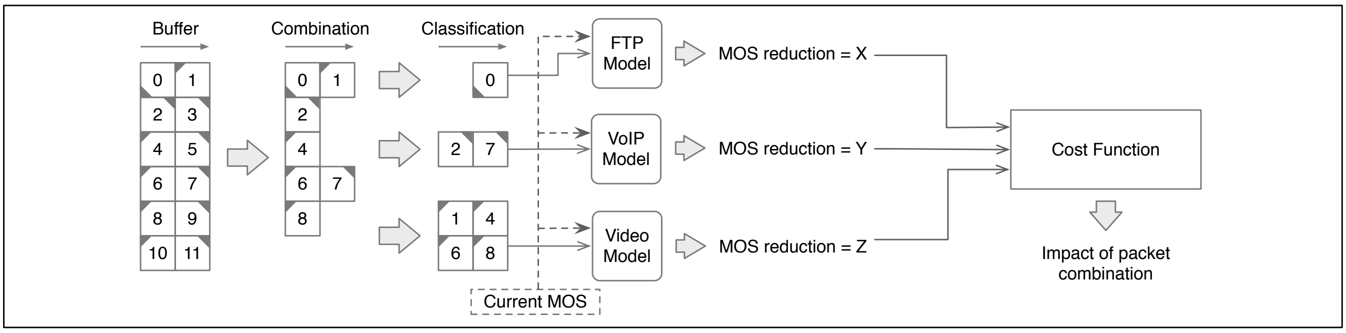


Fig. 1: Determining the impact of a packet combination

base-10 integer, where its base-2 equivalent can be seen as an array of boolean values that indicate which packets belong to the combination. This mapping can be seen in Fig. 2.

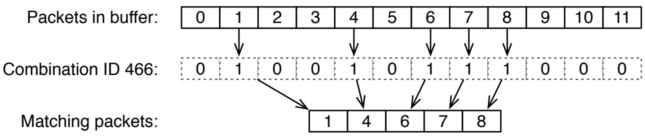


Fig. 2: Mapping a base-10 combination ID to a list of packets

With the list of packet combinations satisfying (3), the QoE models are applied to simulate the effect of dropping packets associated with each combination. The outcome of this process is a list of MOS score decreases, per flow, for each combination. The total and mean reduction in MOS is calculated from these scores, as well as their standard deviation (σ^2). Finally, (1) is applied to find the packet combination with the lowest impact on quality, and the scheduler drops this combination from the buffer.

Our approach of analyzing the impact of packet combinations, instead of just the effect of one packet at a time, can bring improved performance at the expense of a higher computational effort – the exponential increase in the number of combinations, for buffers holding many packets, can be detrimental on performance. However, our analysis shows that limiting the number of evaluated combinations to a sensible value (e.g., 2^{16}) provides a substantial reduction in computational cost at the expense of minor decrease in scheduling performance.

4.2. Methodology

We ran a series of simulations in which we compared the performance of our QoE-based scheduler to the standard *ns2mesh* scheduler. Each simulation is the average of 20 repetitions, each one lasting 10s, where the first second of all measurements was subsequently discarded in order to remove the effect of network transients.

The following simulation parameters were defined: link bandwidth $\approx 6Mbps$; limit on 2^{20} evaluated combinations; $k_i^{ftp} = 0.8$: scheduler is 20% more likely to drop FTP packets; video model configured for a sample with 30-frame GOPs, 10 P-Frames per GOP, 1 frame per packet, bernoulli-type losses; audio model configured for codec G.711; and FTP model tuned to return maximum MOS for 400 kbps, minimum for 10 kbps.

4.3. Video service scenario

In a video stream, in contrast to audio and data streams, there are specific frames that contribute much more to the overall quality of the stream than other frames, thus making video the service with the largest potential for quality improvements due to QoE-aware scheduling. For instance, losing a B-frame from the stream can only cause a minor loss of detail, while losing an I-frame can cause skipping, blockiness, and other artifacts, thereby resulting into much larger distortion values.

Here, we consider a scenario involving only video streams. The first simulation is run on a network grid topology with 9 nodes arranged in a square 3x3 pattern, as illustrated in Fig. 3. We introduce a growing number of video flows in the network (up to 9 flows) with random source and destination node pairs, and plot the average MOS for all flows against that for the case of *ns2mesh*'s standard scheduler, in Fig. 4a.

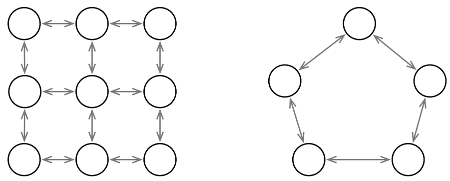


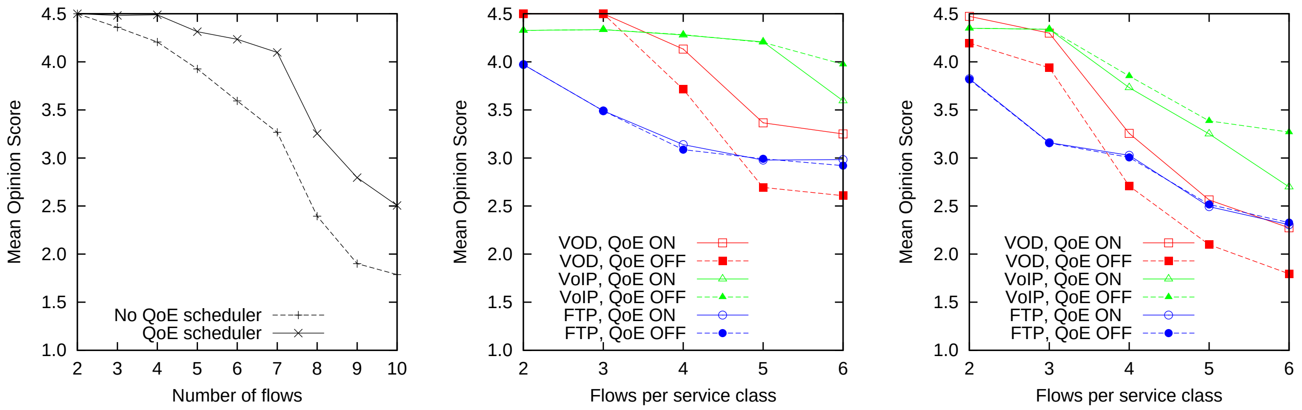
Fig. 3: 9-node grid and 5-node ring topologies

The gains in user perception are significant. As the network load is increased, for more than three concurrent flows, the QoE scheduler consistently improves each stream's quality by more than 0.5 MOS points. By adopting this scheduler, the network can support up to 7 video flows with a MOS score of more than 4 points (near-excellent quality).

4.4. Multi-service scenario

The goal of these simulations is to determine the scheduler's performance when video, voice, and file transfer services are present in the network. Voice and file transfer services, unlike video, are less prone to quality degradation due to random packet dropping.

We use three different service types on the same 9-node grid topology, where flows have random source and destination nodes. We increase the number of flows of each traffic type successively to saturate the network. After that, we repeat the simulation on a 5-node ring network (depicted in Fig. 3) where, due to both the reduced number of nodes and of links, the available bandwidth is exhausted



(a) Video QoE in a 9-node grid network (b) Average QoE: a 9-node grid network (c) Average QoE: a 5-node ring network

Fig. 4: Performance analysis of the proposed QoE scheduler

much faster. Figures 4b and 4c plot the average MOS of all flows per service type, for the grid and ring topologies respectively.

As expected, the QoE gains are mostly seen on the video flows, with an average increase of 0.2 to 0.5 MOS points. Furthermore, since VoIP flows exhibit higher MoS relative to video they are penalized with a higher packet drop rate when network saturation is increased (6 flows per traffic type), as necessitated by (1). For the same reason, FTP flows are relatively unaffected by the QoE scheduling as network saturation increases, since they already have the lowest MOS, as seen from Figures 4b and 4c. Finally, the proposed QoE scheduler reduces the variation in user satisfaction across the different services relative to the case of conventional scheduling, as evident from Figures 4b and 4c.

5. CONCLUSIONS & FUTURE WORK

We have developed a distortion optimized packet scheduler that maximizes the overall QoE in multi-service wireless mesh networks. The proposed approach is based on minimizing a flexible cost function that captures the joint effect of dropping packet combinations over multiple flows in order to achieve an efficient utilization of the available network resources. The optimization takes advantage of the fact that different media types as well as the data units comprising a single media presentation typically exhibit varying degrees of sensitivity to limited network resources. Our simulation results demonstrate a significant increase in user perceived service quality for delivery over WiMAX based mesh networks, with an emphasis on video content. Moreover, the scheduler's approach of analyzing all services combined and of contemplating multiple packet drops from any individual service leads to a more balanced distribution of quality, as packets can be dropped from one service to improve another service.

Potential future work are diverse in nature. To improve the QoE scheduler, important parameters to be considered include the link quality for the different neighbors and the route length. To this extent, an integration of a multi-path routing protocol that can send different packets towards different potential neighbors would allow for a more fine grained load-balancing mechanism that takes into account the contribution of a given packet to an overall QoE measure subject to resource availability.

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