# A cross-layer design for efficient video transmission over wireless networks: statistical QoS optimisation

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*Abstract*: Studies on the cross-layer design for efficient multimedia delivery with QoS assurance over wireless networks utilize the differentiated service architecture to convey multimedia data. The common approach is the partitioning of multimedia data into smaller units, and then maps these units to different classes for prioritized transmission. The partitioned video units are prioritized based on its contribution to the expected quality at the end user, while the priority transmission system provides different QoS guarantees depending on its corresponding service priority. In order to maintain quality of video and uninterrupted service in highly dynamic wireless environment, it is necessary to utilize statistical QoS in cross-layer design and interaction between layers. An in-depth analysis and comparative evolution of optimally strategies for mapping video layers to one of the priority classes, are presented in this paper.

*Key-words:* wireless video, cross-layer optimization, statistical QoS mapping

## 1 Introduction

Cross-layer design breaks away from traditional network design where each layer of the protocol stack operates independently [1]. In an effort to improve the performance of wireless networks there has been increased interest in protocols that rely on interactions between different layers. We discuss key parameters used in cross-layer information exchange, along with the associated cross-layer adaptation and optimization strategies [2]. An in-depth understanding and comparative evolution of these strategies are necessary to effectively access and enable the possible trade-offs in multimedia quality power, consumption, implementation complexity and spectrum utilization that are provided by various layers. This opens the question of cross-layer optimization and its effectiveness [3, 4].

Wireless local area network (WLAN) are balanced to enable a variety of delay-sensitive multiple applications, due to their flexible and low cost infrastructure. However, existing wireless networks provide only limited time-varying quality of service (QoS) for delay-sensitive, bandwidth intense and loss-tolerant multimedia applications. Fortunately, video transport can cope with a certain amount of packet losses depending on the sequence characteristics and error concealment strategies. Consequently video transmission does not require complete insulation from packet losses, but rather that the application layer cooperate with the lower layers to select the optimal wireless transmission strategies that maximizes multimedia performance. This article focuses on statistical QoS cross-layer optimization and interaction between layers [1].

Wireless networks typically have time-varying and non-stationary lines due to the following factors: fading effects coming from path loss, roaming between heterogeneous mobile networks, and the variation in mobile speed average received power and surrounding environments. Consequently, the quality of wireless link varies, which can be measured by the variation of the signal-to-noise ratio (SNR) or the bit error rate (BER). These variations results in time-varying available transmission bandwidth at the link layer, which also leads to time varying delay of arrival video packets at the application layer, especially when retransmission is employed at the link layer [1]. Since the buffer size at the link layer is typically limited, the time-varying channel service rate can induce buffer overflow and therefore video packet loss due to the bit rate mismatch between the transmitting video packet and the channel service rate. At the application layer, due to variation in arrival time of video packets, some packets may become useless during playback if its arrival time exceeds certain threshold.

Existing wireless networks provide only limited, time-varying Quality of Service (QoS) for delay-sensitive, bandwidth-intense, and loss-tolerant multimedia applications. Fortunately, multimedia applications, can cope with a certain amount of packet losses depending on the sequence characteristics and error concealment strategies available at the receiver. Consequently, unlike file transfers, real-time multimedia applications do not require complete insulation from packet losses, but rather the application layer cooperate with the lower layers to select the optimal wireless transmission strategies that maximizes multimedia performance [5, 6].

For video streaming, high bandwidth requirements are coupled with tight delay constraints, as packets need to be delivered in a timely fashion to guarantee continuous media playout. When packets are lost or arrive late, the picture quality suffers, as decoding errors tend to propagate to subsequent partitions of the video. Due to the high bit rate requirements of video, a media stream may congest the network significantly. Hence, it is imperative to account for the potential impact of each video user on the network statistics and guarantee that the network is not operating beyond the capacity [1]. While protocol layering is an important abstraction that reduces network design complexity, it is not well suited to wireless networks since the nature of the wireless medium makes it difficult to decouple the layers.

A cross-layer approach to network enhances the performance of a system by jointly designing multiple protocol layers. This allows upper layers to better adopt their strategies to varying link and network conditions. These concepts are useful for supporting delay-constrained applications such as video. In such a structure each layer is characterized by some key parameters, which are passed to the adjacent layers to help them determine the operation modes that will best sent the current channel, network and application conditions. In such a design, each layer is not obvious of the other layers, but interacts with them to find its optimal operational point. The difficulty in this cross-layer approach resides in characterized by parameters representing the channel capacity, such as Signal-to-Interference-plus-Noise Ratio (SINR), or link layer state information such as Bit Error Rate (BER) or supported data rates. Similarly, the network and Medium Access Control (MAC) layers must exchange the requested traffic rates and supportable link capacity [7, 8, 9].

## 2 Statistical QoS

With time-varying wireless link quality, providing QoS for video applications in the form of *absolute* guarantee may not be feasible. Thus, it is more reasonable to provide QoS in the form of *soft* guarantee, which allows QoS parameters in the priority transmission system to be adjusted along with changing channel conditions. Similarly, on the application layer, it is desirable to have a video bitstream be adaptive to changing channel conditions. Among several possible approaches for video quality adaptation, scalable video has low complexity and high flexibility in rate adaptation.

To coordinate effective adaptation of QoS parameters at video application layer and priority transmission system, cross-layer interaction and QoS mapping mechanism are required. Unfortunately, a good cross-layer QoS mapping and adaptation mechanism that offers a good compromise between the video quality requirement and the available transmission resource is a challenging task. This is because at the priority transmission layer, QoS is expressed in terms of probability of buffer overflow and/or the probability of delay violation at the link layer. On the other hand, at the video application layer, QoS is measured objectively by the mean squared error (MSE) and/or the peak signal- to-noise ratio (PSNR).

The cross-layer architecture for video delivery over wireless networks is shown in Fig. 1 [1]. This is an end-to-end delivery system for a video source which includes source video encoding module, cross-layer mapping and adaptation module, link layer packet transmission module, wireless channel (time varying and nostationary), adaptive wireless channel modeling module, and video decoder/output at the receiver. Since the main challenge here is the time-varying and non-stationary behavior of the wireless link, we will describe its modeling first.

The wireless channel at the link layer instead of physical layer will be modeled since the link layer modeling is more amenable for analysis (delay bound or packet loss rate). The wireless link is expected to be fading, time-varying and nostationary. This will provide time-varying available transmission bandwidth for video service. Although the wireless channel is expected to be time-varying and nonstationary, it can be assumed that within each small time interval, say $g$, the channel rate is stationary bad time-varying. Furthermore, within each small time interval $g$, it can be assumed that service rate for time-varying wireless channel can be modeled by a first-order $L$-state *Markov model* [10].

Denote $X_c(n)$ as the state of the channel at time *n* and $X_c(n) \in \{1,2,...,L\}$. Each state $X_c(n) = i$ corresponds to a channel link condition, which can be characterized by an achievable channel transmission rate of $r_i$. The achievable channel transmission rate at state *i* can be obtained to be as

$$r_i = R \log_2(1+\gamma_i) \text{ [bits/s]} \tag{1}$$

Here, $R$ is the transmission bandwidth in Hz, while $\gamma_i$ represents the SNR value of the wireless channel condition at state *i*. For the *L*-state discrete-time *Markov chain*, denote $p_{ij}$ as the state transition probability from state *i* (at time *n*-1) to state *j* (at time *n*) with a transition time interval of 1 time unit and 1<*g*. That is, $p_{ij} = P\{X_c(n) = j / X_c(n-1) = i\}$. Thus, the *L*-state *Markov chain* can be completely characterized by the *L*x*L* state transition matrix, i.e.,

$$P_{transition} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1L} \\ . & . & . & . \\ p_{L1} & p_{L2} & \cdots & p_{LL} \end{pmatrix} \tag{2}$$

Using the state transition matrix, we can calculate the state probability for *Markov model* within the time interval *g* [1], which we denote as $[p_1, p_2, ..., p_L]$. The expected link layer transmission rate $r_{channel}$, during the time interval *g* is

$$r_{channel} = \sum_{i=1}^{L} r_i \ p_i \tag{3}$$

where $r_i$ is the achievable link layer transmission rate, previously define in (1). At the end of each time interval *g*, the state transition matrix in (2) will be updated by the adaptive channel modeling module to reflect the nonstationary nature of the wireless environment.

In the link-layer transmission control module, we employ a class-based buffering and scheduling mechanism to achieve differentiated services. We maintain *K* quality of service priority classes with each class of traffic being maintained in separate buffers. Priority scheduling policy is employed to serve packets among the classes. That is, packets in a higher priority queue will always be sent first. On the other hand, packets in the lower priority queue will be sent only if there is no packets in the priority queues. Also, packets within the same class queue are served in a first-in-first-out (FIFO) manner. A packed that experiences excess queuing delay (i.e., will miss its scheduled playback time) will be discarded without being sent over the wireless channel. In that way, based on this class-based buffering and strict priority scheduling mechanisms, each QoS priority class will have some sort of statistical QoS guarantees in terms of probability of packet loss and packet delay. Statistical QoS guarantees of multiple priority classes can be translated into rate constraints. The calculated rata constraints will specify the maximum data rate that can be transmitted reliably with statistical QoS guarantee over the time-varying wireless channel. This will classify video substreams into classes and allocate transmission bandwidth for each class. The accumulated amount of data in queuing system for time-varying service rate and channel service rate, which is generated by the source from time 0 to time *t* is a random variable of the form

$$A(t) = \int_0^t \alpha(u)\, du \tag{4}$$

where $\alpha(u)$ is the source data generation rate.

The amount of data *A(t)* will be stored in the buffer of size $B^{max}$ awaiting for transmission. The accumulated channel service from 0 to *t* is of the form

$$S(t) = \int_0^t \alpha^{c(u)}(u)\, du \tag{5}$$

where $\alpha^{c(u)}$ is the channel service rate at time *u*. Note that the time-varying channel service rate has been modeled by a *L*-state discrete-time *Markov chain,* where $\alpha^{c(u)} \in (r_1, r_2, ..., r_L)$. The stochastic behavior of the accumulated channel service *s(t)* can be described by the concept of effective capacity which can be presented in the form

$$\mu(\Theta) = -\frac{\Lambda^{(c)}(\Theta)}{\Theta} \tag{6}$$

Here, $\Lambda^{(c)}(\Theta)$ is the asymptotic log-moment generating function *S(t),* defined as $\Lambda^{(c)}(\Theta) = \lim_{t\to\infty} \frac{\log E\left[e^{-\Theta S(\Theta)}\right]}{t}$ where $\Theta$ is called the QoS exponent corresponding to the effective capacity $\mu(\Theta)$ [1]. The parameter $\Theta$ is related to the statistical QoS guarantee (e.g., packet loss probability) of the time varying channel. The statistical QoS guarantee in terms of packet loss probability can be derived as a function of $\Theta$. Namely,

$$P\{B(t) > B^{\max} | \Theta\} \approx \xi e^{-\Theta B_{\max}} \tag{7}$$

where *B(t)* is the buffer occupancy at time *t*, $B^{max}$ is the maximum buffer size, $\xi$ is the probability that the buffer is not empty, while $\xi e -^{\Theta B_{\max}}$ is the approximate packet loss probability guarantee. Intuitively, it says that the effective capacity in (6) imposes a limit for maximum amount of data that can be transmitted over time-varying channel with statistical QoS guarantee in (7).

Adaptive wireless channel modeling module and link-layer transmission module are application independent. They are installed at wireless end system as a common platform to support a wide range of applications, not limited to video delivery. The advantages of such design are universal applicability, modularity and economy of scale.

Mapping and adaptation module is applications specific. It is designed to optimally match video application layer and the underlying link-layer. Since the QoS measure at the video application layer (distortion and uninterrupted video service perceived by end user) is not directly related to QoS measure in the link layer (packet loss/delay probability), a mapping and adaptation mechanism must be in place to maximize application layer QoS with the time-varying available link layer transmission bandwidth. At the video application layer, each video packet is characterized based on its loss and delay properties, which contribute to the end-to-end video quality and service. Then, these video packets are classified and optimally mapped to the classes of link transmission module under the rate constraint. The video application layer and link-layer are allowed to interact with each other and adopt along with the wireless channel condition. The objective if these interaction and adaptation is to find a satisfactory QoS tradeoff so that each end user's video service can be supported with available transmission resources.

# 3 Optimal mapping algorithm

In this section, we present in-depth algorithm for optimal mapping of each video layer to one of the priority classes [1]. The strategy is applicable to MPEG-4 and H.264/AVC prioritized video coding schemes.

Let $\overset{\rightarrow}{\pi} = [\pi_1,...,\pi_M]$ be the mapping policy from *M* video layers to *K* priority classes, where $\pi_j \in \{0,1,...,K\}$ is the priority class that video layer *j* is transmitted. $\pi_j = 0$ represents the fact that video layer *j* is abstained from transmission. Optimal mapping problem can be formulated as follows:

*Given the se of rate constraints under the priority transmission system and the expected channel service rate* $r_{channel}$*, which can be considered stationary in a time period g corresponding to one MPEG-4 GOP, optimal mapping policy* $\overset{\rightarrow *}{\pi}$ *from one GOP with* $N_{GOP}$ *scalable frames (coded in M video layers) to K priority classes minimize overall expected distortion* $D_{GOP}\left(\overset{\rightarrow}{\pi}\right)$

$$\sum_{\forall j, \pi_j = i} b_j^{\pi_j} \le \mu_i(k_i) \bullet g, \; i = 1,...,K \qquad (8)$$

$$\sum_{i=1}^{K} \mu_i(k_i) < r_{channel} \qquad (9)$$

where $\mu_i(k_i)$ is the rate constraint of priority class *i*, and $b_j^{\pi_j}$ is the size of video layer *j*, which will be conveyed by priority class $\pi_j$.

There are two sets of constraints in the above problem formulation. The first set of constraints say that the source rate of video bitstreams under each priority class must not exceed the rate constraint of the corresponding priority class. The second constraint says that the summation of rate constraints of all priority classes has to be bounded by the expected channel service rate.

The solution to the optimization problem follows a constrained-based search that exploits the dependency among the layers [2]. The tree represents all possible QoS mapping solutions [1]. Each stage of the tree corresponds to one of the video layers. Each node of the tree at a given stage represents a possible cumulative buffer occupancy in each priority class.

Each branch at stage has a cost to account for the expected distortion reduction when video layer is mapped to a particular priority class. The reduction in distortion is zero if video layer is abstained from transmission. Therefore, as we traverse the tree from the root to leaves, it is computed the accumulated expected distortion reduction for each possible mappings.

An exhaustive search of each node for a complete tree is not necessary, due to the rate constraint for each priority class. It is sufficient to prune the branch when the accumulated rate exceeds its corresponding rate. Once we find the maximum accumulated distortion reduction, the optimal mapping solution can be found by traversing back from the leaf node to the root of the tree.

## 4 Concluding remarks

For a cross-layer QoS mapping architecture for video delivery over wireless environment, there are several components which must be taken into account, including a proposal of an adaptive QoS service model that allows QoS parameters to be adaptively adjusted according to the time-varying wireless channel condition, an interactions mechanisms between the priority network and video applications to provide proper QoS selection and a resource management scheme to assign resources based on the QoS guarantee for each priority class under the time-varying wireless channel.

We present in-depth analysis of a QoS mapping mechanism that optimally maps MPEG-4 scalable video classes to statistical QoS guarantees of a priority transmission system.

Proposers of cross-layer design must consider the totality of the design, including the interactions with other layers and also what other potential suggestions might be barred because they would interact with the particular proposal being made. They must also consider the long-term architectural value of the suggestion.

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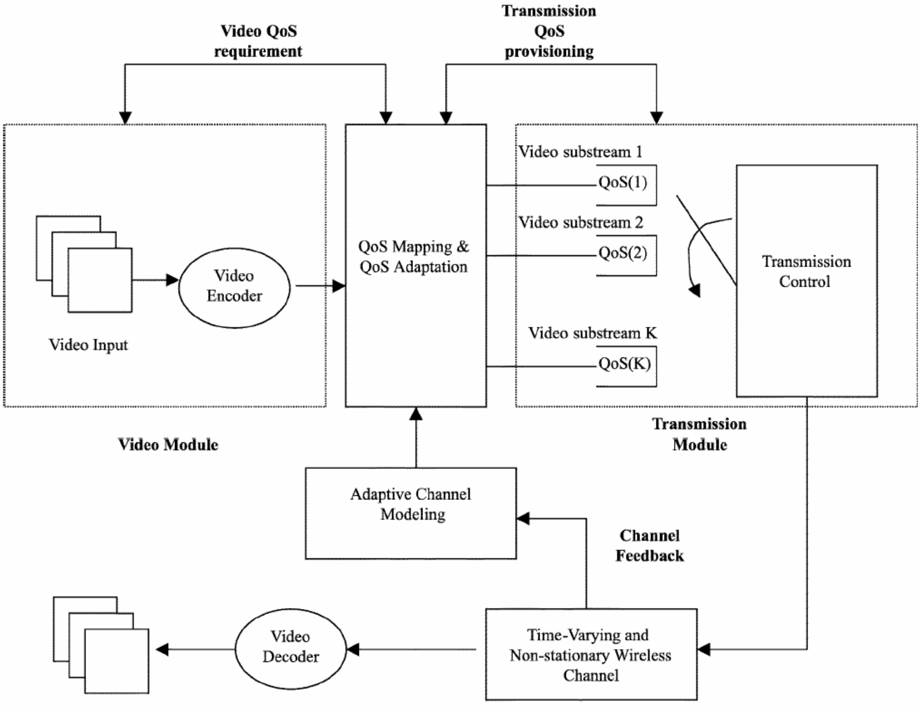

Figure 1. Cross-layer architecture for video delivery over wireless channel [1].