Video Pricing for Wireless Networks

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***Abstract*— The development of pricing schemes that account for the specific challenges in streaming video to wireless clients is one of the key requirements for making wireless video services economically viable. In this paper we develop a conceptual framework for the pricing of wireless video streaming. Our framework incorporates the quality of the delivered video in the given networking context in an earnings model and captures the costs for the video service in a cost model. We discuss these models in the context of cellular, WLAN, and multi-hop wireless networks. We illustrate the developed pricing framework through numerical experiments with videos of a range of quality levels.**

***Index Terms*— wireless, video, multimedia, pricing**

I. Introduction

While strides are being made in solving the technological challenges of streaming video to wireless clients, the development of pricing schemes for wireless video services has received relatively limited interest to date, as detailed in Section V. The development of pricing schemes that account for the specific challenges of wireless video streaming, however, is one of the key requirements for the economic viability, and ultimately the widespread proliferation of wireless video services.

In this paper we lay out a conceptual framework for pricing wireless video services. The two main pillars of our framework are an earnings model and a cost model, which in turn give the revenue from the video service as the difference between earnings and cost. Our earnings model is based on the delivered video quality and considers the utility (willingness to pay) that a typical user associates with the delivered video quality in the context of the given wireless network scenario. Our cost model incorporates fixed infrastructure costs, opportunity costs, and per-byte transmission costs.

We lay out how the specific characteristics of cellular wireless networks, wireless LANs (WLANs), and ad hoc multi-hop networks can be accounted for in our earnings and cost models. We illustrate our pricing frame work through numerical examples for wireless video transmission at different quality levels.

II. Wireless Challenges

The wireless world's most challenging aspects for streaming pre-encoded video are the heterogeneity of the wireless device and access network world, which we outline in the following.

A. Device Diversity

Wireless devices can vary greatly in their abilities. In particular characteristics such as processing power, battery, and display size may deviate greatly not only between device classes, but also within a class of devices. In order to develop a pricing scheme, providers need to build on their experiences from the past, or extrapolate from the currently served clients to determine the mix of devices and access strategies that the client devices utilize for long-term decisions. For a more general approach, we can determine the two major device classes as cellular phones and laptop type devices. We assume for the first device class a low computational power and screen size, whereas for the second class we assume a high computational power and large screen sizes. For video streaming scenarios considered here, we assume that in both cases the battery-powered run-time either exceeds the video duration or that alternatively the batteries can be recharged.

B. Connectivity Diversity

In addition to the diversity of wireless device classes, these devices can connect to the Internet using a variety of access technologies. We identify the three general classes of access types as (i) cellular, (ii) ad-hoc wireless LAN, and (iii) hot-spot wireless LANs, illustrated in Figure 1. In addition to these access network types, the individual technologies may be different, such as UMTS, GPRS, or EDGE for the cellular access or single channel versus multiple channel access protocols for the WLAN based access.

III. Components of a Pricing Scheme

A general video pricing scheme consists of the earnings that a provider can obtain as function of the video quality streamed to the user as well as the costs that the provider incurs by

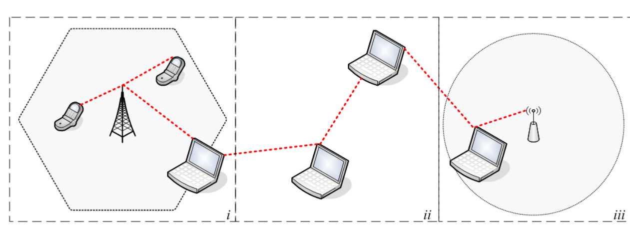

Fig. 1. General wireless network access: (i) cellular, (ii) ad-hoc WLAN, and (iii) hot-spot wireless LAN.

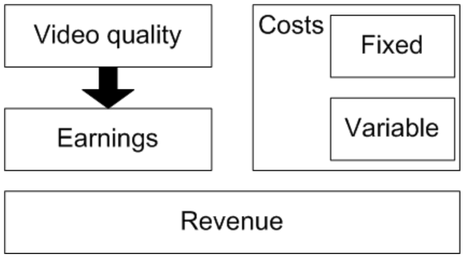

Fig. 2. Components of a video pricing scheme.

streaming. We illustrate these components in Fig. 2. In the following, we examine the individual components closer.

A. Quality Characterization

The quality of an encoded and streamed video can be measured by using subjective tests or objective quality functions such as the PSNR. While the PSNR is commonly used to determine the video quality, alternative metrics such as the Video Quality Metric (VQM) [1] have been recently proposed. In a study by the Video Quality Experts Group (VQEG), the PSNR — as metric that can be easily employed in automated testing — was found to have a correlation around 0.8 to the subjective quality [2]. Although more computational demanding metrics such as the VQM may yield a higher correlation to subjective tests, the PSNR is still the most commonly applied metric due to its simplicity.

To determine the PSNR quality of a video encoded with a quantization scale q, the individual video frames of the original and the encoded (and subsequently decoded) video frames are compared. We denote an individual pixel's luminance value in the nth original video frame at position (x, y) as $F_n(x, y)$ and its encoded (with quantization scale q) and subsequently decoded counterpart by $f_n^q(x, y)$. Let X and Y denote the resolution in pixels of the source video. We calculate the video frame distortion as RMSE for all the luminance differences of an individual frame n encoded with the quantization scale q as

$$RMSE_n^q = \sqrt{\frac{1}{XY} \sum_{x=0}^{X-1} \sum_{y=0}^{Y-1} [F_n(x, y) - f_n^q(x, y)]^2}. \quad (1)$$

The video frame quality as PSNR can be calculated from the RMSE as

$$Q_n^q(0) = 20 \log_{10} \frac{255}{RMSE_n^q}. \quad (2)$$

In addition, we derive the quality losses that are a result of lost video frames by employing a basic error handling scheme as follows. Whenever a video frame cannot be decoded at the client, the client's decoder re-displays the last successfully received video frame. Thus, the video quality for these frames can be calculated from the offset distortion [3] as

$$RMSE_n^q(d) = \sqrt{\frac{1}{XY} \sum_{x=0}^{X-1} \sum_{y=0}^{Y-1} [F_n(x, y) - f_{(n+d)}^q(x, y)]^2}. \quad (3)$$

The corresponding video frame quality can be calculated similar to Eq. (2) as

$$Q_n^q(d) = 20 \log_{10} \frac{255}{RMSE_n^q(d)}. \quad (4)$$

where d denotes the distance or offset of the last successfully received frame to the currently evaluated frame. Video traces and software that enable researchers the utilization of the offset distortion have recently become available [4]. Without loss of generality, we consider here a simple GoP-based approach and let the length of one GoP be 1 scene or video sequence. We employ the basic $IPPP\ldots$ GoP pattern to fix ideas here. Let N denote the total number of frames, G denote the number of frames in a GoP , and R_g denote the last frame received in a GoP. We then derive the average video quality for a given GoP g, $g = 0, 1, \ldots, \lfloor N/G \rfloor - 1$ as

$$\overline{Q}_g^q(R_g) = \frac{1}{G} \left(\sum_{n=g \cdot G}^{g \cdot G + R_g} Q_n^q(0) + \sum_{d=1}^{G - R_g - 1} Q_{g \cdot G + R_g}^q(d) \right). \quad (5)$$

For the remainder of this paper, we assume that the video is encoded open-loop, i.e., without rate control. We note that rate-controlled video can be accommodated in a similar manner.

B. Earnings Function

For the earnings that a video service provider can accrue from streaming to video clients, we have to take the device and network contexts into account. For illustration consider a laptop connected via a cellular (lower bandwidth) network, where the network only supports a lower bandwidths of the video (compared to the WLAN based approaches) yet the client has a large display (and may correspondingly prefer a larger size for the video). One immediate challenge for this example is to determine whether the client would benefit more form receiving a low quality version of the full resolution video or from a higher quality version of the low resolution video (which would then be up-sampled by the decoding software prior the display) by calculating the quality and utility differences.

The earnings that a content provider can achieve therefore depend on the device and network context and the resulting quality displayed on the client's display. One central question is now how to map the quality experienced by a client towards the price that this client is willing to pay for the reception of the video. One common approach is to consider utility functions [5], [6], a principle borrowed from microeconomics. Utility functions are characterized by diminishing marginal utility, i.e., in the context of video quality, increasing the video quality from a very low value initially gives a high increase in utility [7]. As the video quality increases, additional increases in the video quality yield lower increases in the client utility. Let $U_g^q = f(\overline{Q}_g^q(R_g))$ denote the utility for a client and a particular GoP at quantization scale q. One exemplary utility function without incorporation of transmission losses is given as [8]

$$U_g^q = \log_{10} \left[1 + \overline{Q}_g^q - \overline{Q}_g^{q_{\max}} \right], \quad (6)$$

where $q_{\max}$ denotes the largest quantization scale q. The incorporation of losses is not feasible using the utility function introduced above that relies on the encoded video quality and is still under evaluation.

The earnings also depend on the price a client is willing to pay. In general fixed or variable prices can be considered, whereby variable prices could be determined by the time of day, the client location, the length of the video, its actuality (e.g., breaking news), or its popularity (e.g., the latest 'block-buster'). Without loss of generality, let P denote the fixed price that a client is willing to pay for a "unit of quality". We can then calculate the earnings of the content provider as

$$E_g^q = \sum_{g=0}^{\lfloor N/G \rfloor - 1} P \cdot U_g^q. \tag{7}$$

An alternative approach would be to let the price also vary with the quality, such that $p_g^q(R_g) = f(\overline{Q}_g^q(R_g))$.

C. Cost Function

To determine the costs for video service providers, we assume without loss of generality that the service provider and the infrastructure provider are identical. We incorporate the opportunity costs into our model. Opportunity costs C^{opp} are an economic concept used to value the most beneficiary alternative that has to be foregone in order to make an economic decision and to consider these as costs in the planning. As most in most cases the costs for video streaming will also depend on the amount of video traffic, we denote the size of an individual video frame as X_n^q. In the following, we evaluate three different scenarios for provider costs, namely (i) cellular networks, (ii) hot-spot wireless LANs, and (iii) multi-hop networks.

1) Cellular Networks: Cellular networks are highly infrastructure dependent. In addition to the infrastructure, spectrum licences and other operational fees have to be paid. The operation of a cellular network thus incurs high fixed costs. These have to be paid back over time by the network providers and need to be calculated into the costs that a service provider faces which we denote as C^{fix}, which could also be seen as the network access price (for example in terms of monthly fees broken down to the duration of a GoP). Once a cellular network is operational, we can assume that the price for the transmission of data c remains stable and depends only on the amount of transferred data (i.e., the product of price per transmitted byte and the amount of data in byte is referred to as variable costs). For the opportunity costs that arise in this context, we can assume that in case the resources of a cell are not completely used, there are no opportunity costs if we assume that no new users arrive (roaming, handover, or just powered up cell phones). In case that the cell is full, we can assume that the admission of a video stream can incur opportunity costs for not being able to serve other services such as voice calls. Combining the three cost factors, we obtain the general costs for GoP g streamed encoded with quantization scale q as

$$C_g^q(R_g) = \sum_{n=g \cdot G}^{g \cdot G + R_g} X_n^q \cdot c + C_g^{\text{fix}} + C_g^{\text{opp}}. \tag{8}$$

2) Hot-Spot Wireless LANs: Considering the setup costs for infrastructural burden for hot-spot WLANs exhibits only medium fixed costs, as in most cases the base station will be positioned in a place of interest, such as a coffee shop. In addition, the typically used frequencies do not require licensing and hardware is available in affordable mass quantities. Similar to the cellular network case evaluated above, we assume that the fixed costs can be generally broken down to be charged by access time (measured in GoP durations). If we assume that in general, users have similar bandwidth usage and subsequently, there is no additional benefit possible by exchanging between one user and another, we can assume that there are no opportunity costs, and Eq. (8) simplifies to

$$C_g^q(R_g) = \sum_{n=g \cdot G}^{g \cdot G + R_g} X_n^q \cdot c + C_g^{\text{fix}}. \tag{9}$$

3) Multi-hop Networks: Ad-hoc multi-hop networks incur only low fixed costs if the infrastructure is considered as the individual nodes are all that is required. On the other hand, forwarding packets that are not destined for a node will consume battery power and computational power (processor cycles) at the intermediate nodes which may in general be considered as opportunity costs. For the forwarding nodes, we therefore need to consider compensation based on their forwarding burdens. Several authors have started to investigate the pricing and costs of forwarding, see, e.g., [9], [10], [11]. This compensation can take the form of bandwidth use credits or similar mechanisms, see, e.g., [12]. As this form of compensation heavily depends on the amount of traffic, we consider only the variable costs that stem from the traffic forwarding to the destination node. (We note that additional considerations could lead to the incursion of fixed costs in such scenario as well, e.g., the path setup — which is non-video overhead on each involved node — could be regarded in such a manner.) In a multi-hop scenario over T nodes, the costs c_t that occur could be independent for each forwarding node t, $t = 1, \ldots, T$, e.g., nodes with low battery power may request higher forwarding compensations in order to deal with traffic not destined for them. The sum for all forwarding nodes thus determines the total costs as

$$C_g^q(R_g) = \sum_{n=g \cdot G}^{g \cdot G + R_g} X_n^q \cdot \sum_{t=1}^{T} c_t. \tag{10}$$

To fix ideas here, we assume that all nodes have the same compensation requests as costs and let $c_t = c$.

D. Revenue

The revenue a content provider earns is given by the earnings minus the costs that occur as

$$R_g^q = E_g^q - C_g^q. \tag{11}$$

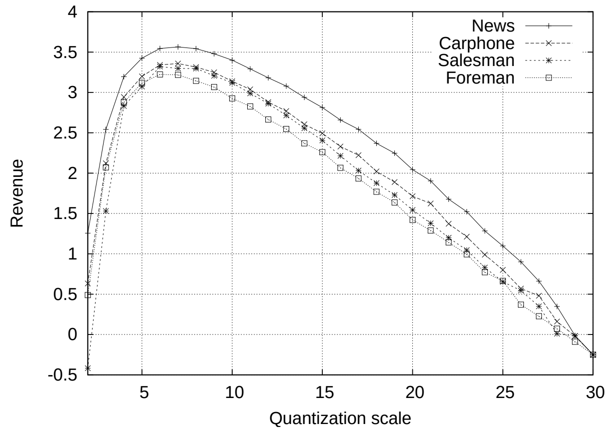

Fig. 3. Revenue as function of the quantization scale q for quality price $P = 5$ and bandwidth cost $c = 0.25$.

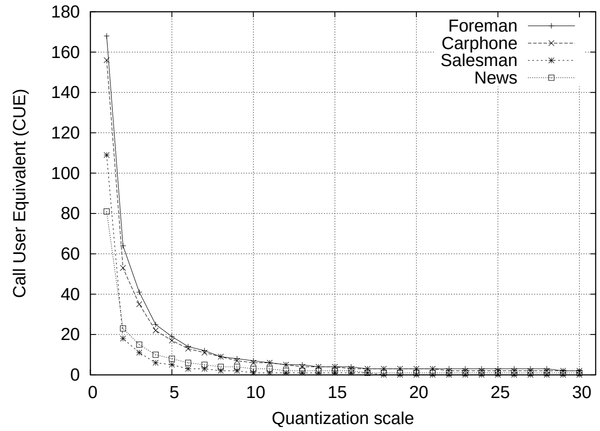

Fig. 4. Opportunity costs in terms of call user equivalent (CUE) with AMR codec at 13.2kbps versus different video sequences as function of quantization scale q.

We consider the case without fixed or opportunity costs and let the variable costs $c = 0.25$, i.e, we assume that the cost of one bandwidth unit is $c = 0.25$. For the costs of the provider, we normalize the bandwidth to the lowest bandwidth, i.e. the bandwidth obtained for $q = 30$, which equals one bandwidth unit. We consider a price of $P = 5$ for a client utility unit as defined in Eq. (6). We consider the *Foreman*, *News*, *Carphone*, and *Salesman* video sequences, all encoded as single GoP with the IPPP... pattern. We illustrate the resulting revenue in Fig. 3. We observe that the maximum revenue for the *Foreman* and *Salesman* sequences is obtained at a quantization scale of $q = 6$, while the maximum for the *News* and *Carphone* sequences is obtained at $q = 7$. We evaluate the outcome for different prices in the extended version [13] due to space constraints here.

1) Cellular Networks: For cellular networks, we consider two different cases, namely (i) the empty cell and (ii) the saturated cell. While adding a video stream to an empty cell is not hindered in any way, the saturated cell poses the challenge that adding a video stream can only be done by allocating otherwise utilized or surely utilized (reserved) bandwidth. For this case, the opportunity costs can be determined without loss of generality by assuming that the available bandwidth could be distributed among video or call (voice) clients. Let B_{video} denote the required bandwidth for the video stream and B_{call} denote the required bandwidth with a commonly used audio codec for a single calling client. Subsequently, an economically oriented call admission scheme has to determine the number of call users that can be supported as call user equivalent (CUE) given by

$$CUE = \left\lfloor \frac{B_{\text{video}}}{B_{\text{call}}} \right\rfloor . \tag{12}$$

The CUE determines the number of users that could be supported using the video bandwidth. Knowing the price charged for the calling clients, the provider would be able to determine the actual earning differences and opportunity costs. Similar considerations can be made to consider other types of services. For illustration of the CUE, we consider an AMR speech codec with 13.2kbps without silence detection and plot the *CUE* in Fig. 4. We observe that the *Foreman* video sequence has the largest call user equivalent of all evaluated video sequences. In other words, due to the resulting video bit rate, the provider has to charge more for the video stream to compensate for the foregone utilization of the bandwidth by call users. Further considerations can be found in [13].

2) Multi-hop Networks: In multi-hop networks, the available path and bandwidth have to be determined before the streaming. For these networks, mobility has an additional impact on the client utility, as paths may break and reconnection timeouts for path resolution may occur. In terms of the revenue that a provider can earn in this scenario, let us consider the initial case presented in this section. We evaluate the multi-hop scenario in the extended version [13] due to space constraints here.

IV. Multiple Clients

In our earlier evaluations, we considered individual clients to point out the main factors influencing the earning and cost functions which in turn determine the revenue of the provider. In general, we can differentiate between multiple clients watching the same video stream simultaneously (i.e., multicasting or broadcasting) and multiple clients who want to watch the same video stream at different times (i.e., multiplexing).

In case of multicasting or broadcasting, costs for distribution may only occur once, as the provider reuses spectrum in a cellular network or hot-spot WLAN scenario.

In case that clients can independently select the time of starting the streaming, multiplexing the video over a given connection is required. For multiplexing video streams, a "hump" behavior for the multiplexing gain exists [8], which has to be taken into consideration when multiplexing.

V. Related Works

In this section we review the existing studies on pricing for wireless video, which have primarily focused on specific aspects of an overall pricing scheme and are thus complementary to the comprehensive pricing framework introduced in this paper.

Previous research initiatives were aimed at resource allocation and power optimization. In [14], the author uses congestion pricing for a distributed wireless system to determine the power levels of the individual nodes. For power or rate selection and pricing with a provider viewpoint, the authors of [15] found the marginal user principle (i.e., the user that is just indifferent between joining or leaving the network). This work incorporates channel gains as one parameter. In [16], the authors present a call admission scheme for wireless networks with guard channels that uses the overall user utility from a network QoS point of view and pricing for call admission. The authors of [17] use game theoretic approaches based on utility and pricing functions that are based on the signal strength of the connected clients and evaluate a CDMA system. For mixed voice and data traffic in a CDMA system, in [18] the authors use utility functions and pricing for resource allocation in a single or two cells with power and bandwidth limitations to optimize resource allocation. Radio resource allocation and client behavior due to pricing was evaluated in [19] and evaluated for a CDMA system. An overview of considerations for cellular networks can be found in [20]. For hot-spots, channel time allocation by pricing was evaluated in [21]. The authors of [22] use dynamic pricing to ensure that the most needy clients receive service in congestion periods.

VI. Conclusion and Outlook

In this paper we have laid out a comprehensive framework for the pricing of video streaming in wireless networks. The framework incorporates the utility that users associate with the delivered video quality in an earnings function, while the infrastructure, opportunity, and per-byte transmission costs are modeled by a cost function. Our numerical investigations indicate that there is generally a particular quality level (corresponding to a specific quantization scale in the encoding) that maximizes the revenue. Our results also indicate that the quality level depends on the specific video content and that the revenue characteristics vary for different videos. We also observed that with increasing price a wider range of quality levels (encoding quantization scales) result in positive revenue.

There are many exciting avenues for future work on pricing for wireless video services. One direction is to develop and validate the parameter settings in the utility models, i.e., to quantitatively determine how much users are willing to pay for video with a particular quality in a given networking context. Another direction is to examine how video content features, such as level of motion and texture in individual scenes, affect the revenue model.

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