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Towards a Framework for Cross Layer Incentive Mechanisms for Multihop Video Dissemination

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***Abstract*—For transmitting data in scenarios showing a high user density, infrastructure based and multihop Ad hoc communication can be combined to benefit from the reliability of a stable backbone network and the increased coverage of multihop communication. Such scenarios have been investigated from a cross layer perspective in the recent years mainly focusing on pure performance optimization. However, the question of providing incentives to nodes to forward data has largely been ignored in the cross layer domain, even though providing incentives is vital for the network: each node represents a user comparing his or her satisfaction and the cost to decide on his or her participation. A likely reason for the gap in cross layer incentive research is the necessity to model users as well as the network in order to express a user's utility, which requires knowledge in both fields. In order to foster future research in the area of cross layer incentive schemes, this work proposes a general cross layer simulation model combining user and network models. Moreover, an instantiation of the simulation model for the use case of live video broadcasting is presented.**

I. Introduction and Motivation

By combining infrastructure based communication (e.g., Wi-Fi access points) and Ad hoc (multihop) communication, the benefits of both paradigms can be utilized: the infrastructure provides a stable backbone in terms of availability, while multihop communication provides increased coverage at the cost of stability. However, it is reasonable to assume users to act rational, i.e., selfish in a game theoretic sense by constantly comparing the benefit received from a service and the cost to participate. Considering this assumption results in a necessity to incentivize users to forward data, as retransmitting data implies additional costs. Research questions touching these economic aspects of networks can be classified into two categories.

The class of *underlay centric* approaches includes all network layers of the ISO/OSI network stack from physical layer to IP layer. The works in this class are mostly content agnostic focusing on Quality of Service (QoS) parameters and on the details of underlay parameters, e.g., minimizing the power consumption [1], increasing the fairness [2], minimizing the number of transmissions [3] or controlling the topology [4] in a network with rational nodes. As opposed to that, the class of *overlay centric* approaches includes all network layers of the ISO/OSI network stack from transport layer to application layer. The related work in this domain is mostly content and user aware, but underlay agnostic, i.e., the Quality of Experience (QoE) as a measure of user satisfaction is a major focus of research. An example is the work on overlay streaming incentive schemes focusing on topology formation [5], mechanism design [6],[7] and layered video codecs [8].

Summing up, each class of approaches takes some simplifying assumptions regarding the models in the other class: *underlay centric* approaches assume that QoS is a good measure for QoE, while at the same time *overlay centric* approaches take simplifying assumptions regarding the network. Therefore, a joint model combining the most precise models from both classes can provide a tool for gaining novel insights regarding the behavior of rational networks as well as for the design of algorithms to provide incentives.

Consequently, this work defines a QoE and underlay aware cross layer simulation model. As a main contribution, an instantiation of the model for the use case of live video broadcasting is presented. Moreover, a cross layer utility function for this use case is provided taking Quality of Experience and low layer energy consumption into account.

II. Simulation Model Design

The considered network in this paper is a wireless network which is composed of a source and a number of receiving nodes. The source has a video for all nodes in the network and it is disseminated in a multihop manner. In general, there could be more than one source in this network, but for the sake of simplicity, we assume just one source.

The simulation model proposed hereinafter is intended to enable follow-up research on cross layer incentive mechanisms and should support the whole toolset from game theory to numerical simulations using MATLAB/Simulink. We discuss each sub-model to be integrated in a bottom up fashion.

A. Physical Model

Each node is equipped with a single antenna and can communicate with any other node either directly or in a multihop manner. The nodes work in half-duplex mode and the radio link between a transmitter and a receiver is affected

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by pathloss, shadowing and fast fading which attenuate the strength of the signal at the receiver. We assume that the transmitting nodes will exploit the fast fading channels by employing adaptive modulation and coding techniques [9]. For a single channel realization, the channel gain between a transmitter and a receiver, say i and j, is given by g_{ji} and the maximum link date rate between i and j is calculated by

$$R_{ji} = W_{ji}\log_2\left(1+\frac{P_i g_{ji}}{\sigma^2}\right) \tag{1}$$

where P_i is the transmit power of node i, W_{ji} is the bandwidth allocated to the link between i and j and σ^2 is the noise power. Let $P_i^{(t)}$ be the transmit power of node i at time t, then if we assume that a chunk of video needs T time slots for transmission, the consumed energy at node i to forward a chunk of video can be obtained by

$$E_i = \int_{t=0}^{T} P_i^{(t)} dt. \tag{2}$$

The nodes have a power constraint and the transmit power cannot exceed the maximum power $P^{\max}$. The maximum energy which can be consumed to transmit a chunk is defined as $E^{\max} = TP^{\max}$.

The transmission power at each time slot is chosen based on the channel gain in a way to guarantee successful decoding at the receiving nodes. From an overlay view, the duration of a chunk of video may be in the scale of seconds while in underlay, the properties of the channel and transmit power may vary in the scale of milliseconds. The transmission strategy and the route from transmitter to receiver in the underlay will be adapted such that the required end-to-end data rate at the overlay is guaranteed.

B. Topology/Connectivity Model

A topology model is necessary, as overlay/application layer based incentive algorithms such as [5] usually utilize a logical topology assuming end-to-end connectivity. However, the logical topology is not necessarily equal to the underlay topology, even though the same set of nodes is used. Thus, we model the system as two interrelated graphs $G_U = (V, E_U)$ for the underlay and $G_O = (V, E_O)$ for the overlay centric perspective, where $V = 1, \ldots, n$ represents the set of nodes. $E_O \subseteq V \times V$ and $E_U \subseteq V \times V$ represent the set of edges in the overlay and underlay graph, respectively.

Although the nodes can communicate to each other in a multihop manner, the quality of the connection in the overlay depends on the channel gain in the underlay graph. For the nodes communicating directly, the maximum data rate between the nodes is calculated based on eq. (1) taking into account the traversed physical hops in the underlay graph. In case the nodes communicate in a multihop manner, i.e., through a sequence of wireless links, the minimum of the data rate of the different links determines the overall available data rate.

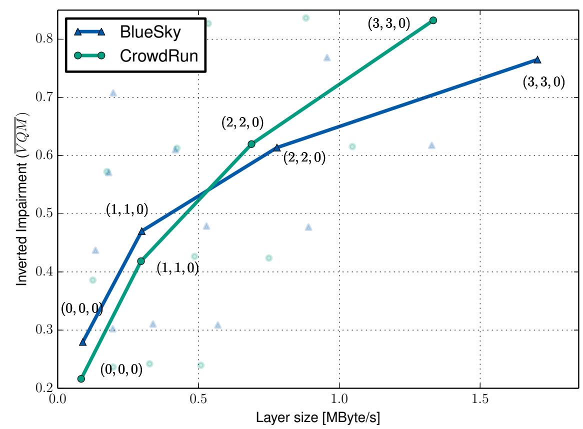

Fig. 1: Layer size in terms of bandwidth and the respective QoE value as measured by $\overline{VQM}$ for two videos (Blue Sky and Crowd Run) from the Xiph.org[1] test video database. The line indicates a path through the layer structure from layer $(0, 0, 0)$ to layer $(3, 3, 0)$ traversing two intermediate layers.

C. Quality of Experience Model

The measurement of Quality of Experience is highly dependent on the service under investigation. As an example service instance, a live video broadcasting service is assumed to run atop of the models described so far.

The broadcasting service uses a scalable video codec, which has been shown to be highly efficient for multihop distribution due its adaptive nature [10]. As opposed to fixed bitrate (FBR) codecs, scalable video codecs (SVC) allow splitting a video into multiple layers to encode multiple quality versions into a single stream. By receiving only parts of the stream, the quality of playback can be adapted to the underlying network.

In particular, a model of the H.264 SVC is incorporated in the simulation model [11]. The codec can scale the quality along three dimensions: frame resolution (*spatial*), frame rate (*temporal*), and frame quantization (*quality*). A layer (s, t, q) is therefore defined as a tuple of indices indicating the three dimensions. If a layer (s, t, q) is to be decoded for playback, all layers (s', t', q') with $s' < s \wedge t' < t \wedge q' < q$ have to be present as well. Moreover, this indicates, that the lowest layer $(0, 0, 0)$ is essential for all other layers and it is the only layer which can be played back independently.

Each layer can be mapped to two property values, one being the respective aggregated size of the layer in terms of needed data rate defined by $d(s, t, q)$. The other is the user perceived quality VQM of layer (s, t, q) when compared to the highest layer, i.e., the layer $(s_{\max}, t_{\max}, q_{\max})$ with the highest quality. Note, that the link data rate has to be larger than or equal to the encoding data rate during a chunk transmission so the receiving node can play back at an appropriate quality. As

[1] https://media.xiph.org/video/derf/, last visited 02/15/2015.

indicated in the notation, the VQM measurement is based on the Video Quality Metric (VQM) algorithm [12], [13]. VQM relies on a spatio temporal comparison of video sequences. The algorithm extracts numerous features related to human visual perception and maps the features to a single perceived quality value using a user validated regression model. Thus, VQM is a very precise model for the benefit a user/node receives from a certain video layer.

As a VQM value of 0 indicates the best available quality and a VQM value of 1 indicates the worst quality, we define the inverted value $\overline{VQM} = 1 - VQM$ for a more convenient handling in formulas. The $\overline{VQM}$ value and required data rate for two sample SVC videos are plotted against each other in Figure 1. In particular, the plot gives a visual indication that user satisfaction is a concave function of encoding data rate.

D. Cross Layer Utility Functions

The proposed utility function is based on the two important parameters for smart phone users: the user experience in terms of perceived service quality, defined by $\overline{VQM}$, and the energy consumption to be spent for the retransmission of content to other nodes. The utility is defined as a difference between benefit and cost. As shown in Figure 1, video quality is a concave function of the encoding data rate and as shown in Equation 1 and Equation 2, the data rate is a concave function of the energy, one can imply that there is a linear relationship between the video quality and the energy. Accordingly, we propose the utility function for node i as:

$$u_i = \overline{VQM_i} - \alpha_i * \frac{E_i}{E^{\max}}, \tag{3}$$

where $0 \leq \alpha_i \leq 1$ shows the importance of the energy consumption (cost) compared to the received quality of video (benefits) for node i. A lower value of α_i means having a better video quality for a user i is more important than losing energy. The utility function cannot be negative and in case that the received relative video quality for a node is lower than the relative energy it spends, the node stops forwarding and leaves the network.

As a performance metric to be maximized for an incentive scheme running atop of the simulation, we consider the *overall social welfare*, i.e., the sum of all utilities. However, this simple definition has the drawback of not including a minimum service guarantees or a notion of fairness. Consequently, we combine the concepts of overall social welfare, minimum service guarantees and Raj Jain's [14, p. 36] well-known fairness index into a single metric:

$$W = \frac{\min\{u_i\}}{\sum_{i \in V} u_i} * \frac{(\sum_{i \in V} u_i)^2}{n * \sum_{i \in V} u_i^2} \tag{4}$$

III. Conclusions and Outlook

This work presented a cross layer simulation model for wireless multihop video streaming. For that purpose, a number of models from two different areas were combined: the area of wireless multihop communication (underlay centric perspective) and the area of overlay networks including automated video quality assessment. Based on the models, a cross layer utility function and a function defining the overall social welfare of the system are defined and discussed. The main outcome of this work is a simulation model taking into account the user experience as well as energy consumption of retransmissions to be used for future research in the area of incentive mechanisms.

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