On Optimization of Network-coded Scalable Multimedia Service Multicasting

Andrea Tassi*, Ioannis Chatzigeorgiou* and Dejan Vukobratović†
*School of Computing and Communications, Lancaster University, United Kingdom
†Department of Power, Electronics and Communication Engineering, University of Novi Sad, Serbia

Abstract—In the near future, the delivery of multimedia multicast services over next-generation networks is likely to become one of the main pillars of future cellular networks. In this extended abstract, we address the issue of efficiently multicasting layered video services by defining a novel optimization paradigm that is based on an Unequal Error Protection implementation of Random Linear Network Coding, and aims to ensure target service coverages by using a limited amount of radio resources.

I. INTRODUCTION AND MOTIVATION

The technological evolution of communication devices has fuelled a surge in demand for new multimedia services over next-generation networks. Several standards for video coding and compression have been proposed. Among them, those that enable layered video streaming are gaining momentum. A layered video stream consists of one base layer and multiple enhancement layers. The base layer ensures a basic reconstruction quality, which progressively improves with the number of recovered enhancement layers. It is natural to adjust the transmission of each video layer according to the user propagation conditions. In that way, users can eventually recover different sets of video layers, i.e., the same service at different quality levels.

Modern communication standards tackle the reliability issues of multicast communications by means of Application Level-Forward Error Correction (AL-FEC) schemes. However, these kind of codes are usually designed to be applied over large source messages. Hence, AL-FEC codes may lead to a non-negligible communication delay, which is an issue in the case of delay-sensitive multimedia services. That issue can be mitigated by using Unequal Error Protection implementations of Random Linear Network Coding (UEP-RLNC) [1].

Since the layers of a video stream have different importance levels, UEP-RLNC allows the transmitter to adjust the error protection capability of RLNC according to the importance level of the transmitted video layer. However, the capability of adjusting the protection level of each service layer is just one part of the general resource allocation issue, which is summarized in the following research questions: [Q1] How to define an optimization framework that can jointly optimize both transmission parameters and UEP-RLNC parameters? [Q2] How can a service provider allocate radio resources such that an existing Service Level Agreement towards users is not violated? In the following sections, we will we will propose an answer to those questions.

II. SYSTEM MODEL AND PROPOSED OPTIMIZATION

Consider an Orthogonal Frequency-Division Multiple Access (OFDMA) cellular system composed by a Base Station (BS) and U users. A layered data stream is transmitted to the users over C orthogonal broadcast erasure subchannels. Since the service is encoded as in the RLNC principle, each subchannel conveys a stream of coded packets. Coded packets transmitted over the same subchannel adopt the same Modulation and Coding Scheme (MCS). Subchannel \( c \) is modeled as a frequency-time structure, which spans a certain bandwidth and multiple OFDM symbols. Each coded packet transmitted over \( c \) spans a fixed number of OFDM symbols and the same bandwidth of \( c \). The bit length of the coded packets is fixed, while the subchannel bandwidth is adapted – in accordance with the MCS \( m_c \) adopted by \( c \) – to fit the bit length of the coded packets.

We model a layered service as a sequence of source messages. Each message \( x \) consists of \( K \) source packets. The elements of \( x \) are grouped into \( L \) layers, as in Fig. 1. We define the user Quality-of-Service (QoS) level as the number of consecutive layers that can be recovered, starting from the first layer. According to the UEP-RLNC presented in [1] Sec. II.B, for each expanding window \( w = \ell \), a stream of coded packets \( \{y_1, \ldots, y_{N_\ell}\} \) is generated, where \( y_j = \sum_{i=1}^{K} g_{j,i} \cdot x_i \) and \( g_{j,i} \) is randomly selected over GF\((q)\) of size \( q \). We propose the UEP Resource Allocation Model (UEP-RAM), which jointly optimizes the number \( N_\ell \) of coded packet transmissions associated with each expanding window \( \ell \), and the MCS \( m_\ell \) used to transmit them. For simplicity, we assume that coded packets associated with different expanding windows are kept separated and transmitted over different subchannels.

We define the indicator variable \( \delta_{u,\ell} \) associated with user \( u \) and QoS level \( \ell \) such that \( \delta_{u,\ell} = 1 \) if the first \( \ell \) service

This work is part of the R2D2 project, which is supported by EPSRC under Grant EP/L006251/1. Collaboration of the authors was facilitated by COST Action IC1104 on Random Network Coding and Designs over GF\((q)\).

Fig. 1. Considered layered source message.
layers are recovered with a probability of at least $\hat{Q}$; otherwise, $\delta_{u,\ell} = 0$. User $u$ will recover the first $\ell$ service layers if it successfully recovers the $\ell$-th expanding window or any of the expanding windows with index greater than $\ell$. Thus, we define

$$\delta_{u,\ell} = I \left( \bigvee_{i=\ell}^L P_{u,i}(N_1, \ldots, N_i, m_1, \ldots, m_i) \geq \hat{Q} \right),$$

where $I(\cdot)$ is the indicator function and $P_{u,i}(\cdot)$ is the probability that $u$ collects $K_i$ linearly independent coded packets associated with expanding windows with indexes $1, \ldots, i$. (1)

We define the system profit $\sum_{u=1}^U \sum_{\ell=1}^L \delta_{u,\ell}$ as the number of video layers that any of the $U$ users can recover, while the system cost is the total number of coded packet transmissions $\sum_{\ell=1}^L N_\ell$. Inspired by a fundamental economics principle, in order to optimize the profit while keeping the cost low, the proposed UEP-RAM maximizes the profit-cost ratio as follows:

\[
\text{(UEP-RAM)} \quad \text{maximize} \quad \sum_{u=1}^U \sum_{\ell=1}^L \delta_{u,\ell} \cdot \frac{L}{\sum_{\ell=1}^L N_\ell} \quad (1)
\]

subject to

$$\sum_{u=1}^U \delta_{u,\ell} \geq U \hat{\ell} \quad \ell = 1, \ldots, L \quad (2)
$$

$$0 \leq N_\ell \leq \hat{N}_\ell \quad \ell = 1, \ldots, L. \quad (3)$$

Constraint (2) ensures that the fraction of users recovering the first $\ell$ video layers shall not be smaller than $\hat{\ell}$. Constraint (3) imposes that the transmission of expanding window $\ell$ shall not require more than $\hat{N}_\ell$ coded packet transmissions. Since MCSs and coded packet transmissions per expanding window are optimized altogether, UEP-RAM is the answer to [Q1]. Furthermore, the constraint set [2]-[4] ensures that predetermined fractions of users recover given subsets of service layers by a certain deadline. That represents the requirements of a SLA to be honoured, hence, [Q2] has also been addressed.

In spite of the apparent complexity of UEP-RAM, it is possible to derive an efficient heuristic strategy by following the same train of thoughts as in [1]. In particular, the proposed heuristic procedure comprises two steps: (i) the optimization of $m_1, \ldots, m_L$, and (ii) the optimization of $N_1, \ldots, N_L$. That heuristic can produce good quality solutions in a finite number of steps [2].

\[\text{If } s \text{ is true, } I(s) = 1, \text{ otherwise } I(s) = 0.\]