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Scalable video multicast using inter-layered superposition and network-coded cooperation over MIMO relay systems

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ABSTRACT

The adoption of scalable video coding (SVC) for video multicast services is a promising solution for providing efficient streaming under channel heterogeneity, since SVC can support quality scalability with high coding efficiency. The scalability allows receivers to experience video quality according to their channel conditions. Nevertheless, the scalable video layers are inter-dependent; if a layer of the scalable video is lost, all subsequent layers that depend on the lost layer are downloaded but not rendered, which leads to a low video quality and bandwidth inefficiency. Consequently, unequal error protection among scalable video layers needs to be addressed in a bandwidth-efficient manner. This paper proposes a scalable video multicast scheme over relay-based cellular networks, consisting of two main components: inter-layered superposition in the first phase and digital network coding in the second phase. In this joint design, the proposed inter-layered superposition coding provides incremental service quality according to average channel conditions, as well as unequal error protection under channel heterogeneity. Furthermore, the network-coded cooperation, implemented by mixing all decoded signals at the relay, improves bandwidth efficiency by reducing the number of transmissions in the second phase. The proposed scheme aims to increase the number of users experiencing a maximal number of rendered video layers as well as bandwidth efficiency. We also derive the relevant channel capacities of scalable layers for performance analysis. Numerical results, consisting of a cumulative distribution function of channel capacity, achievable video data rate, and video quality measurement, confirm that our design objective can be achieved for video multicast over multiple-input and multiple-output relay-based cellular networks.

1. Introduction

Scalable video coding (SVC) has been widely used in many applications with heterogeneous clients [1–5] and for multiple-input and multiple-output (MIMO) systems [6–9]. It can support spatial (i.e., resolution), temporal (i.e., frame rate), and amplitude (i.e., quality) scalability [10], which allows the wireless receiver to experience different levels of video quality depending on the received signal strength. The video content is split into multiple scalable video layers (i.e., several subset bitstreams) consisting of a base layer (BL) and multiple enhancement layers (ELs) [11]. The BL bitstream carries the base video content (i.e., typical quality of the video), while the additional ELs contain refinement information for enhancing the perceived visual quality or high resolution. The scalable video layers form an inter-dependent structure because the higher layer depends on the lower layer. Hence, a bitstream layer is only rendered successfully if the lower layer is rendered. The video quality experienced by the receiver depends on the number of rendered video bitstreams. A greater number of rendered layers leads to a higher perceived video quality. However, two challenges need to be considered, in particular, in scalable video transmission. First, the delivery of additional layer bitstreams carried in transmission causes an increase in terms of time or bandwidth [3,4]. Second, if a layer is lost, subsequent layers depending on the lost layer are useless (i.e., not rendered), even though they can be successfully decoded [5–8]. To address these challenges, we need to provide unequal error protection (UEP) for scalable video layers in a resource-efficient manner.

Cisco Visual Networking Index Forecast predicts an increase in mobile data traffic to 49 exabytes per month by 2021 [12]. To meet the fast increment of mobile data traffic growth, 5G ultra-dense cellular networks have been investigated by jointly composing small cells and macrocells [13]. Small base stations (BSs) (i.e., microcells) are distributed within the macrocell's coverage. Both the macrocell and microcell BSs can independently and transparently manage the data traffic demand from associated subscribers. The small cell concept can increase system throughput in two ways:1) the common bandwidth

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resources can be used by different microcells in various regions and 2) users in a microcell's coverage have a higher probability of line-of-sight connection to microcell BSs [14].

Herein, we study the adoption of SVC for a video multicast service over ultra-dense cellular networks with a single gateway, where a BS (i.e., macrocell BS equipped with multiple antennas) transmits multiple SVC layers to a group of users with the assistance of a dedicated relay (i.e., microcell). Our design objective is to improve system performance in terms of an increase in the number of users experiencing full video quality with bandwidth efficiency (i.e., reduction in the number of transmissions leading to an increase in efficient bandwidth utilization). We propose a video multicast method, named ISC-DNC, which uses inter-layered superposition coding (ISC) to transmit all SVC layers sequentially with different time slots in the first phase. The dedicated relay performs digital network coding (DNC) to transmit an additional signal containing all SVC layers in the second phase. The proposed ISC can provide UEP and improve the system performance as scalable layers are transmitted separately in time-shared transmission with reasonable configuration parameters. In addition, DNC along with an efficient estimation algorithm can increase the bandwidth efficiency since the relay only uses one transmission slot in the second phase through the dedicated MIMO relay-based cooperation. Specifically, our contributions are as follows:

- The proposed ISC-DNC scheme can provide UEP among the SVC layers by simply adjusting the importance-dividing factor (IDF) parameters based on the channel states of user equipment (UEs) (details in Section 3.2.1). Even when almost all UEs experience a bad channel state, they can enjoy typical video quality (i.e., at least the BL rendered) since the importance of the BL is adjusted depending on the distribution of channel states among the UEs.
- The number of multiple SVC layers carried in transmission is increased to allow the UEs to be more flexible, so that users can enjoy the corresponding video quality according to the channel state, with L different classes of video quality. In contrast, the recent studies only allow a superposed signal carrying two SVC layers (i.e., a BL and an EL) [6,7].
- The interference caused by superposed signals is traditionally considered harmful. However, our proposed ISC, along with the efficient estimation algorithm (EEA) for network-coded cooperation, can transform this harmfulness into additional system performance gain and better bandwidth efficiency.
- We conducted a formal capacity analysis to assess the effectiveness of our multicast transmission scheme. A numerical simulation was also performed for the assessment of capacity and achievable video data rate. Based on these analyses, we show that the proposed scheme satisfactorily matches our design objective. Furthermore, video quality measurement was conducted in terms of peak signal-to-noise ratio (PSNR) as a quality metric for comparison with other prevalent schemes.

The remainder of this paper is organized as follows. We describe related work and the system model and our proposed video multicast method in Section 2 and Section 3.2, respectively. In Section 4, we formulate the channel capacity analysis of scalable layers. Furthermore, we derive system performance in terms of achievable video bitrates and video quality measurements and compare our scheme with other schemes in Section 5. Finally, we conclude our paper and present future work in Section 6.

2. Related work

The greatest challenge in multicast systems is channel heterogeneity, whereby the channel states of the UE vary over time. If we define quality of service (QoS) with respect to the user receiving the lowest signal-to-noise ratio (SNR) (i.e., guaranteeing that all users with a better channel condition can achieve at least the defined QoS), it leads to a bottleneck issue since other users who experience better channel conditions must experience the lowest QoS [15]. Thus, such users are provided with the lowest video quality. This bottleneck issue can be solved by cooperative communication. In the literature, cooperative communication consists of two phases: a BS broadcasts the content to the receiver and relay in the first phase, and then, a relay station (RS) relays the received signal (probably using amplify-and-forward (AF) and decode-and-forward (DF)) to the receiver in the second phase. The receiver uses two signals from the BS and RS for decoding. Hence, users experiencing bad channel conditions in the first phase still have a chance to receive information from the relay in the second phase.

To utilize the advantage of cooperative communication, many studies have investigated SVC multicast applications over relay-based networks with the assistance of users [6] or a dedicated relay [7]. The simplest method to create UEP among SVC layers is to use different channels to deliver the SVC layers. The better channel delivers the layer with higher importance. However, this method causes inefficient bandwidth utilization since the use of additional channels increases. Chih-Hung et al. [6] proposed cooperative wireless broadcast for scalable video delivery (CWB-SVC) to tackle the two aforementioned problems of a scalable video (i.e., additional resource burden and UEP). They assumed that the SVC bitstream is partitioned into two-layer bitstreams consisting of a BL and an EL, where the BL is encoded using space-time block coding (STBC) and the additional EL is superposed with the BL into a signal and assigned varying degrees of importance. Instead of using different channels for two SVC layers, the BS broadcasts the superposed signal consisting of the BL and EL to users in the first phase (i.e., BL and EL signals are superposed into a single signal for transmission). Then, the users experiencing good channel conditions help those experiencing bad channel conditions by delivering the decoded BL signal in the second phase. The authors showed that the use of the superposition coding technique can mitigate the issue of additional burden on transmission resources (i.e., time or bandwidth) for multiple video streams, since the BS only uses one superposed signal to carry two SVC layers (i.e., BL and EL are superposed into one signal). Moreover, UEP can be provided by controlling the power-dividing factor (i.e., a parameter can be used for controlling the importance among SVC layers) of the superposed signal. Hwang et al. [7] used the same approach, but employed dedicated relay-based delivery as well as the superposition of beamforming (i.e., conveying BL) and STBC (i.e., conveying EL) for the transmission of an eNB as a BS. Their scheme is called CMS-SVC. There are two main benefits of using dedicated relay-based delivery, compared to user relay-based delivery. First, the channel medium between the eNB and dedicated relay is line of sight, leading to stable and high data-rate transmission. This means that the information transmitted from the dedicated relay supports high reliability. Second, the dedicated relay provides better transmission range without any burden of synchronization issue among users. In [7], users close to the relay had more chance to receive all transmitted scalable layers. This leads to an increase in system performance in terms of the number of users successfully decoding the BL. This dedicated relay does not require any additional transmission for the EL since the relay only broadcasts a decoded BL signal. Recently, Feng et al. [16] studied the problem of joint downlink and device-to-device (D2D) transmissions for SVC streaming using network coded cooperation. Authors formulated the problem into a mixed integer non-linear programming problem to increase the performance as the number of users in multicast group increases. Douik et al. [17] reviewed instantly decodable network coding schemes from centralized to D2D communications. Authors showed that users exchange network coded packets from different users can speed up the recovery capability of the missing packets. Karim et al. [18] proposed rate-aware approach using instantly decodable network coding for video distortion reduction. Authors proposed heuristic algorithm to reduce the video distortion before the deadline and increase the perceptual video quality to individual users