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Efficient scalable video multicast based on network-coded communication

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Abstract In order to increase the efficiency of mobile video transmission in a 5G network, this paper investigates a cooperative multicast of scalable video using network coding with adaptive modulation and coding over dedicated relay-based cellular networks. Different scalable video layers prefer different protection degrees, and user equipments (UEs) in different locations experience different packet loss rates in wireless networks. Guaranteeing that all UEs experience a certain level of video quality is one of the biggest challenges in scalable video multicast. Using the number of satisfied UEs as a metric, the proposed efficient scalable video multicast based on network-coded cooperation (SVM-NC) scheme, combined with adaptive modulation and coding, enhances the attainable system performance under strict time and bandwidth resource constraints for guaranteed smooth playback. Various simulations were performed for performance evaluation. The proposed scheme ensures that the expected percentage of satisfied UEs approximately achieves the maximum number of UEs in a multicast group by using network-coded cooperation over dedicated relay-based cellular networks. In addition, the peak signal-to-noise ratio metric is asymptotic to the maximum performance of high-resolution video quality offered by service providers.

Keywords Network coding · Scalable video multicast · Relay-assisted cellular networks

1 Introduction

Video traffic has increased rapidly and is considered as major data source in mobile networks. In order to efficiently accommodate these huge mobile videos, a combination of video multicasting, cooperative relaying, and network coding (NC) can be a good candidate among 5G network technologies. Multimedia broadcast/multicast service (MBMS) and Evolved MBMS (eMBMS) have been standardized through the Third Generation Partnership Project (3GPP) since 3GPP release 6 [1]. Moreover, Long-Term Evolution (LTE) communication systems also support MBMS single-frequency networks [2]. The design objective of MBMS is to provide stable and high-quality video streaming (i.e., smooth playback and high-resolution) for all user equipments (UEs) in a bandwidth efficient manner.

Scalable video coding (SVC) is widely used in video multicast services [3, 4], as it is able to support spatial, temporal and quality scalability with high coding efficiency [5]. Depending on the amount of received information from the video, a UE experiences corresponding video quality. The video content is split into multiple scalable video layers (i.e., several subset bit-streams) consisting of a base layer (BL) and multiple enhancement layers (ELs). The UE experiencing bad channel conditions can still enjoy typical video quality. The additional received ELs refine the BL

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and provide an increase in visual quality or high-resolution. This characteristic of scalable video allows wireless receivers to experience different levels of video quality depending on the signal strength. Therefore, scalable video coding is a promising solution for heterogeneous networks under channel heterogeneity.

Cooperative communication has been a promising technique for overcoming the performance degradation of wireless broadcast due to multipath fading, shadowing, path loss and interference [6, 7]. The channel states of different UEs vary independently over time. Sendonaris et al. [6] and Laneman et al. [7] proved that particularly severe channel impairment could be mitigated by using cooperative diversity. Hence, the advantages of SVC and cooperative diversity have attracted many works that implement SVC and cooperation into MBMS [8–12]. The fundamental concept is the division of transmissions into two phases. In the first phase, the base station broadcasts the video bitstream. With the assistant of a relay station (RS) in the second phase, UEs that have experienced bad channel conditions in the first phase have a second chance to receive more packets from the relay, enhancing the reliability of the decoding capability.

On the other hand, Ahlswede et al. [13] showed that the maximum network capacity could be achieved by applying NC. Furthermore, Ho et al. [14] showed that the maximum network capacity in multicast could be achieved by adopting random linear NC. There are many benefits, such as minimum delay, minimum energy per bit and maximum throughput, that have been exploited for the Internet, consisting of both wired and wireless networks [15]. Therefore, exploiting NC and cooperation in order to achieve the maximum system throughput has been a focus of many studies [16–19]. Nevertheless, there are few works investigating the combination of NC and cooperation for MBMS [20–26]. These studies considered a cooperative communication with NC between UEs, which was impractical in real scenarios because of synchronization issues and control signaling overhead. The dependency among scalable layers, channel heterogeneity and synchronization among users for cooperation under strict time and bandwidth resource constraints creates challenges for applying the same aforementioned schemes to scalable video multicast.

To the best of our knowledge, the proposed scheme in this paper is the first work on scalable video multicast based on network-coded cooperation (SVM-NC) with adaptive modulation and coding over dedicated relay-assisted cellular networks. Figure 1 provides an illustrative example of the bandwidth-efficient data delivery of the proposed SVM-NC. Suppose that the video is split into three scalable layers, a BL and two ELs. During the first phase, the base station, or Evolved Node B (eNB), broadcasts each original packet without coding for each layer sequentially, from high to low importance. Suppose that the multicast group size is three UEs and that each UE loses a packet at an individual layer after the first phase from the base station. Also assume that the RS successfully decodes three packets. By performing NC at the RS, three successful decoded packets are encoded into a network-coded packet (NCP) by creating a linear combination of the three packets. This is done because the NCP contains all the information of the three original packets, and each UE already has two successful decoded packets. Therefore, only one NCP is required for error-resiliency for all of the UEs in the second phase, as opposed to using all three packets for the three individual layers. This advantage of the NC leads to the significant improvements in the bandwidth efficiency and error-resilient capacity in cooperative communication under channel heterogeneity. Moreover, another important characteristic of scalable video coding is that different layers have different protection degrees. The adaptive modulation and coding technique is applied as a solution for this scalable video characteristic due to its capability of creating unequal error protection.

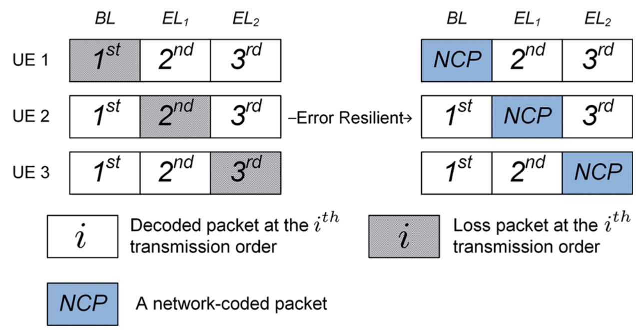

Fig. 1 An illustrative example for the capability of error resiliency from random linear network coding

We consider cooperative multicast, adaptive modulation and NC over dedicated relay-based cellular networks, which can be easily applied in scalable video multicast in real scenarios. We propose a combination of random linear NC at a dedicated RS and adaptive modulation and coding. The desired objective is to understand how to select the best modulation and coding mode for each packet transmission (i.e., original packet without coding and network-coded packet) and the number of NCPs in order to guarantee as many users as possible experience full video quality. The contributions of this work for video multicast over cellular networks can be summarized as follows:

– Dedicated relay-based cooperation for scalable video multicast provides transmission diversity, which improves channel impairment and solves the bottleneck issue in wireless multicast caused by the worst channel state. However, cooperative communication makes it difficult to guarantee smooth playback in video streaming because of the additional transmission time causing long delay. As seen above, the advantage of network-coded cooperative communication leads to significant improvements in bandwidth efficiency (i.e., a reduction of the transmission number in the second phase) and error-resilient capacity. This is the first work investigating the combination of rate adaptation and network-coded cooperation to enhance the efficient scalable video multicast.

- The optimization framework of the SVM-NC is provided to select a set of adaptive modulation and coding modes and a reasonable number of network-coded packets for cooperation in order to guarantee high-resolution video quality and smooth playback, respectively. Moreover, the number of satisfied UEs that enjoy full video quality is asymptotic to the maximum number of UEs in the multicast group under strict time and bandwidth resource constraints. Hence, the proposed scheme guarantees high-resolution and smooth playback video quality, solves the bottleneck issue in wireless multicast, and improves the attainable system performance.
- A performance analysis is provided to evaluate the effectiveness of our proposed scheme. We perform various simulations for numerical results with different values of time and resource constraints, signal-to-noise ratios (SNRs), and number of UEs in the multicast group in order to prove that the proposed scheme can be implemented in many practical scenarios. Lastly, the average peak signal-to-noise ratio (PSNR) metric of the whole system is evaluated to validate the efficiency of video multicast with smooth playback and high-resolution for all UEs in the multicast group, which is the main interest of our work.

The remainder of this paper is organized as follows. Section 2 presents related works of the proposed scheme. We describe our system model and background knowledge in Sect. 3. The proposed multicast scheme for scalable video transmission is presented in Sect. 4. In Sect. 5, we formulate the optimization framework and analyze the performance by using an average spectral efficiency metric and the number of satisfied UEs receiving the transmitted video. In Sect. 6, we provide numerical results through simulations. Finally, we conclude this paper along with future work in Sect. 7.

2 Related work

Cooperative multicast of scalable video has been the focus of many studies, especially user cooperation. In Alay et al. [8], showed that a cooperative multicast, even with a non-layered system, can provide better video quality for all UEs than a conventional direct multicast scheme. In addition, a layered system enables some UEs to enjoy good video quality while guaranteeing other UEs the same video quality or better compared to direct transmission. Alay et al. [9] showed that a two-hop cooperative transmission for scalable video multicast with randomized distributed space time codes provides better network efficiency than the conventional multicast with rate adaption [27]. Niu et al. [10] improved the reliability for wireless multicast by using medium-access-control (MAC) layer cooperation. An optimal time allocation was proposed to maximize the expected number of successful UEs receiving a transmitted packet via a base station and relay. Moreover, in order to address channel heterogeneity, Kuo et al. [11] solved the issue of overall system throughput limitation due to the worst channel state [28]. The UEs experiencing good channel conditions help other UEs in bad channel conditions in order to increase the system throughput. Wang et al. [12] also proposed two schemes for tackling the channel heterogeneity and enhancing the system throughput performance, namely opportunistic listening with conditional demodulating and multi-resolution modulation. Recently, Hwang et al. [29] investigated the cooperative multicast of scalable video over dedicated relay-based cellular networks. The authors showed that video multicast using dedicated relay achieves better performance and is more practical than user cooperation.

On the other hand, Zhang et al. [20] showed that their proposed scheme was able to reduce network traffic by more than half by considering user cooperation together with NC. In Jin and li [21], the authors proposed scheduling protocols to select optimal multicast rates and to efficiently allocate resources in WiMAX. Lin et al. [22] investigated combining time allocation and the rate selection model for each relay in a multicast group. The authors proposed a video-frame selection scheme to efficiently utilize channel bandwidth. In Keller et al. [23], the authors proved that NC is a practical technique by implementing it into a broadcast framework using Wi-Fi overhearing, and they constructed a testbed to evaluate the efficiency of the proposed system. Yang et al. [24] investigated symbol-level NC to further improve the efficiency of bandwidth utilization in vehicular ad hoc networks (VANETs). Recently, Tassi et al. [25, 26] studied resource allocation strategies for network-coded video broadcasting services over LTE-Advanced (LTE-A). The authors proposed a method to implement random network coding in LTE/LTE-A, and they showed that random network coding can be implemented, subsequently achieving better performance than traditional single-hop broadcasting macro-cellular scenarios. Furthermore, Khamfroush et al. [30] showed that the system performance can be improved using network-coded cooperation.

3 System model and background

Our system model for scalable video multicast is depicted in Fig. 2, in which we consider a two-phase cooperative broadcasting scenario. The complete transmission consists of two phases. Assume that the channel state information of UEs is known at eNB, or base station, and the dedicated RS. Control signals between them are also synchronized. The eNB performs our proposed multicast strategy using the channel state information and control signals from the RS. After that, multiple original packets selected from the video bitstreams are multicasted in the first phase to a group of UEs close to one another over dedicated relay-based cellular networks. Next, in the second phase, the dedicated RS decodes the multiple transmitted packets, performs NC for all successful decoded packets into NCPs and forwards the NCPs to all UEs within the multicast group to enhance the number of UEs achieving the full video quality of the provided service. The number of NCPs for transmission is limited by both time and bandwidth resource constraints to guarantee smooth playback of the video. In this section, we present a detailed model and background for the robust-efficient scalable video multicast based on network-coded cooperation. For clarity, commonly used notations used in this paper are presented in Table 1.

3.1 Channel model

For simplicity, the channel is simply modelled as follows, since our main interest is to emphasize the advantage of network-coded cooperation for enhancing the perceived visual quality for each user:

$$r_s = hx + n_o, \tag{1}$$

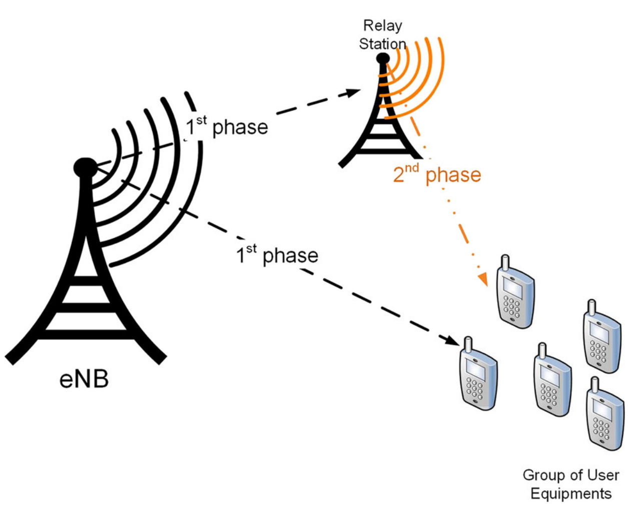

Fig. 2 Illustration of the system model using NC and the assistance of a dedicated RS

where r_s is the received signal at the destination, x is the source transmitted signal, h is the channel gain between the source and destination, n_o is a circularly symmetric complex Gaussian random variable with a zero mean and a variance of one, i.e., $\mathcal{CN}(0,1)$, and the channel states are assumed to be independent identically distributed (i.i.d.) Rayleigh fading channels in which the channel coefficient remains unchanged during symbol transmission duration. Thus, the channel model is parameterized by the SNR as

$$\gamma = \frac{\|h\|^2 P}{N_0}, \tag{2}$$

where $\|h\|$ denotes the l^2-norm of it h, P is the transmission power, and N_0 is the noise variance.

The probability density function (PDF) and cumulative density function (CDF) of the SNR are respectively given by

$$f_\gamma(\gamma) = \frac{1}{\bar{\gamma}} e^{\frac{-\gamma}{\bar{\gamma}}}, \tag{3}$$

$$F_\gamma(\gamma) = 1 - e^{\frac{-\gamma}{\bar{\gamma}}}, \tag{4}$$

where $\bar{\gamma} = P/N_0$ is the common SNR without fading [7].

3.2 Adaptive modulation and coding

Let N be the number of adaptive modulation and coding (AMC) modes, and $\gamma_{\text{th}}(n)$ be the SNR threshold of AMC mode n. The approximate packet error rate (PER) formula for AMC mode n with convolution code over the Rayleigh fading channel is presented as follows:

$$PER_\gamma(n) \approx \begin{cases} 1 & \text{if} \quad 0 < \gamma < \gamma_{\text{th}}(n) \\ a_n e^{-g_n \gamma} & \text{if} \quad \gamma \geq \gamma_{\text{th}}(\text{n}) \end{cases}, \tag{5}$$

where the mode-dependent parameters a_n, g_n and $\gamma_{\text{th}}(n)$ are curve parameters obtained for the fixed packet length of 1024 bits. An illustration of these fitting parameters is shown in [31], Table 2. As observed, $\gamma_{\text{th}}(1) < \cdots < \gamma_{\text{th}}(n) < \cdots < \gamma_{\text{th}}(N)$ is satisfied for the N available AMC modes. Higher modulation and coding causes higher PER at a certain values of the SNR; $PER_\gamma(1) < \cdots < PER_\gamma(n) < \cdots < PER_\gamma(N)$.

Each AMC mode is selected with the following probability:

$$Pr(n) = Pr(\gamma_{\text{th}}(n) \geq \gamma) = \int_{\gamma_{\text{th}}(n)}^{\infty} f_\gamma(\gamma)\, \text{d}\gamma = e^{\frac{-\gamma}{\bar{\gamma}}}. \tag{6}$$

Then, the average PER of AMC mode n can be obtained in the following closed form:

Table 1 Commonly used notation

Notation	Definition
K	The number of users in a multicast group
L	The number of scalable video layers
l	Layer index
V_l	The lth H.264/SVC video bitrate
A	The total number of video packets of a group of pictures (GOP)
A_l	The number of video packets in the lth layer of a GOP
a_l	The lth message assigned for broadcasting within a TTI
$\|a_l\|$	The number of packets in message a_l assigned for broadcasting within a TTI
t	The total number of packets assigned for broadcasting within a TTI
v_i	The ith video packet used for transmission within a TTI with $1 \leq i \leq t$
ENS	The expected number of successful UEs that are able to successfully decode all packets of all scalable layers
$P_e(n)$	The average PER of AMC mode n
$P(i)$	The probability that i UEs successfully decode all layered video packets
p	The probability that a UE successfully decodes all layered video packets
p_i	The probability that a UE successfully decodes the ith video packet
$p_l^{(1)}(n)$	The probability of successfully decoding a packet of the lth layer in the 1st phase with AMC mode n from the eNB to UEs
$p_{l,RS}^{(1)}(n)$	The probability of successfully decoding a packet of the lth layer in the 1st phase with AMC mode n from the eNB to RS
$p_{l,RS}^{(2)}(n)$	The probability of successfully decoding a packet of the lth layer in the 2nd phase with AMC mode n from the RS to UEs
$p_{l,RS}(n)$	The probability of successfully delivering a packet from the eNB to UE through RS
q	Galois field order
G	A generation, in which a group of native packets are coded using linear combinations
f	A coding coefficient chosen randomly from the Galois Field
g_{GOP}	The number of pictures within a GOP
f_{GOP}	Video frame rate
t_{GOP}	Time duration of a GOP

Table 2 AMC modes with convolutionally coded modulation

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Modulation	BPSK	QPSK	QPSK	16-QAM	16-QAM	64-QAM
Coding rate	1/2	1/2	3/4	9/16	3/4	3/4
Rate-bits/sym	0.50	1.00	1.50	2.25	3.00	4.50
a_n	274.7229	90.2514	67.6181	50.1222	53.3987	35.3508
g_n	7.9932	3.4998	1.6883	0.6644	0.3756	0.0900
$\gamma_{\mathrm{th}}(n)$(dB)	−1.5331	1.0942	3.9722	7.7021	10.2488	15.9784

$$P_e(n) = \frac{\int_{\gamma_{\mathrm{th}}(n)}^{\infty} PER_\gamma(n) f_\gamma(\gamma)\,\mathrm{d}\gamma}{\int_{\gamma_{\mathrm{th}}(n)}^{\infty} f_\gamma(\gamma)\,\mathrm{d}\gamma} = \frac{a_n}{g_n\bar{\gamma}+1} e^{-g_n\gamma_{\mathrm{th}}(n)}. \qquad (7)$$

3.3 Scalable video coding

The video bit-stream is split into multiple dependent layers of unequal protection, e.g., L layers consisting of a BL and $(L-1)$ ELs. The BL contains the basic quality of the video and the ELs carry refinement information of the aforementioned BL. The additional received ELs provide better video quality at the destination. The decoding of each layer relies on the successful decoding of the previous layer. When the lth EL is lost, the ELs from lth to $L-1$ are useless. Since the compressed video signals are sensitive to channel fluctuation, a single bit error may cause corruption of the corresponding transmitted layer, and smooth playback under strict time constraint requires non-retransmission in multicast scenarios. Therefore, forward error correction (FEC) and channel coding techniques are typically employed to correct errors at the destination without retransmission from the sender. The PSNR is a widely-used metric to quantify video quality caused by loss during transmission. The measured PSNR at the full resolution without the lth layer can be computed as $PSNR(l) = PSNR_F(l)(1 - w_l z_l)$, where $PSNR_F(l)$ is the PSNR of full video quality, z_l is the number of video packets in the lth layer within one group of pictures (GOP) and w_l $(\in [0, 1])$ is the ratio of the PSNR that degrades the full video resolution. Determining the value of w_l is outside the scope of this paper; refer to [3, 5] further investigations on layered video coding.

Let g_{GOP} and f_{GOP} be the number of pictures and the video frame rate within a GOP, respectively. The number of video packets in the lth layer of a GOP [25] is defined as follows:

$$A_l = \left\lceil \frac{V_l \times g_{GOP}}{Len \times f_{GOP}} \right\rceil, \tag{8}$$

where V_l and Len are the video bitrate of the lth layer and the fixed packet size, respectively, and $A = \sum_{l=1}^{L} A_l$ is the total number of packets of a GOP. In order to guarantee all packets are of fixed length, a zero-padding technique is used as a solution for managing unequal packet sizes of the smaller packets [32].

3.4 Network coding

Coded packets from performing NC are linear combinations of different packets. The form of a coded packet [14] is presented as follows:

$$P_{NC} = \sum_{P_i \in G} f_i \times P_i, \tag{9}$$

where i is the packet index, G is a generation which consists of different packets that are used to perform NC, P_i is a packet in a generation G, and f_i is a coding coefficient randomly chosen over the Galois field q. For random linear network coding, there is no standard method for selecting field size, but there are majority of works that consider a Galois field size of 8 to guarantee linear independence with very high probability [14, 25, 30]. A Gaussian elimination algorithm is used to decode the original packets after receiving a sufficient number of coded packets. The decoding process is successful if and only if the coefficient matrix achieves full rank. The receiver is able to successfully decode the transmitted data without asking for retransmission. Note that further information regarding NC can be found in [13, 14].

4 Proposed SVM-NC scheme

In this section, we describe our proposed scheme, called robust-efficient scalable video multicast based on network-coded cooperation.

First, we explain two baseline schemes, direct multicast (DM) [10] and cooperative multicast (CM) [27], that are used for scalable video broadcasting, as shown in Fig. 3. The rate adaptation is exploited for each packet during the entire transmission based on the channel conditions among users [27]. Suppose that the video bitstream is split into three layers consisting of a BL and two ELs (i.e., $L = 3$). In the DM scheme shown in Fig. 3(a), eNB determines the number of packets $t = \sum_{l=1}^{L} |a_l|$ used for broadcasting under time and bandwidth resource constraints in a radio subframe of 1 millisecond (ms), where a_l is the lth message allocated for transmission and $|a_l|$ denotes the size of the lth message. The eNB maps t original packets without coding sequentially from the BL to EL_2 into a transport block (TB) throughout

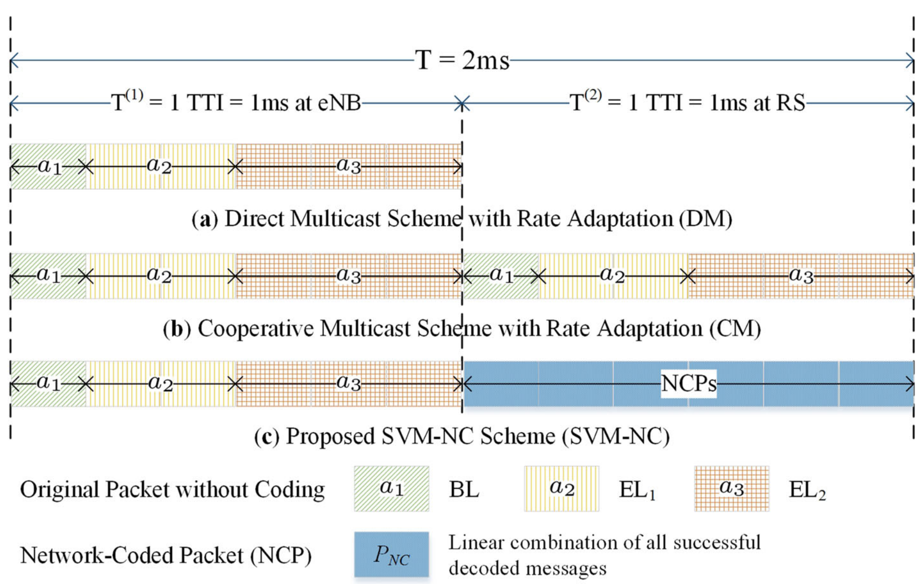

Fig. 3 The rate-optimized strategy of various multicast schemes: *a* direct multicast, *b* cooperative multicast, *c* the proposed SVM-NC scheme

the entire duration of the transmission time interval (TTI) corresponding to LTE TTI (i.e., TTI = 1 ms [33]). The TB is sent to the UEs without any assistance from the RS. Since the time duration of the direct multicast is 1 TTI, the number of packets assigned in the message a_l for broadcasting within a TTI is defined as follows:

$$|a_l| = \left\lceil \frac{A_l \times TTI}{t_{GOP}} \right\rceil, \quad (10)$$

where $t_{GOP} = g_{GOP} \big/ f_{GOP}$ is the time duration of a GOP. Note that A_l is the number of video packets in the lth layer of a GOP. We use the multicast strategy in [10] for each transmission of each individual video layer.

In the CM scheme, as shown in Fig. 3(b), the whole transmission duration is divided into two phases with $T = \sum_{j\in 1,2} T^{(j)}$. In the first phase, the eNB multicasts t multiple original packets without coding, determined by (11) sequentially from the BL to EL_2 throughout the duration of $T^{(1)}$, and then the dedicated RS performs the decode-and-forward cooperative protocol [9] to deliver all received packets to other UEs for the remaining duration $T^{(2)}$ in the second phase. The eNB and RS must select the optimal transmission rate for each packet without exceeding the time and bandwidth resource constraints in order to guarantee smooth playback with good video quality. This is because the RS needs more than one TTI to deliver the received packets in the second phase. Hence, the DM scheme uses less resource blocks (RBs) compared to the CM scheme. The total number of packets $|a_l|$ in the lth message assigned for transmission within a TTI in the case of the CM scheme is defined as follows:

$$|a_l| = \left\lceil \frac{A_l \times 2 \times TTI}{t_{GOP}} \right\rceil, \quad (11)$$

where 2 TTIs are the required time for complete transmission in cooperative communication.

The proposed SVM-NC scheme is illustrated in Fig. 3(c). Three scalable dependent layers are multicasted by eNB so the maximum number of UEs possible are able to enjoy full high-resolution visual quality and smooth playback, which is our design objective. The eNB broadcasts t original packets without coding, similar to the above cooperative multicast scheme in the first phase. The highest-importance packet is mapped into the lower AMC mode in order to provide unequal error protection. Different UEs experience different channel states and enjoy different video qualities depending on their received refinement information. UEs that do not receive enough refinement information will be assisted by the dedicated RS in the second phase. The RS performs the NC to all decoded packets and forwards the NCPs to all UEs in the multicast group.

Figures 4 and 5 present the LTE/LTE-A protocol stack and a part of the radio subframe at eNB and RS, respectively. Transmission rates adapted in a scheduling frame should not exceed the whole transmission duration $T = 2$ ms (i.e., one TTI for eNB and another one for RS) to guarantee smooth playback. The rate-optimized strategy is performed at each of the two TTIs. Assume that the control signals between eNB and RS, such as channel state information and rate adaptation, are synchronized. The streams composed of L video layers enter the communication stack as protocol data units (PDUs) in the packet data conversion

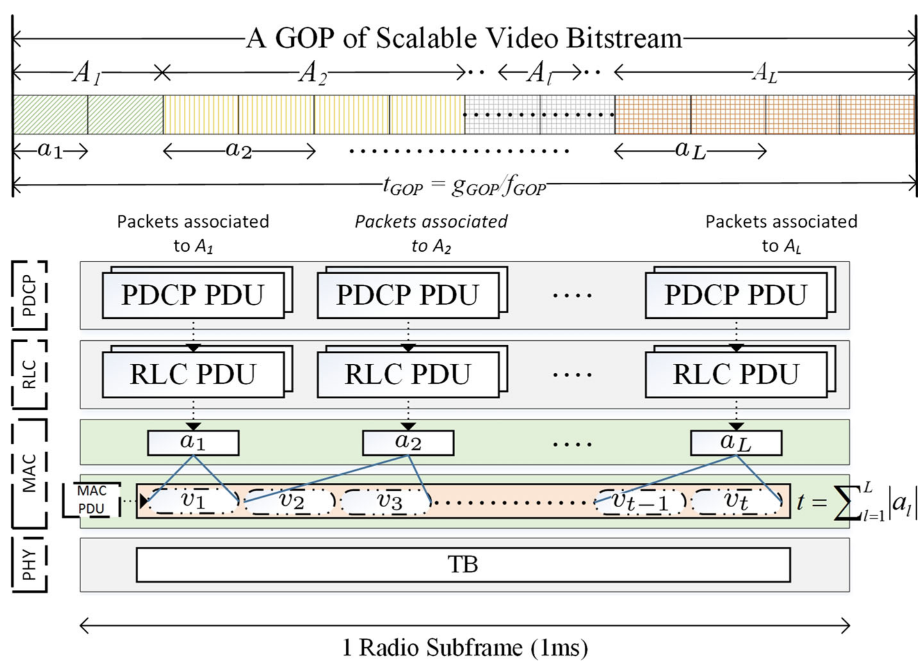

Fig. 4 LTE/LTE-A protocol stack at eNB and a part of the radio subframe ($T^{(1)} = 1$ ms)

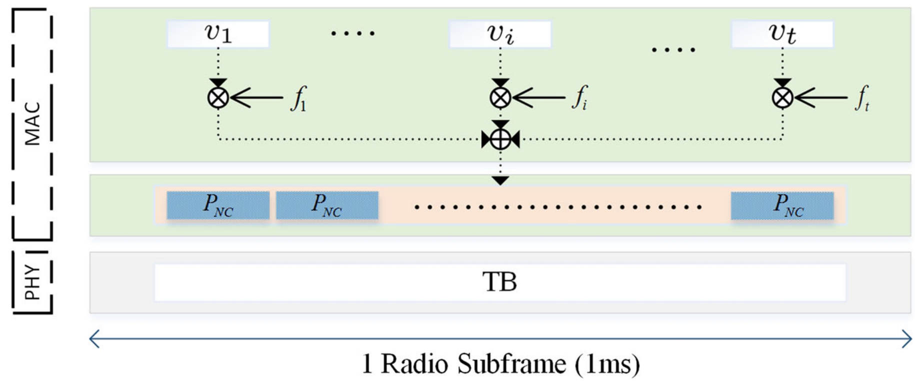

Fig. 5 LTE/LTE-A protocol stack at RS and a part of the radio subframe ($T^{(2)} = 1$ ms)

protocol layer (PDCP) [34]. Then, the radio link control layer (RLC) performs concatenation/segmentation and sends them to the MAC layer. Note that $t = \sum_{l=1}^{L} |a_l|$ is the number of MAC PDUs after mapping L messages from a_1 through a_L. The packets belonging to the lth message are allocated with the same modulation. After that the MAC PDUs are mapped into a transport block (TB) that consists of N_{RBP} resource block pairs (RBPs) [34]. The eNB broadcasts this TB to the RS and UEs during the first phase. The RS decodes the transmitted TB and performs NC with rate adaptation, as shown in Fig. 5.

$$P_{NC}(RS) = \sum_{v_i(RS) \in G(RS)} f_i \times v_i(RS), \tag{12}$$

where $0 \le i \le t$ is the symbol index at the MAC layer, $v_i(RS)$ is a decoded symbol at the RS, $G(RS)$ is the generation of coded packets which are all successfully decoded packets at the RS, and f_i is a coding coefficient. Assume that both RS and UE are synchronized so that the coding coefficient can be recomputed for decoding using a random number generator seed [25, 26]. A stream of coded symbols is mapped in the MAC PDUs. The MAC layer then maps these MAC PDUs into a TB and sends them to the physical layer (PHY) in order to broadcast them to the UEs during the second phase. Since the generation size of the coded symbol is negligible compared to the large number of users in a multicast group, the encoding and decoding delay at the RS can be assumed to be negligible without affecting the system performance [35]. Refer to [30, 36, 37] for further information on the effect of generation size and decoding delay in NC.

The outputs of our proposed SVN-NC scheme are the optimal rates for all transmissions within the whole transmission duration and the number of NCPs needed for transmission in the second phase. This is because the RS transmits NCPs under strict time and bandwidth resource constraints. Each receiver only needs to receive a sufficient number of NCPs to successfully decode the original packets. Therefore, UEs that are in poor channel conditions are able to increase their video quality with the assistance of the RS. This leads to a significant improvement in the attainable system performance.

5 Optimization framework and performance analysis

In this section, we provide the optimization framework for selecting the best set of AMC modes and a corresponding reasonable number of NCPs for an efficient multicast strategy for a subset of bitstreams L after layered video compression. We also analyze the performance of the proposed SVM-NC, comparing it to other schemes in terms of the number of satisfied UEs, both with and without NC cooperative communication.

Our design objective of the optimization framework is to maximize the expected number of successful UEs (ENS), which is the expected number of UEs that are able to successfully decode all packets of all scalable layers or experience the full video quality of the provided service.

The radio resource allocation can be formulated as follows:

$$\max_{\{R_l^{(1)}(n),\, R_{nc}^{(2)}(n)\}} \quad ENS_{SVM-NC}, \tag{13}$$

subject to:

$$\sum_{l=1}^{L} T_l^{(1)}(n) = \sum_{l=1}^{L} T_l^{(2)}(n) = 1\, TTI. \tag{14}$$

$$\sum_{l=1}^{L} N_{RBP,l} \le \hat{N}_{TH}. \tag{15}$$

$$R_l^{(1)}(n) \le R_{l+1}^{(1)}(m),\ n \le m\, and\, n,\ m \in [1, N]. \tag{16}$$

$$R_l^{(1)}(n),\ R_{nc}^{(2)}(n) \in \Phi. \tag{17}$$

$$l = \{1,\ 2, \cdots,\ L\}. \tag{18}$$

The complete transmission consists of two phases corresponding to two TTIs, one TTI for each phase. Let $T_l^{(j)}(n)$ denote the transmission time for the packets of message a_l with transmission mode n at phase $j(j = \{1, 2\}), N_{RBP,l}$ be the number of RBPs allocated for packets from the lth message, $\hat{N}_{TH}$ be the maximum number of RBs used for the video multicast service (which depends on the allocated bandwidth, e.g., $\hat{N}_{TH} = 50$ with a channel bandwidth of 10 MHz [33]), $R_l^{(1)}(n)$ be the transmission rate in ascending-order of the AMC mode n $(n = 1, 2, \cdots, N)$ for the packets at the lth message in the first phase, and $R_{nc}^{(2)}(n)$ be the transmission rate for delivering NCPs in the second phase. The design objective is to find (i) a set of AMC modes in the first phase, $R_l^{(1)}(n)$, for all multiple original packets belonging to scalable layers transmitted from the eNB and (ii) the transmission rate $R_{nc}^{(2)}(n)$ of NCPs transmitted from the RS in the second phase, which are necessary for maximizing the ENS. Constraint (14) guarantees that the transmission time of two phases is no greater than the time constraint of an individual video packet to guarantee smooth playback. Depending on the time constraint and bandwidth resource, the best AMC mode is selected according to the successful probability of the transmission derived in (7). Constraint (15) guarantees the allocated bandwidth resource is limited. The unequal error protection is guaranteed by constraint (16). Therefore, the transmission rate of a higher layer must be equal to or greater than the lower layers for achieving unequal error protection, since the dependency of scalable layers has a significant effect on the perceived visual quality. The successfully received packets in higher layers are useless if the primary packets are lost in the corresponding lower layers because of their dependency characteristic in scalable video coding. Hence, we assume that the higher priority layers have a lower AMC mode since the greater AMC mode causes greater PER at a certain SNR value, as presented in Subsect. 3.2. Constraint (17) means that the transmission rate is only selected in the set Φ of all possible AMC modes. Constraint (18) ensures that all L layers are considered and assigned with the set of best AMC transmission modes.

Note that the outputs of the algorithm are the set of transmission rates $R_l^{(1)}(n)$ for L layers, referred to as the guarantee of unequal error protection in the first phase, and the transmission rate $R_{nc}^{(2)}(n)$ for delivering NCPs, referred to as the activation of error-resilient capability in the second phase, under strict time and resource constraints. The exhausted algorithm is used to find the best set of the corresponding AMC modes for all scalable layers with a time complexity of $\mathcal{O}(N^L)$ where it N is the number of AMC modes and L is the number of layers. Since the values of N and L are small, e.g., $N = \{1 \sim 15\}$ in LTE [33] and $L = \{1 \sim 6\}$ [38], the time complexity is acceptable for fast searching in a finite number of steps. The eNB runs the algorithm and informs the optimization results to the RS by using a control information signal channel with negligible overhead. After receiving all t packets from the eNB and control signals, the RS performs NC and transmits the optimal number of NCPs with the best AMC mode to the multicast group based on the optimization results.

We now compare the analytical performance of three schemes in Fig. 3 in terms of ENS. The ENS is given in (19).

$$ENS = \sum_{i=1}^{K} i \times P(i) = \sum_{i=1}^{K} i \times \binom{K}{i} p^i \times (1-p)^{(K-i)}, \tag{19}$$

where K is the number of UEs in the multicast group, $P(i)$ is the probability that i UEs successfully decode all layered video packets after the transmission duration, and p is the probability that a UE successfully decodes all layered video packets. We analyze various measurements of p corresponding to the above three multicast schemes.

For the DM scheme, let $p_l^{(1)}(n) = 1 - P_e(n)$ be the probability of successfully decoding a packet of the lth message in the first phase with AMC mode n from the eNB to UEs. The computation of $P_e(n)$ is provided in (7), depending on the channel condition among UEs and time constraint of each packet corresponding to an individual message. The transmission time of each packet of an individual lth message is computed as $T_l^{(1)}(n) = Len/R_l^{(1)}(n)$, where Len is the fixed packet length and $R_l^{(1)}$ is the corresponding transmission rate, since eNB uses one-hop broadcasting transmission for multiple packets in the DM scheme. The probability of successfully delivering all packets is defined as the product of all individual successful probabilities for each transmitted packet:

$$p_{DM} = \prod_{l=1}^{L} p_l^{(1)}(n)^{|a_l|}. \tag{20}$$

Note that $|a_l|$ is the total number of packets in the lth message assigned for transmission within a TTI, which are transmitted using same the transmission rate.

For the CM scheme, let $p_{l,RS}^{(1)}(n)$ be the probability of successfully decoding a packet of the lth message in the first phase with AMC mode n from the eNB to RS and let $p_{l,RS}^{(2)}(n)$ be the probability of successfully decoding a packet of the lth message from the RS to UEs in the second phase. Let $p_{l,RS}(n) = p_{l,RS}^{(1)}(n) \times p_{l,RS}^{(2)}(n)$ be the probability of successfully delivering a packet from the eNB to UEs through the RS. Then p_{CM} can be defined as follows:

$$p_{CM} = \prod_{l=1}^{L}\left(\left(\sum_{i=0}^{1} p_l^{(1)}(n)^i \times \left(1 - p_l^{(1)}(n)\right)^{1-i} \times p_{l,RS}(n)^{1-i} \times \left(1 - p_{l,RS}(n)\right)^i\right) + p_l^{(1)}(n) \times p_{l,RS}(n)\right)^{|a_l|}. \quad (21)$$

Here, we present the analysis for our proposed SVM-NC. As the error recovery capability and bandwidth efficiency for lost packets increase, RS encodes all successfully decoded packets into NCPs and then transmits only NCPs in the second phase. For simplicity, since there are a total of $t = \sum_{l=1}^{L} |a_l|$ packets assigned for broadcasting in the first phase, we define the probability of successful decoding for each packet as follows:

$$p_i = \begin{cases} p_1^{(1)}(n) & \text{with } i \le |a_1| \text{and} l = 1 \\ p_l^{(1)}(n) & \text{with} \sum_{l=1}^{l-1} |a_l| < i \le \sum_{l=1}^{l} |a_l| \text{and} l \ge 2 \end{cases} \quad (22)$$

For instance, there are 3 layers, with message a_1 containing 1 packet, message a_2 containing 2 packets, message a_3 containing 2 packets (refer to Fig. 4 with $L = 3$). Hence, $p_1 = p_1^{(1)}(n), p_2 = p_2^{(1)}(n), p_3 = p_2^{(1)}(n), p_4 = p_3^{(1)}(n)$ and $p_5 = p_3^{(1)}(n)$.

Let $\bar{t}_{UE}$ and $\bar{t}_{RS}$ be the expected number of successful decoded packets at the UE and RS, respectively.

$$\bar{t}_{UE} = \sum_{k=1}^{t} k \sum_{\alpha_i \in \beta_k}^{\binom{t}{k}} \prod_{i=1}^{t} p_i^{\alpha_i} \times (1 - p_i)^{1-\alpha_i}, \quad (23)$$

$$\bar{t}_{RS} = \sum_{k=1}^{t} k \sum_{\alpha_i \in \beta_k}^{\binom{t}{k}} \prod_{i=1}^{t} p_{i,RS}^{\alpha_i} \times (1 - p_{i,RS})^{1-\alpha_i}, \quad (24)$$

where $\beta_k = \{\alpha_i \mid \sum_{i=1}^{t} \alpha_i = k, \alpha_i = \{0, 1\}\}$ is the set of t binary elements whose sum of all elements is equal to k. Since the RS uses all $\bar{t}_{RS}$ successful decoded packets to encode into NCPs using (12), the generation size can be defined as $G = \bar{t}_{RS}$. Because the channel medium between eNB and RS operates in the line of sight and is stable, we assume $\bar{t}_{RS} \approx t$. Furthermore, the value of t is generally small, hence a Galois field of size 8 can be selected with a high probability of generating linearly independent coding coefficients. Since the computational capacity of the RS is so powerful nowadays [39], then without loss of generality, we assume that the encoding/decoding delay at RS is negligible.

Since, the UE does not care about packet types or transmission order, error resiliency could be completed by receiving enough NCPs or achieving full rank [13–15]. Let M be the number of NCPs used for transmission in the second phase and let $M \le t$. Denote by $p_{nc}^{(2)}(n)$ the probability of successfully transmitting an NCP from the RS to the multicast group corresponding to AMC mode n. Then the probability that a UE successfully decodes all layered video packets can be expressed as follows:

$$p_{SVM-NC} = \sum_{k=t}^{t+M} \sum_{\alpha_i \in \beta_k}^{\binom{t+M}{k}} \prod_{i=1}^{t+M} p_i^{\alpha_i} \times (1 - p_i)^{1-\alpha_i}, \quad (25)$$

where $p_i = p_{nc}^{(2)}(n)$ with $i > t$. Note that the number of NCPs M for transmission depends on the set of optimal AMC modes selected to maximize the ENS.

Note that a stand-alone RS without wired Internet connectivity will be much cheaper in terms of deployment and maintenance than an eNB requiring wired Internet connectivity, so the additional cost of the RS is beneficial to efficient scalable video multicast using NC [39].

6 Numerical results

In this section, we show the numerical results of our SVM-NC compared to the CM and DM schemes. We consider a network of an eNB and a dedicated RS. UEs in the multicast group are located in the coverage of both eNB and RS. Table 3 summarizes the simulation parameters and H.264/SVC video stream [25] used in the simulation. Each simulation was run 100,000 times with a confidence interval of at least 95% in the Matlab environment.

First, we used the results of the normalized throughput provided in Fig. 6, which are widely used to estimate the effective performance of the communication system, to demonstrate the advantage of using the combination of rate adaptation and NC at RS. We use AMC modes 2, 3, and 4 to deliver BL, EL_1, and EL_2 in the first phase, respectively. Figure 6(a, b) present the performances of each AMC mode used to deliver NCPs in the second phase with bandwidth resources of 5 and 10 MHz, respectively. The performances of each mode become different according to the channel condition. Hence, the optimal AMC selected for transmission should depend on the channel conditions. As seen, the throughput increases as more bandwidth resources are used. Especially, the performance behavior of each AMC mode varies greatly. For instance, AMC mode 3 is the best choice for an SNR of 0 dB, but when more bandwidth resources are allocated, AMC mode 2 exhibits the best performance. Consequently, the NC can achieve more advantages through selection of the best transmission rate for strict residual times.

Second, we evaluate the impact of the channel conditions and allocated bandwidth resources on the number of

Table 3 Simulation parameters

Parameter	Value
System bandwidth	5, 10 MHz
Number of scalable video layers	$L = 3$
Fixed packet size	1024 bits
Total modulation	6
Galois field order	8
Channel	Rayleigh channel
H.264/SVC streams [kbps]	BL: 117.1, EL_1:402.5, EL_2:1506.3
g_{GOP}	16 frames
f_{GOP}	30 fps

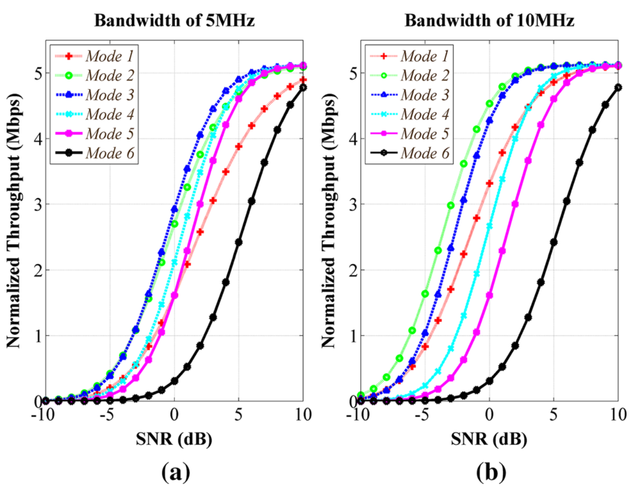

Fig. 6 Normalized throughput with different transmission modes versus channel condition: **a** bandwidth resource of 5 MHz, **b** Bandwidth resource of 10 MHz

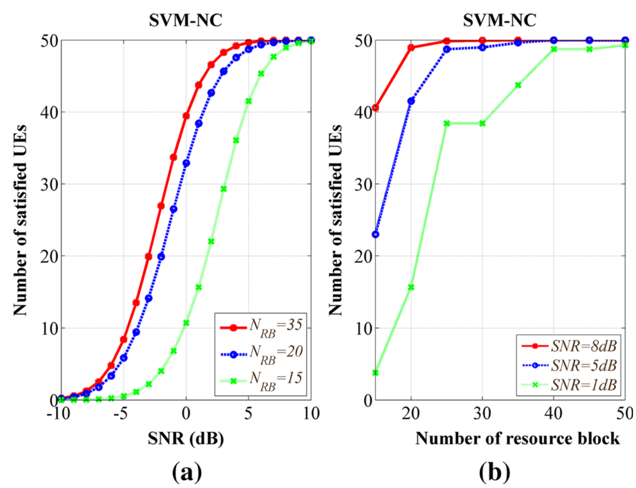

Fig. 7 Number of satisfied UEs versus SNR and bandwidth resources

satisfied UEs (i.e., the number of UEs who experience full video quality). As shown in Fig. 7(a), we evaluate the impact of the number of resource blocks (such as 15, 20 and 35) on the performance according to an increase in the SNR value from −10 to 10 dB. The results clearly emphasize our previous conclusion that additional allocated bandwidth resources produce a greater number of satisfied UEs. This is because a higher number of resource blocks corresponds to a lower AMC mode (i.e., an increased reliability), so the RS is able to generate and transmit more network-coded packets with a smaller packet error rate. Therefore, the packet loss rate can be significantly reduced in the second phase by using network-coded cooperation. Inversely, as shown in Fig. 7(b), we evaluated the impact of SNR (1, 5 and 8 dB) on the performance according to increases in the number of resource blocks from 15 to 50. A higher SNR indicates a better performance, and additionally, a higher transmission rate can be selected with high reliability. Hence, the proposed scheme produces a greater number of UEs that successfully decode all of the transmitted scalable video layers. From these results, we can optimally allocate resources depending on the channel conditions in order to maximize the attainable system performance.

Third, we evaluated the efficiency of our SVM-NC scheme compared to other traditional schemes, using 50 UEs in the multicast group and a bandwidth of 10 MHz. Figures 8 and 9 show that SVM-NC has the best performance, followed by the CM and DM schemes, in terms of the number of satisfied UEs and normalized throughput, respectively. As the channel conditions improve, this leads to greater performance achievement in terms of the number of satisfied UEs and normalized throughput. As seen in the Fig. 8, in terms of number of satisfied UEs, SVM-NC is improved by factors 1.03 and 1.41 for CM and DM respectively, at an SNR of 5 dB. On the other hand, SVM-NC increased by factors of 1.13 and 1.97 for CM and DM respectively, in terms of normalized throughput shown in Fig. 9.

Figure 10 shows the performance efficiency according to changes in the multicast group size with an SNR of 4 dB and a bandwidth resource of 10 MHz. The expected number of successful UEs increases linearly in the three schemes. As observed, the results illustrate that SVM-NC

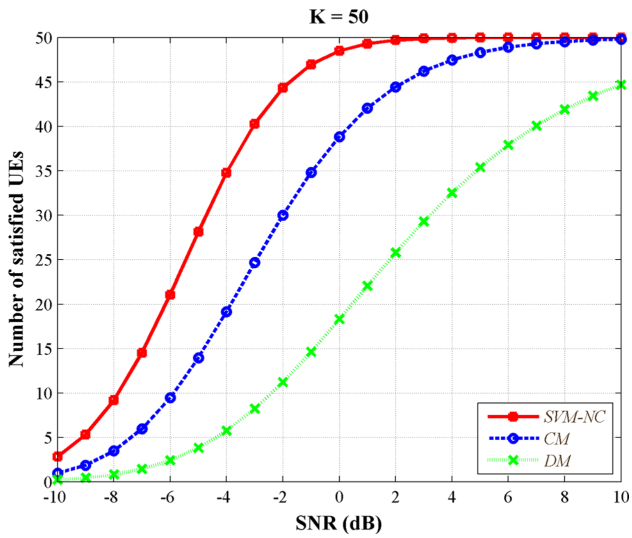

Fig. 8 Number of satisfied UEs versus SNR value

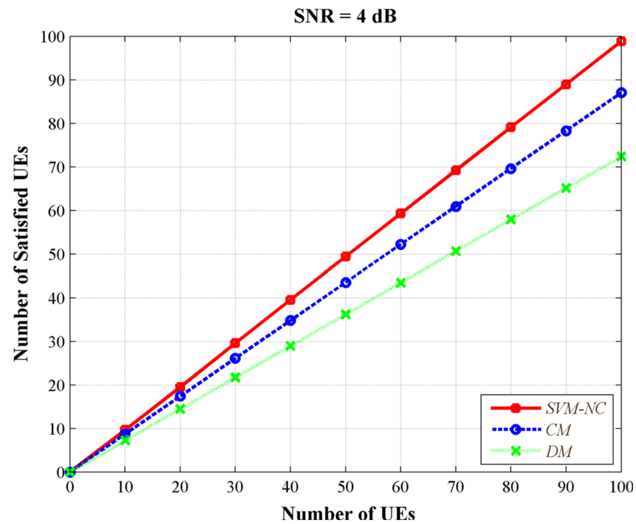

Fig. 10 Number of satisfied UEs versus the number of UEs in the multicast group

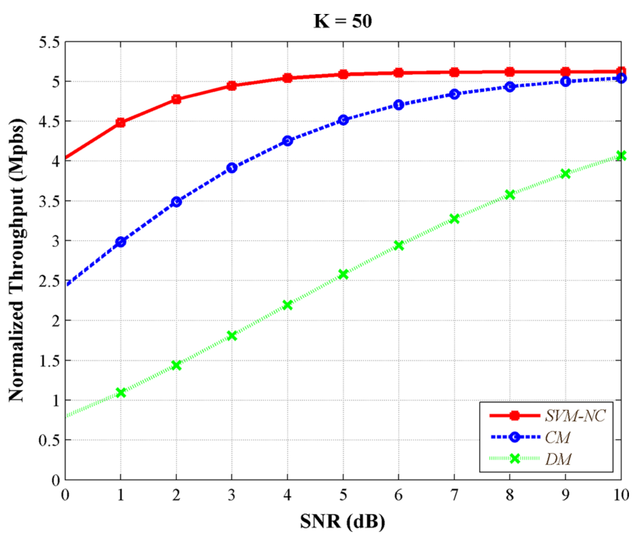

Fig. 9 Normalized throughput versus different SNR values

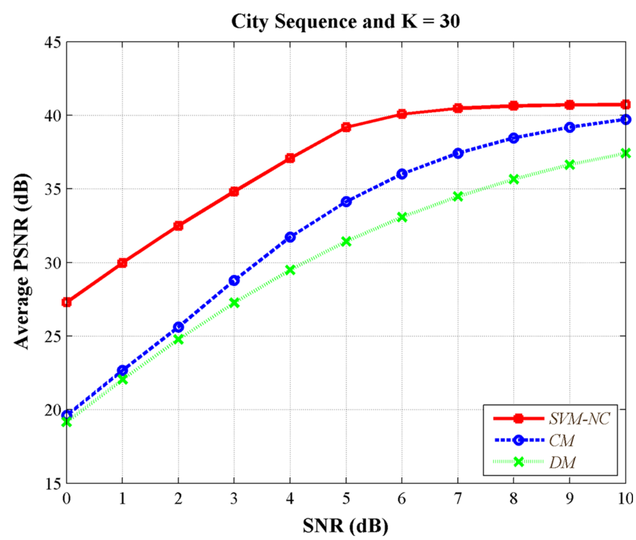

Fig. 11 Average PSNR of different multicast schemes versus SNR

asymptotically achieves the maximum performance for any multicast group size; the SVM-NC improved by factors of 1.36 and 1.14 for DM and CM, respectively. As seen in the figure, as the multicast group size increases, the performances of DM and CM schemes decrease. Since the gap between the best and worst channel states is large, it becomes more challenging to maintain performance among users.

Lastly, the performance metric in terms of PSNR is evaluated to indicate the perceived visual quality after transmission. The test sequence video titled City is split into three subsets of bit-streams with a frame rate of 30 frames per second (fps). The GOP has 16 frames with a hierarchical prediction structure, corresponding to a time duration of 0.533 s for the GOP. The average PSNR metric is evaluated using a network size of 30 UEs. As shown in Fig. 11, SVM-NC achieves the best performance, followed by CM and DM. In addition, the results also indicate that SVM-NC is able to provide full high-resolution video quality to all UEs in the multicast group.

From the simulation results, it is concluded that our design objective (i.e., maximization of the number of satisfied UEs) can be achieved by SVM-NC since almost all of the UEs in the network are able to experience full video quality with high-resolution and smooth playback. Therefore, it can be concluded that our SVM-NC scheme will be a promising solution for efficient scalable video multicast services in potential 5G cellular networks.

7 Conclusion

An efficient scalable video multicast based on network-coded cooperation (SVM- NC) has been proposed to enhance the attainable system performance using the number of satisfied UEs as a metric. SVM-NC achieves average gains of 1.03 and 1.41 compared to the cooperative and direct multicast schemes, respectively, at a signal-to-noise ratio (SNR) of 5 dB. Moreover, SVM-NC achieves average gains of 1.13 and 1.97 compared to the cooperative and direct multicast schemes, respectively, in terms of normalized throughput. The numerical results show that the expected percentage of satisfied UEs reaches approximately 100% by using network-coded cooperation for scalable video multicast. The efficiency of the SVM-NC is also estimated by the PSNR, which is a widely used metric for video quality evaluation. The results indicate that the proposed scheme is much better than the others, and asymptotically provides the full video quality of the provided service. Our proposed scheme achieved an expected ratio of successful UEs of 100% and a PSNR that is asymptotically equal to the maximum value in the multicast group. For future work, we will extend our scheme to high-mobility networks, such as vehicular ad hoc networks.

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