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Cooperative Network-Coded Multicast for Layered Content Delivery in D2D-Enhanced HetNets

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***Abstract*—The rapid growth in multimedia applications over cellular networks calls for multicast services. Multicast is an efficient means of delivering contents to multiple users while efficiently utilizing network resources. Layered streaming, e.g., scalable video coding (SVC) provides an excellent solution to handle channel diversities in wireless multicast. This paper presents a cooperative multicast scheme for scalable video content delivery in D2D-enabled heterogeneous cellular networks (HetNets). To extend the multicast service beyond base stations (BSs), D2D links are used to help relay content for cellular multicast. Network coding (NC), implemented through random linear network coding (RLNC) with unequal error protection (UEP) is incorporated in layered contents to enhance reliability and throughput. This paper tries to optimize the multicast scheduling procedures, aiming to assign the optimal modulation and coding schemes (MCSs) for transmissions. The constraints on cache size, backhaul capacity and channel fading are comprehensively considered. Besides, this paper also presents a interference-aware approach for D2D link selection in order to further improve the cooperative multicast. Sufficient numerical results have demonstrated the improvement brought by the proposed scheme significantly on the content delivery efficiency as well as quality of experience (QoE).**

***Index Terms*—D2D Communication, Heterogeneous Cellular Network, Layered Multicast, Network Coding**

I. Introduction

With the increasing volume of multimedia traffic, multicast service has become a critical issue since point-to-multipoint transmission is a natural choice for multimedia service. In the fifth-generation (5G) mobile communication system, the evolved multimedia broadcast multicast service (eMBMS) [1] standardized by 3GPP is likely to be included [2]. A challenge for wireless multicast service is the channel diversities among multiple receivers due to different distances to the base stations or fading conditions. Even though adaptive modulation and coding (AMC) is deployed, the selected modulation and coding scheme (MCS) still has difficulty to accommodate all receivers. On the other hand, to guarantee all receivers to decode the selected MCS, there will be a worst-case limit on the data transmission rate and saturated system data throughput. Scalable video coding (SVC) [3] provides an excellent solution for multicast video delivery. SVC is a stream splitting approach that divides a video stream into multiple layers (sub streams), including a base layer (BL) and multiple enhanced layers (EL). The BL is necessary to watch the video while the ELs can augment the video's quality (more ELs accessed, higher video quality achieved). There have been several studies on the SVC coded multicast in cellular networks [5]–[7] focusing on the optimal transmission rate, power efficiency and resource allocation. Network coding (NC) has also been proved to be able to improve the performance of content delivery for layered multimedia multicast services [7]–[9].

Heterogeneous cellular network (HetNet) is a promising architectural technique to support the 1000-fold higher throughput in 5G networks. Traffic are offloaded via small base stations (SBSs) deployed within the coverage of a macro-cell base station (MBS) [10]. The area spectral efficiency is thus increased but significantly relies on the backhaul links. With the further densification of cellular networks, it becomes impractical to deploy high-speed backhaul links and backhaul congestions will largely degrade network performance. A large portion of mobile data traffic is generated by duplicate downloads of a few popular contents [11]. Therefore, exploiting content reuse is deemed to tackle the data tsunami. Besides multicast delivery, another candidate solution is caching, which is tightly coupled with the former due to the spatiotemporal characteristics of user requests [12]. Mobile edge caching is a feasible technique to relieve the backhauls by storing contents at the wireless edge, i.e., base stations (BSs) and user equipment (UE). Cached contents can be delivered directly to users without transmissions over backhaul links or core networks [13], [14]. According to [15], edge caching can reduce the backhaul capacity requirement to 35%. Since the cost of memory device is relatively low compared with the storage capacity, [16] suggests to replace SBSs with femto base stations (FBSs) with quite constrained backhaul (or even without backhaul) but high capacity caches.

The coexistence of SBSs and MBSs results in additional inter-cell interference in the HetNets with shared spectrum resources [17]. Coordinated multipoint (CoMP) technique allows geographically separated BSs to communicate cooperatively. Hence, inter-cell interference is mitigated and both network coverage and throughput are increased [18]. CoMP provides a new perspective of wireless caching and transmission mainly aiming for physical layer cooperation gain. E.g. CoMP joint transmission for downlink in HetNets has been studied in [19]. [20] tries to balance diversity and cooperation gain in a cache-assisted joint transmission scenario via the optimal placement. [21] further optimizes the balance via a cluster-centric small cell network with combined design of caching and transmission policy. When D2D communication is incorporated in the HetNets, content sharing and relay assisted transmission can further enhance the content delivery efficiency [22], [23]. Integrating D2D communication into cellular multicast networks has been proposed by [24] to handle the dilemma of throughput saturation. User association and interference mitigation have been investigated by [25] to further increased the system capacity.

In this paper, we propose a cooperative network-coded multicast scheme for layered content delivery. Instead of a coarse-grained subgrouping approach for multicast service [2], we use layered multicast to exploit the channel diversities in cellular networks. To efficiently utilize the network resources, we try to leverage the cooperation in the HetNets, i.e. content sharing and joint transmissions enabled by the coordinated multiple cells and D2D communications. The dynamic network conditions and constrains on network resources are detailedly investigated, including the fading channels, communication interferences, cache size and backhaul capacity. The SVC multicast is further enhanced with RLNC which considers the unequal error protection (UEP).

The remainder of this paper is organized as follows. Section II takes an overview of the network model with the architecture of a HetNet and the multicast scenario. Section III presents the cooperation multicast scheme and illustrates how NC is incorporated into SVC and how to assign the optimal MCSs and select the D2D links. Numerical experiments are carried out in Section IV and simulation results are also provided. Section V concludes the paper and discusses the future work.

II. Network Model

Fig.1 shows the cooperative multicast transmission in a D2D-enhanced HetNet. This single-macro-cell scenario has one MBS (which can be directly extended for more macro cells). N SBSs are uniformly distributed within the macro cell while K UEs are distributed according to a homogeneous Poisson Point Process (PPP). We assume the K UEs request for the same multicast service and can be drawn into one multicast group. The MBS is equipped with multiple antennas while the SBSs and UEs are only equipped with a single antenna. Within the coverage of a single MBS, Multiple SBSs densify the cellular system and the backhauls for the SBSs are limited due to the high cost to deploy the optimal fiber links. The backhaul capacity of the MBS is sufficient to download the on-demand requested contents for UEs. In a cache-enabled HetNet, caches are deployed at BSs and UEs and requested files can be proactively cached.

The MBS can associate to any UE in the macro cell, but the SBSs can only associate to UEs within their own coverage. The SBS backhauls are usually used for periodically cache content refreshing. The downloading of on-demand contents through SBS backhauls are constrained by the backhaul capacity. Therefore, a UE can be served by the covering SBSs that

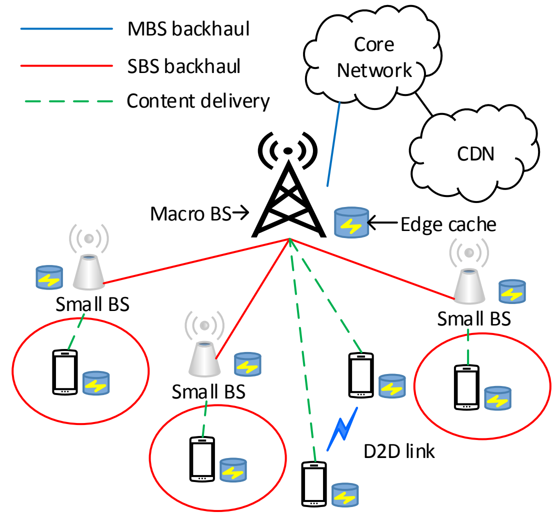

Fig. 1: System Architecture of a cache-enabled HetNet

have cached the requested contents or have enough available backhaul bandwidth (set as B_n for the backhaul link of SBS n). Otherwise, the UE can only be served by the MBS. If D2D links are active for a UE, requested content can be retrieved from nearby UEs which have cached the content rather than through cellular downlink. Content sharing among UEs can alleviate the burden of BSs especially for SBSs with constrained backhaul or cache capacity. If the cellular links are under severe attenuation, content delivery can be significantly enhanced by D2D relay transmission.

LTE has proposed eMBMS to support multicast delivery and introduced the concept of multimedia broadcast multicast service single frequency network (MBSFN) [26]. We assume the scenario in the network model to be a MBSFN area where the cells coordinate their transmissions. A UE can perceive multiple transmissions from multiple cells as a single transmission, and thus alleviating interferences of dense small cells. Besides, the UEs in the overlapping area can receive multiple signals from a set of BSs with enhanced signal-to-interference-plus-noise ratio (SINR). To avoid interference between D2D and cellular communications, independent single frequency bands are available to them. The UEs are equipped with separate RF modules for each frequency band and can simultaneously receive and forward data. D2D communication is confined within one-hop in case of the complicate inferences introduced by multi-hop transmissions.

For a UE k in the non-overlapping area served by a single BS n, the SINR is calculated by

$$\gamma_{k,n} = 10 * log_{10}(P_{k,n}|h_{k,n}|^2(d_{k,n})^{-\eta}/\sigma^2)(dB). \quad (1)$$

where $P_{k,n}$ is the desired signal power, and σ^2 is the addictive white gaussian noise (AWGN) variance. The instantaneous channel gain is formulated as

$$G_{k,n} = |h_{k,n}|^2(d_{k,n})^{-\eta}. \quad (2)$$

where $|h_{k,n}|^2$ captures the small-scale Rayleigh fading effect and this is commonly modeled as an exponentially distributed random variable with a unit mean; $d_{k,n}$ is the transmission distance and $d_{k,n}^{-\eta}$ signifies the path loss with the path loss exponent $\eta \geq 2$. If UE k is in the overlapping area served by a set of BS Q_k, the SINR is calculated by

$$\gamma_{k,n} = 10 * log_{10}(\sum_{Q_k} P_{k,n}|h_{k,n}|^2(d_{k,n})^{-\eta}/\sigma^2)(dB). \quad (3)$$

For a D2D link i, the SINR is calculated by

$$\gamma_i = 10 * log_{10}\frac{P_i|h_i|^2(d_i)^{-\eta}}{\sigma^2 + \sum_{j \in D\backslash\{i\}} P_j|h_j|^2(d_j)^{-\eta}}(dB). \quad (4)$$

where the cross-interference among D2D multicast communications are taken into account.

The available capacity of both cellular link and D2D link is determined by a mapping from channel quality indicator (CQI, i.e., the SINR level) to MCS given in [27]. The number of available MCS levels is $M = 15$. MCS of the higher level m has the higher spectral efficiency c_m. In the frequency domain, a resource block (RB) in LTE is composed of 12 subcarriers with fixed bandwidth $15kHz$, which means the bandwidth of a RB is $S = 15 \times 12 = 180kHz$. In the time domain, a RB is a $0.5ms$ time slot. Then the data rate for one RB is $R_m = c_m S$ if it is transmitted with the m-th MCS level. The adaptive modulation and coding (AMC) is adopted for cellular transmission and the D2D links use fixed MCS. Cellular transmission can adjust the physical layer data rate to fulfill the requirement on bit error rate. D2D links with SINR over the threshold can be activated.

III. Layered Multicast Scheduling

A. Network coding for scalable video coding

A scalable message composed of K elements $X = \{x_1, x_2, ..., x_k\}$ is split into L layers $\{v1, v2, ..., v_L\}$. v_1 represents the base video layer and the others represent the $L-1$ enhancement video layers, as illustrated in Fig. 2. QoE relies on the number of recoverable video layers starting from v_1. The $l-th$ video layer consists of k_l elements and the layers are arranged in descending order of importance. The first layer holding the first elements of the message is the most important while the $L-th$ layer is the least important. To improve reliability, each message is transmitted using random linear network coding (RLNC). RLNC scheme generates a stream of $N \geq K$ coded blocks (elements) $Y = \{y_1, y_2, ..., y_N\}$ by linear combining the elements of X. The coding coefficient $g_{i,j}$ is randomly selected from a finite field $GF(q)$ of size q and the coded element y_j is defined as $y_j = \sum_{i=1}^{K} g_{i,j} x_i$. Source message X can be recovered through Gaussian elimination as long as the receiver collects K linearly independent coded blocks.

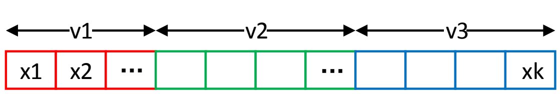

Fig. 2: An example of 3-layer scalable message

To address the dilemma that a receiver is unable to recover the source elements of X if it has not received enough coded blocks, UEP is adopted to the NC implementation for SVC. Rather than linearly combining all packets of the source message X, RLNC is taken place over a nested structure of L windows. In cellular multicast, network coding is implemented intra-layer. Coded blocks are mapped into packet data units (PDUs), and each PDU holds the coded elements within the same non-overlapping window. Within the same video layer. AMC helps assign the optimal MCS for each PDU, making the tradeoff between physical layer transmitting rate and error-correcting capability. For the relay forwarding over D2D links, UEs play the role of help node for content delivery and intra-layer network coding should be adopted which uses the expanding window RLNC.

B. MCS assignment for AMC

The MCSs supported in LTE is listed in Table 1. MCS selection should consider the conditions of the whole network, i.e., whether the channel qualities and the constraints on the BS backhauls and caches can support the data transmission rate. The CQI of each UE is periodically reported to the associated BS. Since in the MBSFN scenario all BSs transmit the same signals, the MBS collects all the CQI messages and selects the optimal MCS applied to all BSs. The layered multicast, aims not to just maximize the data throughput, but the total number of video layers that the UEs successfully receive. This is mathematically described as

$$\theta = \arg\max \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{j=1}^{m} x_{j,l} v_{k,l} \quad (5)$$

subject to

$$\sum_{j=1}^{m} x_{j,l} = 1 \quad (6)$$

$$\sum_{k=1}^{K} v_{k,l} = K \quad (7)$$

$$\sum_{j=1}^{m} x_{j,l} c_j B_W \geq R_l \quad (8)$$

$$\sum_{j=1}^{m} x_{j,l} c_j B_W \leq B_n + \frac{C_n}{T} \quad (9)$$

$x_{j,l}$ denotes the j-th MCS assigned to video layer l, and only one MCS can be assigned. $v_{k,l}$ denotes whether the video layer l is valid, i.e., can be recovered by UE k. This depends on whether the UE k is able to decode the MCS under its received SINR. B_W is the allocated bandwidth. It needs to be guaranteed that the content of base layer can be decoded and totally recovered by all UEs. The physical layer transmission rate achieved by the selected MCS should meet the data rate R_l of corresponding video layer. Besides, the data transmission rate is also constrained by the backhaul bandwidth B_n of the SBS n and the size of cached files C_n that SBS n holds during the video session T.

CQI Index	Modulation Scheme	Code Rate	Spectral Efficiency [bit/s/Hz]
1	QPSK	0.076	0.1523
2	QPSK	0.120	0.2344
3	QPSK	0.190	0.3770
4	QPSK	0.300	0.6016
5	QPSK	0.440	0.8770
6	QPSK	0.590	1.1758
7	16-QAM	0.370	1.4766
8	16-QAM	0.480	1.9141
9	16-QAM	0.600	2.4063
10	64-QAM	0.450	2.7305
11	64-QAM	0.550	3.3223
12	64-QAM	0.650	3.9023
13	64-QAM	0.750	4.5234
14	64-QAM	0.850	5.1152
15	64-QAM	0.930	5.5547

Table 1 CQI-MCS Mapping in LTE [27].

C. D2D link Selection

The SINR threshold of D2D link is set as 19.6dB in this scenario to meet the peak data rate over 4 Mbps according to 3GPP LTE specification. The MCS for D2D communication is thus fixed. To avoid the cross-pair interference among D2D communication shown in Fig. 3, D2D links should be carefully selected. D2D pairs that have distinct disparity on cellular receiving conditions need to have active links since there are innovative data to be retrieved. The selection aims to fulfill the objective function written as

$$\pi = max \sum_{i=1}^{D} c^{D2D} B_W z(i). \tag{10}$$

subject to

$$z(i) = 1, \quad |\gamma_{d_1,n} - \gamma_{d_2,n}| \geq \psi_c \quad \& \quad \gamma_{d_1,d_2} \geq \psi_d. \tag{11}$$

$$z(i) = 0, \quad Otherwise. \tag{12}$$

D2D communication aims to maximize the data throughput under certain constraints. The disparity between cellular link SINR of a D2D pair should be over than the threshold ψ_c. Hence, the UE under poor channel quality can retrieve innovative data from the other UE connected to it. The SINR of a D2D link should also be over the threshold ψ_d so that transmitted data can be decoded over this link. We take a suboptimal selection approach as follows.

- All potential D2D links are sorted in descending order according to their disparity on cellular link SINR.
- Then allocate all the D2D links with severe cross-link interference to a subsequence.
- Finally eliminate the D2D links in the rear of the sorted subsequence until all other D2D links can work.

IV. Performance Evaluation

A. Simulation Scenario and Parameters

Numerical experiments are based on a LTE-advanced HetNet with a single macro cell. N SBSs are uniformly distributed, while the distribution of K UEs follows a homogeneous PPP. We assume the backhaul and cache capacity of the MBS can handle all on-demand requests but these are constrained for SBSs. Parameters for the simulation are listed in Table 2. The hypothetical video sequences, lasting for 15 minutes, have 4 to 6 layers and the data rate for each layer ranges from 256 kbps to 2 Mbps.

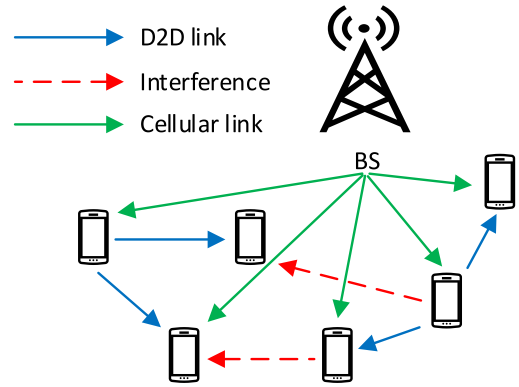

Fig. 3: Interference in D2D communication

Simulation Parameter	Value
Macro cell radius [m]	500
Small cell radius [m]	50
D2D communication rage [m]	10
MBS Tx power [dBm]	46
SBS Tx power [dBm]	30
UE max Tx power [dBm]	23
Cellular link	3GPP case 1 [28]
D2D link	ITU-R IMT UMi [29]
Cellular Carrier Frequency/Bandwidth	3.5GHz/10MHz
D2D Carrier Frequency/Bandwidth	2.5GHz/10MHz
SINR Threshold for D2D link	19.6 [dB]
Modulation and coding scheme	AMC for Cellular and fixed for D2D
Thermal noise density [dBm/Hz]	-174
UE cache size [Mb]	250
SBS cache size [Gb]	1
UE mobility	0.7 m/s with random direction

Table 2 Main Simulation Parameters.

B. Numerical results

Numerical experiments are carried out under circumstances with different number of SBSs N, UEs K and different capacity of SBS backhauls. Network performance is evaluated by data throughput while user QoE is evaluated by peak-signal-to-noise ratio (PSNR). We compared the average data throughput for non-cooperative multicast scheme without D2D relaying and cooperative multicast with D2D communication. Besides, we also compare the average PSNR for non-layered and layered content delivery separately.

For layered content multicast (with a fixed SBS backhaul capacity $B_n = 0.5Mbps$), Fig. 4 shows the average data throughput for scenarios with the number of SBSs N, ranging from 0 to 30 and a constant number of UEs $K = 250$. Fig. 5 shows the average data throughput for scenarios with the number of UEs K ranging from 50 to 500 and a constant number of SBSs $N = 25$. Both illustrate the improvement on data dissemination with the increase on SBS density, and D2D communication significantly enhances data throughput. This

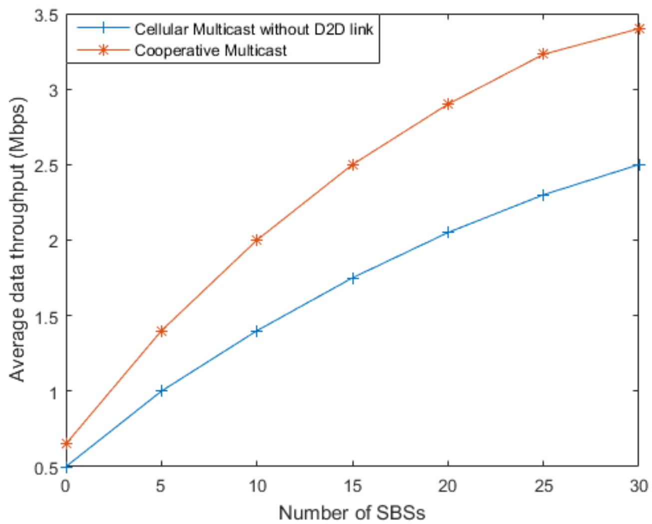

Fig. 4: Average data throughput for different number of SBSs

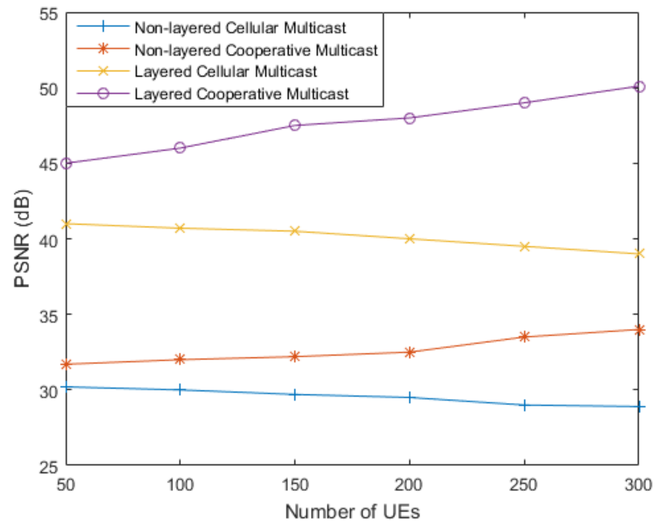

Fig. 7: PSNR for different number of UEs

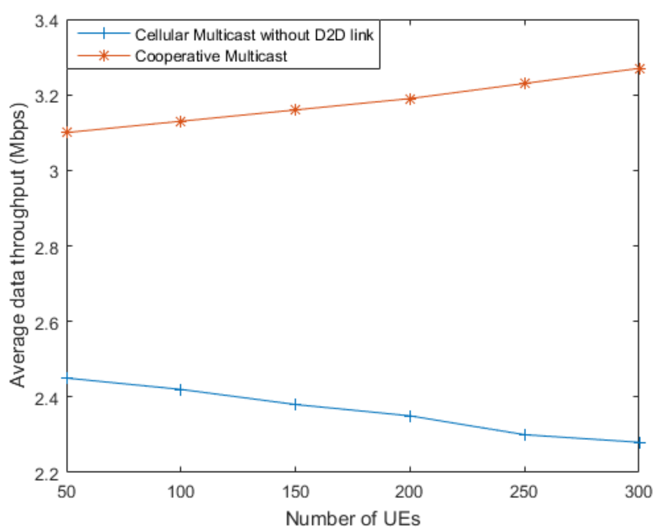

Fig. 5: Average data throughput for different number of UEs

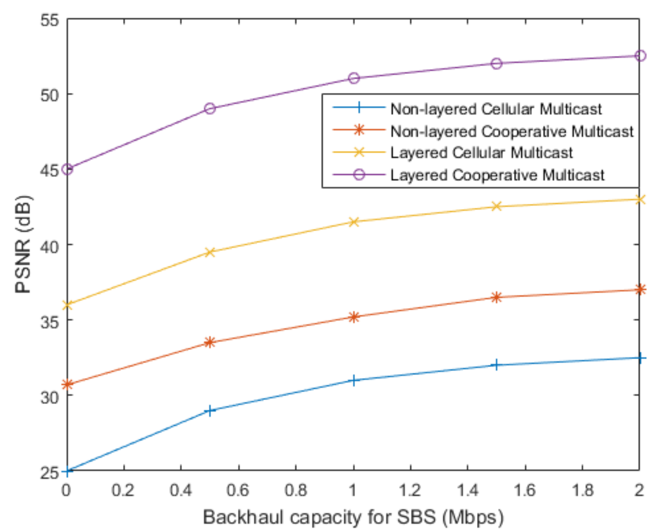

Fig. 8: PSNR for different SBS backhaul capacity

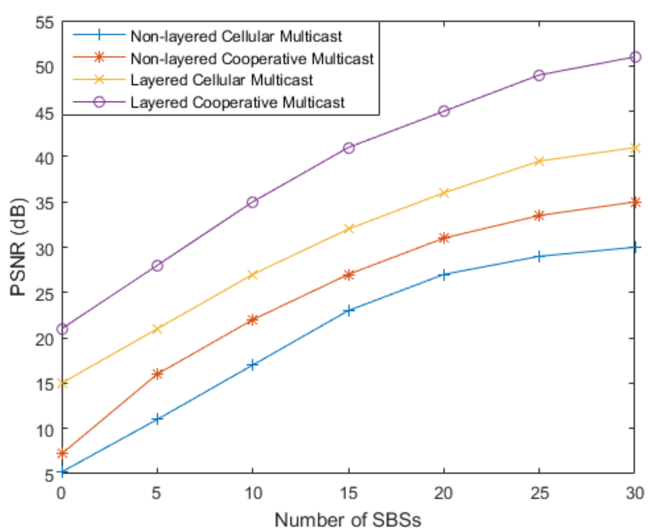

Fig. 6: PSNR for different number of SBSs

demonstrates the advantage of cooperative multicast scheme especially for dense network scenarios.

Besides the network performance, the user QoE is also evaluated by the PSNR of received video under different levels of network density ($B_n = 0.5Mbps$) shown in Fig. 6 (N ranging from 0 to 30 and $K = 250$) and Fig. 7 (K ranging from 50 to 500 and $N = 25$). It is obvious that with higher data throughput, cooperative multicast schemes outperform non-cooperative multicast on PSNR. Both figures also demonstrate the advantage of SVC, which is a definitely efficient technique to improve user QoE for wireless multicast. Fig. 8 illustrate the impact of SBS backhaul capacity. Higher backhaul capacity do bring notable improvement at first, but as it increases to certain degree, the constraints of fading channels will become the main bottleneck other than the backhaul. This is the same case for the cache size as cache is deployed to replace the backhaul, though it is not included in the simulations.

V. CONCLUSION

This paper proposes a cooperative multicast for layered content delivery in HetNets. SVC enables a stream splitting solution which can exploit wireless channel diversities in a fine-grained manner. We incorporate network coding into SVC to further enhance the reliability and data throughput. RLNC is processed both at BSs and UEs in intra-layer and inter-layer way separately. To efficiently utilize the network resources, this paper makes an optimization for the multicast while considering multiple constraints and network conditions, including the fading channels, communication interferences, cache storage and backhaul capacity. Besides an optimal MCS assignment for data transmission, this paper also gives a interference-mitigating approach to select D2D links for relaying contents. Sufficient numerical results are provided to demonstrate the superiority of our scheme on network performance and the enhancement of QoE. Future work may study the impact of caching policies, especially the cooperative caching on the content delivery in our scheme. New scenarios where D2D communication is confronted with cross-tier interference and power control problem will also be included.

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