BIT ALLOCATION OF WWAN SCALABLE H.264 VIDEO MULTICAST FOR HETEROGENEOUS COOPERATIVE PEER-TO-PEER COLLECTIVE

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ABSTRACT

By exploiting multiple network interfaces on one device, e.g., Wireless Wide Area Network (WWAN) and Wireless Local Area Network (WLAN), peers receiving different subsets of WWAN broadcast/multicast packets can perform Cooperative Peer-to-peer Repair (CPR) by exchanging received WWAN packets with their local WLAN peers. This effectively improves the transmission success from a WWAN broadcast/multicast source to a CPR collective.

In this paper, we propose a novel joint source/channel bit allocation scheme for WWAN scalable video multicast that leverages the CPR paradigm. One key observation is that given a peer can successfully receive a packet either from the WWAN channel directly, or via a CPR neighbor using ad-hoc WLAN connections, more bits can be redistributed from channel to source coding out of a fixed WWAN bit budget to further minimize individual node's expected visual distortion. In our proposal, groups of peers requiring different video resolutions are assigned to the same multicast group, and we perform one WWAN resource allocation and subsequent CPR over heterogeneous peers of different resolutions together. Our simulations show that our joint multicast group optimization can improve video quality by up to 2.84 dB, compared to a scheme where both WWAN resource allocation and WLAN CPR are separately performed for heterogeneous peers.

1. INTRODUCTION

Recent research on cooperative ad-hoc group of multi-homed devices [1, 2], each with multiple network interfaces like Wireless Wide Area Network (WWAN) and Wireless Local Area Network (WLAN), proved that useful transmission paradigms beyond traditional server-client model can be constructed. [1] showed that aggregation of an ad-hoc group's WWAN bandwidths can speed up individual peers' infrequent but bursty large content downloads. [2] showed that smart striping of FEC-protected (forward error correction) time-sensitive media packets across WWAN links can alleviate single-channel burst losses, while avoiding interleaving delay experienced in a typical single-channel FEC interleaver.

Cooperative Peer-to-peer Repair (CPR) is another new paradigm exploiting peers' multi-homing property, and has proven to be effective in improving video quality [3]. With CPR, multi-homed peers listening to the same WWAN video broadcast/multicast and connected to each other via ad-hoc WLAN exchange received WWAN packets locally via WLAN to repair WWAN losses. By imposing structures on network coding [3] (SNC), we have shown that performance can be further improved given limited WLAN resources.

Multi-homing property can also be exploited to optimize WWAN joint source/channel bit allocation. Due to the well-known NAK implosion problem [4], many video broadcast/multicast schemes over WWAN [5] have forgone feedback-based error recovery schemes and opted instead for FEC. While FEC helps receivers with channels as good as the targeted nth-percentile receiver's, receivers with worse-than-targeted channels suffer great losses. CPR alleviates the problem by providing *path diversity*: a WWAN multicast packet can be delivered to a peer either directly from WWAN source through a WWAN link, or indirectly via a WLAN neighbor through CPR. This means a WWAN packet is lost by a peer *only if* it is lost via WWAN links by all CPR peers, *or if* CPR fails during recovery—a much stronger loss condition than non-CPR-performing peers. WWAN source can hence optimize joint source/channel bit allocation for the peer collective by exploiting this stronger loss condition: expend more resource for source coding and less for channel coding [6], in order to minimize peer's expected distortion due to combination of source coding loss (quantization noise) and channel coding loss (packet loss induced distortion).

At the media processing layer, technology for scalable video [7]—single encoded bitstream where different subsets can be extracted for video playback at different bitrates and/or different temporal and spatial resolutions—has continued to mature, and the latest reincarnation in H.264 has received both academic and industrial attention. Our previous joint source/channel bit allocation work [6] has targeted a non-scalable, real-time video encoding scenario for homogeneous peers interested in the same video stream. In this paper, using H.264 SVC, we target instead streaming of pre-encoded scalable video for store-and-playback applications for heterogeneous peers interested in different resolutions of the video.

In particular, in this paper we propose a joint source/channel bit allocation scheme for WWAN scalable video multicast to a CPR collective of heterogeneous peers, where a scalable video is disseminated in the same WWAN channel to all peers requiring different resolutions, and subsequent CPR repairs are performed jointly for all peers. Though optimized scalable video streaming over lossy networks has a fairly long history [8], in our work we perform resource allocation for an *entire* collective of heterogeneous peers using scalable video, where we drop temporal frames and add NC-based FEC packets to each spatial layer optimally.

Given peers are interested in the same WWAN multicast video but require different spatial resolutions, one system optimization approach is to first assign peers requiring the same resolution to the same WWAN multicast channel and the same CPR repair group, and then extract the right subset from a scalably encoded bitstream corresponding to the desired resolution for distribution. While this approach is simple in system setup, it suffers from transmission contention from the peers and opportunities for collaboration among different CPR groups are wasted. Our simulations show that our joint multicast group optimization can improve video quality over this separate group approach by up to 2.84dB.

Our paper is organized as follows. Section 2 describes the video source and network models, and overviews the CPR framework. We discuss SNC optimization for WWAN video multicast in Section 3. We report simulation studies that verify the effectiveness of our framework in Section 4 and conclude in Section 5.

2. VIDEO MULTICAST SYSTEM AND COOPERATIVE PEER-TO-PEER REPAIR

We assume N peers are watching video multicast simultaneously. WWAN source prepares a scalable video bitstream *a priori* for later WWAN multicast, and different peers subscribe to different spatial resolutions of video due to device constraints. Devices are multi-homed and CPR enabled. They receive one Group of Pictures (GOP) of video through WWAN multicast in epoch of duration T, and then during the next epoch perform local CPR repair on that GOP via ad-hoc WLAN, while receiving the next GOP from WWAN multicast. Playback buffer delay is hence $2T$. Given this setup, the following questions must be addressed: 1) how should peers be organized into WWAN multicast channels for WWAN distribution and CPR groups for local repair? 2) how to perform joint WWAN source/channel bit allocation for given WWAN multicast and CPR group?

In this section, we present the video source model, network model, and previously proposed Structured Network Coding (SNC) framework, in which resource is allocated across scalable video layers to address the above two issues. We also briefly introduce WWAN-FEC and WLAN-CPR.

2.1. Video Source Model & Assumptions

We use H.264 SVC [7] for video encoding where *spatial* scalability is enabled. We assume two spatial layers: base layer L_0 and enhancement layer L_1. Base layer video is of QCIF resolution, and combining both layers can provide CIF resolution. Note that our model and subsequent optimization can be easily generalized to multiple spatial layers. A H.264 video stream is a series of GOPs. Each layer in a GOP is composed of a starting I-frame followed by $M-1$ P-frames. Within each spatial layer, the frames can be tail-dropped from the end of GOP, leading to fewer source coding bits selected. Layer L_i is encoded with source coding rates r_s^i, which is subsequently divided into $R_s^i = \left\lceil \frac{r_s^i}{S_{pkt}} \right\rceil$ packets for transmission, $\mathcal{P}_i = \{p_{i,1}, p_{i,2}, ..., p_{i,R_s^i}\}$. S_{pkt} is the maximum packet size.

2.2. Network Model & Assumptions

We assume peers listening to the same WWAN multicast channel experience different loss conditions, resulting in different subsets of received WWAN packets. For WLAN, though raw transmission rate like 802.11 is relatively large, peers need to contend for the shared medium. In this work, we rely on the underlying 802.11 MAC layer scheduling protocol to resolve potential contention. We assume that the MAC-layer will constantly scan for transmission opportunity, and define R_n as the average number of CPR packets that a peer n can receive in an epoch time T. The remaining question at the application layer—what CPR packet should peer n send to its neighbors when he detects a transmission opportunity (from the MAC layer)—is discussed in Section 2.4.2.

2.3. Structured Network Coding

We now overview SNC, using which WWAN-FEC and CPR repair packets are both generated. Consider first a peer n that is interested in CIF resolution, requiring both QCIF layer packets $\mathcal{P}_0$ and CIF layer packets $\mathcal{P}_1$ in a GOP for decoding. Rather than raw received packets from source, we have shown [3] that NC-encoding a repair packet, q_n, as a randomized linear combination of raw received *native* packets $\mathcal{G}_n$ from source and repair packets $\mathcal{Q}_n$ from neighbors, can improve packet recovery performance:

$$q_n = \sum_{p_{i,j} \in \mathcal{G}_n} a_{i,j} p_{i,j} + \sum_{q_m \in \mathcal{Q}_n} b_m q_m \quad (1)$$

where $a_{i,j}$'s and b_m's, random numbers in Galois Field $GF(O)$, are coefficients for the native packets and the received NC-coded CPR packets, respectively. We call this approach *Unstructured Network Coding* (UNC). The shortcoming of UNC is that if a peer receives fewer than $R_s^0 + R_s^1$ *innovative* packets (not a linear combination of previously received packets), then peer n cannot recover *any* native packets using the received NC packets.

To address UNC's shortcoming, we proposed SNC [3]. By imposing structure on the coefficients, we seek to partially decode at a peer when fewer than $R_s^0 + R_s^1$ innovative packets are received; in particular, if R_s^0 innovative packets are received, one can decode the GOP in QCIF and spatially upsample it to CIF for viewing.

Mathematically, we define two *SNC groups*, $\Theta_0 = \mathcal{P}_0$ and $\Theta_1 = \mathcal{P}_0 \cup \mathcal{P}_1$, where $\Theta_0 \subset \Theta_1$. Corresponding to each group Θ_x is a *SNC packet type* x. Let $g(j)$ be the index of the smallest group that includes spatial layer L_j. Peer n can now generate NC packet $q_n(x)$ of type x given $\mathcal{G}_n$ and $\mathcal{Q}_n$ as:

$$q_n(x) = \sum_{p_{i,j} \in \mathcal{G}_n} U(g(i) \leq x)\, a_{i,j} p_{i,j} + \sum_{q_m \in \mathcal{Q}_n} U(\Phi(q_m) \leq x)\, b_m q_m \quad (2)$$

where $\Phi(q_m)$ returns the SNC type of received CPR packet q_m, and $U(\mathtt{c})$ evaluates to 1 if clause $\mathtt{c}$ is true, and 0 otherwise. In words, peer n constructs NC packet of type x by linearly combining received or decoded native packets of frames in Θ_x and received NC packets of type $\leq x$. A peer can now decode QCIF layer when R_s^0 innovative packets of type 0 are received.

2.4. NC-based CPR and NC-based FEC

We use SNC for the dual purpose of WLAN-CPR packet recovery and WWAN-FEC protection. The process works as follows. WWAN source first appends NC-encoded FEC packets to the source packets. During subsequent local repair, peers treat the received FEC packets from source the same as repair packets received from other peers through CPR. The benefit of this dual usage of SNC is that a peer can construct and exchange CPR packets without first decoding WWAN-FEC, and peers receiving insufficient number of WWAN packets for WWAN-FEC decoding can still participate in CPR.

2.4.1. WWAN-FEC

WWAN source first determines the number of video frames (and corresponding packets) to be sent at each spatial layers: $\mathcal{P}_0$ and $\mathcal{P}_1$ for QCIF and CIF layers, respectively. For each SNC group Θ_x, appropriate number of SNC packets $q(x)$'s of type x are then generated using native packets $p_{i,j} \in \Theta_x$ as FEC for WWAN transmission:

$$q(x) = \sum_{p_{i,j} \in \Theta_x} c_{i,j} p_{i,j} \quad (3)$$

where $c_{i,j}$ are random coefficients. Note that WWAN-FEC packets are generated using only native packets in frame group Θ_x, all of which are available at the source. We denote R_c^i as the number of WWAN-FEC packets appended to layer i.

2.4.2. WLAN-CPR

When a peer detects a transmission opportunity (from the MAC layer) during CPR, he determines the SNC type x to construct a CPR packet $q_n(x)$ using (2) for local broadcast to his neighbors as follows. During the first γ_0 fraction of time T, peer n will choose SNC type 0, and after $\gamma_0 T$, peer n will choose SNC type 1. Note that unlike [3] which used randomization to select SNC types, the selection of SNC type here is deterministic, and we have shown experimentally that such deterministic selection outperformed randomization. Intuitively, deterministic method has the advantage that more important packets are sure to be repaired first.

3. OPTIMAL RESOURCE ALLOCATION FOR COOPERATIVE MULTICAST GROUP USING SVC

With the discussed models and network loss protection mechanism using network coding for both WWAN-FEC and WLAN-CPR, we now address the questions raised in Section 2. For group formation, we propose to use a *single* WWAN multicast channel and form a corresponding *single* WLAN CPR group for *all* heterogeneous peers requiring video of different resolutions. The reason is bandwidth efficiency for *both* WWAN multicast and CPR repair. For WWAN multicast, a single WWAN multicast channel would mean base layer L_0 is transmitted only once, while for CPR repair, a single repair group would mean a lost QCIF packet to a geographical region of peers is only repaired once.

Note that joint CPR means that QCIF peers must on occasion relay CIF packets for other CIF peers. We will show experimentally that the difference in quality for QCIF peers using joint CPR instead of separate CPR is negligible, and hence joint CPR group provides no disincentive for QCIF peers not to participate.

3.1. Optimization Objective

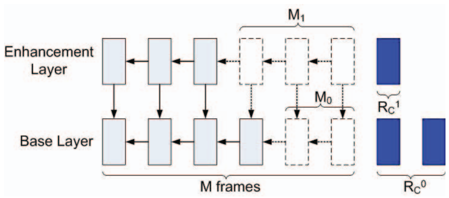


Fig. 1. Two Spatial Layers SVC with NC-FEC.

We assume that among N participating peers, N_0 (N_1) of them are subscribed to QCIF (CIF) video. Frame dependencies for two spatial layers are shown in Fig. 1. Among a total of M frames in a GOP, trailing M_0 (M_1) frames will not be transmitted for QCIF (CIF) resolution. Because of spatial dependency, we enforce requirement $M_0 \leq M_1$. For each layer FEC packets are appended by applying NC to the source packets that are selected for transmission. Given the WWAN transmission budget is fixed, selection of M_0 and M_1 directly influence the number of FEC packets that can be appended.

Given the structure above, the expected distortion for the QCIF video peer group is:

$$D^0 = D_{init} - \left(\sum_{i=1}^{M-M_0} d_i^0 \right) \alpha^0 \tag{4}$$

where D_{init} is the initial distortion before any frame (base or enhancement layer) is recovered. To enable direct performance comparison with CIF visual distortion, QCIF distortion is calculated as the reconstructed QCIF frames, up-sampled to CIF resolution, and compared to the original CIF video. d_i^0 is the video distortion reduction for each frame i at the base layer. α^0 is the probability that all source packets transmitted in layer L_0 (total $M - M_0$ frames) are recovered at a peer. Note that the frames in the base layer can be recovered either through NC-decoding of SNC group 0, i.e., base layer itself, or through NC-decoding of SNC group 1. α^0 is related to M_0, WWAN-FEC and WLAN-CPR packet recovery capabilities, which we will discuss in Section 3.2.

Similarly, the expected distortion for CIF video peer group is:

$$D^1 = D_{init} - \left(\sum_{i=1}^{M-M_0} d_i^0 \right) \alpha^0 - \left(\sum_{i=1}^{M-M_1} d_i^1 \right) \alpha^1 \tag{5}$$

where d_i^1 is the *additional* distortion reduction for frame i in the enhancement layer. It is generated by comparing the reconstructed CIF frame to the original CIF frame, *minus* d_i^0. Note that α^1 is related with both M_0, M_1, as well as the WWAN-CPR, WWAN-FEC recovery capabilities.

Combining (4), (5), we minimize the expected distortion for the two resolution groups as:

$$\min_{M_0, M_1, R_C^i, \Theta_x, \gamma_x} \left(\frac{N_0}{N_0 + N_1} \right) D^0 + \left(\frac{N_1}{N_0 + N_1} \right) D^1 \tag{6}$$

with total rate constraint as follows:

$$\sum_{i=1}^{M-M_0} \left\lceil \frac{r_s^{i,0}}{S_{pkt}} \right\rceil + \sum_{i=1}^{M-M_1} \left\lceil \frac{r_s^{i,1}}{S_{pkt}} \right\rceil + R_c^0 + R_c^1 \ \leq \ \bar{R} \tag{7}$$

3.2. SNC Group Recovery Probability

We first derive SNC group recovery probability α^0. Assuming that along with R_s^0 source packets there are R_c^0 WWAN-FEC packets, we first write probability $p_{grp}(R_s^0, R_c^0)$ that CPR *cannot* recover SNC group 0 by a peer as an expectation of a binomial, given independent and identically-distributed WWAN packet losses with probability l:

$$p_{grp}(R_s^0, R_c^0) = \sum_{i=R_c^0+1}^{R_s^0+R_c^0} \binom{R_s^0 + R_c^0}{i} l^i (1-l)^{R_s^0+R_c^0-i} p_{col}(i, R_c^0) \tag{8}$$

where $p_{col}(i, R_c^0)$ is the probability that the collective cannot recover sufficient number of packets given i packets were lost by a peer via WWAN transmission. $p_{col}(i, R_c^0)$ depends on $p_{isuf}(i, R_c^0)$, the probability that insufficient number of packets have been delivered via WWAN to the collective for CPR to operate at all:

$$p_{col}(i, R_c^0) = p_{isuf}(i, R_c^0) + \left[1 - p_{isuf}(i, R_c^0)\right] \left[1 - Q(i - R_c^0, 0, 0)\right] \tag{9}$$

Insufficient probability $p_{isuf}(i, R_c^0)$ is the probability that more than R_c^0 out of a total of $R_s^0 + R_c^0$ packets are lost to the collective, given i packets have been lost to a peer via WWAN already. It can be written as:

$$p_{isuf}(i, R_c^0) = \sum_{j=0}^{i-R_c^0-1} \binom{i}{j} (1 - l'_{col})^j (l'_{col})^{i-j} \tag{10}$$

where l'_{col} is the probability that a packet is lost to the collective given it has been lost to a peer already. If the losses among peers are not spatially correlated, then l'_{col} is simply a product of loss probabilities of other peers in the collective. If there is spatial correlation, then a correlation factor ρ can be introduced in the loss probability product as done in [6]. In words, (10) computes the probability that only j of the i WWAN lost packets by a peer are received by the collective for sufficiently small j.

$Q(\Omega, x_s, x_e)$ in (9) is the probability that CPR can NC-decode SNC group x_e given Ω lost packets occurred from SNC group x_s to x_e. It is written as:

$$Q(\Omega, x_s, x_e) = \frac{LP_R(x_s, \Omega)}{LP_A(x_s, \Omega)} \tag{11}$$

where $LP_A(x_s, \Omega)$ is the number of *all* possible packet loss patterns in SNC groups from x_s to x_e given Ω losses, and $LP_R(x_s, \Omega)$ is the number of loss patterns that are recoverable given R_n total CPR repair packets in an epoch and γ_0 fraction of repair packets of SNC type 0. Both $LP_A(x_s, \Omega)$ and $LP_R(x_s, \Omega)$ can be computed recursively and are not further elaborated here for brevity.

For two SNC groups, suppose first that R_s^0, R_s^1 are the source packets selected for the two SNC groups. Define $C_0(C_1)$ as the event that SNC group $0(1)$ is NC-decodeable. Define $B_0(B_1)$ as the event that source packets in layer $0(1)$ are recoverable (through NC-decoding of SNC group 0 or 1). Obviously $B_0 = C_0 \cup C_1$ and $B_1 = C_1$. We derive the probabilities of the events as follows:

$$\begin{aligned} Pr(\bar{B}_0) &= Pr(\bar{C}_0) Pr(\bar{C}_1 | \bar{C}_0) \\ &\approx p_{grp}(R_s^0, R_c^0) \times p_{grp}(R_s^0 + R_s^1 - 1, R_c^1 - 1) \end{aligned} \tag{12}$$

where "-1" accounts for the fact that given SNC group 0 cannot be recovered with their own WWAN-FEC packets, SNC group 1 must expend at least one WWAN-FEC packet to help SNC group 0.

$$Pr(\bar{B}_1) = Pr(\bar{B}_0) + (1 - Pr(\bar{B}_0))Pr(\bar{B}_1|B_0),$$
$$Pr(\bar{B}_1|B_0) = Pr(\bar{C}_1|C_0 \cup C_1) \approx p_{grp}(R_s^1, R_c^1)\frac{Pr(C_0)}{Pr(B_0)} \quad (13)$$

With the derivations above, we can now write $\alpha^0 = 1 - Pr(\bar{B}_0)$ and $\alpha^1 = 1 - Pr(\bar{B}_1)$.

3.3. Efficient Optimization

Eq. (6) involves the optimization of four sets of variables: number of dropping packets M_i's, NC groups Θ_x's, WWAN-FEC R_c^i's, and γ_x's. Exhaustively searching for the best solution has exponential complexity and is not scalable when spatial layers number increases. Hence we use the following method to solve the problem.

We iterate through all possible combinations of M_0 and M_1. For each combination, we first find R_s^i's, the number of packets in each layer given our video is pre-encoded. We then find the maximum number of FEC packets that can be generated for the whole video. With R_s^i's and the number of FEC packets, we allocate FEC packets and γ to each SNC group via local search, i.e., starting from equal allocation of resources to both SNC groups, we move resource from one SNC group to the other to reduce expected distortion. We continue until distortion cannot be further reduced. The resource allocation scheme that results in the most distortion reduction is returned.

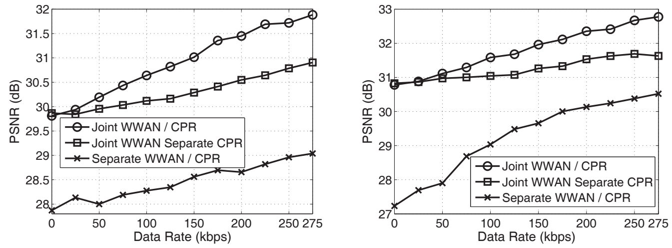
4. EXPERIMENTATION

Two test video sequences `city` and `foreman` were used for simulations with both QCIF (176 × 144) and CIF (352 × 288) resolutions. The GOP size was chosen at 15 frames: one I-frame followed by 14 P-frames, for both QCIF and CIF spatial layers.

We performed simulations using QualNet. The underlying CPR scheduling was 802.11 MAC with broadcast enabled. We set up a compact CPR network by uniformly placing 25 QCIF video peers and 25 CIF video peers in a $200 \times 200m^2$ area and the WLAN transmission range was set to 280m so that each transmission could reach all other peers. Given one GOP was 15 frames and video was encoded at 15 fps, repair epoch T was 1s.

We compared the performance of our proposed single WWAN multicast channel/single CPR collective scheme with two other schemes which we call `joint-WWAN` and `separate-WWAN`. In both of these two alternate schemes, we assumed peers subscribed to different video resolutions were in different CPR groups. In `joint-WWAN`, there was only one multicast channel and all WWAN transmission budget was optimized for the CIF video group; the QCIF video group extracted the base layer from the CIF video distribution. In `separate-WWAN`, there were two multicast channels that were completely separated and the WWAN transmission budget was shared between the two channels. For both `joint-WWAN` and `separate-WWAN`, since peers in different resolution groups were in different CPR groups, each CPR group will not help the other group to repair packets.

Performance of the three schemes in average PSNR for all peers as a function of the available WLAN-CPR repair bandwidth is shown in Fig. 2 for the two test sequences. We see that the top two curves of Fig. 2a are far above the bottom curve. This is because the resource allocation for `separate-WWAN` is distinct for the two multicast channels, and the WWAN transmission budget was wasted due to redundant transmission of QCIF layer, resulting in poor performance. Our proposed scheme is better than `joint-WWAN` due to repair cooperation between the two resolution groups. At its maximum we observed 0.98dB improvement over `joint-WWAN` and



a) `City` b) `Foreman`

Fig. 2. Joint WWAN-CPR optimization versus joint WWAN separate CPR, and separate WWAN-CPR optimizations.

2.84dB improvement over `separate-WWAN`. In Fig. 2b, we observed similar trend for the `foreman` sequence, and the PSNR improvements were 1.14dB and 2.25dB, comparing to `joint-WWAN` and `separate-WWAN`, respectively.

For QCIF peers only, we observe a marginal average PSNR loss of 0.1dB over `joint-WWAN` and a gain of 0.74dB over `separate-WWAN` for the `city` sequence, and loss of 0.14dB over `joint-WWAN` and a gain of 0.06dB `separate-WWAN` for the `foreman` sequence. Given the difference in quality between our scheme and `joint-WWAN` is negligible for the QCIF peers, and given the large improvement for the CIF peers, there is global incentive for QCIF peers to relay CIF packets for CIF peers in our proposed single multicast / single CPR scheme.

5. CONCLUSION

In this paper, we propose an optimal resource allocation scheme of WWAN scalable video multicast to CPR collectives. In our scheme, peers belonging to different resolution groups are optimized jointly to take advantage of the collaboration between CPR groups. We show through simulations that our joint optimization can improve video quality by 2.84 dB comparing to a scheme where both WWAN and WLAN CPR are separately performed for heterogeneous peers.

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