Joint Source/Channel Coding of WWAN Multicast Video for A Cooperative Peer-to-Peer Collective using Structured Network Coding

Xin Liu #1, Gene Cheung *2, Chen-Nee Chuah #3

Electrical & Computer Engineering, University of California, Davis
Kemper Hall, Davis, CA 95616-5294, USA
1 `xyzliu@ucdavis.edu`
3 `chuah@ucdavis.edu`

* *Hewlett-Packard Laboratories Japan*
3-8-13, Takaido-higashi, Suginami-ku, Tokyo 168-0072, Japan
2 `gene-cs.cheung@hp.com`

***Abstract*—Because of frequent wireless packet losses and inapplicability of retransmission-based schemes due to the well-known NAK implosion problem, providing high quality video multicast over Wireless Wide Area Networks (WWAN) remains difficult. Traditional joint source/channel coding schemes for video multicast—optimal bit allocation among source coding and channel coding such as Forward Error Correction (FEC) subject to a bitrate constraint—target a chosen nth-percentile WWAN user. Not only is FEC bitwise expensive, users with poorer reception than nth-percentile user suffer substantial channel losses, while users with better reception have more channel coding than necessary, meaning too few bits are devoted for source coding to reduce quantization noise and sub-optimal video quality.**

Instead, in this paper we perform joint source/channel coding of WWAN video multicast for an entire collective of multi-homed ad-hoc peers in the same multicast group and connected via Wireless Local Area Networks (WLAN). In a cooperative peer-to-peer repair (CPR) scenario, after each peer received a different subset of WWAN packets, the peer group repairs WWAN losses locally by packet-forwarding to each other via WLAN. From an end-to-end system view, CPR means that a packet can be transmitted from source to a peer either via WWAN directly, or via WLAN local repairs exploiting neighboring peers' WWAN links; the overall more general transmission condition means a clever joint source/channel coding scheme can now allocate more bits to source coding without suffering more packet losses, leading to higher video quality. To efficiently implement both WWAN FEC and WLAN CPR repairs, we propose to use network coding for this dual purpose to reduce decoding complexity at the peers. We show through simulations that using our proposed scheme dramatically improves video quality over existing optimization scheme where joint source/channel coding was performed, but WLAN CPR was not used, by up to 8.4 dB, and over scheme when WLAN CPR and WWAN joint source/channel coding were performed separately by up to 4.4 dB.

I. INTRODUCTION

Providing sustained, high quality video multicast over Wireless Wide Area Networks (WWAN) over multicast channels like Multimedia Broadcast/Multicast Service (MBMS) in 3G networks [1] remains challenging because of two technical difficulties: i) unavoidable packet losses due to temporary wireless link failures; and ii) unlike unicast, automatic retransmission request for link losses cannot be implemented per packet and per receiver due to the well-known NAK implosion problem [2]. Given a large receiver group with a range of channel conditions, previous works like [3] have allocated channel coding bits from a fixed transmission budget for forward error correction (FEC) to protect source packets from WWAN losses, targeting a chosen nth-percentile receiver[1]. Not only is channel coding bitwise expensive, receivers with channels worse than nth-percentile receiver's (poor receivers) suffer substantial losses, while receivers with better channels (rich receivers) have more channel coding than necessary, i.e., not enough bits are devoted to source coding to reduce quantization noise, resulting in sub-optimal video quality.

To improve video quality for poor receivers, we have previously proposed a new packet-recovery paradigm for receivers in the same video multicast group with multi-homed capability—ones with both WWAN and WLAN (Wireless Local Area Network) network interfaces —called *Cooperative Peer-to-peer Repair* (CPR) [4]. The idea is simple: after receiving different subsets of packets from WWAN source, receiver group forms an ad-hoc peer-to-peer network called a *CPR collective* and cooperatively exchange received packets via WLAN. The incentive for a peer to participate in CPR is an increase in streaming video quality in return. We have also shown that by first encoding received WWAN packets into coded packets [5] using network coding (NC) before CPR exchange, further gain in packet recovery can be observed.

From an end-to-end system view, CPR presents a new and more general packet transmission condition than previous point-to-multipoint WWAN systems: a packet can be transmitted from source to a receiver either via a WWAN link directly, or indirectly via CPR repair routed through a neighboring peer's WWAN link. Under this CPR paradigm, a transmitting WWAN source optimizing joint source/channel coding (JSCC) for the whole collective can now exploit this more general transmission condition in two ways. First, the source no longer needs to expend substantial channel coding

MMSP'09, October 5-7, 2009, Rio de Janeiro, Brazil.
978-1-4244-4464-9/09/$25.00 ©2009 IEEE.

---

[1] 50th-percentile is the average receiver, and 0th-percentile is the worst receiver.

for targeted n-percentile receiver, who can now depend on rich receivers' WWAN channels and subsequent CPR for reliable transmissions—we call this the *disparity gain*. Second, even if all receivers experience similar WWAN channels, i.e., there is no differentiation between poor and rich receivers, a packet is lost to the collective *only if* WWAN transmissions to all peers in the entire collective fail. The source can also exploit this multiplier effect to allocate more bits to source coding without incurring more losses—we call this the *ensemble gain*.

To efficiently implement WWAN-FEC and WLAN-CPR, we propose to use NC for the dual purpose. Our proposal has two advantages: i) a WWAN receiver can encode and forward received WWAN packets without first decoding WWAN-FEC, so that peers receiving insufficient number of WWAN packets for WWAN-FEC decoding can still participate in CPR right away; and ii) WWAN-FEC decoding and WLAN-CPR decoding can be done at the same time, reducing decoding complexity. In summary, our contributions are summarized below:

- Instead of targeting an *n*th-percentile receiver, we propose a WWAN JSCC framework targeting the entire CPR collective to exploit both ensemble and disparity gain.
- We propose to use network coding for both WWAN-FEC and WLAN-CPR to achieve end-to-end optimality.
- We propose a fast iterative algorithm to solve the complex multi-parameter optimization problem.
- We show through simulations that our JSCC improves over a previous scheme by up to 8.4 dB where JSCC is performed but CPR is not used, and up to 4.4 dB when CPR is used but WWAN JSCC is optimized separately.

The outline of the paper is as follows. In Section II, we review related works and clarify our contributions comparing to our previous works. We then overview CPR in Section III and discuss system model in Section IV. We present our JSCC optimization for a CPR collective in Section V. Simulation results and conclusions are presented in Section VI and VII.

II. Related Work

Due to the well-known NAK implosion problem [2], many video broadcast/multicast schemes over MBMS [3] 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, receivers with worse-than-targeted channels suffer great losses.

Recent research on ad-hoc group of multi-homed devices [6], [7] proved useful transmission paradigms beyond traditional server-client model can be constructed. [6] showed that aggregation of an ad-hoc group's WWAN bandwidths can speed up individual peer's infrequent but bursty large content download. [7] showed that smart striping of FEC-protected delay-constrained media packets across WWAN links can alleviate single-channel burst losses, while avoiding interleaving delay experienced in a typical single-channel FEC interleaver. [8] extends this research line on ad-hoc multi-homed peers to local recovery of WWAN multicast packets.

In essence, CPR exploits disparity gain in a heterogeneous collective by redistributing received WWAN broadcast/multicast packets from rich receivers to poor receivers via WLAN. ([9] proposed similar scheme recovering WWAN broadcast/multicast losses, though our first work [4] predates theirs.) We have also designed structure on network coding [8] for a group of video pictures (GOP) to optimize video quality in a rate-distortion optimal manner given limited WLAN resources. Our current work differs in that we focus on the optimization combining WWAN JSCC and WLAN CPR, exploiting both disparity and ensemble gain made available from the CPR paradigm to achieve end-to-end optimality, while our previous works focused only on the local CPR side.

Network Coding (NC) has been a popular research area since Ahlswede's seminal work [10]. [11] has shown generally that structures can be imposed in NC to induce partial decoding, and recent works [12], [13] have optimized NC structures for video streaming in different settings. While our structured network coding work [8] also performed rate-distortion optimized streaming, application of NC in the context of CPR, including a clever use of randomization when a peer selects a NC group to code and transmit a packet in a distributed manner, is novel. Moreover, our proposal to use NC for the dual purpose of both WWAN-FEC and WLAN-CPR is new.

III. Cooperative Peer-to-peer Repair

To motivate our JSCC optimization, we overview CPR in this section. We first discuss source and network models. We then discuss two types of NC peers can use to encode WWAN packets: traditional *unstructured networking coding* (UNC) and our proposed *structured network coding* (SNC).

A. Video Source Model & Assumptions

We use H.264 codec for video encoding. A H.264 video stream is a series of GOP, each composed of a starting I-frame followed by $M-1$ P-frames. CPR repairs one GOP at a time: after a media source transmits a GOP of M frames via WWAN in time duration Y (one *epoch*), peers exchange CPR packets via WLAN to repair this GOP in time Y during WWAN multicast of the next GOP. The initial playback buffer delay is thus two epochs, which usually is only several seconds.

Each P-frame F_i uses its previous frame F_{i-1} for motion compensation, and the GOP forms a dependency chain. We assume that a frame F_i is correctly decoded if it is correctly received, and the frame it referenced F_{i-1} is correctly decoded. Each video frame F_i is encoded from original picture F_i^o with source coding rate r_s^i. r_s^i is subsequently divided into $R_s^i = \left\lceil \frac{r_s^i}{S_{pkt}} \right\rceil$ packets, $\mathcal{P}_i = \{p_{i,1}, p_{i,2}, ..., p_{i,R_s^i}\}$, for transmission, where S_{pkt} is the packet size. If F_i is correctly decoded, the resulting *distortion reduction* is d_i.

B. Network Model & Assumptions

We assume a set $\mathcal{N}$ of peers of size N watch the same video multicast using their multi-homed devices. For WWAN, we assume peers in the same multicast group experience different channel 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 a distributed manner so that the occurrences of collision and interference are reduced. For brevity, we omit the discussion on a distributed algorithm [5] that schedules peer transmissions. We assume a peer can receive B repair packets successfully via WLAN-CPR in an epoch, which varies depending on available WLAN resources for CPR.

C. *Unstructured and Structured Network Coding based CPR*

At a given WLAN-CPR transmission opportunity, what packet should a peer broadcast locally to its neighbors via WLAN? We have proposed to encode received WWAN packets using NC before performing CPR exchange [5]. Given M frames in a GOP, $\mathcal{F} = \{F_1, \ldots, F_M\}$, we first denote $\mathcal{P}^*$ as the set of *native packets* in the GOP, i.e., $\mathcal{P}^* = \{\mathcal{P}_1, \ldots, \mathcal{P}_M\}$.

We denote $\mathcal{G}_n \subseteq \mathcal{P}^*$ as the subset of native packets peer n received via WWAN multicast from media source, and $\mathcal{Q}_n$ as the NC packets peer n received via WLAN from peers. Peer n can then compute a UNC packet q_n for WLAN-CPR exchange using $\mathcal{G}_n$ and $\mathcal{Q}_n$ as follows:

$$q_n = \sum_{p_{i,j} \in \mathcal{G}_n} a_{i,j} p_{i,j} + \sum_{q_m \in \mathcal{Q}_n} b_m q_m = \sum_{p_{i,j} \in \mathcal{P}^*} c_{i,j} p_{i,j}, \qquad (1)$$

where $a_{i,j}$'s and b_m's, random numbers in Galois Field $GF(O)$, are coefficients for the original packets and the received encoded NC packets, respectively. As shown in Eq. (1), q_n can be rewritten as a linear combination of only native packets using *native coefficient vector* $\mathbf{v} = [c_{1,1}, \ldots, c_{1,R_s^1}, \ldots, c_{M,1}, \ldots, c_{M,R_s^M}]$.

The shortcoming of UNC is that if a peer n receives fewer than P *innovative* (native coefficient vector of a packet is not a linear combination of native coefficient vectors of other packets) packets, then this peer cannot recover *any* native packets using the received NC packets.

To address UNC's shortcoming, we have proposed SNC [8]. By imposing structure in the coefficient vector, we seek to partially decode at a peer even when fewer than P innovative native or NC packets are received. Specifically, we define a series of X *SNC frame groups*, $\Theta_1, \ldots, \Theta_X$, where $\Theta_1 \subset \ldots \subset \Theta_X = \mathcal{F}$. Θ_1 is the most important frame group, followed by Θ_2, etc. Corresponding to each SNC frame group Θ_x is a *SNC packet type* x. Let $g(j)$ be index of the smallest frame group that includes frame F_j. The NC packet $q_n(x)$ of type x given peer's set of received or decoded native packets $\mathcal{G}_n$ and set of received NC packets $\mathcal{Q}_n$ can now be written as:

$$\begin{aligned} q_n(x) \;&=\; \sum_{p_{i,j} \in \mathcal{G}_n} U(g(i) \leq x)\; a_{i,j} p_{i,j} \qquad (2) \\ &+ \sum_{q_m \in \mathcal{Q}_n} U(\Phi(q_m) \leq x)\; b_m q_m = \sum_{p_{i,j} \in \Theta_x} c_{i,j} p_{i,j}, \end{aligned}$$

where $\Phi(q_m)$ returns the SNC type of packet q_m, and $U(\mathsf{c})$ evaluates to 1 if clause c is true, and 0 otherwise. In words, peer n constructs NC packet of SNC type x by linearly combining received or decoded native packets of frames in Θ_x and received NC packets of SNC type $\leq x$. We write the probability that fewer than m NC packets of group $\leq x$ can be delivered in a CPR epoch as:

$$Q(m,x) \approx \sum_{k=0}^{m-1} \binom{B}{k} \left(\sum_{i=1}^{x} \beta(i) \right)^{k} \left(\sum_{i=x+1}^{X} \beta(i) \right)^{B-k} \qquad (3)$$

Eq. (3) is the summation of a binomial random variable with probability of occurrence $\sum_{i=1}^{x} \beta(i)$ from 0 to $m-1$, given B trials. Because of the superiority of SNC over UNC, our optimization will be built on SNC, as shown in Section V.

IV. VIDEO MULTICAST SYSTEM OVERVIEW

Given the existence of a CPR collective, we show how NC-based FEC can be added for WWAN transmission to protect video packets end-to-end in combination with WLAN-CPR.

A. *Network Coding based WWAN-FEC*

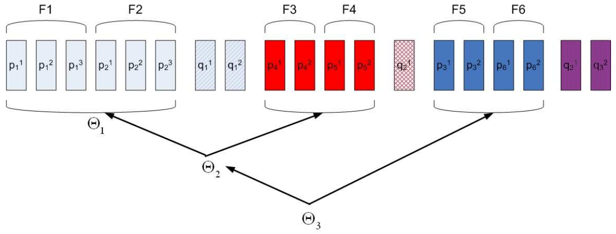

Fig. 1. An example NC-FEC GOP with three frame groups.

We use NC for the dual purpose of WWAN-FEC loss protection and WLAN-CPR packet recovery as follows. First, media source generates FEC packets $q(x)$'s for each defined SNC frame group Θ_x as follows:

$$q(x) = \sum_{p_{i,j} \in \mathcal{P}_i, F_i \in \Theta_x} c_{i,j} p_{i,j}. \qquad (4)$$

Note FEC packets are generated using only native packets in frame group Θ_x, all of which are available at the source. We define *segment* s_x as the set of frames in frame group Θ_x but not Θ_{x-1}, i.e., $F_i \in \Theta_x \setminus \Theta_{x-1}$. As an example, Fig. 1 shows an NC-FEC encoded GOP with three frame groups.

The WWAN-FEC packets are sent along with source packets via WWAN multicast to peers. Because WWAN-FEC are encoded using the same SNC, to a receiving peer, received WWAN-FEC packets are no different from WLAN-CPR packets. In so doing, a peer can construct and exchange CPR packets without first decoding WWAN-FEC, so that peers receiving insufficient number of WWAN packets for WWAN-FEC decoding can still participate and contribute to CPR.

B. *WWAN Collective Packet Loss Model*

The working assumption for CPR is that a source packet is received by at least one peer in the collective via WWAN multicast for CPR recovery to function. This is valid when WWAN JSCC is optimized for the nth-percentile receiver; rich receiver with better channel statistics will correctly receive packets with high probability. However, as we allocate more bits to source coding out of a fixed budget to exploit disparity and ensemble gain, *WWAN collective packet loss probability*—the likelihood that a packet is lost to the entire collective, becomes larger and must be modeled carefully.

If packet losses are spatially uncorrelated, the collective packet loss probability is simply the product of individual peer loss rate. Due to shadow effect and signal strength attenuation with respect to distance, peers with similar physical locations may experience spatially correlated WWAN losses. We introduce ρ as the *spatial correlation factor* which captures this effect. $\rho = 0$ $(= 1)$ implies fully spatially correlated (uncorrelated) packet loss. The *conditional WWAN collective packet loss probability*, l'_{col}, given a targeted peer n has lost the packet, can now be written as:

$$l'_{col} \approx \prod_{m \in \mathcal{N} \setminus n} (l_m)^{\rho} \approx (l_{avg})^{\rho(N-1)}, \tag{5}$$

where l_m is the individual loss rate for peer m. In the absence of per peer channel statistics, source can instead use l_{avg}, the average packet loss rate as the loss rate for all the users. In practice l_m's are difficult to obtain, and hence we will use l_{avg} for the rest of the paper.

V. JSCC FOR A CPR COLLECTIVE USING SNC

We introduce our JSCC optimization for a CPR collective in this section. Beyond searching for the best resource allocation for WWAN source and channel coding, we need to consider jointly the SNC optimization. We first introduce the optimization objective, derive the optimization formulation and then provide a fast JSCC optimization algorithm.

A. Optimization Objective

The expected distortion D_{S+C} in one GOP for a CPR collective, assuming X frame groups Θ_x's, can be written as:

$$D_{S+C} = D - \sum_{x=1}^{X} \left(\sum_{j \in s_x} d_j(r_s^j, r_s^{j-1}) \right) \alpha(x), \tag{6}$$

where D is the distortion of the GOP if no packets are received at a peer, $d_i(r_s^i, r_s^{i-1})$ is the distortion reduction for F_i given F_i and previous frame F_{i-1} are encoded with rates r_s^i and r_s^{i-1}, and $\alpha(x)$ is segment s_x recovery probability. $\sum_{j \in s_x} d_j(r_s^j, r_s^{j-1})$ is the distortion reduction for segment s_x.

Our objective is to minimize the expected distortion:

$$\min_{r_s^i, R_c^i, \Theta_x, \beta(x)} D_{S+C}, \tag{7}$$

with WWAN transmission constraint:

$$\sum_{i=1}^{M} \left\lceil \frac{r_s^i}{S_{pkt}} \right\rceil + \sum_{i=1}^{M} R_c^i \le \bar{R}, \tag{8}$$

where $\sum_{i=1}^{M} R_c^i$ is the total number of WWAN-FEC packets and $\bar{R}$ is the WWAN packet budget available for a GOP. We assume $\bar{R}$ is fixed, while l_{avg} varies from GOP to GOP.

B. Optimization Formulations

We derive the segment recovery probability $\alpha(x)$ as follows. We first define the following events:

- C_x: NC frame group Θ_x is *recoverable*.
- B_x: frames in segment s_x is *correctly decodeable*. $B_x = C_x \cup C_{x+1} \cup \ldots \cup\ C_X$.

With the two events, we can express the probability that frames in segment s_1 are not decodeable as:

$$\begin{aligned} Pr(\bar{B}_1) &= Pr(\bar{C}_1 \cap \bar{C}_2 \cap ... \cap \bar{C}_X) \\ &= Pr(\bar{C}_1) Pr(\bar{C}_2 | \bar{C}_1) ... Pr(\bar{C}_X | \bar{C}_{X-1}, ..., \bar{C}_1). \end{aligned} \tag{9}$$

Each of the product terms in Eq. (9) can be obtained as:

$$Pr(\bar{C}_y | \bar{C}_{y-1}, ..., \bar{C}_1) \approx p_{grp}(\sum_{i=1}^{y} R_s^i - 1, R_c^y - 1, y), \tag{10}$$

where $p_{grp}(R_s - 1, R_c - 1, y)$ is the *group loss probability* for NC group y, if $R_s - 1$ source and $R_c - 1$ WWAN-FEC packets were used. The ”-1” means at least one WWAN-FEC packet of frame group y must be used to repair the lost packets in previous frame groups, given there are packet loss in previous frame groups already. In words, Eq. (10) says that given the previous frame groups $\Theta_i, 1 \le i \le y-1$, are not recovered, the probability that the current frame group Θ_y cannot be recovered is roughly the probability that all $\sum_{i=1}^{y} R_s^i$ source packets cannot be recovered given R_c^y WWAN-FEC packets.

Group loss probability $p_{grp}(R_s, R_c, y)$ is the probability that more than R_c packets are lost in WWAN, *and* CPR cannot recover enough of those losses for full recovery:

$$\begin{aligned} p_{grp}(R_s, R_c, y) &= \sum_{i=R_c+1}^{R_s+R_c} \binom{R_s + R_c}{i} l_{avg}^i (1 - l_{avg})^{R_s + R_c - i} \\ &\quad * p_{col}(i, R_c, y), \end{aligned} \tag{11}$$

where $p_{col}(i, R_c, y)$ is the *collective loss probability*—the probability that the CPR collective cannot recover sufficient number of packets for group y's recovery given i packets were lost by the collective on average, which can be represented as:

$$p_{col}(i, R_c, y) = p_{isuf}(i, R_c) + (1 - p_{isuf}(i, R_c))\, Q(i - R_c, y). \tag{12}$$

If the CPR collective has sufficient number of packets for CPR with probability $1 - p_{isuf}(i, R_c)$, then CPR is functional and the peer suffers losses only when CPR fails. The collective insufficient probability, $p_{isuf}(i, R_c)$, can be written as:

$$p_{isuf}(i, R_c) = \sum_{j=0}^{i-R_c-1} \binom{i}{j} (1 - l'_{col})^j (l'_{col})^{i-j}. \tag{13}$$

Eq. (13) says among the i lost packets by the peer, only j packets are received through the collective and the rest are also lost by the collective. Hence there is no way that the peer can recover the whole packet group.

Using $Pr(\bar{B}_1)$, we can express $Pr(\bar{B}_2)$ as:

$$Pr(\bar{B}_2) = Pr(\bar{B}_1) + [1 - Pr(\bar{B}_1)] Pr(\bar{B}_2 | B_1). \tag{14}$$

In words, frames in segment s_2 cannot be decoded if frames in s_1 are not decodeable. $Pr(\bar{B}_2 | B_1)$ can be written as:

$$\begin{aligned} & Pr(\bar{C}_2 \cap \bar{C}_3 \cap ... \cap \bar{C}_X | B_1) \\ = \;& Pr(\bar{C}_2 | B_1) Pr(\bar{C}_3 | \bar{C}_2, B_1) \ldots Pr(\bar{C}_X | \bar{C}_{X-1} \ldots \bar{C}_2, B_1), \end{aligned}$$

where:

$$\begin{aligned} Pr(\bar{C}_2 | B_1) &\approx p_{grp}(R_s^2, R_c^2, 2) \frac{Pr(C_1)}{Pr(B_1)} \\ Pr(\bar{C}_y | \bar{C}_{y-1}, ..., \bar{C}_2, B_1) &\approx p_{grp}(\sum_{i=2}^{y} R_s^i - 1, R_c^y - 1, y). \end{aligned}$$

In words, given segment s_1 is decodeable, R_c^2 WWAN-FEC packets can be used to protect R_s^2 source packets only. See [14] for a derivation of scaling factor $\frac{Pr(C_1)}{Pr(B_1)}$.

By calculating $Pr(\bar{B}_i)$ iteratively from segment s_1 to s_X, we find all the segment irrecoverable probabilities where $\alpha(x) = 1 - Pr(\bar{B}_x)$.

C. Fast JSCC Optimization

Eq. (7) involves the optimization of four sets of variables: source coding rates r_s^i's, NC groups Θ_x's, WWAN-FEC R_c^i's, and $\beta(x)$'s. Exhaustively searching for the best combination has exponential complexity and is not practical. Hence we propose to use an iterative algorithm to optimize source/channel coding and SNC structure in turn separately.

We first initialize the total number of WWAN-FEC packets to be T. Given T and an initial segment recovery probability α's, we find the optimal source bit allocation r_s^i's. Then given source bit allocation r_s^i's, we find the optimal SNC frame groups Θ_x's and corresponding probabilities $\beta(x)$'s. We iterate until we converge to a solution. We perform this for all feasible values of T to find the best solution.

1) Source Bit Allocation: To obtain optimal source bit allocation given total available resource R_S^{budget}, we use a well-known heuristic algorithm in [15]. The crux of the algorithm is as follows. First, build a M-stage dependency trellis from left to right where a stage corresponds to a frame. Each stage has multiple states corresponding to possible quantization levels. Then, starting from the first stage, iteratively trace all feasible paths from all possible states from one stage to all possible states in the neighboring stage, calculate the corresponding Lagrangian costs for the paths along the way. Finally, identify the path in the trellis that yields the minimum Lagrangian cost; the optimal quantization levels of frames correspond to the states of stages in the optimal path.

2) SNC Optimization: Given r_s^i's returned from source bit allocation, we obtain the distortion reduction d_i's for each frame F_i. Then, our SNC optimization algorithm finds the best SNC structure Θ_x's, peers' NC group selection probabilities $\beta(x)$'s, and the WWAN-FEC packet allocation R_c^i's. We observe the following: because a GOP is a dependency chain, a frame is of greater importance than its descendant frames, and frame F_i should not be allocated more resource than frame F_j, $j < i$. This implies that a parent frame should not be assigned a NC type larger than its children frames. which motivate our design of a fast optimization scheme summarized as follows.

To find the best NC structure, we start by assigning M NC types to the M frames. Then we iteratively find the best "merging" of neighboring frames, i.e., assign the same NC type to the merged group. To obtain R_c^i allocation, we divide T by two and then assign half of T to the first group and the rest half evenly allocated to the other frames. We increase the number of frame groups to use the first half of T until the second implication is violated. β_x is obtained similarly. Due to space constraint, we refer readers to [14] for details.

VI. EXPERIMENTATION

In this section, we verify the effectiveness of our JSCC optimization for a CPR collective. We first discuss simulation setup. Next we compare our system performance with previous JSCC schemes under various network settings.

A. Simulation Setup

Two test video sequences were used for simulations: 300-frame MPEG class A `news` and class B `foreman` sequences at CIF resolution (352×288), at 30 fps and sub-sampled in time by 2. The GOP size was chosen at 15 frames: one I-frame followed by 14 P-frames.

We considered a CPR network of size 500×500 m^2 where peers were uniformly distributed. All the peers used the broadcast mode of WLAN. Given one GOP was 15 frames and video was encoded at 15 fps, one epoch time Y was 1s. Maximum packet size was set to 1000 bytes. We assume the MBMS multicast transmission budget is 220 kbps.

We explored two WWAN packet loss models: Homogeneous (`HM`) and Heterogeneous (`HT`) loss. In `HM`, the WWAN packet loss was iid and all peers have the same loss rate 0.3. In `HT`, peers within the $\frac{500}{\sqrt{2}} \times \frac{500}{\sqrt{2}} m^2$ square had HM loss with loss rate 0.15, while peers outside of the square had HM loss with loss rate 0.45, which captured the spatial packet loss. The overall average packet loss rate, however, remains 0.3. We assume WWAN losses among peers are not spatially correlated [16], and spatial correlation factor ρ is 1. We used QualNet [17] for simulations. To have the freedom to vary CPR bandwidth to reflect different WLAN resources for CPR under different network settings, we selected Abstract PHY in QualNet and used 802.11 MAC layer.

B. Simulation Results

We compared resulting visual quality (PSNR) when the JSCC was optimized for the whole collective and for the disparate average peer. Note for the latter case, we still performed CPR to assist poor receivers recover lost WWAN packets. We also compared performance of traditional system optimization scheme where JSCC was optimized for the average peer and CPR was disabled. Note that we did not include tranditional FEC scheme comparison due to the following reasons: 1) NC is a perfect code and can be no worse than other FEC schemes in terms of packet recovery; 2) in terms of overall decoding complexity, using NC for both WWAN and WLAN removes the need to decode before performing local repair.

The top graph of Fig. 2 shows the video quality for the `foreman` sequence with `HM` packet loss model and CPR data rates ranged from 0 to 1000 kbps. When the system was optimized for the collective, we see that with the increase of CPR data rate, video quality was greatly improved. This was in sharp contrast to the system optimized for the disparate average peer, where CPR was only helpful at the beginning. This is due to the fact that when the system was optimized for the disparate average peer, the WWAN loss rate was fixed, which resulted in a limited maximum PSNR achieved. On the other hand, our proposed JSCC optimization can still exploit

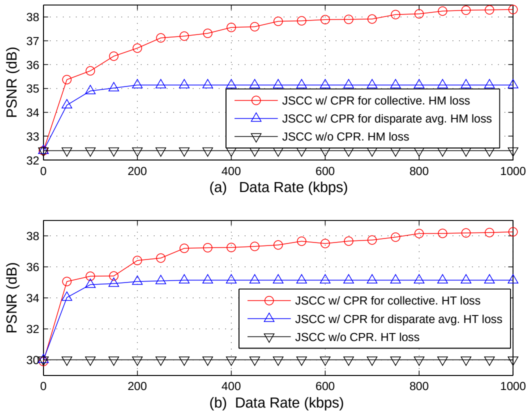

Fig. 2. Performance comparison between optimization for the collective and for the disparate average peers. `foreman` sequence.

the *ensemble* gain in `HM` for better video quality. The maximum gain was 3.2 dB when the data rate was 1000 kbps.

The bottom graph of Fig. 2 shows the video quality for `foreman` with `HT` packet loss model. We observe that optimizing for the collective brought similar trend of performance improvement. However, when the system was optimized for the disparate average peers, we see a gradual video quality improvement and the improvement was larger compared to the case of `HM`. This is due to the fact that CPR can now exploit *disparity* gain unattainable before in HM. By disabling CPR, in both the plots in Fig. 2, we have the performance of the system under traditional average-peer optimization criterion. Our scheme outperformed traditional scheme by 5.9 dB for `HM`, and by 8.4 dB for `HT`.

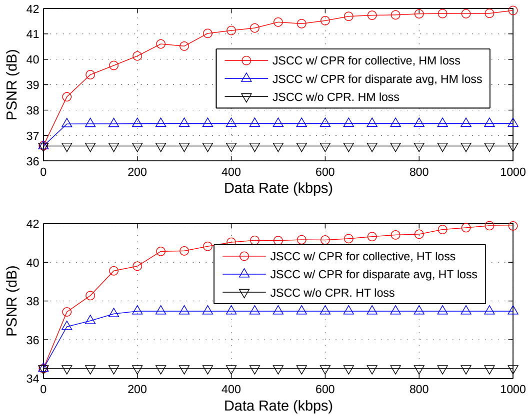

Fig. 3. Performance comparison between optimization for the collective and for the disparate average peers. `news` sequence.

We saw similar performance trends for the `news` sequence in Fig. 3. We obtained 5.3 dB and 7.4 dB improvements over traditional scheme under `HM` and `HT` models, respectively. Comparing to JSCC scheme optimized for disparate average user with CPR, we obtained 4.4 dB performance improvement under both `HM` and `HT` models.

VII. CONCLUSION

In this paper, we optimize joint source/channel coding (JSCC) for a CPR collective for WWAN video multicast and achieve significant performance gain over traditional system optimization schemes. Specifically, we devote more bits to source coding out of a fixed WWAN budget without an increase in channel losses by exploiting the strength of CPR. Simulations showed that our joint source/channel coding optimization scheme outperformed a previous scheme by up to 8.4 dB where JSCC is performed but CPR is not used, and up to 4.4 dB when CPR is used but JSCC is optimized separately.

REFERENCES

[1] *Technical Specification Group Services and System Aspects; Multimedia Broadcast/Multicast Service (MBMS) user services; stage 1 (Release 6) (3GPP TS.26.246 version 6.3.0*, March 2006.

[2] J. Crowcroft and K. Paliwoda, “A multicast transport protocol,” in *ACM SIGCOMM*, New York, NY, August 1988.

[3] J. Zfzal, T. Stockhammer, T. Gasiba, and W. Xu, “Video streaming over mbms: A system design approach,” in *Journal of Multimedia*, vol. 1, no.5, August 2006, pp. 25–35.

[4] S. Raza, D. Li, C.-N. Chuah, and G. Cheung, “Cooperative peer-to-peer repair for wireless multimedia broadcast,” in *IEEE International Conference on Multimedia and Expo*, Beijing, China, July 2007.

[5] X. Liu, S. Raza, C.-N. Chuah, and G. Cheung, “Network coding based cooperative peer-to-peer repair in wireless ad-hoc networks,” in *IEEE International Conference on Communications*, Beijing, China, May 2008.

[6] P. Sharma, S.-J. Lee, J. Brassil, and K. Shin, “Distributed communication paradigm for wireless community networks,” in *IEEE International Conference on Communications*, Seoul, Korea, May 2005.

[7] G. Cheung, P. Sharma, and S. Lee, “Smart media striping over multiple burst-loss channels,” in *IEEE Transactions on Selected Topics in Signal Processing*, vol. 1, no.2, August 2007, pp. 319–333.

[8] X. Liu, G. Cheung, and C.-N. Chuah, “Structured network coding and cooperative local peer-to-peer repair for mbms video streaming,” in *IEEE 2008 International Workshop on Multimedia Signal Processing*, Cairns, Queensland, Australia, October 2008.

[9] K. Sinkar, A. Jagirdar, T. Karakis, H. Liu, S. Mathur, and S. Panwar, “Cooperative recovery in heterogeneous mobile networks,” in *IEEE Conference on Sensor and Ad Hoc Communications and Network*, San Francisco, CA, June 2008.

[10] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeun, “Network information flow,” in *IEEE Trans. Info. Theory*, vol. 46, no.4, July 2000, pp. 1204–1216.

[11] Y. Lin, B. Li, and B. Liang, “Differentiated data persistence with priority random linear codes,” in *International Conference on Distributed Computing Systems (ICDCS)*, Toronto, Canada, June 2007, pp. 47–54.

[12] K. Nguyen, T. Nguyen, and S.-C. Cheung, “Video streaming with network coding,” in *accepted to The Springer Journal of Signal Processing Systems Special Issue: ICME07*, Feb. 2008.

[13] H. Seferoglu and A. Markopoulou, “Opportunistic network coding for video streaming over wireless,” in *IEEE 16th International Packet Video Workshop*, Lausanne, Switzerland, November 2007.

[14] X. Liu, G. Cheung, and C.-N. Chuah, “Joint source/channel coding of wwan multicast video for a cooperative peer-to-peer collective using structured network coding,” University of California, Davis, Tech. Rep. ECE-CE-2009-2, April 2009, http://www.ece.ucdavis.edu/cerl/techreports/2009-2/.

[15] K. Ramchandran, A. Ortega, and M. Vetterli, “Bit allocation for dependent quantization with applications to multiresolution and mpeg video coders,” in *IEEE Trans. on Image Processing*, vol. 3, no.5, Sept. 1994.

[16] J. Proakis, *Digital Communications*, 3rd ed. McGraw Hill, 1995.

[17] “Qualnet,” http://www.scalable-networks.com/.