Rate-Distortion Optimized Joint Source/Channel Coding of WWAN Multicast Video for A Cooperative Peer-to-Peer Collective

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***Abstract*—Because of unavoidable wireless packet losses and inapplicability of retransmission-based schemes due to the well-known negative acknowledgment implosion problem, providing high quality video multicast over wireless wide area networks (WWAN) remains difficult. Traditional joint source/channel coding (JSCC) schemes for video multicast target a chosen *n*th-percentile WWAN user. Users with poorer reception than *n*th-percentile user (poor users) suffer substantial channel losses, while users with better reception (rich users) have more channel coding than necessary, resulting in sub-optimal video quality. In this paper, we recast the WWAN JSCC problem in a new setting called cooperative peer-to-peer repair (CPR), where users have both WWAN and wireless local area network (WLAN) interfaces and use the latter to exchange received WWAN packets locally. Given CPR can mitigate some WWAN losses via cooperative peer exchanges, a CPR-aware JSCC scheme can now allocate more bits to source coding to minimize source quantization noise without suffering more packet losses, leading to smaller overall visual distortion. Through CPR, this quality improvement is in fact reaped by all peers in the collective, not just a targeted *n*th-percentile user. To efficiently implement both WWAN forward error correction and WLAN CPR repairs, we propose to use network coding for this dual purpose to reduce decoding complexity and maximize packet recovery at the peers. We show that a CPR-aware JSCC scheme dramatically improves video quality: by up to 8.7 dB in peak signal-to-noise ratio for the entire peer group over JSCC scheme without CPR, and by up to 6.0 dB over a CPR-ignorant JSCC scheme with CPR.**

***Index Terms*—Cooperative peer-to-peer repair, joint source-channel coding, network coding.**

I. Introduction

PROVIDING sustainable high quality video over multicast channels of wireless wide area networks (WWAN) such as multimedia broadcast/multicast service (MBMS) [1] in 3G networks remains challenging because of two technical difficulties: 1) unavoidable packet losses due to temporary wireless link failures, and 2) unlike unicast, automatic retransmission request for link losses cannot be implemented per packet/per receiver due to the point-to-multipoint negative acknowledgment (NAK) implosion problem [2].

Given a multicast receiver group with a range of statistical channel conditions, previous works like [3]–[6] have optimally divvied up bits from a fixed WWAN transmission budget between *source coding* (e.g., by varying frame-level quantization parameters in H.264 video [7]) and *channel coding* [e.g., by varying amount of forward error correction (FEC) like Raptor Code [8]], to minimize the visual distortion for a chosen *n*th-percentile receiver[1] resulting from the combined effects of source quantization noise and packet losses due to residual channel noise. This WWAN bit allocation problem to minimize end-to-end visual distortion will be called joint source/channel coding (JSCC) in the sequel. Though clearly a point-to-multipoint problem, previous works [3]–[6] nevertheless use channel characteristics of a single *n*th-percentile receiver to represent a possibly large and diverse multicast group when allocating resources. Hence, receivers with channels worse than *n*th-percentile receiver's (poor receivers) suffer substantial losses due to insufficient FEC, while receivers with better channels (rich receivers) have more FEC than necessary, resulting in sub-optimal 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 network capabilities—ones with both WWAN and wireless local area network (WLAN) network interfaces like 802.11—called cooperative peer-to-peer repair (CPR) [9]. The idea is simple: after receiving different subsets of packets from WWAN source (due to different WWAN channel conditions experienced), receiver group forms an ad-hoc peer-to-peer network called a *CPR collective* and cooperatively exchange received packets via WLAN to mitigate WWAN losses. We have also shown [9] that by first encoding received WWAN packets into coded packets using network coding (NC) [10] before CPR exchange, and by imposing structures on NC, further gain in packet recovery can be observed.

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

In this paper, we recast the well-studied JSCC problem in the context of CPR: given a group of multi-homed peers listening to the same WWAN video multicast and participating in ad-hoc WLAN CPR recovery, how to optimally allocate bits between source and channel coding out of a fixed WWAN bit budget so that the sum of visual distortion of *the entire peer collective* is minimized? Unlike previous JSCC work minimizing distortion for an *n*th-percentile receiver (thus resulting in sub-optimal poor and rich receivers), our proposal minimizes distortion for the *entire peer collective*, so that every peer will benefit from lower visual distortion by participating in CPR. We explain intuitively how CPR alters the JSCC problem fundamentally as follows.

From an end-to-end system view, CPR presents a new *multi-path* packet transmission paradigm: a packet can be transmitted from the source to a receiver either via a WWAN link directly, or indirectly via CPR repair routed through a neighboring peer's WLAN link. Because of this *path diversity* enabled by the multi-homed devices, a *CPR-aware* JSCC scheme can now exploit this more general transmission condition in two ways. First, the system no longer needs to expend substantial channel coding efforts for a poor receiver, who can now depend on rich receivers' WWAN channels and subsequent CPR repairs for reliable transmissions—we call this the *disparity gain*. Second, even if all receivers experience similar WWAN channels statistically, a packet is lost to the collective *only if* WWAN transmissions to every single peer in the entire collective fail—a much stronger loss condition than when JSCC was optimized for a single *n*th-percentile receiver. A CPR-aware JSCC scheme can hence exploit this multiplying effect—we call this the *ensemble gain*—to allocate more bits to source coding without incurring more losses.

The technical difficulty then is how to decide the "right" amount of bits for source versus channel coding in a CPR-aware JSCC scheme to maximally exploit the aforementioned disparity and ensemble gain. More precisely, the challenge is twofold. First, computation-efficient implementations of WWAN FEC and WLAN CPR must be designed for good end-to-end packet recovery. Second, for chosen WWAN FEC and WLAN CPR implementations, a carefully formulated rate-distortion optimization, accurately taking into account effects of source quantization noise and packet losses due to potential WWAN channel noise and CPR recovery failure, must be constructed and solved efficiently to find the minimum expected end-to-end distortion possible for the CPR collective. Our major contributions in this paper are as follows.

1) We propose to apply NC for the dual purpose of WWAN-FEC and WLAN-CPR, which we show to recover end-to-end packet losses well compared to other FEC schemes and has low decoding complexity.
2) Given unstructured network coding (UNC) is used for WWAN-FEC and WLAN-CPR, we formulate a CPR-aware WWAN JSCC optimization, carefully modeling source, WWAN and CPR recovery process, targeting the entire CPR collective to maximally exploit both ensemble and disparity gain. We derive boundary cases for our optimization to provide intuition to the optimization.
3) Using instead the more complex but better performing structured network coding (SNC) for WWAN-FEC and WLAN-CPR, we reformulate the CPR-aware WWAN JSCC optimization to minimize end-to-end distortion for the collective. We propose an efficient iterative local search algorithm to find a locally optimal solution. For CPR using SNC, we provide a counter-based deterministic SNC selection scheme for each peer to select a SNC type during each CPR transmission.

Extensive simulations show that our CPR-aware JSCC scheme improves over traditional JSCC scheme without CPR by up to 8.7 dB in peak signal-to-noise ratio (PSNR), and up to 6.0 dB over a CPR-ignorant JSCC scheme with CPR.

The outline of this paper is as follows. We first review related works in Section II. We then overview our CPR-aware JSCC framework, video source model, and network models in Section IV. We discuss how NC can be applied to both WWAN-FEC and WLAN-CPR in Section III. We present our JSCC optimization in two parts: JSCC for UNC and JSCC for SNC in Sections V and VI, respectively. Simulation results are presented in Section VII. We conclude in Section VIII.

II. Related Work

We overview related works in four subsections. We first discuss previous works in JSCC for wireless video transmission. We then discuss recent network optimizations for multi-homed communication—a group of cooperative devices each with multiple network interfaces to connect to multiple orthogonal networks. We then overview NC, the new network transmission paradigm and methodology where routers, instead of simply forwarding received packets to outgoing links, actively encode received packets before transmission. Finally, we discuss our earlier works in CPR and contrast our current contribution against these earlier works.

A. Joint Source/Channel Coding

Due to the well-known NAK implosion problem [2], many video broadcast/multicast schemes over MBMS [5] have forgone feedback-based error recovery mechanisms like [11] and opted instead for FEC like Raptor Codes [8] to perform rate-distortion optimized JSCC. JSCC for video streaming has been a popular research topic for well over a decade [3]–[6], [12]. In essence, JSCC optimally allocates available bits out of a fixed bit budget to video source coder and channel coder to combat the combined effects of source quantization noise and packet losses from a lossy channel. The authors in [3] proposed an algorithm to optimally partition source and channel bits for scalable video using a 3-D subband video coder. For video broadcast over MBMS, [5] assumed the video source was pre-encoded in different bit rates, then optimized the selection of source bit rates as well as FEC parameters depending on channel conditions. Both [4] and [6] considered a receiver-controlled JSCC architecture where multiple multicast groups were available and the receiver chose a multicast group based on its own channel condition.

When performing JSCC, all previous works targeted *n*th-percentile receivers, resulting in great losses for receivers with worse-than-targeted channels. Note that choosing the lowest denominator (receiver with the worst channel or the 0th-percentile receiver) does not relieve sub-optimality; optimizing JSCC for the worst receiver in a large diverse group would mean expending majority of transmission budget for channel coding, leaving few source bits to eliminate source quantization noise and resulting in poor video quality. In contrast, in this paper, we perform rate-distortion optimized JSCC for the entire CPR collective exploiting ensemble and disparity gain so that every receiver can benefit.

B. Multi-Homed Mobile Devices

Recent research on ad-hoc group of multi-homed devices [13]–[17]—each equipped with both a WWAN interface like 3G and WLAN interface like 802.11—proved that useful transmission paradigms beyond traditional server-client model can be constructed. In [13], the authors showed that aggregation of an ad-hoc group's WWAN bandwidths can speed up individual peer's infrequent but bursty large content download like web access. The authors in [14] proposed ICAM, an integrated cellular and ad-hoc multicast architecture, in which the cellular base station delivered packets to proxy devices with good channel conditions, and then proxy devices utilized local WLAN ad-hoc network to relay packets to other devices. The authors in [16] showed that smart striping of FEC-protected delay-constrained media packets across WWAN links can alleviate single-channel burst losses. The authors in [15] and [17] also proposed to use WLAN ad-hoc networks to cooperatively recover video packet losses through cellular broadcast.

Like works in [15] and [17], our CPR work [9] also relies on local packet exchanges with cooperative neighbors in ad-hoc WLAN to recover from WWAN multicast losses, but doing so in a *rate-distortion optimal* way, so that for given available WLAN repair bandwidth, the expected distortion at a peer is minimized. Instead of focusing on the WLAN exchanges, the key novelty of this paper is a CPR-aware rate-distortion optimized JSCC scheme.

C. Network Coding

NC has been a popular research area since Ahlswede's seminal work [18], where wired network routers perform NC to combine received packets before forwarding them downlink for improved network throughput. Application of NC to wireless networks [19], [10] has also been proposed, where XOR-based NC protocols were designed for wireless ad-hoc networks to obtain similar throughput improvement. At the application layer, previous works [20]–[22] have also optimized video streaming using NC. The authors in [20] utilized a hierarchical NC scheme for content delivery networks and P2P networks alike to combat Internet bandwidth fluctuation. The authors in [21] discussed a rate-distortion-optimized NC scheme on a packet-by-packet basis for a wireless router, assuming perfect state knowledge of its clients. The authors in [22] discussed the application of Markov decision process [23] to NC, in which NC optimization is performed at the access point.

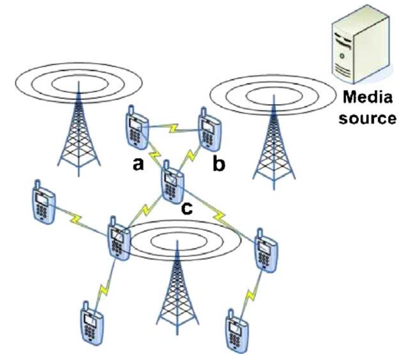


Fig. 1. Illustration of cooperative peer-to-peer repair network.

In this paper, our novelty lies not in the application of NC for typical server-client video streaming in unicast/multicast scenarios, which has been addressed previously in different contexts. Rather, our major contribution lies in a CPR-aware, rate-distortion optimized JSCC scheme, minimizing distortion for the entire CPR collective in a CPR setting. Further, our proposal to use NC for the dual purpose of both WWAN-FEC and WLAN-CPR in a CPR scenario is new.

D. Cooperative Peer-to-Peer Repair

The concept of cooperative peer-to-peer repair was first proposed in [24], where we proved that finding a schedule for peer transmission in CPR to minimize transmission time is NP-hard. In [25], we proposed a heuristic based scheduling protocol for CPR, and in [26] we showed that by combining NC with CPR, further performance gain can be achieved. In our recent work [9], we designed SNC for a group of video pictures to optimize video quality in a rate-distortion optimal manner if only a subset of the lost WWAN packets can be recovered given limited WLAN network resources.

Compared to our previous works focusing on WLAN recovery of WWAN broadcast/multicast losses, the major contribution of this paper is at the WWAN end: a CPR-aware JSCC optimization scheme at WWAN source targeting the *entire collective* of CPR users. As will be shown in later sections, the benefit of a CPR-aware WWAN JSCC scheme can be reaped whether we use unstructured or structured NC for CPR exchanges. Hence, our current contribution is *orthogonal* to our previous contributions.

III. System Overview and Models

In this section, we first overview our WWAN video multicast system with CPR. We then discuss the video source and network models that our JSCC scheme uses for rate-distortion optimization. Network model will be discussed into two parts: WWAN model for direct WWAN-source-to-peer transmission, and WLAN model for CPR exchanges.

A. WWAN Video Multicast System with CPR

We consider a scenario where a group $\mathcal{N}$ of N peers are watching the same WWAN multicast video using their wireless multi-homed mobile devices. Each device is also equipped with a WLAN interface, and the peers are physically located in sufficiently close proximity (a few hundreds of meters [27]) that a peer-to-peer wireless ad-hoc network can be formed. After each peer receives a potentially different subset of multicast video packets through his/her WWAN interface (due to different network conditions experienced), they use their WLAN interfaces to exchange received WWAN packets to collectively recover packet losses in WWAN channels. This repair process is called cooperative peer-to-peer repair (CPR). As an example, in Fig. 1, locally connected peers `a`, `b`, and `c` perform CPR to repair packet losses due to lossy WWAN transmissions from the media source to the peers.

In more details, the operation of our WWAN video multicast system with CPR can be explained in three phases. In the first phase, for a given WWAN transmission budget, i.e., the maximum number of bits that can be transmitted via the WWAN multicast channel in an *epoch* of T seconds, the media source allocates bits to source coding for a group of pictures (GOP) of playback duration of the same T seconds. The resulting encoded source bits are packetized into source packets, and the remaining WWAN bit budget is expended for WWAN-FEC packets. Both source and FEC packets are then transmitted from media source to peers in the multicast group.

In the second phase, peers exchange CPR packets via WLAN to repair this GOP in time T during WWAN multicast of the next GOP. (CPR repairs one GOP at a time) When a peer is permitted to transmit a CPR packet in WLAN, the peer uses both packets received from the source via WWAN, i.e., source packets and WWAN-FEC packets, as well as the CPR packets received from other peers, to construct a CPR packet for transmission to CPR neighbors within range.

In the third phase, after CPR completes its repair of a GOP in repair epoch of duration T, each peer recovers missing source packets from the received WWAN-FEC packets and locally exchanged CPR packets, decodes video from source packets, and displays decoded video for consumption. Note that T is hence also the *repair epoch* in which CPR must complete its repair in a given GOP. The initial playback buffer delay for each peer is therefore two repair epochs. In practice, a GOP is on the order of 10–30 frames, hence at 15 frames/s, initial playback buffer delay of two repair epochs is on the order of several seconds, and is imperceptible to non-interactive video viewers once streaming starts.

B. Video Source Model and Assumptions

We next describe a video source model that delineates the relationship between encoded bit count of a frame in a GOP and the resulting visual distortion. The media source uses H.264 [7] codec for video encoding. Each GOP of video consists of a starting I-frame followed by $M-1$ P-frames. 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 is correctly decoded.

Each video *frame* F_i is encoded from original *picture* F_i^o with bit count r_s^i, chosen by a JSCC scheme. r_s^i bits are subsequently divided into $R_s^i = \left\lceil \frac{r_s^i}{S_{pkt}} \right\rceil$ source packets, $\mathcal{P}_i = \{p_{i,1}, p_{i,2}, ..., p_{i,R_s^i}\}$, for transmission, where S_{pkt} is the maximum packet size.

We adopt a dependent source distortion model similar to the one introduced in [23]. Each frame F_i has an associated d_i, the resulting *distortion reduction* if F_i is correctly decoded. d_i can be calculated as follows [28]: it is the visual quality (peak signal-to-noise ratio[2]) of using decoded frame F_i for display of original picture F_i^o, *plus* the error concealment quality of using decoded frame F_i for display of later pictures F_j^os in the GOP, $j > i$, in the event that F_js are incorrectly decoded, *minus* the error concealment quality of F_{i-1} (if F_{i-1} exists). This means $d_i(r_s^i, r_s^{i-1})$ is a function of both source coding rate for F_i, r_s^i, and source coding rate for F_{i-1}, r_s^{i-1}. Note since F_i is encoded using a discrete set of source quantization levels, both the source coding rate r_s^i and distortion $d_i(r_s^i, r_s^{i-1})$ are also discrete values.

C. WWAN Network Models and Assumptions

We assume peers in the same WWAN multicast group experience different WWAN statistical channel conditions—each peer experiences independent (in time) and identically distributed packet losses with a different loss probability—resulting in different subsets of received WWAN packets in a GOP. This assumption is reasonable because although the distance between any two peers is restricted by WLAN transmission range, it is still substantially larger than the WWAN packet loss correlation distance. In fact, [29] has shown that even when two peers are co-located, the channel fading experienced by the two peers is very different, resulting in very different packet loss patterns.

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 individual 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 WWAN transmission budget to exploit disparity and ensemble gain for the entire CPR collective, *WWAN collective packet loss probability*—the likelihood that a packet is lost to the entire collective, becomes larger and must be modeled carefully.[3]

Assuming the packet losses are spatially uncorrelated [29], the conditional WWAN collective packet loss probability, $l'_{n,col}$, given a peer n has lost the packet can be written as

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

where l_{avg} is the average packet loss rate. l_m is the individual loss rate for peer m. l_ms could be channel estimates sent infrequently but periodically from receivers' to WWAN source, or estimated by WWAN source based purely on receivers'

[2]PSNR is a function of mean squared error: $PSNR = 10 \log_{10}\left(\frac{255^2}{MSE}\right)$.

[3]Note that we assume we are optimizing JSCC for a known WWAN *multicast* CPR collective $\mathcal{N}$, where the size of collective N and corresponding channel statistics (to some degree of precision) are known. This is in contrast to a WWAN *broadcast* scenario, where the number of receivers and their respective channel statistics are unavailable.

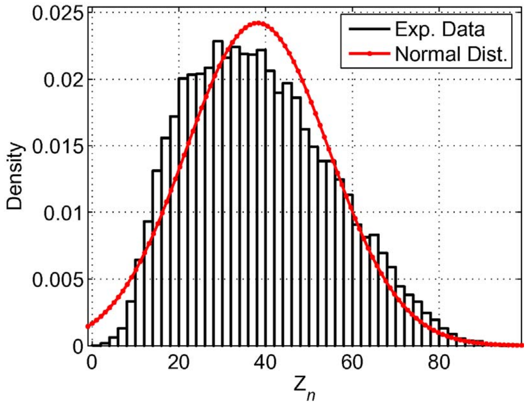


Fig. 2. Curve fitting using *Normal* function.

proximity to WWAN base stations. In the absence of per peer channel statistics, source can instead use l_{avg} for all the users.

D. WLAN Network Models and Assumptions

We assume that peers are stationary during the repair of the current GOP and can change their locations in the next GOP. Peers utilize the underlying 802.11 broadcast mode and rely on the 802.11 MAC layer scheduling protocol, i.e., carrier sense multiple access/collision avoidance, to coordinate transmissions. Note that since we consider broadcast mode, RTS/CTS are disabled and there are no retransmissions. Because each transmitted CPR packet by a peer is destined for his/her immediate neighbors within range, no application-specific routing protocol is required. Whenever the MAC layer senses a transmission opportunity, it informs the application layer, and the peer constructs a CPR packet based on received WWAN packets from source and CPR packets from neighbors and transmits it. At a given WLAN transmission opportunity, one question is how to construct a good CPR packet for WLAN transmission. We will discuss this in Section VI-D.

In order to model WLAN-CPR packet exchange capability, we assume that peer n receives a random variable number Z_n of CPR packets in time T, and the mean of Z_n is Z. Because of the heterogeneous network topology, wireless transmission contentions and interference, there exists variance in Z_n. We denote σ^2 as the variance of Z_n.

Experimentally, we can construct a statistical distribution of Z_n shown in Fig. 2.

As shown, the experimental data can be approximated using a *Gaussian distribution* with mean Z and variance σ^2. We will use Z_n to model CPR packet recovery capability. Details of how Z_n is related to CPR packet recovery probability can be found in [30]. Note that since Z_n is the number of CPR packets *successfully received* by peer n, it inherently captures packet losses in WLAN.

IV. Network Coding for WLAN-CPR and WWAN-FEC

In this section, we discuss our proposal to use NC for the dual purpose of WWAN-FEC and WLAN-CPR. We first overview our previously proposed NC-based CPR framework [9], where peers use NC to encode received WWAN packets into coded packets for local recovery. We then discuss how NC can be applied to WWAN and serve as WWAN-FEC.

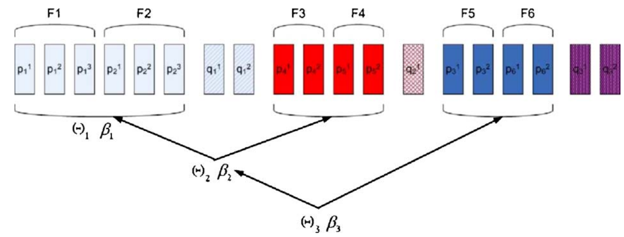


Fig. 3. Example SNC-FEC GOP with three frame groups.

A. Network Coding Based CPR

In order to improve CPR efficiency, we have proposed for each peer to encode received WWAN packets into a coded packet using NC [31] before performing CPR exchange [9]. 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., $\mathcal{P}^* = \{\mathcal{P}_1, \ldots, \mathcal{P}_M\}$. There are a total of $P = |\mathcal{P}^*| = \sum_{i=1}^{M} R_s^i$ native packets to be disseminated among the peers.

Rather than raw received packets from source, we have shown [9] that NC-encoding a CPR packet, q_n, as a randomized linear combination of raw received native packets $\mathcal{G}_n$ from source and CPR packets $\mathcal{Q}_n$ from neighbors can improve packet recovery performance

$$q_n = \sum_{p_{i,j} \in \mathcal{G}_n} a_{i,j} p_{i,j} + \sum_{q_m \in \mathcal{Q}_n} b_m q_m \tag{2}$$

where $a_{i,j}$s and b_ms are coefficients for the received native and CPR packets, respectively. We call this approach UNC. The advantage of UNC is that *any* set of $|\mathcal{P}^*|$ received *innovative*[4] packets can lead to full recovery of all packets in the GOP. The shortcoming of UNC is that if a peer receives fewer than P innovative packets, then this peer cannot recover *any* native packets.

To address UNC's shortcoming, we impose structure in the coefficients $a_{i,j}$s and b_ms in (2) when encoding a CPR packet, so that partial recovery of important frames in the GOP at a peer when fewer than P innovative packets are received is possible. Specifically, we define *X SNC groups*, $\Theta_1, \ldots, \Theta_X$, where each Θ_x covers a different subset of frames in the GOP and $\Theta_1 \subset \ldots \subset \Theta_X = \mathcal{F}$. Θ_1 is the most important SNC group, followed by Θ_2, etc. Corresponding to each SNC group Θ_x is a *SNC packet type x*. Each SNC frame group Θ_x is associated with a *transmission weight* β_x; i.e., given Z_n number of CPR packets is received by peer n, the expected number of CPR packets of type x is $Z_n\beta_x$. Further, let $g(j)$ be index of the smallest SNC group that includes frame F_j.

As an example, in Fig. 3 frames F_1, F_2 are in SNC group Θ_1 and $F_1, \ldots, F_4$ are in SNC group Θ_2. $\beta_1, \beta_2, \beta_3$ are the transmission weights associated with the three SNC groups and $\sum_{i=1}^{3} \beta_i = 1$. The smallest SNC group that includes F_3, F_4 is Θ_2, with index $2 = g(3) = g(4)$.

[4]A new packet is innovative for a peer if it cannot be written as a linear combination of previously received packets by the peer.

With the definitions above, a SNC packet $q_n(x)$ of type x can now be generated as follows:

$$q_n(x)=\sum_{p_{i,j}\in\mathcal{G}_n} U(g(i) \leq x)\ a_{i,j} p_{i,j}+\sum_{q_m\in\mathcal{Q}_n} U(\Phi(q_m) \leq x)\ b_m q_m \quad (3)$$

where $\Phi(q_m)$ returns the SNC type of packet q_m, and $U(\mathtt{c})$ evaluates to 1 if clause $\mathtt{c}$ is true, and 0 otherwise. In words, (3) states that a CPR packet $q_n(x)$ of type x is a random linear combination of received native packets of frames in SNC group Θ_x and received CPR packets of type $\leq x$. Using (3) to generate CPR packets, a peer can now recover frames in SNC group Θ_x when $|\Theta_x| < P$ innovative packets of types $\leq x$ have been received.

B. Network Coding Based WWAN-FEC

Though FEC like Raptor Code [8] is commonly used to protect source packets from WWAN multicast losses, we propose to use NC for the purpose of WWAN packet loss protection (WWAN-FEC). Theoretically, NC can be used simply as FEC: $n-k$ parity packets can be computed using NC to protect k source packets. Like Reed-Solomon Code [32], it is a *perfect code*; i.e., receiving any k of n transmitted packets constitutes full source packet recovery. However, NC requires matrix inversion to solve k equations for k unknowns to recover original packets, leading to a $O(k^3)$ complexity. Given we are optimizing one GOP of 15 frames at a time and typically a frame has only a few packets for CIF resolution video, the total number of source packets (k) is relatively small, and decoding complexity is not a major concern.

We apply NC for WWAN-FEC as follows. First, the media source generates FEC packets $q(x)$s for each defined SNC frame group Θ_x as follows:

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

where $c_{i,j}$ is the native random coefficient. FEC packets are generated using only native packets in frame group Θ_x, all of which are available at the source. For ease of later JSCC formulation, 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 illustrating example, Fig. 3 shows an NC-FEC encoded GOP with three frame groups. There are two WWAN-FEC packets generated for Θ_1 of two frames and six source packets.

The computed 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 from source are no different from WLAN-CPR packets from neighbors*, and subsequent CPR process can proceed exactly the same as done previously. In doing so, 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 nevertheless participate and contribute to CPR. Moreover, WWAN-FEC decoding and WLAN-CPR decoding can be done at the same time at the end of a repair epoch, reducing decoding complexity.

Note that rateless codes [8], [33] have been shown in the literature to be useful for different video streaming scenarios. The decision to use NC for the dual purpose of WWAN-FEC and WLAN-CPR instead of rateless codes is twofold. First, it is not clear how rateless codes can be directly applied to our WWAN video multicast system with CPR, as we have done for NC, where received WWAN-FEC packets by a peer can be used immediately to construct WLAN-CPR packets *without* first decoding WWAN-FEC. Second, as previously discussed, given NC decoding complexity is not a major concern for small number of source packets in a GOP (separately, [34] has demonstrated the practicality of using network coding in a live peer-to-peer streaming system), there can be no theoretical performance advantage of rateless code over NC, since NC is already a perfect code.

V. JSCC Optimization Using Unstructured Network Coding

In this section, we describe how CPR-aware JSCC can be performed using UNC. We first derive the optimization mathematically. We then derive JSCC solutions at the two boundary cases when CPR is unhelpful or perfect in packet recovery. The derived solutions provide intuition as to how an optimized JSCC scheme should behave to maximally exploit disparity and ensemble gain inherent in CPR.

A. Joint Source/Channel Optimization for Single Frame Group

Suppose we want to optimize transmission of a GOP using UNC. Let the optimization variables be R_s, the number of source packets, and R_c, the number of WWAN-FEC packets. Our JSCC optimization objective is to minimize the average of *all* N peers' expected distortions in the CPR collective as

$$\min_{R_s,R_c} \frac{1}{N}\sum_{n=1}^{N}\left\{D-[1-p_{n,grp}(R_s,R_c)]\ \sum_{i=1}^{M} d_i(r_s^i, r_s^{i-1})\right\}$$
$$\text{s.t. } R_s + R_c \leq \bar{R} \quad (5)$$

where D is the distortion if no packets are received at a peer, and $p_{n,grp}(R_s, R_c)$ is the *frame group loss probability* for peer n—the likelihood that the entire frame group (GOP) cannot be correctly decoded, given R_s source and R_c WWAN-FEC packets were transmitted via WWAN. $\bar{R}$ is the WWAN packet budget available for transmission of a GOP. Note that there is a source bit allocation problem here: optimal allocation of R_s source packets worth of bits to M frames, each frame F_i of r_s^i bits. Because the entire GOP is either lost or correctly decoded using UNC, the source bit allocation can be solved using [35] assuming no channel losses.

Frame group loss probability $p_{n,grp}(R_s, R_c)$ is the probability that more than R_c packets are lost in WWAN by peer n, *and* CPR cannot help to recover enough of those losses

$$p_{n,grp}(R_s,R_c)=\sum_{i=R_c+1}^{R_s+R_c}\binom{R_s+R_c}{i} l_n^i(1-l_n)^{R_s+R_c-i}$$
$$*p_{n,col}(i,R_c) \quad (6)$$

where $p_{n,col}(i, R_c)$ is the *collective loss probability*—the probability that the collective cannot recover sufficient number of packets for recovery given i packets were lost by peer n via WWAN transmission. $p_{n,col}(i, R_c)$ depends on $p_{n,isuf}(i, R_c)$, the *collective insufficient probability* that insufficient number of packets have been delivered via WWAN to the collective for CPR to operate, given peer n has i WWAN losses already

$$p_{n,col}(i, R_c) = p_{n,isuf}(i, R_c) + \left[1 - p_{n,isuf}(i, R_c)\right] [1 - Q_n(i - R_c, s_1, s_1)] \quad (7)$$

where $Q_n(\Omega, s_s, s_e)$ is *CPR recovery probability*—the likelihood that CPR can recover Ω WWAN lost packets in segments from s_s to s_e. $Q_n(\Omega, s_s, s_e)$ describes CPR packet recovery capability and is decided by Z_n, the number of CPR packets received by peer n. Since UNC is a special case for SNC where there is only one SNC group and one segment s_1, both s_s and s_e are the same s_1. In this case, $Q_n(\Omega, s_1, s_1) = 1$ when $Z_n \geq \Omega$; and 0 otherwise. In words, since peer n receives Z_n packets during CPR, as long as the number of received CPR packets is no fewer than the number of lost packets, all the lost packets in the GOP can be recovered. In general when there are X SNC groups, CPR recovery probability $Q_n(\Omega, s_s, s_e)$ also depends on how SNC type selection is performed at each peer to achieve desired proportions β_xs for SNC group Θ_x. We discuss this in Section VI-D. Detailed derivation of $Q_n(\Omega, s_s, s_e)$ is provided in [30].

When calculating CPR recovery probability $Q_n(\Omega, s_s, s_e)$ for peer n, the number of CPR packets received by peer n, Z_n, is assumed to be known. However, in practice, it is hard to accurately predict the number of CPR packets received by each peer n, Z_n, in the collective *a priori*. Given Z_n can be modeled by a Gaussian distribution with mean Z and variance σ^2 as described in Section III-D, for ease of implementation, we first divide a CPR collective into three equal-sized *sub-classes*, each with Z^-, Z, and Z^+ average number of CPR packets, respectively. A peer n is hence equally likely to fall into one of three sub-classes, and $Q_n(\Omega, s_s, s_e)$ for peer n will be a weighted sum of probabilities of the three CPR sub-classes. Z^- represents the "WLAN-poor" peers who receive fewer CPR packets than average peers, and Z^+ represents the "WLAN-rich" peers who receive more CPR packets. The three sub-class divisions properly account for both poor and rich peers in WLAN, while keeping a representative middle class with average CPR capability and small intra-class variance. Simulations also show that using more sub-classes reaped marginal improvement compared to the three sub-classes divisions, while the increase in computation complexity due to more sub-classes is significant.

Given the assumption that Z_n has Gaussian distribution and the three CPR sub-classes are of equal size, one can locate the boundaries of the three sub-classes as $Z - \frac{3\sqrt{2}}{10}\sigma$ and $Z + \frac{3\sqrt{2}}{10}\sigma$. We can then calculate the mean of the three sub-classes as $Z^- \approx Z - \sigma$, Z, and $Z^+ \approx Z + \sigma$. See [30] for more details.

Now continuing with (7), the collective insufficient probability, $p_{n,isuf}(i, R_c)$, can be written as

$$p_{n,isuf}(i, R_c) = \sum_{j=0}^{i-R_c-1} \binom{i}{j} (1 - l'_{n,col})^j (l'_{n,col})^{i-j}. \quad (8)$$

In other words, (8) states that only j of the i WWAN lost packets by peer n are received by the collective. Hence, the collective cannot recover sufficient number of packets for peer n to recover the whole frame group.

B. Boundary Cases

We now derive JSCC solutions for the two boundary cases in UNC as follows. Suppose CPR is utterly useless in packet recovery and $Q_n(\Omega, s_1, s_1) = 0$. Then collective loss probability $p_{n,col}(i, R_c) = 1$. Frame group loss probability $p_{n,grp}(R_s, R_c)$ is then simply the likelihood that at least $R_c + 1$ packets are lost via WWAN transmission

$$p_{n,grp}(R_s, R_c) = \sum_{i=R_c+1}^{R_s+R_c} \binom{R_s + R_c}{i} l_n^i (1 - l_n)^{R_s+R_c-i}. \quad (9)$$

We see now that the optimization (5) and (9) defaults to optimizing JSCC over WWAN for N peers *in the absence of CPR*. In other words, given there is no disparity and ensemble gain to exploit when CPR is utterly ineffective, a CPR-aware JSCC scheme essentially becomes a CPR-ignorant JSCC scheme. This agrees with our intuition of how a CPR-aware rate-distortion optimized JSCC scheme should operate.

Suppose now CPR is perfect in packet recovery and CPR loss probability $Q(\Omega, s_1, s_1) = 1$. Then collective loss probability $p_{n,col}(i, R_c) = p_{n,isuf}(i, R_c)$. Substituting $p_{n,isuf}(i, R_c)$ back to (6), we have

$$p_{n,grp}(R_s, R_c) = \sum_{i=R_c+1}^{R_s+R_c} \binom{R_s + R_c}{i} l_n^i (1 - l_n)^{R_s+R_c-i} \times \sum_{j=0}^{i-R_c-1} \binom{i}{j} (1 - l'_{n,col})^j (l'_{n,col})^{i-j}. \quad (10)$$

Rearranging the two sums, the product terms in (10), and expressing the combinations explicitly, we get

$$p_{n,grp}(R_s, R_c) = \sum_{i=R_c+1}^{R_s+R_c} \sum_{j=0}^{i-R_c-1} \frac{(R_s + R_c)!}{(R_s + R_c - i)!\ (i - j)!\ j!} \times (1 - l_n)^{R_s+R_c-i} \left[l_n(1 - l'_{n,col})\right]^j \left(l_n l'_{n,col}\right)^{i-j}. \quad (11)$$

Now change the variables j to k, i to $m+k$, and change the corresponding upper and lower limits of the sums in (11), we can write $p_{n,grp}(R_s, R_c)$ as follows (assuming $R_s + R_c = \bar{R}$):

$$\begin{aligned} p_{n,grp}(R_s, R_c) &= \sum_{m=R_c+1}^{\bar{R}} \sum_{k=0}^{\bar{R}-m} \frac{(\bar{R})!}{(\bar{R} - m - k)!\ m!\ k!} \times (1 - l_n)^{\bar{R}-m-k} \left[l_n(1 - l'_{n,col})\right]^k \left(l_n l'_{n,col}\right)^m \\ &= \sum_{m=R_c+1}^{\bar{R}} \binom{\bar{R}}{m} \left(l_n l'_{n,col}\right)^m \times \sum_{k=0}^{\bar{R}-m} \binom{\bar{R} - m}{k} (1 - l_n)^{\bar{R}-m-k} \left[l_n(1 - l'_{n,col})\right]^k \\ &= \sum_{m=R_c+1}^{R_s+R_c} \binom{R_s + R_c}{m} \left(l_n l'_{n,col}\right)^m (1 - l_n l'_{n,col})^{R_s+R_c-m}. \end{aligned} \quad (12)$$

The last step is due to binomial theorem. Our optimization (5) and (12) now defaults to optimizing for *anycast*: if enough packets are received by *any one peer* within the collective—each packet is successfully transmitted to the collective with probability $1 - l_n l'_{n,col}$—then the entire collective can recover the GOP. In this boundary case, it is intuitive that a CPR-aware JSCC scheme would essentially treat the entire collective as a single entity when optimizing JSCC, since a transmitted packet to a single peer is equivalent to a transmitted packet to the entire collective. Hence, this JSCC result also agrees with our intuition of how a CPR-aware JSCC scheme would maximally exploit disparity and ensemble gain.

VI. JSCC Optimization Using Structured Network Coding

In this section, we extend the CPR-aware JSCC optimization to SNC. Beyond searching for the best resource allocation for WWAN source and channel coding, we need to consider jointly the optimal structures in SNC and associated weights β_xs for different NC groups during CPR exchanges as well. We first define the new JSCC objective function and derive the optimization. We then present heuristics to obtain locally optimal optimization parameters efficiently.

Since SNC is considered for JSCC optimization, at a given WLAN-CPR transmission opportunity, what NC packet type to encode a CPR packet for local exchange to achieve the weighted proportions β_xs remains to be answered. We thus describe a *counter-based, deterministic* SNC packet selection scheme, which ensures that the important SNC packets are always transmitted before less important ones in a local region. This is an improved SNC selection scheme over our previously used *randomized* SNC selection [9]. Last, given the counter-based deterministic SNC selection scheme, we present a SNC selection local optimization scheme that utilizes limited (and possibly stale) available neighbor state information to make more locally optimal SNC selections.

A. Optimization Objective

Similar to (5), the average of expected visual distortions for all N peers in the collective in one GOP, assuming X frame groups Θ_xs in the NC structure, can be written as follows:

$$D_{S+C} = \frac{1}{N}\sum_{n=1}^{N}\left\{D - \sum_{x=1}^{X}\left[\sum_{j\in s_x} d_j(r_s^j, r_s^{j-1})\right]\ \alpha_n(x)\right\} \quad (13)$$

where D is the distortion if no packets are received at a peer. $d_j(r_s^j, r_s^{j-1})$ is the distortion reduction if F_i is successfully received and decoded. $\sum_{j\in s_x} d_j(r_s^j, r_s^{j-1})$ is thus the distortion reduction for segment s_x. $\alpha_n(x)$ is *segment s_x recovery probability* for peer n.

Our JSCC optimization objective is to minimize the expected distortion with WWAN transmission constraint

$$\min_{r_s^i, R_c^i, \Theta_x, \beta_x} D_{S+C} \quad \sum_{i=1}^{M}\left\lceil \frac{r_s^i}{S_{pkt}}\right\rceil + \sum_{i=1}^{X} R_c^i \ \leq\ \bar{R} \quad (14)$$

where $\sum_{i=1}^{X} R_c^i$ is the total number of WWAN-FEC packets. The objective here differs from the UNC case (5) in that individual segments s_xs in GOP can be decoded without having the entire GOP recovered, resulting in partial distortion reductions d_js. Thus, rather than frame group loss probability $p_{n,grp}(R_s, R_c)$ in the UNC case (5), it is important to trace the recovery probability $\alpha_n(x)$ of each segment s_x. We perform the derivation next.

B. Optimization Formulations

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

1) C_x: NC frame group Θ_x is recoverable.
2) B_x: frames in segment s_x can be correctly decoded. $B_x = C_x \cup C_{x+1} \cup \ldots \cup\ C_X$.

With the two events, we can express the probability that frames in segment s_1 cannot be decoded as

$$\begin{aligned} Pr_n(\bar{B}_1) &= Pr_n(\bar{C}_1 \cap \bar{C}_2 \cap \ldots \cap \bar{C}_X) \\ &= Pr_n(\bar{C}_1)Pr_n(\bar{C}_2|\bar{C}_1)\ldots Pr_n(\bar{C}_X|\bar{C}_{X-1}, \ldots, \bar{C}_1). \end{aligned} \quad (15)$$

Each of the product terms in (15) can be obtained by utilizing the frame group loss probability (6) derived for UNC, with extra arguments to identify particular frame groups in question

$$Pr_n(\bar{C}_y|\bar{C}_{y-1}, \ldots, \bar{C}_1) \approx p_{n,grp}\left(\sum_{i=1}^{y} R_s^i - 1,\ R_c^y - 1, s_1, s_y\right) \quad (16)$$

where $p_{n,grp}(R_s, R_c, s_s, s_e)$ is now the group loss probability for peer n and the WWAN packet losses are in segments from s_s to s_e. s_s and s_e are in turn passed into $Q_n(\Omega, s_s, s_e)$ for the calculation of CPR recovery probability [30]. In words, (16) says that given the previous frame groups Θ_is, $1 \leq i \leq y-1$, are not recovered, the probability that the current frame group Θ_y cannot be recovered is roughly the probability that all $\sum_{i=1}^{y} R_s^i - 1$ source packets cannot be recovered given only $R_c^y - 1$ WWAN-FEC packets are available for channel protection. The intuition is as follows: we know previous frame groups (of size $\geq$ 1 packet) cannot be recovered with their own WWAN-FEC packets, so the current frame group must expend at least one WWAN-FEC packet to help previous frame groups, resulting in the "-1" term in both source and channel coding packets. Note that when $R_c^y = 0$, there is no FEC packet to use to repair the assumed lone lost source packet. In this case, we expend one CPR repair packet in SNC group y to help with the source packet.

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

$$Pr_n(\bar{B}_2) = Pr_n(\bar{B}_1) + [1 - Pr_n(\bar{B}_1)]Pr_n(\bar{B}_2|B_1). \quad (17)$$

In words, frames in segment s_2 cannot be decoded if frames in s_1 cannot be decoded, or if s_1 can be decoded but s_2 itself cannot be decoded. $Pr_n(\bar{B}_2|B_1)$ can be written as

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

where

$$Pr_n(\bar{C}_2|B_1) \approx p_{n,grp}(R_s^2, R_c^2, s_2, s_2)\frac{Pr_n(C_1)}{Pr_n(B_1)} \quad (18)$$

$$Pr_n(\bar{C}_y|\bar{C}_{y-1}, ..., \bar{C}_2, B_1) \approx p_{n,grp}\left(\sum_{i=2}^{y} R_s^i - 1, R_c^y - 1, s_2, s_y\right). \quad (19)$$

In other words, given segment s_1 can be decoded, R_c^2 WWAN-FEC packets can be used exclusively to protect R_s^2 source packets only. See [30] for a derivation of scaling factor $\frac{Pr_n(C_1)}{Pr_n(B_1)}$. We can similarly derive the general case formulations as follows:

$$Pr(\bar{B}_y) = Pr(\bar{B}_{y-1}) + [1 - Pr(\bar{B}_{y-1})]Pr(\bar{B}_y|B_{y-1}) \quad (20)$$

where $Pr(\bar{B}_{y-1})$ can be calculated iteratively

$$\begin{aligned} Pr(\bar{B}_y|B_{y-1}) &= Pr(\bar{C}_y \cap \bar{C}_{y+1} \cap ... \cap \bar{C}_X|B_{y-1}) \\ &= Pr(\bar{C}_y|B_{y-1})Pr(\bar{C}_{y+1}|\bar{C}_y, B_{y-1}) \\ &\quad ...Pr(\bar{C}_X|\bar{C}_{X-1}, ..., \bar{C}_y, B_{y-1}) \end{aligned} \quad (21)$$

where

$$Pr(\bar{C}_y|B_{y-1}) \approx p_{grp}(R_s^y, R_c^y, s_y, s_y)\frac{Pr(C_{y-1})}{Pr(B_{y-1})} \quad (22)$$

and

$$\begin{aligned} &Pr(C_{y-1}) \\ &\quad = Pr(C_{y-1}|C_{y-2})Pr(C_{y-2}) + Pr(C_{y-1}|\bar{C}_{y-2})Pr(\bar{C}_{y-2}) \\ &\quad \approx p_{grp}(R_s^{y-1}, R_c^{y-1}, s_{y-1}, s_{y-1})Pr(C_{y-2}) \\ &\quad + p_{grp}\left(\sum_{i=1}^{y-1} R_s^i - 1, R_c^{y-1} - 1, s_1, s_{y-1}\right)(1 - Pr(C_{y-2})). \end{aligned} \quad (23)$$

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

C. Fast JSCC Optimization

Equation (14) involves the optimization of four sets of variables: source coding rates r_s^is, WWAN-FEC for the NC groups R_c^is, NC groups Θ_xs, and peers' NC group transmission weights β_xs. We outline an NP-hardness proof in [30] to show that the optimal solution in general cannot be found in polynomial time unless P = NP. Given the optimization is NP-hard, we outline a computation-efficient Algorithm 1 that finds a locally optimal solution as follows.

We first set the total number of WWAN-FEC packets to be K. Given K and initial segment recovery probabilities αs, we find the optimal source bit allocation r_s^is using Algorithm *OptimizeSource*(). Then given source bit allocation r_s^is, we find the optimal SNC frame groups Θ_xs and transmission weights β_xs using Algorithm *OptimizeSNC*(). We iterate until we converge to a solution. We then perform a modified binary search (*ModifiedBinarySearch*()) of K with search space from 0 to $\bar{R}$ to find the best solution. In the following, we describe *OptimizeSource*(), *OptimizeSNC*() and *ModifiedBinarySearch*() in more details.

Algorithm 1: Iterative CPR-aware Joint Source/Channel Optimization using SNC

```
D^{min}_{S+C} = ∞;
while true do
    K=ModifiedBinarySearch();
    R^{budget}_S = R̄ − K;
    while converge = 0 do
        r^i_s s = OptimizeSource(αs, R^{budget}_S);
        [D^{cur}_{S+C}, αs, Θ_x s, β_x s, R^i_c s] = OptimizeSNC(r^i_s s);
        if D^{cur}_{S+C} < D^{min}_{S+C} then
            D^{min}_{S+C} = D^{cur}_{S+C};
        end
    end
    Break when search space of K is small enough;
end
return r^i_s s, Θ_x s, R^i_c s, β_x s;
```

1) *OptimizeSource():* To obtain optimal source bit allocation given total available resource R_S^{budget}, we use a well-known heuristic algorithm in [35]. The difference here is that our source bit allocation is a *weighted* version of the one in [35], where the weighting factor is $\alpha_n(x)$. 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—a weighted combination of distortions and encoding rates—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 [35].

2) *OptimizeSNC():* Given r_s^is returned from source bit allocation, we obtain the distortion reduction d_i for each frame F_i. Then, *OptimizeSNC*() finds the best SNC groups Θ_xs, peers' SNC group transmission weights β_xs, and the WWAN-FEC packet allocation R_c^is. We first observe the following: because a GOP is a dependency chain, a frame in the chain is of greater importance than it descendant frames, and frame F_i should not be allocated more resource than frame F_j, $j < i$. The observation has the following implication that a parent frame should not be assigned a NC type larger than its children frames. With the implication above, we design the following.

We first assign M NC types to the M frames from first frame onward. We then compute β_xs and R_c^is that result in the smallest distortion (to be discussed next). Next, we find the best "merging" of neighboring frames—assigning the same NC type to the merged group—that results in the largest decrease in expected distortion. Each merging results in a new NC structure, again we compute β_xs and R_c^is that result in the smallest distortion. We continue until all distortion-reducing mergings are explored.

To obtain possible R_c^i allocation, we perform a *local search* type packet assignment as follows. We start by evenly allocating the K FEC packets to all the frame groups. Then, starting from frame group one, we gradually increase the number of FEC packets allocated to frame group one, by evenly reducing the FEC packets allocated to the rest of the frame groups. Once we encounter an increase in distortion performance, we reverse the direction by decreasing the number of FEC packets allocated to frame group one and evenly increase the FEC packets for the rest frame groups. After finishing the search on frame group one, we then perform the same operation on the rest of the frame groups. Similar local search method is performed for the allocation of β_x.

3) *ModifiedBinarySearch():* Theoretically, for a given set of peers' WWAN statistics and corresponding CPR recovery statistics, there should be a uniquely optimal amount of resource out of the total WWAN bit budget devoted to WWAN-FEC, beyond which there is too much channel coding and source quantization noise dominates the peers' expected distortions, and below which there is too little channel coding and channel noise dominates. This observation means that there should be a unimodal plot of expected distortion with respect to WWAN-FEC resource K, and a binary search for K would suffice. However, due to sub-global-optimality of our fast local searches, for a given K we on occasion do not find the truly optimal division of resource among frames for source coding and among frame groups for channel coding. This means we may fail to achieve a true unimodal plot, resulting in an "almost" unimodal plot instead. For this reason, we propose a *ModifiedBinarySearch*() for K as follows.

Initially, the search space of K is from 0 to $\bar{R}$. We start by calculating the total distortions when K equals $\frac{\bar{R}}{2}$, and two probing points $\frac{\bar{R}}{4}$ and $\frac{3\bar{R}}{4}$. Let us assume the results are represented as d_{mid}, d_{left} and d_{right}. If d_{left} is less than $d_{\text{right}} - \delta$, then the search is moved to the left half space, where δ is a positive number used to accommodate the exception points. On the contrary if d_{right} is less than $d_{\text{left}} - \delta$, search is moved to the right half space. If the difference between d_{left} and d_{right} is less than 2δ, we further probe the points $\frac{\bar{R}}{8}$, $\frac{3\bar{R}}{8}$, $\frac{5\bar{R}}{8}$ and $\frac{7\bar{R}}{8}$ to make proper search space reduction decision. We continue this process until the search space is small enough.

4) *Computation Complexity:* Our modified binary search has complexity $\log \bar{R}$. With the heuristic algorithm in [35], source bit allocation has complexity $\mathcal{O}(MQ)$, where Q is the quantization levels. With our local search based SNC optimization, we need to check at most M merging operations for M frames in each iteration, and there are at most M iterations. Hence, there are at most M^2 merging operations and roughly $\mathcal{O}(M^2)$ NC group choices. Our local search based WWAN-FEC and transmission weights allocations have complexity of $\mathcal{O}(\bar{R}^2)$ and $\mathcal{O}(L^2)$, respectively, where L is the number of transmission weight choices. Since source bit allocation and SNC optimization are performed separately, in all the search space size is roughly $\mathcal{O}(MQ \log \bar{R} + M^2 \bar{R}^2 L^2 \log \bar{R})$, which is polynomial and significantly less than an exhaustive search.

D. Counter Based Deterministic SNC Selection

When SNC is used in JSCC, at each WLAN-CPR transmission opportunity at a given peer, what NC type to encode a CPR packet for local exchange needs to be answered. In our previous work [9], we proposed a *randomized* scheme where a peer randomly selects a SNC type according to global transmission weights β_xs. While it enforces the desired packet proportions in SNC groups, it does not conform to a logical order where small (hence more important) SNC types are transmitted first. When there is non-negligible variance in Z_n, a logical transmission order ensures that poor peers receiving few CPR packets would get important packets in larger proportions than indicated by the global weights β_xs, ensuring a minimum satisfactory level of quality.

To impose a logical order, we propose a *counter-based deterministic* SNC selection scheme for peer n to select the SNC type x. Peer n keeps track of the number Z'_n of received CPR packets thus far. When a transmission opportunity arises for peer n, he transmits SNC type 1 if $Z'_n < Z\beta_1$. Peer n transmits SNC type 2 if $Z\beta_1 \leq Z'_n < Z(\beta_1 + \beta_2)$, and so on. If $Z'_n > Z$, peer n selects SNC type based on a timer instead; i.e., if the current time is in-between $T \sum_{i=1}^{j-1} \beta_i$ and $T \sum_{i=1}^{j} \beta_i$, then the chosen SNC type is j. One can thus enforce β_x globally and yet maintain a logical order.

Note we use *reception* counter instead of *transmission* counter to maintain the logical order. The reason is twofold. First, using WLAN broadcast mode, the number of packets received by a collective can far exceed the number of packets transmitted (each transmitted packet is received by multiple listening peers). Hence, using transmission counter would mean too many packets of small types if the number of packets transmitted per peer is small. Second, a transmitted packet may not be correctly received in time by neighbors due to in-air collision and interference. Hence, reception counter provides a more accurate estimate of neighbors' current states.

Because of deterministic transmissions, packets of small SNC types are always transmitted earlier than packets of large SNC types. This property has three implications: 1) peers receive packets of more important SNC types earlier than less important SNC types; 2) if Z_n is smaller than Z, then ns neighbors receive more packets of more important SNC types than indicated by β_xs, which benefits peer ns poor neighbors; and 3) peers can perform local optimization based on neighbor state to further optimize local SNC type selection.

E. Local Optimization Given Deterministic SNC Selection

During CPR exchange, a peer can learn of their immediate neighbors' (possibly stale) state information, if state information is piggybacked on top of each exchanged CPR packet. Armed with neighbors' state information, a peer can now choose a smaller SNC type, if the peer deduces that his neighbors have not fully recovered that SNC type. Doing so means more important SNC types are more likely to be recovered before peers can progress to select larger SNC types. Note that this simple local optimization is not possible with a randomized SNC selection approach, where at any given time it is more difficult to deduce the appropriate SNC type to transmit to a peer's neighbors. Moreover, compared to the more complex RD-based local optimization [9] for the randomized approach, our simple local optimization requires very small computation overhead.

Based on the discussion above, we piggyback *SNC group recovery status* on top of each CPR packet. The status information reveals how many packets the transmitting peer has for each SNC group. Since there are at most M SNC types, and generally M is not a large number (15 in our setup), this exchanged status information requires minimum bit overhead. Based on the status information, peer n does the following.

1) Before deciding which SNC type to encode, peer n first checks whether its neighbors have recovered the previous SNC group. If not, peer n continues to transmit packets of the previous SNC type.
2) After making a decision on SNC type, peer n checks whether its neighbors have recovered the decided SNC group. If so, n moves on to check the next SNC type.

When peer n checks whether its neighbors have recovered SNC group Θ_x, for each neighbor m, peer n first calculates the time difference τ between the current time and the timestamp when the neighbor information was received. The expected number of packets m can receive during τ is $\frac{\tau Z}{T}$. If the expected number of received packets is greater than the number of packets neighbor m needs to recover SNC group Θ_x, then m is assumed to have recovered Θ_x; otherwise peer n assumes that m still needs packets of type x.

VII. Experimentation

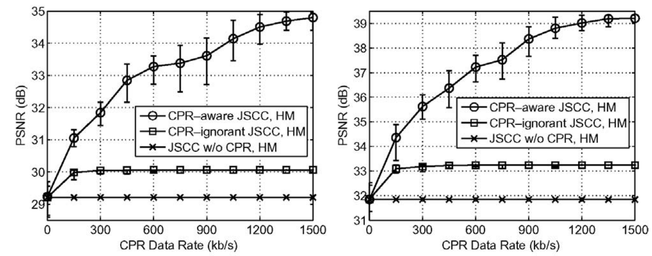
We performed extensive simulations to validate our proposal. We first discuss the simulation setup. We then demonstrate the performance gain of our CPR-aware rate-distortion optimized JSCC scheme using UNC over a CPR-ignorant JSCC scheme. Then, we compare JSCC using SNC and UNC and conclude that SNC outperforms UNC in a range of network conditions. Last, we provide further discussions by analyzing the ensemble and disparate gains inherent in CPR.

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 frames/s and sub-sampled in time by 2. The GOP size was chosen to be 15 frames: one I-frame followed by 14 P-frames. There are 10 GOPs for each video sequence. The H.264 codec used was JM 12.4, downloadable from [36].

We performed simulations using QualNet [37]. To have the freedom to vary CPR bandwidth to reflect different amount of WLAN resources available for CPR under different network settings, we selected *Abstract PHY* in QualNet and used 802.11 MAC layer. The underlying CPR scheduling was 802.11 MAC with broadcast enabled, and so no feedback messages were sent from the receivers and no transmission rate adaption was performed. Given one GOP was 15 frames and video was encoded at 15 frames/s, one epoch time was 1s. We assumed the WWAN multicast transmission budget was 150 kb/s. Our WWAN transmission budget setting inherently takes background traffic into consideration because 3G downlink bandwidth can be much higher than 150 kb/s. Each CPR packet has a fixed size of 1000 bytes. CPR network size was set to $1000 \times 1000\,\text{m}^2$.

Given this setup, after performing JSCC optimization, one GOP was divided into fewer than 30 packets. Since CPR is performed for each GOP, the decoding complexity for NC is



(a) (b)

Fig. 4. CPR-aware rate-distortion optimized JSCC versus CPR-ignorant JSCC using UNC. WWAN loss rate 0.3. (a) *Foreman* sequence. (b) *News* sequence.

upper bounded by 30×30 matrix inversion operations. This did not pose a complexity problem for our optimization; similar NC conditions were also shown to be practical for live video streaming in [34]. We used 257[5] as the finite field size for NC. Each simulation is performed 50 times and the performance benchmark was visual quality (PSNR) with unit in dB.

In the following we considered two WWAN packet loss models: *homogeneous packet loss* (`HM`) and *heterogeneous packet loss* (`HT`). In `HM`, the WWAN packet loss was iid and all peers had the same loss rate l. In `HT`, peers were separated into two regions. Peers within the $\frac{1000}{\sqrt{2}} \times \frac{1000}{\sqrt{2}}\,\text{m}^2$ square had HM loss with loss rate $0.5l$, while peers outside of the square had HM loss with average loss rate $1.5l$, capturing possible spatial packet loss diversity in wireless networks. The overall average packet loss rate, however, remained l.

B. CPR-Aware Rate-Distortion Optimized JSCC Scheme Outperforms Conventional JSCC Schemes

We first compare video quality between our proposed CPR-aware JSCC scheme and a CPR-ignorant JSCC scheme, both using UNC for WWAN-CPR for local packet recovery. Note for the latter case, we still performed CPR to assist poor receivers to recover lost WWAN packets, but JSCC was performed ignorant of the presence of CPR. We also compare the performance of a conventional JSCC scheme optimized for the average peer when CPR is disabled. `HM` WWAN loss model was used in the simulation.

Fig. 4(a) shows the average video quality for the *Foreman* sequence for all N peers and CPR data rates ranged from 0 to 1500 kb/s. CPR WWAN loss rate was 0.3. For our proposed CPR-aware JSCC, the vertical bar shows the maximum and minimum PSNR in our simulated data. Note the range of CPR data rates already takes background traffic into consideration because typical WLAN bandwidth is much higher.

When CPR-aware JSCC was performed, we see that with the increase of CPR data rate, video quality was greatly improved. The improvement over the CPR-ignorant JSCC scheme is significant, where CPR was only helpful at the beginning and then flat-lined. The reason is as follows: when the system was optimized ignorant of CPR, JSCC cannot take advantage of improving CPR recovery to allocate more

[5]257 was used as the NC encoding finite field size because our external tool [38] used to perform matrix manipulation only takes in prime number as the field size.

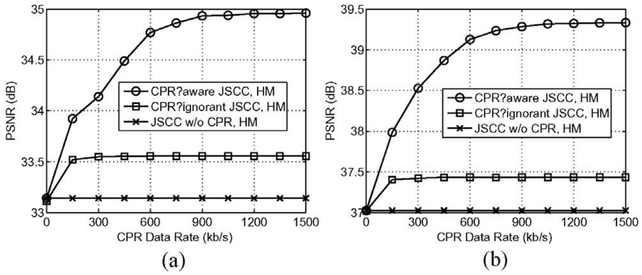


Fig. 5. CPR-aware rate-distortion optimized JSCC versus CPR-ignorant JSCC using UNC. WWAN loss rate 0.1. (a) *Foreman* sequence. (b) *News* sequence.

WWAN bits to source coding to further eliminate quantization noise, resulting in a maximum achievable PSNR due to fixed source coding. The maximum gain of CPR-aware JSCC over CPR-ignorant JSCC was 4.7 dB when the data rate was 1500 kb/s. We see also that our CPR-aware JSCC scheme outperformed the conventional JSCC scheme without CPR by up to 5.6 dB. Fig. 4(b) shows similar video quality improvement for the *News* sequence. Our CPR-aware JSCC scheme obtained 6.0 dB gain over CPR-ignorant JSCC scheme, and 7.4 dB gain over conventional JSCC scheme where CPR was not available. As shown by the confidence intervals, both test sequences and across the whole range of CPR data rates, all data points are within 1 dB distance away from the average values in PSNR, demonstrating stability of our scheme. The dynamic range for the CPR-ignorant JSCC scheme is really small and most data points are closed to the average (hence the vertical bars are not visible).

Fig. 5 shows the average video quality for the *Foreman* and *News* sequences when WWAN loss rate was 0.1. Similar to the previous simulation setup, we obtain significant performance improvement with our CPR-aware JSCC scheme. For the *Foreman* sequence, the maximum gain of CPR-aware JSCC over CPR-ignorant JSCC was 1.4 dB. Our CPR-aware JSCC scheme outperformed the conventional JSCC scheme without CPR by up to 1.8 dB. For the *News* sequence, CPR-aware JSCC outperformed CPR-ignorant scheme by 1.9 dB and outperformed conventional JSCC without CPR by up to 2.3 dB. We can hence conclude that our proposed CPR-aware JSCC scheme reaps more gain when the WWAN channel is poor.

C. CPR-Aware JSCC Using UNC and SNC

We next compare the performance of CPR-aware JSCC using UNC to JSCC using SNC. As discussed in our previous work [9], SNC can achieve further performance gain over UNC given limited WLAN resource. We consider HT model with two settings: HT1 and HT2. For HT1 loss model, WWAN loss rates in the two HT regions were 0.15 and 0.45. For the HT2 case, WWAN loss rate difference in the two regions was larger and set at 0.1 and 0.5.

As shown in Fig. 6, we see that CPR-aware JSCC using SNC outperformed JSCC using UNC. We can see that with the increase of the variance in WWAN packet loss rate, SNC obtained more performance gain over UNC. This is due to the fact that SNC provides more structure in NC and can better accommodate the heterogeneous environment. When CPR data rate was higher, the gap between SNC and UNC was reduced. This is because with the increase of CPR data rate, UNC can recover more packets and the effect of heterogeneity in CPR reduces. Since JSCC using SNC outperformed UNC, we use SNC in our following discussions.

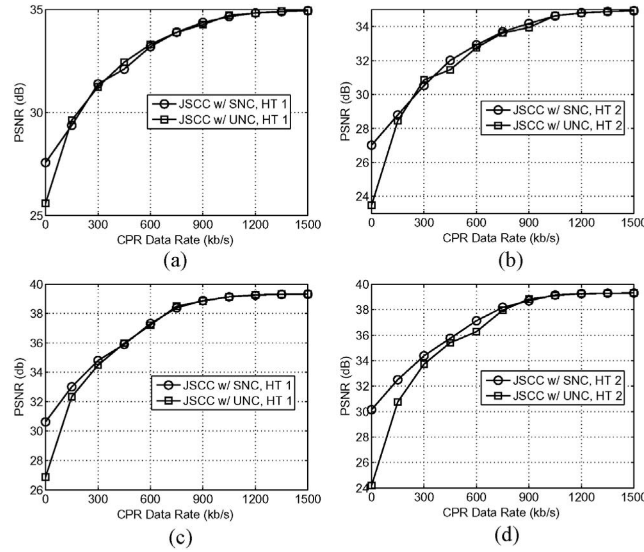


Fig. 6. Performance comparison between CPR-aware JSCC using UNC and SNC. (a) *Foreman* sequence, HT 1 loss. (b) *Foreman* sequence, HT 2 loss. (c) *News* sequence, HT 1 loss. (d) *News* sequence, HT 2 loss.

D. Insights into CPR-Aware JSCC

1) *Ensemble Gain and Disparate Gain:* As discussed before, with our CPR-aware rate-distortion optimized JSCC scheme, peers in the CPR network can obtain both *ensemble* gain and *disparate* gain. In order to quantify these gains, we performed simulations with both the HM and HT loss models using SNC and WWAN loss rate was set to 0.3.

Fig. 7(a) shows the visual quality for the *Foreman* sequence. With the HM loss model, we can see that our proposed CPR-aware JSCC scheme provided significant video quality improvement (up to 4.1 dB) over CPR-ignorant JSCC. This performance gain is clearly *ensemble* gain alone, since each peer experienced the same WWAN channel statistics and there was no differentiation between poor and rich peers. The ensemble gain was reaped due to "strength in numbers:" a packet was correctly delivered to a peer n if it was correctly delivered to *any* one peer in the CPR collective, and subsequent CPR propagated the transmitted packet to peer n.

More interestingly, comparing Fig. 7(a) and (b), i.e., the HM and HT loss models, we observed larger performance improvement in the latter case. This is due to the fact that CPR can now exploit *disparity* gain, in addition to ensemble gain. In particular, a CPR-aware JSCC scheme can selectively exploit strong channels of rich peers (for disparity gain), while still leveraging channel of poor peers (for ensemble gain), to optimize the collective's performance. We see that our CPR-aware JSCC scheme outperformed the CPR-ignorant JSCC scheme by up to 4.5 dB.

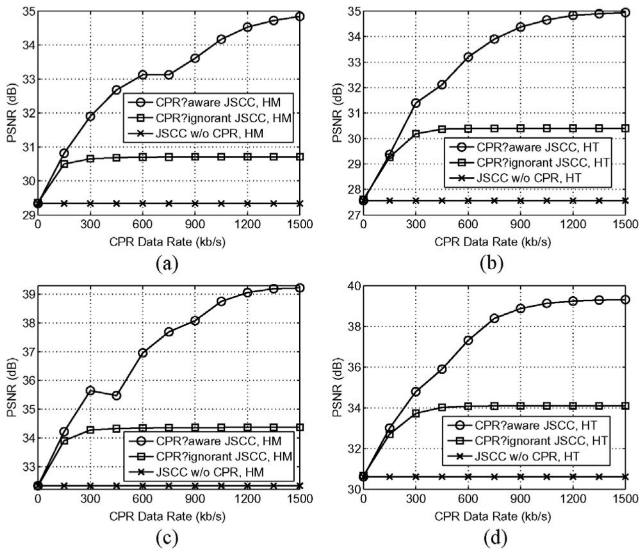


Fig. 7. Ensemble gain and disparate gain with CPR-aware JSCC. (a) *Foreman* sequence, HM loss. (b) *Foreman* sequence, HT loss. (c) *News* sequence, HM loss. (d) *News* sequence, HT loss.

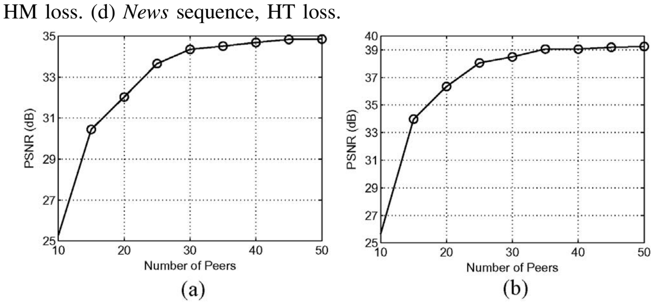


Fig. 8. CPR-aware rate-distortion optimized JSCC with various network density. (a) *Foreman* sequence. (b) *News* sequence.

Comparing to conventional JSCC scheme where CPR was not available, our scheme achieved 5.5 dB gain for HM loss model, and 7.4 dB gain for HT loss model.

We saw similar performance trends for the *News* sequence in Fig. 7(c) and (d). We obtained 6.9 dB and 8.7 dB improvements over conventional JSCC scheme under HM and HT models, respectively. Comparing to the CPR-ignorant JSCC scheme, we obtained 4.9 dB and 5.2 dB performance improvement under HM and HT models, respectively.

2) *CPR-Aware JSCC with Various Network Density:* We also validate the performance of our CPR-aware JSCC scheme under various network density settings. The network size is fixed and the same as before. However we change the number of peers participating in CPR.

Fig. 8 shows our CPR-aware JSCC scheme with peers ranging from 10 to 50 for both *Foreman* and *News* sequences. When there are fewer peers performing CPR, video quality is low because of less CPR packet exchange opportunity. However, when more than 20 peers are participating in CPR, PSNR is already in 30 dB range for both two sequences, which implies good video quality.

VIII. CONCLUSION

In this paper, we proposed a CPR-aware rate-distortion optimized JSCC scheme for a cooperative peer-to-peer collective for WWAN video multicast. We showed that our scheme achieved significant performance improvement over CPR-ignorant JSCC schemes with or without CPR. We achieved the gain by devoting more WWAN bits to source coding out of a fixed WWAN transmission budget without an increase in channel losses by exploiting disparity and ensemble gain inherent in a CPR transmission paradigm. Our simulations showed that our CPR-aware JSCC optimization scheme outperformed the existing JSCC scheme where CPR is not available by up to 8.7 dB, and up to 6.0 dB for a CPR-ignorant JSCC scheme.

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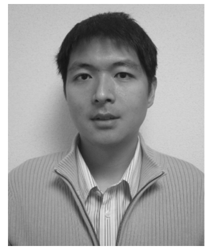

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