

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

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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 n th-percentile WWAN user. Not only is FEC bitwise expensive, users with poorer reception than n th-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 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 (from different channel conditions experienced), 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 extensive simulations that using our proposed scheme dramatically improves video quality for the entire collective over existing optimization scheme where joint source/channel coding was performed, but WLAN CPR is not used, by up to 8.4 dB, and over scheme when WLAN CPR repair is used but WWAN joint source/channel coding was 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 (ARQ) for link losses cannot be implemented per packet and per receiver due to the well-known point-to-multipoint NAK (negative acknowledgment) implosion problem [2]. Given a large receiver group with a range of statistical channel conditions, previous works like [3] have allocated channel coding bits from a fixed transmission budget for forward error correction (FEC) like Raptor Code to protect source packets from WWAN losses, targeting a chosen n th-percentile receiver. Not only is channel coding bitwise expensive, receivers with channels worse than n th-percentile receiver's (poor receivers) suffer substantial packet losses, while receivers with better channels (rich receivers) have more channel coding than necessary, i.e., not enough bits out of the budget are devoted to source coding, and 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 network capabilities—ones with both WWAN and WLAN (Wireless Local Area Network) network interfaces like 802.11—called *Cooperative Peer-to-peer Repair* (CPR) [4]. 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 [5] that by first encoding received WWAN packets into coded packets using network coding [6] 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 targeted n th-percentile receiver can now exploit this more general transmission condition in two ways. First, the source no longer needs to expend substantial channel coding efforts 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 statistically, i.e., there is no differentiation between poor and rich receivers, a packet is lost to the collective *only if* WWAN transmissions to every single peer in entire collective fail—a much stronger loss condition than when JSCC was optimized for individual n th-percentile receiver. 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*.

Note that optimizing JSCC in the CPR paradigm means *all receivers*, not just the targeted n th-percentile receiver, can benefit from disparity and ensemble gain by polling their WWAN and WLAN resources together for a common cause, improving overall system performance. This JSCC approach for CPR collective is a complete departure from previous JSCC works [3] for WWAN multicast for disparate individual receivers, where targeting a chosen n -percentile receiver always leads to a large group of sub-optimal receiver group with different statistical channels from the target.

As an illustrative example, consider the case where after a single peer has received a given packet directly from WWAN multicast, WLAN resources are abundant enough to guarantee CPR recovery of the given packet to all peers. No matter what n th-percentile receiver the source is targeting, it should then only allocate just enough bits for channel coding such that a given packet is received by at least one peer in the collective; i.e., *anycast*. To exploit disparity gain, that means optimizing for the best receiver with the best channel statistics. To exploit ensemble gain, that means optimizing for the WWAN collective loss condition, which is surely stronger than disparate individual loss condition. Our optimization aims to cover this anycast case and all other cases where CPR recovery is imperfect due to limited WLAN resources.

To efficiently implement WWAN-FEC and WLAN-CPR, we propose to use network coding for the dual purpose. Our proposal has two advantages: i) a WWAN receiving peer 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 and contribute to CPR right away; and ii) WWAN-FEC decoding and WLAN-CPR decoding can be done at the same time at the peers after WWAN transmission and CPR are both completed, reducing decoding complexity. Extensive simulation experiments show that our JSCC scheme improves over a previous JSCC scheme by up to 8.4 dB where joint source/channel coding 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. We first review related work in Section II. We then overview CPR in Section III. We discuss our end-to-end system for WWAN video multicast in Section IV. We present our JSCC optimization in two parts: unstructured network coding case and structured network coding case in Section V and VI, respectively. Simulation results and conclusions are presented in Section VII and VIII.

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 mechanisms like [7] and opted instead for FEC like Raptor Codes [8]. While FEC helps receivers with channels as good as the targeted n th-percentile receiver's to recover packets, receivers with worse-than-targeted channels will suffer great losses. Note that setting target to the lowest denominator (receiver with the worst channel) does not relieve sub-optimality; targeting JSCC for the worst receiver in a large 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. Common practice like [3] advocates targeting the average user ($n = 50$) as a good tradeoff point¹.

Recent research on ad-hoc group of multi-homed devices [9], [10]—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. [9] 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. [10] 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

¹It can be shown that our proposed scheme can outperform conventional schemes when n is set to any value; $n = 50$ is used simply as a convenient known comparison point.

a typical single-channel FEC interleaver. Our CPR work [4], [5], [11], [12] extends this research line on ad-hoc multi-homed peer group to local recovery of WWAN multicast packets via WLAN packet exchanges.

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. ([13] have independently proposed similar WLAN cooperative scheme recovering WWAN broadcast/multicast losses, though our first work [4] pre-dates theirs.) We have also designed and imposed structure on network coding [11], [12] for a group of video pictures (GOP) 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. Our proposed JSCC in this paper differs in that we can exploit both disparity and ensemble gain, so that even in a scenario where the peers' channel statistics are similar and CPR is marginally helpful (to be shown in Section VII), our scheme can still improve performance greatly by exploiting ensemble gain.

Network Coding (NC) has been a popular research area since Ahlswede's seminal work [14], which showed that network capacity can generally be achieved using NC. Recent works [15], [16], [17] have proposed to optimize video streaming using NC. While our structured network coding work [11], [12] also performed rate-distortion optimization, 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.

In [18], the authors proposed priority random linear codes for P2P and sensor networks such that more important data has a higher probability to be recovered through node failures. The structure of the priority codes is similar to our SNC. However, our application of NC is in video streaming and we provide a rate-distortion optimization framework to find the best NC structure.

III. COOPERATIVE PEER-TO-PEER REPAIR

To motivate our JSCC optimization for a CPR collective, we overview our CPR work in this section. We first discuss source and network models that are also used for our current work in Section III-A and III-B. We then discuss two types of network coding a peer can use to encode received WWAN packets into coded packets before CPR exchange for improved recovery: traditional *unstructured networking coding* (UNC) in Section III-C and our proposed *structured network coding* (SNC) in Section III-D. Our

proposed NC-based FEC for WWAN, to be discussed in Section IV, is also based on SNC.

A. Video Source Model & Assumptions

We use H.264 [19] codec for video encoding because of its proven superior rate-distortion performance over previous coding standards. A H.264 video stream is a series of *Group of Pictures* (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 multicast in time duration Y , peers exchange CPR packets via WLAN to repair this GOP in time Y during WWAN multicast of the next GOP. Y is hence also the *repair epoch* in which CPR must complete its repair on a given GOP. The playback buffer delay for each peer is two repair epochs.

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. If a frame F_i fails to decode, the decoder will display the most recent correctly decoded frame F_j , $j < i$, for simple error concealment.

Each video frame F_i is encoded from original picture F_i^o with source coding rate r_s^i . Rate r_s^i is subsequently divided into $R_s^i = \left\lceil \frac{r_s^i}{S_{pkt}} \right\rceil$ source packets, $\mathcal{P}_i = \{p_{i,1}, p_{i,2}, \dots, p_{i,R_s^i}\}$, for transmission, where S_{pkt} is the maximum packet size. If a frame cannot be divided into an integer number of packets, the last packet is padded with zeros, similarly done in [16]. Note this is only performed for the purpose of CPR. When the packets are transmitted through WWAN, the padding bits are removed and there is no bandwidth waste. Each frame F_i has an associated d_i , the resulting *distortion reduction* if F_i is correctly decoded. d_i is calculated as follows: it is the visual quality (PSNR) 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^o 's in the GOP, $j > i$, in the event that F_j 's are incorrectly decoded, minus the error concealment quality of F_{i-1} (if one exists). This means d_i is a function of both source coding rate for F_i , r_s^i , and coding rate for F_{i-1} , r_s^{i-1} .

B. Network Model & Assumptions

We assume N peers are listening to the same WWAN video multicast using their multi-homed devices, which are also equipped with WLAN interfaces. We assume also that the peers are physically located in close enough proximity that a peer-to-peer wireless ad-hoc network can be formed. For simplicity, we

denote *media source* to mean both a media encoder (where video streams are encoded), and the actually video multicasting entity over WWAN.

For WWAN, we assume peers in the same WWAN multicast group experience different statistical channel conditions, resulting in different subsets of received WWAN packets in a GOP. For WLAN, though raw transmission rate like 802.11 is relatively large, peers need to contend for the shared medium for transmission in a distributed manner so that the occurrences of collision and interference are reduced. For brevity, we omit the discussion on a distributed algorithm [20] that schedules WLAN ad-hoc peer transmissions. We simply assume a peer can on average receive B total repair packets successfully via WLAN-CPR in a repair epoch, which varies depending on available WLAN resources for CPR (constrained by factors such as power [11], [12], contending cross traffic [20], etc).

C. Unstructured Network Coding based CPR

At a given WLAN-CPR transmission opportunity (as dictated by a scheduling algorithm [20]), what packet should a peer broadcast locally to its neighbors via WLAN? We have proposed for each peer to encode received WWAN packets into a coded packet using NC [21] before performing CPR exchange [20]. The traditional UNC method [21] in the CPR context works as follows. Given M frames in a GOP, $\mathcal{F} = \{F_1, \dots, F_M\}$, we first denote \mathcal{P}^* as the set of corresponding *native packets* in the GOP, i.e., $\mathcal{P}^* = \{\mathcal{P}_1, \dots, \mathcal{P}_M\}$. There are a total of $P = |\mathcal{P}^*| = \sum_{i=1}^M R_s^i$ native packets to be disseminated among the peers.

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:

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

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 (1), q_n can be rewritten as a linear combination of only native packets using *native coefficient vector* $\mathbf{v} = [c_{1,1}, \dots, c_{1,R_s^1}, \dots, c_{M,1}, \dots, c_{M,R_s^M}]$.

For UNC, *all* available native packets and NC packets at a peer are used for every NC encoding. A peer can reconstruct *all* P native packets when an *innovative set* of P native or NC packets are received, recovering all frames. By innovative set, we mean that the native coefficient vector of a packet in the set

cannot be a linear combination of native coefficient vectors of other packets in the set. The shortcoming of UNC is that if a peer n receives fewer than P innovative packets, then this peer cannot recover *any* native packets using the received NC packets. This happens when WLAN resources for CPR are limited, leading to small B total CPR exchanges available for possibly large number of WWAN packet losses.

D. Structured Network Coding based CPR

To address UNC's shortcoming, we have proposed SNC. 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. We accomplish that by forcing some chosen coefficients $a_{i,j}$'s and b_m 's in (1) to be zeros during NC packet generation, so that when a peer receives m innovative packets, $m < P$, it can decode m packets (m linear equations for m unknowns) and a subset of video frames in a GOP can be recovered.

More precisely, we first define a series of X SNC frame groups, $\Theta_1, \dots, \Theta_X$, where $\Theta_1 \subset \dots \subset \Theta_X = \mathcal{F}$. 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 :

$$g(j) = \arg \min_{x=1, \dots, X} |\Theta_x| \quad \text{s.t. } F_j \in \Theta_x. \quad (2)$$

Native packets of frame F_j are of SNC packet type $g(j)$. 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:

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

where $U(c)$ 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 $\leq x$.

At each WLAN-CPR transmission opportunity, a peer randomly selects one NC group Θ_x with NC group selection probability $\beta(x)$ for transmission. Group Θ_x can be decoded if $\sum_{F_i \in \Theta_x} R_s^i$ innovative packets are received. By selecting $\beta(x)$'s appropriately, a peer can have a high probability of decoding important frame groups Θ_x 's even if a peer fails to receive all P innovative packets after a CPR repair epoch.

For the ease of later derivation, we write the probability that fewer than m NC packets of frame group x can be delivered in a CPR epoch as follows:

$$Q(m, x) \approx \sum_{k=0}^{m-1} \binom{B}{k} \left(\sum_{i=1}^x \beta(i) \right)^k \left(\sum_{i=x+1}^X \beta(i) \right)^{B-k} \quad (4)$$

IV. VIDEO MULTICAST SYSTEM OVERVIEW

Given the existence of a CPR collective, we now discuss how NC-based FEC can be added for WWAN transmission to protect against packet losses end-to-end in combination with WLAN-CPR. We first overview how we use NC for the dual purpose of WWAN-FEC and WLAN-CPR. We then discuss a WWAN collective packet loss model used to construct an objective function for our JSCC optimization.

A. Network Coding based WWAN-FEC

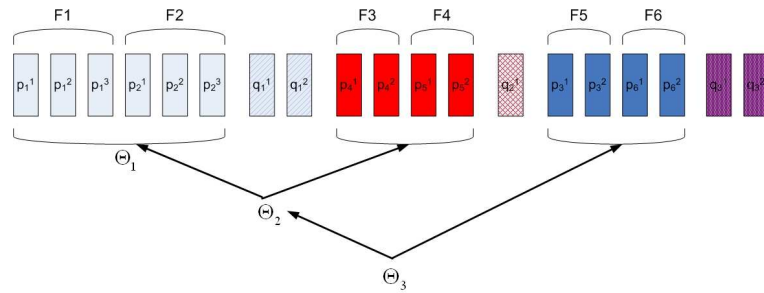


Fig. 1. An example NC-FEC GOP with three frame groups.

Though FEC like Raptor Code [8] are commonly used to protect source packets from WWAN multicast losses, we propose to use NC for the dual purpose of WWAN packet loss protection (WWAN-FEC) and WLAN-CPR packet recovery (WLAN-CPR). 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 [22], it is a *perfect code*; i.e., receiving any k of n transmitted packets constitutes full recovery. However, NC requires matrix-inversion to solve k equations for k unknowns to recover original packets. Given we are optimizing one GOP at a time, the total number of source packets are relatively small, and decoding complexity is not a major concern.

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

$$q(x) = \sum_{p_{i,j} \in \mathcal{P}_i, F_i \in \Theta_x} c_{i,j} p_{i,j}. \quad (5)$$

Though similar to (3), 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 illustrating example, Fig. 1 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, and one WWAN-FEC packet generated for Θ_2 of four frames and ten source packets, etc.

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 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 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.

B. WWAN Collective Packet Loss Model

The working assumption for CPR is that a source packet is received (or if FEC of k source and $n - k$ FEC packets are used, at least k of n packets are 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 n th-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 transmission 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 in our JSCC work.

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.

If packet losses are spatially uncorrelated, the collective packet loss probability is simply the product of individual peer loss probabilities. Due to shadow effect and signal strength attenuation with respect to distance, however, 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 n th-percentile peer has lost the packet, can now be written:

$$l'_{col} \approx \prod_{m \in \mathcal{N} \setminus n} (l_m)^\rho \approx (l_{avg})^{\rho(N-1)}, \quad (6)$$

where \mathcal{N} are the peers in the CPR collective, and l_m is the individual loss rate for peer m . l_m 's could be channel estimates sent infrequently but periodically from receivers' to WWAN source, or estimated by WWAN source based purely on receivers' proximity to WWAN base stations.

In the absence of per peer channel statistics, source can instead use l_{avg} , the packet loss rate for the average peer in typical network condition, as the loss rate for all peers.

V. UNSTRUCTURED NETWORK CODING CASE

To impart intuition, we first describe how JSCC for a CPR collective can be performed using UNC. JSCC using SNC, to be described in Section VI, will be a natural extension. We first derive the optimization mathematically. We then show it agrees with our intuition at the two boundary cases when CPR is unhelpful or perfect in packet recovery.

A. Joint Source/Channel Optimization for Single Frame Group

Let the optimization variables be R_s , the number of source packets, and R_c , the number of WWAN-FEC packets. The objective is to minimize the expected distortion at the average peer ($n = 50$):

$$\min_{R_s, R_c} \{D - d(R_s)(1 - p_{grp}(R_s, R_c))\} \quad \text{s.t. } R_s + R_c \leq \bar{R}, \quad (7)$$

where D is the distortion if no packets are received at a peer, $d(R_s)$ is the distortion reduction if R_s source packets were used to encode the GOP, $p_{grp}(R_s, R_c)$ is the *group loss probability* if R_s source and

R_c WWAN-FEC packets were used, and \bar{R} is the WWAN packet budget available for transmission for a GOP.

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

$$p_{grp}(R_s, R_c) = \sum_{i=R_c+1}^{R_s+R_c} \binom{R_s+R_c}{i} l_{avg}^i (1-l_{avg})^{R_s+R_c-i} * p_{col}(i, R_c), \quad (8)$$

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

$$p_{col}(i, R_c) = p_{isuf}(i, R_c) + (1 - p_{isuf}(i, R_c)) Q(i) \quad (9)$$

where $Q(i)$ is *CPR loss probability* for UNC, as compared to Eq. (4) for SNC. $Q(i)$ is 1 if i is greater than B and 0 otherwise. 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:

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

(10) 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. Therefore there is no way that the peer can recover the whole packet group.

B. Boundary Cases

We check the two boundary cases for our derivation as follows. If CPR is unhelpful and $Q(i) = 1$, then collective loss probability $p_{col}(i, R_c) = 1$. Our optimization (7) and (8) defaults to optimizing JSCC for the average peer without CPR, agreeing with our intuition.

If CPR is perfect and loss probability $Q(i) = 0$, then collective loss probability $p_{col}(i, R_c) = p_{isuf}(i, R_c)$. Substituting $p_{isuf}(i, R_c)$ back to (8), we have:

$$p_{grp}(R_s, R_c) = \sum_{i=R_c+1}^{R_s+R_c} \binom{R_s+R_c}{i} l_{avg}^i (1-l_{avg})^{R_s+R_c-i} \times \sum_{j=0}^{i-R_c-1} \binom{i}{j} (1-l'_{col})^j (l'_{col})^{i-j}. \quad (11)$$

Rearranging the two sums, the product terms in (11), and expressing the combinations explicitly, we get:

$$p_{grp}(R_s, R_c) = \sum_{i=R_c+1}^{R_s+R_c} \sum_{j=0}^{i-R_c-1} \frac{(R_s+R_c)!}{(R_s+R_c-i)! (i-j)! j!} \times (1-l_{avg})^{R_s+R_c-i} [l_{avg}(1-l'_{col})]^j (l_{avg}l'_{col})^{i-j}. \quad (12)$$

Now change the variables j to k , i to $m+k$, and change the upper and lower limits of the sum in (12), we can write $p_{grp}(R_s, R_c)$ as follows (assuming $R_s + R_c = \bar{R}$):

$$\begin{aligned} &= \sum_{m=R_c+1}^{\bar{R}} \sum_{k=0}^{\bar{R}-m} \frac{(\bar{R})!}{(\bar{R}-m-k)! m! k!} \times (1-l_{avg})^{\bar{R}-m-k} [l_{avg}(1-l'_{col})]^k (l_{avg}l'_{col})^m \\ &= \sum_{m=R_c+1}^{\bar{R}} \binom{\bar{R}}{m} (l_{avg}l'_{col})^m \times \sum_{k=0}^{\bar{R}-m} \binom{\bar{R}-m}{k} (1-l_{avg})^{\bar{R}-m-k} [l_{avg}(1-l'_{col})]^k \\ &= \sum_{m=R_c+1}^{R_s+R_c} \binom{R_s+R_c}{m} (l_{avg}l'_{col})^m (1-l_{avg}l'_{col})^{R_s+R_c-m}. \end{aligned}$$

The last step is due to Binomial Theorem. Our optimization now defaults to optimizing for *anycast*: if enough packets are received by any one peer within the collective, then the whole collective can recover the GOP. This agrees with our developed intuition in the Introduction.

VI. STRUCTURED NETWORK CODING CASE

In this section, we extend the JSCC optimization for a CPR collective discussed previously to SNC. Beyond searching for the best resource allocation for WWAN source and channel coding, we need to consider jointly the optimal SNC as well. We first define the objective function and derive the optimization. We then present heuristics to obtain locally optimal optimization parameters in a time-efficient manner.

A. Optimization Objective

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

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

where $d_i(r_s^i, r_s^{i-1})$ 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} , respectively, 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:

$$\min_{r_s^i, R_c^i, \Theta_x, \beta(x)} D_{S+C}, \quad (14)$$

with WWAN transmission constraint:

$$\sum_{i=1}^M \left\lceil \frac{r_s^i}{S_{pkt}} \right\rceil + \sum_{i=1}^M R_c^i \leq \bar{R}, \quad (15)$$

where $\sum_{i=1}^M R_c^i$ is the total number of WWAN-FEC packets. Note with source coding rate r_s^i , frame i is packetized into R_s^i packets to perform NC.

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. $B_x = C_x \cup C_{x+1} \cup \dots \cup C_X$.

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

$$\begin{aligned} Pr(\bar{B}_1) &= Pr(\bar{C}_1 \cap \bar{C}_2 \cap \dots \cap \bar{C}_X) \\ &= Pr(\bar{C}_1) Pr(\bar{C}_2 | \bar{C}_1) \dots Pr(\bar{C}_X | \bar{C}_{X-1}, \dots, \bar{C}_1). \end{aligned} \quad (16)$$

Each of the product terms in (16) can be obtained by utilizing the group loss probability (8) derived for UNC, with an extra parameter to identify the particular frame group in question:

$$Pr(\bar{C}_y | \bar{C}_{y-1}, \dots, \bar{C}_1) \approx p_{grp}(\sum_{i=1}^y R_s^i - 1, R_c^y - 1, y), \quad (17)$$

where $p_{grp}(R_s, R_c, y)$ is now the group loss probability for NC group y . In words, (17) says that given the previous frame groups $\Theta_i, 1 \leq i \leq y-1$, 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 $R_c^y - 1$ WWAN-FEC packets. Note since we know previous frame groups cannot be recovered with their WWAN-FEC packets, the current frame group must spend at least one WWAN-FEC

packet to help the previous frame groups, which results in the -1 in both the source and channel coding packets.

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

$$Pr(\bar{B}_2) = Pr(\bar{B}_1) + [1 - Pr(\bar{B}_1)]Pr(\bar{B}_2|B_1). \quad (18)$$

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:

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

where:

$$Pr(\bar{C}_2 | B_1) \approx p_{grp}(R_s^2, R_c^2, 2) \frac{Pr(C_1)}{Pr(B_1)} \quad (19)$$

$$Pr(\bar{C}_y | \bar{C}_{y-1}, \dots, \bar{C}_2, B_1) \approx p_{grp}\left(\sum_{i=2}^y R_s^i - 1, R_c^y - 1, y\right). \quad (20)$$

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 Appendix 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

(14) involves the optimization of four sets of variables: source coding rates r_s^i 's, NC groups Θ_x 's, WWAN-FEC for the NC groups R_c^i 's, and peers' NC group selection probabilities $\beta(x)$'s. Exhaustively searching for the best combination is simply not practical. Hence we use Algorithm 1 to iteratively optimize source coding and SNC structure in turn separately.

We first initialize the total number of WWAN-FEC packets to be $T = \sum_{i=1}^M R_c^i$. Given T and an initial segment recovery probability α 's, we find the optimal source bit allocation r_s^i 's using Algorithm *OptimizeSource()*. 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 using Algorithm *OptimizeSNC()*. We iterate until we converge

to a solution. We perform this for all feasible values of T to find the best solution. We describe *OptimizeSource()* and *OptimizeSNC()* in more details below.

Algorithm 1: Iterative Joint Source/Channel Optimization

```

 $D_{S+C}^{min} = \infty;$ 
for  $T = 1$  to  $\bar{R}$  do
   $R_S^{budget} = \bar{R}S_{pkt} - TS_{pkt};$ 
  while  $converge = 0$  do
     $r_s^i$ 's = OptimizeSource( $\alpha$ 's,  $R_S^{budget}$ );
    [ $D_{S+C}^{cur}$ ,  $\alpha$ 's,  $\Theta_x$ 's,  $\beta(x)$ 's] = OptimizeSNC( $r_s^i$ 's);
    if  $D_{S+C}^{cur} < D_{S+C}^{min}$  then
      |  $D_{S+C}^{min} = D_{S+C}^{cur};$ 
    end
  end
end
return  $r_s^i$ 's,  $\Theta_x$ 's,  $R_c^i$ 's,  $\beta(x)$ 's;
```

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 [23]. 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. The key heuristic used is *monotonicity*, i.e., the dependent frame's family of R-D curves are monotonic in the fineness of the quantizer choice associated with the parent frame from which they are derived. Note that along the growing of the dependency trellis, only the paths that pass the heuristic test are selected. Therefore, the computation complexity of the path identification process is greatly reduced. See [23] for details.

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 first observe

the following: because a GOP is a dependency chain, a frame in the chain is of greater importance than its descendant frames, and frame F_i should not be allocated more resource than frame F_j , $j < i$. The observation has two implications: i) a parent frame should not be assigned a NC type larger than its children frames; and ii) NC group selection probabilities and WWAN-FEC packets for each NC group should be monotonically non-increasing. Using the two implications above, we design the following scheme.

We first assign M NC types to the M frames from first frame onwards. We then compute $\beta(x)$'s and R_c^i 's 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 result in the largest decrease in expected distortion. Each merging results in a new NC structure, again we compute $\beta(x)$'s and R_c^i 's that result in the smallest distortion. We continue until all distortion-reducing mergings are explored.

To obtain possible R_c^i allocation, we observe the second implication. We first divide T by two and allocate half of the packets to frame group 1. The rest of the packets are evenly allocated to the rest of the frame groups. Then, we allocate half of the packets to the first two frame groups, and the other half to the rest of the frame groups. We stop this procedure when we must allocate more FEC packets to the latter frame groups, i.e., after $\frac{X}{2}$ allocation rounds. We use similar resource allocation procedure for the generation of β_x .

With the above local search scheme, 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 merge operations performed. As for the resource allocation regarding \vec{R}_c and β_x , each takes $\frac{X}{2}$ rounds. Combining the three resource allocation problems, in all the search space size is $\frac{M^2 X^2}{4}$, which is significantly less than an exhaustive search. With this fast scheme we can bound the optimization in a reasonable amount of time for fast online implementation.

VII. EXPERIMENTATION

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

Algorithm 2: Optimize SNC Structure

Input : \vec{r}_s, T
Output: $D_{S+C}^{cur}, \vec{\alpha}, X, \Theta_x, \beta_x$
 $X = M$;

 $D_{S+C} = \infty$;

for $i = 1$ **to** M **do**

 for $j = 1$ **to** $M - i$ **do**

 Based on the merge result of round $i - 1$, merge Θ_j and Θ_{j+1} ;

 Set X to current;

 for $k = 1$ **to** $\frac{X}{2}$ **do**

 Allocate $\frac{T}{2}$ packets evenly to first k frame groups ;

 Allocate $\frac{T}{2}$ packets evenly to the rest $X - k$ frame groups ;

 for $m = 1$ **to** $\frac{X}{2}$ **do**

 Allocate $\frac{1}{2}$ evenly to first m frame groups as transmission probabilities;

 Allocate $\frac{1}{2}$ evenly to the rest $X - m$ frame groups as transmission probabilities ;

 Calculate D_{S+C}^{cur} ;

 if $D_{S+C}^{cur} < D_{S+C}$ **then**

 $D_{S+C} = D_{S+C}^{cur}$;

 Set $\vec{r}_s, \vec{R}_c, X, \Theta_x, \beta_n(x)$ to current;

 end

 end

 end
end
end

 return $\vec{r}_s, \vec{R}_c, X, \Theta_x, \beta_n(x)$;

A. Simulation Setup

Two test video sequences were used for simulations: 300-frame MPEG class A news and class B foreman sequences at QCIF 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. The H.264 codec used was JM 12.4, downloadable from [24].

We considered a CPR network of size $500 \times 500 m^2$ where peers were uniformly distributed. All the

peers used the broadcast mode of WLAN, and so no feedback messages were sent from the receivers and no transmission rate adaption was performed. We assume that the peers do not move during the CPR process. 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 packet loss (HM) and Heterogeneous (HT) packet 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 average loss rate 0.45, which captured the spatial packet loss characteristic. The overall average packet loss rate, however, remains 0.3. We assume WWAN losses among peers are not spatially correlated [25], and the correlation factor ρ is 1.

We used QualNet [26] to conduct the simulations. To have the freedom to vary CPR bandwidth to reflect different amount of WLAN resources available for CPR under different network settings [20], we selected *Abstract PHY* in QualNet and set all of the parameters to be the default values in 802.11.

B. Simulation Results

1) *Optimization Results:* We first show the effectiveness of our JSCC optimization by presenting some of the solutions returned, i.e., the number of WWAN-FEC packets, number of frame groups, and quantization levels, with respect to three CPR working scenarios: CPR recovery is unhelpful, CPR recovery is helpful but not perfect, and CPR recovery is very good. The parameters shown in Table I used the first GOP of foreman sequence. WWAN loss rate was 0.3.

	CPR Good	CPR Half-helpful	CPR Unhelpful
# WWAN-FEC	2	7	14
# FG	5	10	1
QP	7 frames 30 & 8 frames 31	32	8 frames 35 & 7 frames 36

TABLE I
JOINT SOURCE/CHANNEL OPTIMIZATION PARAMETERS

From Table I we can see that when CPR was unhelpful, substantial network resources were allocated to WWAN-FEC packets, and thus few resources were left for source coding, resulting in coarse quantization

levels and bad video quality. When CPR was unhelpful, there was only one frame group. This is intuitive because all the WWAN-FEC packets were devoted to protect the all the native packets. When CPR was half-helpful, there was 10 frame groups. This again verifies our intuition of SNC that as long as the important frames can be recovered, performance can be greatly improved. When CPR was good, the number of frame groups reduced as compared to CPR half-helpful. The number of WWAN-FEC packets also reduced due to the improved CPR quality.

2) *Optimization for a CPR Collective vs. Optimization for Average Peers:* We compared resulting visual quality (PSNR) when the JSCC was optimized for the average peer in the 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.

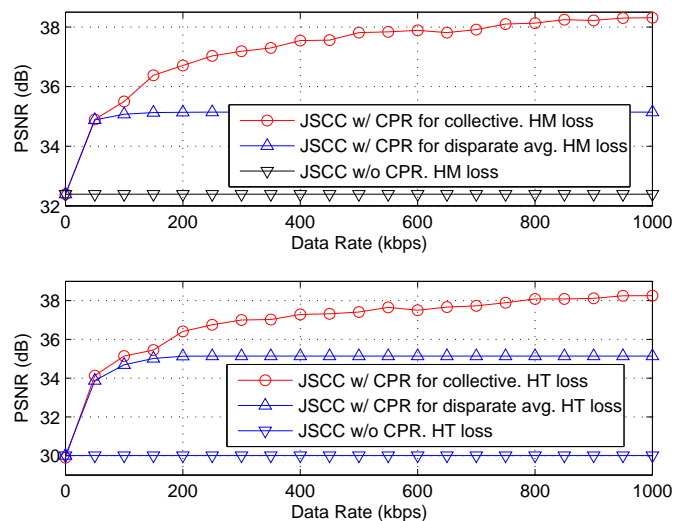


Fig. 2. Performance comparison between optimization for the collective and for the disparate average peers. foreman sequence.

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

Bottom 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, unlike HM we see a gradual video quality improvement. 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.

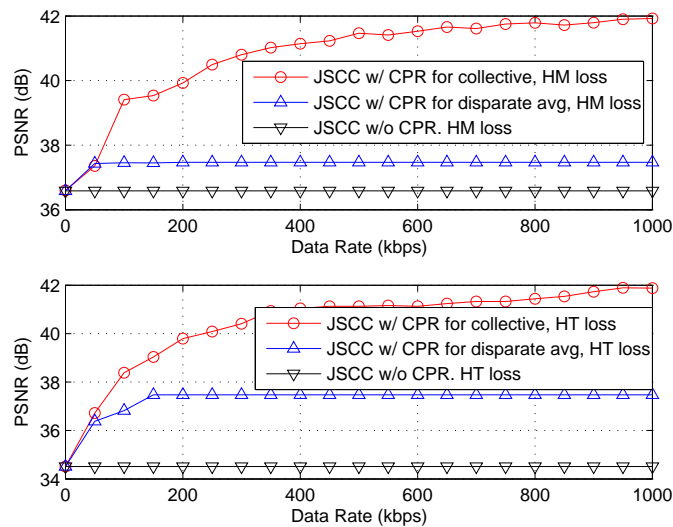


Fig. 3. Performance comparison between optimization for the collective and for the disparate average peers. news sequence.

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.

VIII. CONCLUSION

In this paper, we optimize joint source/channel coding for a CPR collective for WWAN video multicast and achieve significant performance improvement over traditional system optimization schemes.

Specifically, we can afford to devote more 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 joint source/channel coding optimization scheme outperformed a previous scheme by up to 8.4 dB where joint source/channel coding is performed but WLAN CPR is not used, and up to 4.4 dB when CPR is used but WWAN source/channel coding is optimized separately.

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IX. APPENDIX

A. General Case for Segment Recovery Probability

We extend Eq. (18) to general case as follows:

$$Pr(\bar{B}_y) = Pr(\bar{B}_{y-1}) + [1 - Pr(\bar{B}_{y-1})]Pr(\bar{B}_y|B_{y-1}) \quad (21)$$

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

$$\begin{aligned} Pr(\bar{B}_y|B_{y-1}) &= Pr(\bar{C}_y \cap \bar{C}_{y+1} \cap \dots \cap \bar{C}_X|B_{y-1}) \\ &= Pr(\bar{C}_y|B_{y-1})Pr(\bar{C}_{y+1}|\bar{C}_y, B_{y-1})\dots Pr(\bar{C}_X|\bar{C}_{X-1}, \dots, \bar{C}_y, B_{y-1}), \end{aligned} \quad (22)$$

where

$$Pr(\bar{C}_y|B_{y-1}) \approx p_{grp}(R_s^y, R_c^y, y) \frac{Pr(C_{y-1})}{Pr(B_{y-1})}. \quad (23)$$

$$\begin{aligned} Pr(C_{y-1}) &= Pr(C_{y-1}|C_{y-2})Pr(C_{y-2}) + Pr(C_{y-1}|\bar{C}_{y-2})Pr(\bar{C}_{y-2}) \\ &\approx p_{grp}(R_s^{y-1}, R_c^{y-1}, y-1)Pr(C_{y-2}) + p_{grp}\left(\sum_{i=1}^{y-1} R_s^i, R_c^{y-1}, y-1\right)(1 - Pr(C_{y-2})). \end{aligned} \quad (24)$$

B. Derivations for the scaling factor in Eq. (19)

Due to the definition of event B_1 , Eq. (19) can be expanded as follows:

$$\begin{aligned}
& Pr(\bar{C}_2|B_1) \\
&= Pr(\bar{C}_2|C_1 \cup C_2 \cup C_3) \\
&= Pr(\bar{C}_2|C_1)Pr(C_1|C_1 \cup C_2 \cup C_3) \\
&\quad + Pr(\bar{C}_2|\bar{C}_1 \cap C_2)Pr(\bar{C}_1 \cap C_2|C_1 \cup C_2 \cup C_3) \\
&\quad + Pr(\bar{C}_2|\bar{C}_1 \cap \bar{C}_2)Pr(\bar{C}_1 \cap \bar{C}_2|C_1 \cup C_2 \cup C_3) \\
&\approx p_{grp}(R_s^2, R_c^2, 2) \frac{Pr(C_1)}{Pr(B_1)} + \frac{Pr(C_3|\bar{C}_1 \cap \bar{C}_2)Pr(\bar{C}_1 \cap \bar{C}_2)}{Pr(C_1 \cup C_2 \cup C_3)}. \tag{25}
\end{aligned}$$

The last term in Eq. (25) can be ignored as long as not too many FEC packets are allocated to the last frame group. This is true in our setup because the importance of the frame groups are monotonically non-increasing. By omitting the last term in Eq. (25), we obtain the approximation in Eq. (19). The general case for Eq. (19) can be similarly obtained.