GAME THEORETICAL ANALYSIS OF WIRELESS MULTIVIEW VIDEO MULTICAST USING COOPERATIVE PEER-TO-PEER REPAIR

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ABSTRACT

Receivers of wireless video broadcast can suffer catastrophic decoding errors when experiencing heavy packet losses due to transmission channel fades. Cooperative repair schemes, exploiting the "uncorrelatedness" in wireless channels of peers physically located more than one transmission wavelength apart, call for neighboring peers listening to the same video stream to locally share received packets via a secondary network. Since the likelihood of the entire peer group suffering fades in statistically independent channels at the same time is very small, cooperative peers can collectively recover lost packets via local packet sharing with high probability.

For interactive multiview video streaming (IMVS), where a client receives and watches only one periodically selected view out of N available, the packet recovery problem is more challenging, since the likelihood of a neighboring cooperative peer watching the same view as a channel-corrupted peer is now $1/N$. To enable cooperative recovery even when neighboring peers are watching different but correlated video views, cleverly designed redundantly coded information (RCI) such as Distributed Source Coded (DSC) frames are inserted into streams of different views. On one hand, RCI in the video streams promotes cooperative repair among peers watching different views; on the other, it leaves fewer available bits for channel coding, given a fixed transmission budget, to combat channel noise. In this paper, using game theoretical analysis, we search for the optimal amount of RCI in the video streams to foster the right balance between cooperation among peers and leftover bits for channel coding to maximize decoding success. Experimental results show that expected video decoding probability can be increased noticeably compared to non-optimized resource allocation schemes.

Index Terms— Wireless video streaming, cooperative communication, multiview video, game theory

1. INTRODUCTION

Wireless video streaming is known to be difficult because of stringent packet playback deadlines and unavoidable packet losses due to transmission channel fades. It is particularly challenging in the broadcast/multicast scenario, where server cannot perform packet retransmission on a per-packet, per-client basis due to the well-known NAK implosion problem [1]. One solution is to employ strong forward error correction codes (FEC), so that source packets are well protected even in the face of deep fades [2]. However, this leaves preciously little leftover bit budget for source coding, resulting in large quantization errors and poor visual quality for the viewer.

One promising alternative is *cooperative peer-to-peer repair* (CPR) [3], where neighboring peers listening to the same video broadcast in the primary network (such as Wireless Wide Area Network (WWAN)) share received video packets locally via an orthogonal secondary network (such as ad hoc Wireless Local Area Network (WLAN)). Because peers physically located more than one transmission wavelength apart experience (more or less) uncorrelated channels to the broadcasting server [4], the likelihood of an entire cooperative peer group suffering channel fades at the same time is very small. That means for a sufficiently large peer group, the probability of each packet being correctly received by at least one peer is very high, and CPR can then ensure the received packet is shared among all cooperative peers for perfect recovery.

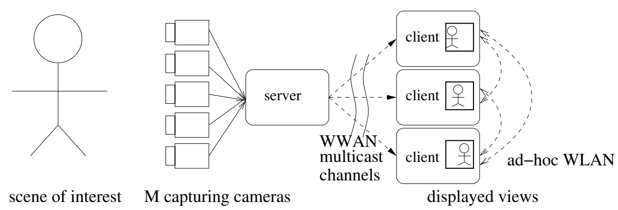

Fig. 1. Overview of wireless multiview video streaming system with cooperative peer-to-peer repair.

In an orthogonal development, the decreasing cost of consumer-level cameras means video of a scene of interest can now be shot by multiple closely spaced cameras from different viewpoints. In an interactive multiview video streaming (IMVS) scenario [5], a client periodically requests one of N available views from the server as the video is played back in time uninterrupted. While the view-switching capability offers clients a new media interaction, wireless video streaming is now more difficult, since the likelihood of a neighbor watching the same view as a channel-corrupted peer (and hence can participate in CPR for packet recovery) is now $1/N$.

To enable cooperative packet recovery even when neighboring peers are viewing different but correlated video views, cleverly designed *redundantly coded information* (RCI) such as Distributed Source Coded (DSC) [6] frames were inserted periodically to video stream of each view to promote cooperative repair among peers of different views [7]. On one hand, added RCI in the video streams of different views promotes cooperative repair among peers watching different views; on the other, it leaves fewer available bits for channel coding, given a fixed transmission budget, to combat channel noise. In this paper, using game theoretical analysis, we search for the optimal amount of RCI in video streams to foster the right balance between cooperation among peers and leftover bits for channel coding to maximize decoding success. Experimental results show that expected video decoding probability can be increased noticeably compared to non-optimized resource allocation schemes.

The outline of the paper is as follows. We first briefly discuss related work in Section 2. We then describe our system model, including an overview of DSC and its role as RCI in cooperative recovery, in Section 3. We formalize our game theory analysis of wireless multiview video streaming using CPR in Section 4. Results and con-

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Table 1. Definitions for Game Theoretical Analysis

M	number of available video views
N	number of local peers in cooperative repair
$a = N/M$	number of peers in each view (integer)
$\mathcal{H}_v$	view set a peer of view v can help or receive help
α_d	probability a peer cannot decode a coding unit
α_r	probability a peer fail to receive a coding unit via WWAN multicast
γ	raw WWAN packet transmission loss probability
R	WWAN transmission budget in one video epoch
g	gain to stop error propagation
p	price for each seller to share a decoded frame
c	cost for seller to share a decoded frame
$\mathbf{n} = [n_1, \ldots, n_M]$	$n_v \leq a$ is number of *undecodable peers* in view v who cannot decode previous unit
$\tilde{\mathbf{n}} = [\tilde{n}_1, \ldots, \tilde{n}_M]$	$\tilde{n}_v \leq n_v$ is number of *potential buyers* who are undecodable peers but received current unit
$\mathbf{b} = [b_1, \ldots, b_M]$	$b_i \leq \tilde{n}_v$ is number of *willing buyers* who pay for cooperative repair service
l_v	number of successful users who can help buyer(s) watching view v

clusions are presented in Section 5 and 6, respectively.

2. RELATED WORK

The selected IMVS application [5] we study in this paper is an example of *high-dimensional media data navigation* [8], where only a small subset of the large original dataset is accessed along a client's own uniquely chosen trajectory. The common thread for different applications in this class is the challenge in achieving both compression efficiency of media data and navigation flexibility within the data. To be discussed in Section 3 in details for IMVS, flexible media data navigation is achieved through insertion of cleverly designed RCI such as DSC [6] into the coded dataset, at a modest cost in coding efficiency. Besides navigation flexibility, RCI can also promote cooperation among peers in different viewing trajectories in collaborative tasks such as content sharing and loss recovery. It is hence foreseeable that our developed game theory analysis for IMVS here can be extended to other applications in this class of high-dimensional media data navigation, for example, interactive light field streaming with cooperative cache [9].

While we discuss IMVS in the wireless multicast scenario, our analysis also applies to cooperative loss recovery in the unicast case, with the stipulation that the unicasted video contents of different views to different local clients must be synchronized in time, so that cooperative recovery of frames in different views but same time instants can take place.

Incentive mechanisms have been well studied for peer-to-peer video streaming over Internet [10, 11, 12, 13], while little has been done to stimulate user cooperation in wireless multicast applications. In [14, 15], payment based incentive mechanisms were proposed for ad hoc networks where some receivers do not have direct connection with the source node. There, each node in the network claims the cost to relay a packet, based on which the source calculates an optimal multicast tree that spans all receivers with the lowest cost. The work in [16] considered single-view 2-hop multicast with direct link between the source and all receivers, and proposed a multi-seller multi-buyer price based scheme, where users pay to receive relay service and get paid if they forward packets to others.

3. SYSTEM MODEL

We first overview the wireless multiview video streaming system with cooperative repair in Section 3.1. We then describe the use of DSC in the video coding structure and its role in cooperative recovery in Section 3.2.

3.1. System Overview

The WWAN multiview video multicast system under investigation is shown in Fig. 1. M cameras in a one-dimensional array captured a scene of interest from different viewing angles. A server compresses video of each view into chunks of *coding units* of e frames each (to be discussed). Server transmits different video views, synchronized in time, in different WWAN multicast channels such as Multimedia Broadcast/Multicast Service (MBMS) in 3GPP [17]. A peer interested in a particular view will subscribe to the corresponding multicast channel and can switch to a neighboring view interactively by switching multicast channels every e frames (of *epoch* duration in time).

The WWAN server first multicasts an epoch worth of video to peers. Then during WWAN transmission of the second epoch, cooperative peers, locally connected via ad hoc WLAN, will exchange received packets / decoded frames in the first video epoch. When the server multicasts the third epoch, peers repair the second epoch, and video frames in the first epoch are played back and displayed. View-switching delay is hence two epochs, or $2e$ frames.

3.2. Distributed Source Coding in IMVS

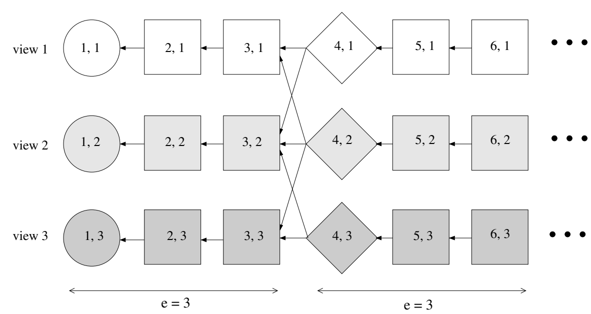

Fig. 2. Example of frame structure for $M = 3$ views and coding unit of size $e = 3$. Circles, squares and diamonds are I-, P- and DSC frames, respectively. Each frame $F_{t,v}$ is labeled by its time index t and view v.

[7] proposed to encode captured multiview video frames as follows: for each view v, encode a starting intra-coded I-frame $F_{1,v}$ with $e - 1$ trailing P-frames, each differentially coded from previous frame, followed by one DSC frame $F_{e+1,v}$ and $e - 1$ trailing P-frames, following by another DSC frame $F_{2e+1,v}$ and $e - 1$ trailing P-frames, etc. A frame group composed of a DSC frame and $e - 1$ trailing P-frames is termed a *coding unit*, which is transmitted by the WWAN server in epoch time duration as described earlier. See Fig. 2 for an illustration of two coding units for three views.

[7] encodes each DSC frame $F_{ie+1,v}$, $i \in \mathcal{I}$, using (at most) $2h + 1$ decoded P-frames $F_{ie,\max(1,v-h)}, \ldots, F_{ie,\min(M,v+h)}$ of time instant ie in the previous coding unit as predictors. In other words, the set of predictors' views for DSC frame of view v is $\mathcal{H}_v = \{\max(1, v-h), \ldots, \min(M, v+h)\}$. By DSC's construction [6], as long as *one* of the predictor frames is correctly decoded and available at the client's buffer as side information, DSC frame $F_{ie+1,v}$ can be correctly decoded. Size of a DSC frame increases with h; typically, DSC frame size falls between a P-frame and an I-frame.

Using the proposed structure with DSC frames ($h \geq 1$) inserted, a client can switch from view v to a neighboring view $v \pm 1$ at the

DSC frame boundary (by subscribing to a different WWAN multicast channel). An alternative coding structure that uses I-frames instead can also facilitate view-switching, but requires significantly more transmission bandwidth due to the large size of I-frames. DSC frame is hence an example of smartly designed RCI that offers some data navigation flexibility (view-switching in this IMVS application) while incurring a modest cost in coding efficiency.

3.3. Game Model for Cooperative Repair

In this work, we use view-switch-enabling DSC frames to also *facilitate cooperative repair among peers watching different views*. We assume N local peers participate in cooperative repair. For simplicity, we assume each view has $a = N/M$ viewers (a is an integer). For each given coding unit, $n_v \leq a$ *undecodable peers* of view v did not decode it correctly, due to WWAN transmission losses in that coding unit, or error propagation from previous coding unit. $a - n_v$ peers of view v are *potential sellers* of CPR recovery service: peers who have correctly decoded their coding units can help undecodable peers by locally forwarding correctly decoded frames. Among n_v undecodable peers, $\tilde{n}_v \leq n_v$ are *potential buyers* who receive the next coding unit correctly, and hence have motivation to buy cooperative repair service to ensure correct decoding of the next unit. Among $\tilde{n}_v$ potential buyers, $b_v \leq \tilde{n}_v$ choose to purchase the service to become *willing buyers*. See Table 1 for a list of definitions.

During cooperative repair, a potential seller of view v' can share her decoded P-frame $F_{ie,v'}$ with a willing buyer of view v, where $v' \in \mathcal{H}_v$, so that buyer of view v can correctly decode the next coding unit using decoded $F_{ie,v'}$ as predictor for DSC frame $F_{ie+1,v}$. If a willing buyer in b_v can identify such a potential seller in $a - n_{v'}$ peers of view v', then the buyer becomes a *paying buyer* and the seller a *paid seller*. Paying buyers collectively need to pay each seller a price p, which can be shared if a seller's forwarded frame can help multiple buyers.

4. PROBLEM FORMULATION

In our IMVS system, there are two sets of players who interact with each other: potential sellers who successful decode the previous coding unit, and potential buyers who fail to decode the previous coding unit but have the next coding unit correctly received. In this section, we build a game-theoretic framework to analyze their strategies and find the stable Nash equilibrium of the game from which no one has incentive to deviate.

We first analyze the seller game and study how potential sellers determine whether to share a decoded frame. Let c be the cost for a seller to share a decoded frame with neighbors. We assume the price p paid to a seller is larger than the cost c to motivate peers to help. Thus, all peers who successfully decode the previous coding unit have sufficient incentive to share correctly decoded frames.

We next analyze the buyer game. For each potential buyer who cannot decode the previous coding unit but receive the next coding unit correctly, there are two decisions to make. First, she needs to determine if she is willing to purchase the cooperative repair service and become a willing buyer. Second, given a set of potential sellers, collectively the willing buyers need to select paid sellers to satisfy as many willing buyers' requests as possible at the lowest cost. In the following, we will analyze potential buyers' strategies.

4.1. Seller Selection

Given sets of willing buyers b_v's and potential sellers $a - n_v$'s, paying buyers have incentive to minimize payment while receiving the same requested service. Towards that goal, we construct algorithm `Seller Set Minimization` to select the smallest number of potential sellers while serving as many willing buyers as possible.

`Seller Set Minimization`

1: Initialize $S = 0$ and $v = 1$.
2: **if** $b_v = 0$ or $l_v = 0$ **then**
3: View v requires no action, $v \leftarrow v + 1$.
4: **else**
5: $S \leftarrow S + 1$.
6: $s(v) \leftarrow \max\{j\}$ s.t. $v \in \mathcal{H}_j$ and $n_j < a$.
7: $v \leftarrow s(v) + h + 1$.
8: **end if**
9: Goto step 2 if $v \leq M$.

In words, the algorithm operates as follows. Starting with the first view $v = 1$, we check if there exists willing buyers in view v ($b_v > 0$), and if there exists potential sellers who can help willing buyers in view v ($l_v > 0$). Potential sellers who can help willing buyers in view v, l_v, can be derived simply:

$$l_v = \sum_{j \in \mathcal{H}_v} (a - n_j) \tag{1}$$

If either is false, then nothing should/can be done for view v, and we move to view $v+1$. If both are true, then we identify *one* potential seller with the largest view index $s(v)$ that can help willing buyer(s) in view v. This is done so that the same seller of view $s(v)$ can help as many other willing buyers of views $> v$ as possible to minimize the size of the seller set. We then move to view $s(v) + h + 1$, the next smallest view index not already served by seller of view $s(v)$. The algorithm repeats until all M views are considered.

We can write the algorithm in mathematical form to derive minimum number of potential sellers $S(\mathbf{n}, \mathbf{b})$ as follows:

$$S(\mathbf{n}, \mathbf{b}) = S_1, \text{ where}$$
$$S_v = \begin{cases} 0 & \text{if } v > M \\ S_{v+1} & \text{else if } b_v = 0 \text{ or } l_v = 0 \\ 1 + S_{s(v)+h+1} & \text{o.w.} \end{cases} \tag{2}$$

where S_v is the recursive term that counts the number of potential sellers required to satisfy willing buyers in view v to M.

We now analyze the number of paying buyers. We first note that from the analysis of the seller game and the above seller selection algorithm, a willing buyer watching view v is a paying buyer if at least one peer watching view in $\mathcal{H}_v$ successfully decodes the previous coding unit, that is, $l_v \geq 1$. We can hence write the number of paying buyers given $\mathbf{n}$ and $\mathbf{b}$ as follows:

$$B(\mathbf{n}, \mathbf{b}) = \sum_{v=1}^{M} I\left[l_v\right] b_v, \tag{3}$$

where $I[\cdot]$ is the indicator function.

4.2. When to Buy

For a potential buyer who failed to decode the previous coding unit but successfully received the current coding unit, we analyze how she decides whether to purchase the cooperative repair service and become a willing buyer. Assume all peers have the same probability α_d to incorrectly decode the previous coding unit and the same probability α_r to incorrectly receive the current coding unit via WWAN. Let g be the gain if a potential buyer can stop error propagation and correctly decode the current coding unit.

In the buyer game, potential buyers interact with each other in their decision making, and the number of willing buyers depends on their collective strategies. However, due to the broadcast nature of the wireless medium, if one peer buys a cooperative repair service, other peers can overhear the packets and enjoy a free ride. Therefore, each peer in the buyer game faces a dilemma: on one hand, every peer wants to overhear the cooperative repair service bought by other peers and pays nothing; on the other, if nobody pays, there will be no sharing and everyone will suffer from low performance. To help peers solve this dilemma and stimulate cooperation, we model the buyer game as an *evolutionary game* [18], and derive an *Evolutionarily Stable Strategy* (ESS) for each player. ESS is a stable Nash equilibrium; i.e., even though at some time instance, some players may deviate from the ESS, they will still converge to ESS eventually, since the one who uses ESS will receive a higher payoff.

To derive the ESS, evolution game theory provides a very useful tool, called *replicator dynamics*. Each peer in the buyer game has two strategies: B ("buy") and NB ("do not buy and free ride"). Let X_v be the population share in view v that play strategy B (or the probability that a peer decides to purchase the service), and the rest $1-X_v$ population share in view v play strategy NB (or the probability that a peer decides not to buy). From replicator dynamics, we have $\dot{X}_v = \eta[\pi_v^B(\mathbf{X}) - \bar{\pi}_v(\mathbf{X})]X_v$, where η is a constant step size, $\pi_v^B(\mathbf{X})$ is the average payoff using strategy B, and $\bar{\pi}_v(\mathbf{X})$ is the average payoff of the entire population. The intuition behind this differential equation is that if buying the service gives players a higher payoff than the average payoff of the entire population, the population share of pure strategy B should increase. At the stable state, this differential equation should be equal to 0.

To find the ESS, the first step is to calculate $\pi_v^B(\mathbf{X})$ and $\bar{\pi}_v(\mathbf{X})$. For any potential buyer watching view v and uses strategy B, the expected benefit π_v^B is:

$$\pi_v^B = \sum_{n_v \geq \tilde{n}_v \geq b_v \geq 1} \left[g - \frac{pS(\mathbf{n},\mathbf{b})}{B(\mathbf{n},\mathbf{b})} \right] P_v^{pb}(\mathbf{n}) P_v^B(\mathbf{b}|\tilde{\mathbf{n}}) P_v^D(\mathbf{n},\tilde{\mathbf{n}}), \quad (4)$$

where $P_v^{pb}(\mathbf{n})$ is the probability that given $\mathbf{n}$, service request of a potential buyer in view v can be satisfied; $P_v^B(\mathbf{b}|\tilde{\mathbf{n}})$ is the probability that given $\tilde{\mathbf{n}}$, $\mathbf{b}$ are willing buyers, including at least one willing buyer of view v; and $P_v^D(\mathbf{n},\tilde{\mathbf{n}})$ is probability that WWAN transmission and coding unit decoding result in $\mathbf{n}$ and $\tilde{\mathbf{n}}$, and there is at least one willing buyer of view v. $P_v^D(\mathbf{n},\tilde{\mathbf{n}})$ and $P_v^B(\mathbf{b}|\tilde{\mathbf{n}})$ can be derived as follows:

$$\begin{aligned} P_v^D(\mathbf{n},\tilde{\mathbf{n}}) &= \binom{a-1}{n_v-1}\binom{n_v-1}{\tilde{n}_v-1}\prod_{j\neq v}\binom{a}{n_j}\binom{n_j}{\tilde{n}_j}\alpha_d^{\sum n_k} \quad (5) \\ &\times (1-\alpha_d)^{N-\sum n_k}(1-\alpha_r)^{\sum \tilde{n}_k}\alpha_r^{\sum(n_k-\tilde{n}_k)}, \\ \text{and } P_v^B(\mathbf{b}|\tilde{\mathbf{n}}) &= \binom{\tilde{n}_v-1}{b_v-1}(X_v)^{b_v-1}(1-X_v)^{\tilde{n}_v-b_v} \\ &\times \prod_{j\neq v}\binom{\tilde{n}_j}{b_j}(X_j)^{b_j}(1-X_j)^{\tilde{n}_j-b_j}. \quad (6) \end{aligned}$$

For a willing buyer watching view v, given $n_v \geq \tilde{n}_v \geq b_v \geq 1$, the probability that he is a paying buyer is $P_v^{pb}(\mathbf{n}) = I[l_v]$.

If a peer watching view v decides to "free ride", then his/her utility is

$$\pi_v^{NB} = \sum_{n_v \geq \tilde{n}_v \geq 1, \tilde{n}_v > b_v} g P_v^{fr}(\mathbf{n},\mathbf{b}) P_v^{NB}(\mathbf{b}|\tilde{\mathbf{n}}) P_v^D(\mathbf{n},\tilde{\mathbf{n}}), \quad (7)$$

where P_v^{fr} is the probability that given $\mathbf{n}$ and $\mathbf{b}$, a peer watching view v can free ride. $P_v^{NB}(\mathbf{b}|\tilde{\mathbf{n}})$ is the probability that given $\tilde{\mathbf{n}}$, $\mathbf{b}$ are the willing buyers and a peer of view v decides to free ride. We can similarly derive $P_v^{NB}(\mathbf{b}|\tilde{\mathbf{n}})$ as previously done for $P_v^B(\mathbf{b}|\tilde{\mathbf{n}})$:

$$\begin{aligned} P_v^{NB}(\mathbf{b}|\tilde{\mathbf{n}}) &= \binom{\tilde{n}_v-1}{b_v}(X_v)^{b_v}(1-X_v)^{\tilde{n}_v-b_v-1} \\ &\times \prod_{j\neq v}\binom{\tilde{n}_j}{b_j}(X_j)^{b_j}(1-X_j)^{\tilde{n}_j-b_j}. \quad (8) \end{aligned}$$

For a potential buyer of view v, she may free ride if at least one selected paid seller can help, that is,

$$P_v^{fr}(\mathbf{n},\mathbf{b}) = I(P_{v,1}^{fr}) \quad (9)$$

where $P_{v,i}^{fr}$, similar to S_v in (2), is the recursive term that checks if peers in view v can free-ride given willing buyers from view i to M:

$$= \begin{cases} 0 & \text{if } i > M \\ P_{v,i+1}^{fr} & \text{else if } b_i = 0 \text{ or } l_i = 0 \\ I(v \in \mathcal{H}_{s(i)}) + P_{v,s(i)+h+1}^{fr} & \text{o.w.} \end{cases} \quad (10)$$

Then given $\mathbf{X} = [X_1, \cdots, X_M]$, the average utility for a potential buyer of view v is

$$\bar{\pi}_v(\mathbf{X}) = X_v \pi_v^B(\mathbf{X}) + (1-X_v)\pi_v^{NB}(\mathbf{X}), \quad (11)$$

and $\mathbf{X}$ satisfies

$$\begin{aligned} \dot{X}_v &= f_v(\mathbf{X}) = \eta[\pi_v^B(\mathbf{X}) - \bar{\pi}_v(\mathbf{X})]X_v \\ &= \eta[\pi_v^B(\mathbf{X}) - \pi_v^{NB}(\mathbf{X})](1-X_v)X_v \quad (12) \end{aligned}$$

for $v = 1, \cdots, M$ from replicator dynamics [18].

To find the equilibrium of this buyer game, we first find the optimal strategy $\mathbf{X}^*$ that satisfies $\dot{X}_v = f_v(\mathbf{X}) = 0$ for $v = 1, \cdots, M$, from which no peer will deviate. In addition, if the equilibrium of the replicator dynamics is a locally asymptotically stable point in a dynamic system, then the optimal strategy $\mathbf{X}^*$ is an evolutionarily stable strategy (ESS). To determine if an strategy $\mathbf{X}^*$ is stable, we first calculate the Jacobian matrix of the dynamic system in (12), which is

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial X_1} & \cdots & \frac{\partial f_1}{\partial X_M} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial X_1} & \cdots & \frac{\partial f_M}{\partial X_M} \end{bmatrix}, \quad (13)$$

and find its eigenvalues $\lambda_1, \cdots, \lambda_M$. If all the eigenvalues have negative real parts at $\mathbf{X}^*$, then $\mathbf{X}^*$ is an ESS.

4.3. Optimizing IMVS System Performance

We see that a potential seller of view v can satisfy willing buyers of views $v-h$ to $v+h$. So if h is large, a given seller can satisfy more buyers, meaning the price to purchase the seller's service can be shared by a larger buyer group. This is not a strictly beneficial gain, however; a large h also means the DSC frame has large number of predictors, leading to a large encoded DSC frame. For a fixed WWAN transmission budget, that means fewer bits are left over for channel coding, and coding unit loss probability α_r increases.

More specifically, let R denote the WWAN transmission budget for an epoch in number of packets. Let z be the number of packets in frames other than the DSC frame in a coding unit, and $z'(h)$ be the number of packets in a DSC frame given h. Assuming $z'(h)+z < R$, there are $R-(z'(h)+z)$ leftover transmission budget for forward error correction (FEC) packets to combat WWAN packet losses. If

Table 2. System parameters for IMVS simulations.

parameter	M	N	γ	R	z_p	z_o	g	p
value	3	6	0.15	110	3	1	1.0	0.8

we now assume WWAN is an independent and identically distributed (iid) channel with raw packet loss rate γ, the probability $\alpha_r(h)$ that a coding unit is incorrectly received is:

$$\alpha_r(h) = \sum_{i=0}^{z'(h)+z-1} \binom{R}{i} (1-\gamma)^i \gamma^{R-i} \tag{14}$$

where (14) assumes FEC used is a perfect code. For $z'(h)$, we assume here the simple model where the size of a DSC frame is approximately linear with respect to h; i.e., $z'(h) = z_p + z_o h$, where $z'(0) = z_p$, the size of a P-frame.

We can derive the optimal h that leads to the largest expected utility $\bar{\pi}_v(\mathbf{X})$ for an undecodable peer as follows. For given h, we calculate the corresponding coding unit loss probability $\alpha_r(h)$ for a fixed WWAN transmission budget R. We then perform the previous analysis to find probabilities X_v's potential buyers of views v's will purchase cooperative repair service. The expected utility $\bar{\pi}_v(\mathbf{X})$ is then computed using (11). The process is repeated for different values of h to find optimal h^*.

5. EXPERIMENTATION

5.1. Experimental Setup

In our simulations, we consider an IMVS system with $M = 3$ views and $N = 6$ peers. That means each view has $a = N/M = 2$ users. For simplicity, we assume that users do not switch views for the duration of the experiment. We assume initially raw WWAN packet loss rate $\gamma = 0.15$, and a WWAN transmission budget of $R = 110$ packets per video epoch. The size of a P-frame is $z_p = 3$ packets, and assuming $z_0 = 1$, the sizes of a DSC frame for $h = 1$ and 2 are 4 and 5 packets, respectively. We assume there are 29 P-frames following a DSC frame in a coding unit.

We assume user utility gain to stop error propagation is $g = 1.0$, and the price to pay each seller is $p = 0.8$. We consider the simplified scenario where $\alpha_d = \alpha_r$, that is, the probability to incorrectly decode the previous coding unit and that to incorrectly receive the current coding unit are the same. Table 2 shows the system parameter values used for our experiment.

5.2. Experimental Results

Fig. 3 plots X_v and the fraction of users who successfully decode the current coding unit after cooperative repair (including those who succeed in WWAN broadcast) for different DSC span h. First, we observe that for $h = 0$, i.e., when DSC frame is actually a P-frame, the probability of peers in any view buying the cooperative repair service is 1. This is because when DSC frame is not used, peers of one view cannot free-ride on repair service of a different view, and given $a = 2$, not purchasing the service will necessarily mean not being able to decode the current coding unit.

We next observe that for $h \geq 1$, undecodable users of view 2 have the smallest probability to buy, while undecodable users of view 1 always become buyers. This is because with our system setup, undecodable users of view 2 can free ride as long as there is a paying buyer of any view; while users of view 1 have the smallest probability to free ride since our seller selection algorithm in Section 4.1 always look for a potential seller with the largest view $s(v)$ that can help buyer(s) in view v. In addition, from Fig. 3, when $h = 2$, the probability of undecodable users of view 2 and 3 buying the service is zero, since both groups can free-ride from buyer(s) of view 1.

Table 3. Fraction of successful viewers for different γ's.

	$\gamma = 0.15$	$\gamma = 0.17$	$\gamma = 0.20$
$h = 0$	0.9372	0.7666	0.3572
$h = 1$	0.9378	0.7716	0.5287
$h = 2$	0.8578	0.7323	0.4280

We also study the impact of raw WWAN packet loss probability γ on the system. Table 3 shows the fraction of successful users (of any view) for different γ. We observe that though the resulting fraction of successful users vary quite dramatically, the optimal DSC span h that maximizes user decoding success is 1 for this range of γ. This shows that though a larger h creates a larger incentive for peers to share the cost of a seller's frame forwarding service, the resulting larger unsuccessful coding unit transmission probability α_r creates a more serious problem and drags down the system-wide performance. Using our derived game theoretical analysis, we are able to find this optimal DSC span h^* to optimize system-wide performance.

6. CONCLUSION

In this paper, we study system optimization of a wireless multi-view multicast system using game analysis. An interactive multi-view video streaming (IMVS) system allows a client to switch to neighboring video views as the video is played back uninterrupted by periodically re-subscribing to different WWAN multicast channels. Distributed source coding (DSC) frames are periodically inserted into the video streams of different views to facilitate view-switching without resorting to bandwidth-expensive intra-coded I-frames. DSC frames are also used to promote peer cooperation, so that clients, locally connected via ad hoc WLAN, who are watching different video views can nevertheless share decoded frames to alleviate error propagation. Due to the wireless broadcast property, a shared decoded frame can be overheard by multiple receiving peers, meaning a paid cooperative repair service by a single seller can be overheard by multiple willing buyers, but also free-riders. We derive Nash-equilibrium-stable solutions where the optimal proportion of peers suffering decoding losses in each view will opt to purchase the cooperative repair service from potential sellers. We then find the optimal set of predictors for DSC frames that maximizes user utility, balancing the overhead in encoding DSC frames and its ability to promote cooperation among peers.

Though in this paper we focus exclusively on the system optimization of the IMVS application, more generally, we believe our game theoretical analysis can be extended to find the optimal amount of redundantly coded information (RCI) used in other applications of high-dimensional media data navigation to foster the right degree of cooperation from peers navigating in their own viewing trajectories. More thorough investigation into other applications in this class would be future work.

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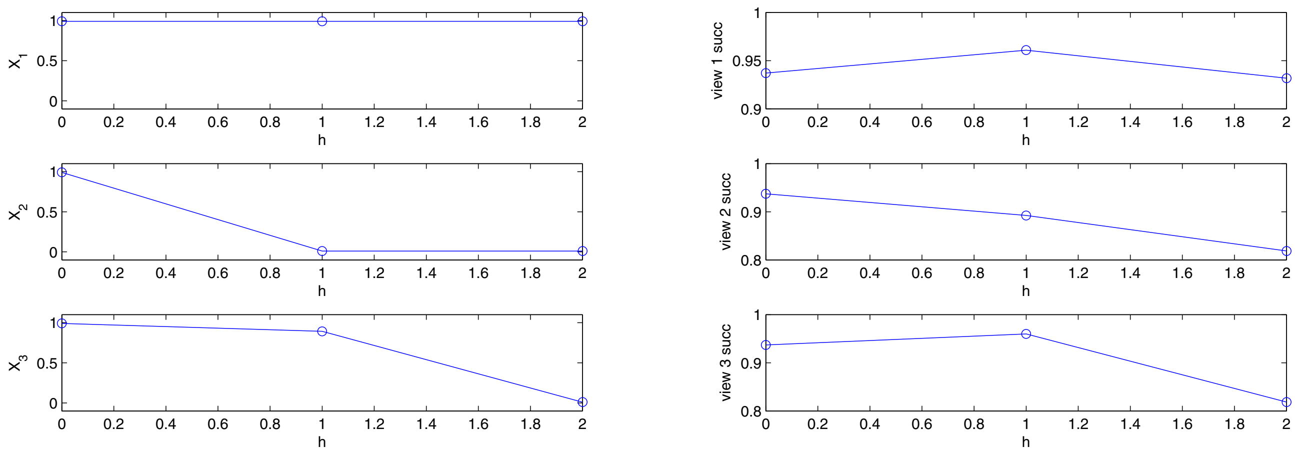

Fig. 3. System performance with different DSC span h. (Left) X_v, and (right) fraction of users who successfully decode the current coding unit after cooperative repair.

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