Cooperative Layered Video Multicast using Randomized Distributed Space Time Codes

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Abstract

With the increased popularity of mobile multimedia services, efficient and robust video multicast strategies are of critical importance. Cooperative communications has been shown to improve the robustness and the data rates for point-to-point transmission. In this paper, a two-hop cooperative transmission scheme for multicast in infrastructure-based networks is used, where multiple relays forward the data simultaneously using Randomized Distributed Space Time Codes (R-DSTC). This randomized cooperative transmission is further integrated with layered video coding and packet level Forward Error Correction (FEC) to enable efficient and robust video multicast in infrastructure-based wireless networks. Three different schemes are proposed to find the system operating parameters based on the availability of the channel information at the source station: R-DSTC with full channel information, R-DSTC with limited channel information and R-DSTC with node count. The performance of these three schemes are compared with rate adaptive direct transmission and conventional multicast that does not use rate adaptation. The results show that while rate-adaptive direct transmission provides better video quality than conventional multicast, all three proposed randomized cooperative schemes outperform both strategies significantly as long as the network has enough nodes. Furthermore, the performance gap between R-DSTC with full channel information and R-DSTC with limited channel information or node count is relatively small, indicating the robustness of the proposed multicast R-DSTC.

Index Terms: layered video coding, user cooperation, randomized distributed space time coding, wireless networks, video multicast

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I. Introduction

In recent years, the progress in multimedia technology has given rise to the demand for video applications over wireless networks. Multicasting is a bandwidth efficient method to deliver popular events to many wireless nodes, since it saves network resources by spreading the same data stream across multiple nodes. However, the high packet loss ratio and bandwidth variations of wireless channels make video multicast over wireless networks a challenging problem.

In this paper, we consider multicast in the coverage area of an infrastructure-based network (i.e. Wireless Local Area Networks(WLAN) or a cellular networks), rather than a self-organizing network such as ad-hoc networks. The problem we are studying is to maximize the video quality for the multicast nodes in this coverage range considering both the wireless network and multimedia characteristics. To achieve this goal, we propose to utilize user cooperation techniques to combat the path loss and fading of wireless channels as well as to boost the transmission rates. We further employ packet level Forward Error Correction (FEC) to handle packet losses in the network. Considering the multimedia data, we choose the amount of packet level FEC applied such that there is no observable quality degradation in the video. Furthermore, we benefit from layered video coding in a way that different nodes receive the video at different quality levels based on their channel qualities.

Wireless video multicast has been studied both in infrastructure based networks and self-organizing networks. In infrastructure-based wireless networks, authors in [1]-[2] studied error control in wireless video multicast. A rate-adaptive multicast where rate adaptation is integrated with packet level FEC is considered in [3] and the authors showed that joint rate and FEC adaptation significantly improves the quality in a multicast system. Scalable (layered) video coding is utilized in [4]-[7] to address the heterogeneity of multicast nodes. In [8],[9], multicast routing protocols have been discussed for ad-hoc networks. The authors of [10],[11] also considered video multicast over ad-hoc networks, where the use of multiple description video is proposed to overcome the unreliability of wireless links. Studies on multicast in mesh networks in general consider building an efficient multicast tree. Chou et al. [12] considered video multicast for multi-rate wireless mesh networks where the construction of the multicast tree along with scheduling for low latency multicast were explored. Layered video multicast has been studied in mesh networks [13]. Although these studies consider layered video multicast in a multi-hop network, none of those papers have considered the use of user cooperation combined with layered video and application layer FEC in order to provide robust video multicast. Recently, we studied a multi-hop layered multicast system (with no physical layer combining), where multiple relays transmit sequentially in time, and showed the benefits of such a scheme both numerically and experimentally [14]. However, with such an approach, the throughput of the system is limited due to the sequential transmission.

User cooperation where terminals process and forward the overheard signal transmitted by other nodes to their intended destination is one effective technique to combat path loss and fading is user cooperation [15], [16]. Cooperation techniques can be used to provide spatial diversity [17] as well as reduction in source distortion (including video) in point-to-point (unicast) communications by providing unequal error protection [18], [19]. The majority of the research on cooperation (including the above mentioned studies) considers a unicast (point-to-point) communication scenario. However, cooperative transmission is especially suitable for multicast not only because of its ability to substantially reduce the packet losses, but also because the relays are part of the multicast group, and hence are free from the incentive and security concerns that may impact the deployment of cooperation for point-to-point communications. Furthermore, most of the research considers a single relay case. In general, there may be more than one node that can overhear the packets sent by the source station. If we let these nodes transmit cooperatively to the destination, significant diversity gains can be accomplished. Without physical layer cooperation (i.e. utilizing cooperation in MAC and upper layers), these nodes can only relay sequentially, but this results in a loss of spectral efficiency. A more efficient way is for the nodes to relay simultaneously utilizing cooperation at physical layer. Simultaneous transmission by multiple relays can be achieved using a distributed space-time code (DSTC) [17].

The basic idea behind DSTC is to coordinate and synchronize the relays such that each relay acts as one antenna of a regular Space Time Codes (STC) [20],[21]. However, in order to realize such a system, each relay participating in a DSTC needs to know exactly which antenna it will mimic in the underlying STC. Furthermore, based on the dimension of the underlying STC used, a fixed number of relays is chosen. Even though there may be other nodes who decode the source information correctly, they are not allowed to transmit, thus forfeiting the potential diversity and coding gains. Finally, a DSTC requires tight synchronization of the relay nodes, putting a heavy burden on the MAC and physical layers.

In order to circumvent these problems, Randomized DSTC (R-DSTC) [22] can be used where each relay transmits a random linear combination of antenna waveforms. R-DSTC not only eliminates the antenna index assignment, but also allows variable number of relays that are selected on the fly. Furthermore, R-DSTC does not need as tight synchronization among relays as that required by DSTC [24]. Randomized coding for unicast transmission in a wireless network is described in [25], where the impact on the MAC layer performance is also discussed. A joint physical and MAC design for unicast transmission using a randomized cooperative scheme is described in [26], [27]. R-DSTC is especially attractive for multicast since the nodes that receive the packets can act as relays and transmit simultaneously, without the need for relay selection and scheduling.

In order to handle packet losses at each hop, we further employ packet level FEC. Note that in a multicast system, since each node experiences different packet loss patterns than its neighbors, a simple ARQ (Automatic Repeat reQuest) based scheme results in a large number of retransmissions. The advantage of using packet level FEC for multicasting is that any parity packet can be used to correct independent packet losses among different receivers.

The contribution of this paper is the integration of layered video coding, user cooperation and packet level FEC to enable efficient and robust video multicast. Our emphasis is selection of system operating parameters that maximizes the video rate for randomized cooperative video multicast used in conjunction with packet level FEC. In order to maximize the performance, proper selection of the STC dimension, transmission rates of the first and second hops, as well as the FEC rate, is essential. We use video quality to evaluate the performance of the system, however, the approach can be extended to include the power consumption and coverage range as a performance metric. We propose three different schemes which differ in the available channel information. The first one (R-DSTC with full channel information), assumes that the source station knows the average received SNRs between itself and each receiver node as well as between all pairs of nodes. This scheme was also partially studied in [28] and [29]. The second scheme (R-DSTC with limited channel information), assumes that the source station only knows the channel information between the nodes and itself. Finally, the third scheme (R-DSTC with node count) considers that the source station only knows the number of nodes in its coverage range. For each of these schemes, we optimize the system operating parameters (transmission rates of both hops, and consequently the STC dimension and the FEC rate) based on the channel information, and evaluate the achievable video rate. We compare the results of the above three schemes with rate adaptive direct transmission [3] and conventional multicast. We further consider a layered cooperative multicast system, which provides better video quality to the nodes with better channel conditions.

This paper is organized as follows. We introduce the system model in Section II. Section III formulates the computation of bit error rates for both direct transmission and R-DSTC. We discuss the packet level FEC along with the resulting video rate in Section IV. We formulate the video rate for randomized cooperation for both single layer and layered transmission in Section V. In Section VI, we discuss the selection of system operating parameters under full channel information as well as partial channel information. Section VII discusses the simulation setup and reports the results for different schemes. We conclude the paper in Section VIII.

II. System model

We study an infrastructure-based wireless network (such as Wireless LAN or cellular), and assume a source station (a base station or access point) is multicasting a compressed video stream to nodes

R_d	Direct transmission rate for single layer (bits/sec)
$R_{d,b}, R_{d,e}$	Direct transmission rates for base and enhancement layers (bits/sec)
R_1, R_2	First and second hop transmission rates for single layer R-DSTC (bits/sec)
$R_{1,b}, R_{2,b}$	First and second hop transmission rates for the base layer (bits/sec)
$R_{1,e}, R_{2,e}$	First and second hop transmission rates for the enhancement layer (bits/sec)
γ_d, γ_c	FEC rates for single layer direct transmission and R-DSTC
$\gamma_{d,b}, \gamma_{d,e}$	Base and enhancement layer FEC rates with direct transmission
γ_b, γ_e	Base and enhancement layer FEC rates with R-DSTC
t_b, t_e	Base and enhancement layer transmission time fractions (for both direct and R-DSTC)
R_{v_d}, R_{v_c}	Received video rates for single layer direct transmission and R-DSTC (bits/sec)
R_{v_b}, R_{v_e}	Received video rates for base and enhancement layers (for both direct and R-DSTC)(bits/sec)
L, L_b, L_e	Space time code dimension (for single layer, base and enhancement layers)
N_T	Total number of nodes
ϵ_{max}	Maximum packet error rate among all nodes
N	Number of relays

TABLE I

NOTATION

within its coverage range of radius, r_d. We assume the nodes are randomly uniformly distributed and we define the *node placement*, as one realization of the node locations. All nodes in the network are equipped with one antenna and can transmit at different transmission rates supported by the underlying physical layer. Note that each physical layer transmission rate, R, corresponds to a modulation level, and channel code rate. In accordance with IEEE 802.11g [30], we consider only square constellations. We assume that the channel between the source station and each node, and that between each pair of nodes, experience independent slow Rayleigh fading. Note that when the minimum spacing between two antennas is sufficiently greater than half wavelength, the correlation introduced by the antennas is low enough that the fading associated with these antennas can be considered independent. The wavelength of an 802.11g transmission is roughly 12.5cm. We believe it is reasonable to assume that the distance between nodes are well above 6cm which is the half wavelength. We assume that the fading is constant over the transmission time of a single packet, but changes independently from packet to packet. This is reasonable for video communication as a typical video frame (with multiple packets) lasts for 33 ms, whereas the coherence time for the IEEE802.11a/g is typically range from 1.3ms (for a vehicle moving at 50km/h) to 16ms (for a person moving at 5km/h) [31]. We also assume each channel experiences path loss such that the received power decays with a path loss exponent.

Before describing the details of the proposed system, we summarize the notation used in this paper in Table I. For the baseline direct transmission system, the source station transmits the packets at a physical layer transmission rate of R_d bits/sec. In order to correct the remaining packet errors after physical layer

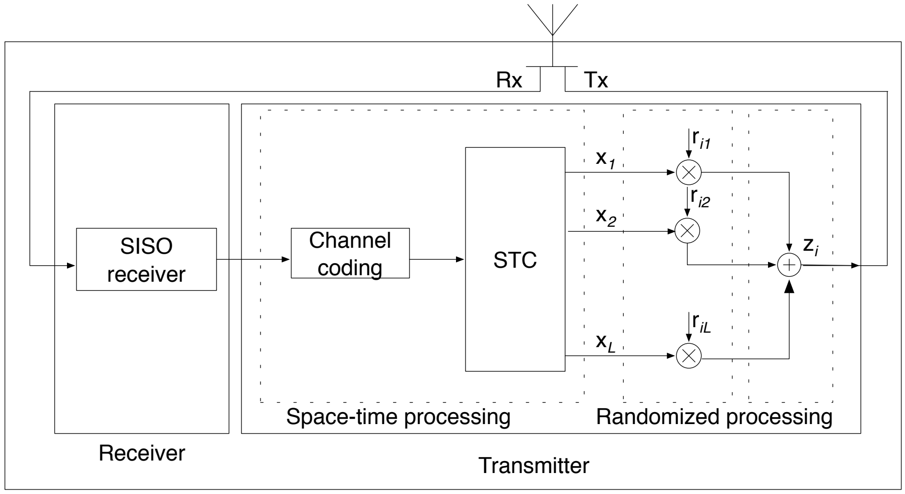


Fig. 1. Transmitter and receiver architecture at the relay nodes

channel coding, we employ packet level FEC across video packets. In our design, we apply a packet level FEC rate of γ_d such that all the nodes in the coverage area receive the video with a FEC decoding failure probability below a certain threshold. We will further discuss the packet level FEC in Section IV.

The proposed cooperative system employs R-DSTC [22] as illustrated in Figure 1, wherein a single-antenna relay employs a regular single-input and single output (SISO) decoder to decode the information sent by the source station in the first hop. Each potential relay detects bit errors in each received packet using cyclic redundancy check (CRC) and forwards the packet only when the packet is correctly received. To forward, the relay re-encodes the information and then passes the coded bits through a space-time code (STC) encoder. The output from the STC encoder is in the form of L parallel streams with each stream corresponding to an antenna in a system with L transmit antennas. However, in contrast to a multi-antenna transmitter, in a R-DSTC system, the relay transmits a random linear weighted combination of all L streams, where the weights are denoted by $\mathbf{r}_n = [r_{n1}\ r_{n2}\ \ldots\ r_{nL}]$, with n denoting the index of each node, $n = 1, 2, \cdots, N$. The effect of different randomization vectors $\mathbf{r}_i$ is discussed in [22]. The diversity of R-DSTC based cooperation is the minimum of the STC dimension L and the number of relays. At the receiver, the equivalent channel gain (which includes the channel gain and the randomization matrix) is estimated using pilot signals [22]. Therefore, decoders already designed for space-time code reception can be directly used for R-DSTC decoding.

For multicast with R-DSTC, the source station transmits a packet at a physical layer transmission rate of R_1 bits/sec. The nodes that receive the packet correctly form the relay set, and are called the Hop-1 nodes, as depicted in Figure 2 where a snapshot of the network for some fixed fading state is illustrated. All nodes that can correctly receive a packet from the source station re-encode and transmit the packet

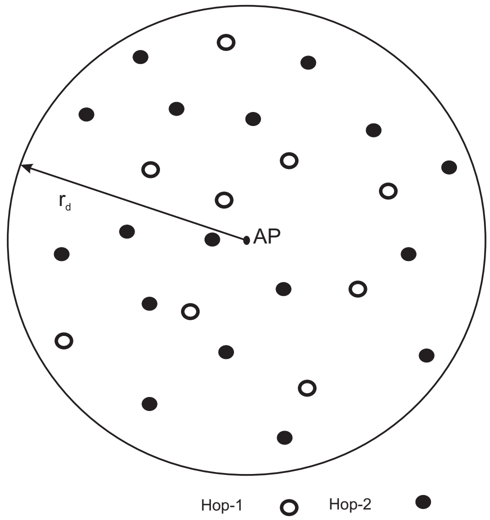


Fig. 2. Snapshot of the network.

simultaneously at a physical layer transmission rate of R_2 bits/sec using R-DSTC with dimension L. The nodes which fail to receive the source station transmission correctly are called Hop-2 nodes, and they listen to relay transmissions to decode the original source packet. We assume that the source station does not transmit with the relays in the second hop, and Hop-2 nodes do not use the noisy signal received from the source station in Hop-1 in decoding. Combining source station and relay signals would increase the performance at Hop-2 nodes at the expense of a more complex receiver. Note that as we increase R_1, the number of Hop-1 nodes reduces. Therefore, the sustainable data rate for the second hop, R_2, is expected to be lower in order to cover all the nodes. On the other hand, if the first hop rate, R_1 is lower, more nodes participate in the second hop transmission, and hence the second hop transmission rate, R_2 can be higher. In order to handle packet losses, the source station employs packet level FEC at a rate γ_c. Here, we assume the Hop-1 nodes do not differentiate between the source and FEC (parity) packets. The source station chooses γ_c such that after two hop transmission, the FEC decoding failure probability at each node is below a threshold. Note that due to fading, successful reception of a packet does not necessarily depend on the distance to the source station. Therefore, some of the nodes that are closer to the source station may experience a bad fading level and may not be able to receive the packet. On the other hand, there are some nodes that observe a good fading level and receive the packet even though they are far away from the source station. Also, due to different fading levels for each packet, whether a node belongs to Hop-1 or Hop-2 can change from packet to packet.

Scalable video compression (i.e. H.264/SVC [23]) allows for coding a video into multiple layers so that reception of more layers leads to better quality. In multicast, layered coding allows differentiated quality for different nodes based on their average channel conditions. Furthermore, layered coding can be combined with cooperation and FEC for unequal error protection. In addition to the aforementioned non-layered system, we also examined a layered system where the source station and relays transmit packets from different layers in separate time slots. For direct transmission, we assume the source station transmits the base layer packets at a rate $R_{d,b}$ bits/sec with a FEC rate of $\gamma_{d,b}$ and the enhancement layer packets at a rate $R_{d,e}$ bits/sec with a FEC rate of $\gamma_{d,e}$. For cooperative multicast, the source station transmits the base layer packets at a rate $R_{1,b}$ bits/sec and the relays transmit the base layer packets at a rate $R_{2,b}$ bits/sec and STC dimension L_b, both with a FEC rate of γ_b. Similarly, the transmission rates for enhancement layer packets for the first and second hop are $R_{1,e}$ and $R_{2,e}$, respectively, with a STC dimension of L_e and FEC rate of γ_e. We denote the percentage of nodes that receive both base and enhancement layers by μ. We configure the transmission rates and FEC rates so that $(100 - \mu)$ percent of the nodes get quality better than or similar to direct transmission, whereas the remaining μ percent observe significantly better quality than direct transmission.

III. Computation of Bit and Packet Error Rates

In the following subsections, we first discuss the computation of the instantaneous Bit Error Rate (BER) (for each channel realization), both for direct transmission and R-DSTC. Then, using this BER and the underlying channel code, we will describe the computation of average Packet Error Rate (PER). The PER in return will be used to determine the required packet level FEC rate.

A. BER of Single Link

We assume that at time k the source station transmits a symbol $\mathbf{x}(k)$ with energy $E_{s,s}$ and m^{th} node experiences an instantaneous channel gain of h_m from the source station. Then the received signal at the m^{th} node at time k can be written as:

$$y_m(k) = \sqrt{E_{s,s}} h_m x(k) + w_m(k) \tag{1}$$

where w_m is additive complex white Gaussian noise with variance N_0, and h_m is the Rayleigh random variable representing the channel gain. We can express the instantaneous received SNR at the m^{th} node, ζ_m, as

$$\zeta_m(\bar{\zeta}, h_m) = \frac{E_{s,s} \|h_m\|^2}{N_0} = \bar{\zeta} \|h_m\|^2 \tag{2}$$

where $\bar{\zeta}$ is the average transmit SNR.

For a M-QAM square constellation, the symbol error rate can be computed as [33]:

$$P_s(M, \zeta_m) = 1 - [1 - P_{\sqrt{M}}(M, \zeta_m)]^2 \tag{3}$$

with

$$P_{\sqrt{M}}(M,\zeta_m) = 2(1-\frac{1}{\sqrt{M}})\ erf(\sqrt{\frac{3\zeta_m}{(M-1)}}) \tag{4}$$

where the *erf* function is defined as:

$$erf(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy \tag{5}$$

With Gray coding, the bit error rate for the M-QAM can be approximated by,

$$P_b(M,\zeta_m) \approx \frac{1}{\log_2 M} P_s(M,\zeta_m) \tag{6}$$

B. BER for RDSTC

Note that the instantaneous BER computation for the first hop of R-DSTC is the same as for the direct transmission. For the second hop, we assume N nodes receive the packet correctly and participate as relays. Each relay transmits its data with a symbol energy of $E_{s,r}$.

We consider an underlying STC of size $L \times K$ for R-DSTC, where L is the number of antennas and K is the block length. We assume the STC is based on real orthogonal designs [32]. For $L = 2, 4, 8$, the orthogonal design provides full rate for square QAM constellation [33],[32]. For R-DSTC weights represented by a vector $\mathbf{r}_n$ for relay n, we can express the transmitted signal from the n^{th} relay at time k, as

$$z_n(k) = \sqrt{E_{s,r}}\mathbf{r}_n \mathbf{X}(k), \tag{7}$$

where $n = 1, 2, \cdots, N$ and $k = 1, 2, \cdots, K$. Here, $\mathbf{X}(k)$ is the k^{th} column of the STC. We assume that each element of $\mathbf{r}_n$ is an independent complex Gaussian random variable with zero mean and variance $\frac{1}{L}$ [22]. Note that $\mathbf{X}(k)$ is a function of the source symbols, with the mapping determined by the underlying STC.

The receiver architecture in Hop-2 is similar to a regular STC receiver with one antenna. The received signal at node m at the k^{th} symbol interval can be expressed as

$$y_m(k) = \mathbf{h_m}\mathbf{Z}(k) + w_m(k) = \sqrt{E_{s,r}}\ \mathbf{h_m}\mathbf{R}\mathbf{X}(k) + w_m(k) \tag{8}$$

where $\mathbf{h_m}$ is the $1 \times N$ channel vector, $\mathbf{h_m} = [h_{1m} ... h_{Nm}]$ with h_{im} representing channel gain from i^{th} relay to the m^{th} node, $w_m(k)$ denotes additive white Gaussian noise with variance N_0. $\mathbf{Z}(\mathbf{k})$ and $\mathbf{R}$ can be written as, $\mathbf{Z}(\mathbf{k}) = [z_1(k)\ z_2(k)\ \ldots\ z_N(k)]^T$, $\mathbf{R} = [\mathbf{r}_1\ \mathbf{r}_2\ \ldots\ \mathbf{r}_N]^T$.

Using pilot signals, estimation of the equivalent channel gain $\mathbf{h_m}\mathbf{R}$ can be done similarly to the estimation of channel gain $\mathbf{h_m}$ in conventional STC [22]. Assuming the m^{th} node estimates $\mathbf{h_m}\mathbf{R}$ perfectly and using the orthogonality of the STC, the equivalent received SNR at node m is:

$$\zeta_m(\bar{\zeta}, \mathbf{h_m}, \mathbf{R}) = \frac{E_{s,r}\|\mathbf{h_m}\mathbf{R}\|^2}{N_0} = \bar{\zeta}\|\mathbf{h_m}\mathbf{R}\|^2 \tag{9}$$

We can compute the instantaneous BER by inserting (9) in (4) and then using (6).

C. Computation of PER

Following the specifications of IEEE 802.11g standard, we employ convolutional codes of rates 1/2, 2/3 and 3/4 with generator polynomials given in [30]. We assume the bit errors in the received stream, which serves as the input to the channel decoder, are independent and identically distributed with the instantaneous BER given as in Section III-A and Section III-B, and we numerically compute the corresponding PER. For both schemes, we first generate a bit stream and encode it using a chosen convolutional code. The coded bits are flipped randomly according to the BER derived above. The output of the decoder is compared to the bitstream to determine whether a packet is received or not at a particular fading level. Note that due to fading, the received channel strength, and hence the reception of a packet at each node changes over time. For direct transmission, at each node and for a particular fading level, we first determine whether a packet is received or not using the single link BER. Then, using channel simulations, the average PER is computed over all possible fading levels. Hence, the average PER between the two nodes only depends on the modulation and the channel code as well as the distance between the nodes. For cooperative multicast, we compute the average PER from the source station to each node in two steps. We first determine whether a packet is received or not after first hop transmission based on single link BER. The nodes that receive the packets becomes relays. We then compute the BER of the link from relays to each node using the BER computation for R-DSTC. Similar to the single link case, using channel simulations, we compute the average PER over all possible fading levels. As in Section III-A and Section III-B, we find the maximum PER, ϵ_{max}, among all nodes, based on the average PER at each node.

IV. Packet Level FEC and Direct Transmission

In order to handle packet losses, we further employ packet level FEC. The basic idea of packet level FEC is that redundant information is sent a priori by the source station, in order to be used by the receivers to correct errors/losses without contacting the source station. The advantage of using packet level FEC for multicasting is that any parity packet can be used to correct independent packet losses among different nodes. This way, we can avoid the feedback implosion problem, which occurs when the source station is overwhelmed by feedback messages from the receivers in a large multicast system. However, such a scheme introduces overhead since extra parity packets are now transmitted by the source station. Furthermore, since the FEC is applied across packets, it also introduces additional delay which will be discussed in Section VII. Despite additional overhead and delay, considering the benefits for error recovery, such a scheme is widely used in a multicast environment.

Transmission Rate, R	6Mbps	9Mbps	12Mbps	18Mbps	24Mbps	36Mbps	48Mbps	54Mbps
Modulation	BPSK	BPSK	QPSK	QPSK	QAM-16	QAM-16	QAM-64	QAM-64
Channel Code Rate	1/2	3/4	1/2	3/4	1/2	3/4	2/3	3/4

TABLE II

TRANSMISSION RATES FOR IEEE 802.11G AND THEIR CORRESPONDING MODULATION SCHEMES AND CHANNEL CODES

We assume that by using CRC at the link layer, each receiver is able to decide whether a packet is correctly received or not. The packets that are lost can be viewed as *erasures* and an erasure code at the packet level can be used to recover the lost packets. In particular, for every s source packets, if we add p parity packets, we can recover all the source packets as long as the number of erasures is at most p using *perfect* codes. Reed-Solomon (RS) code provides a good example of a perfect code [34].

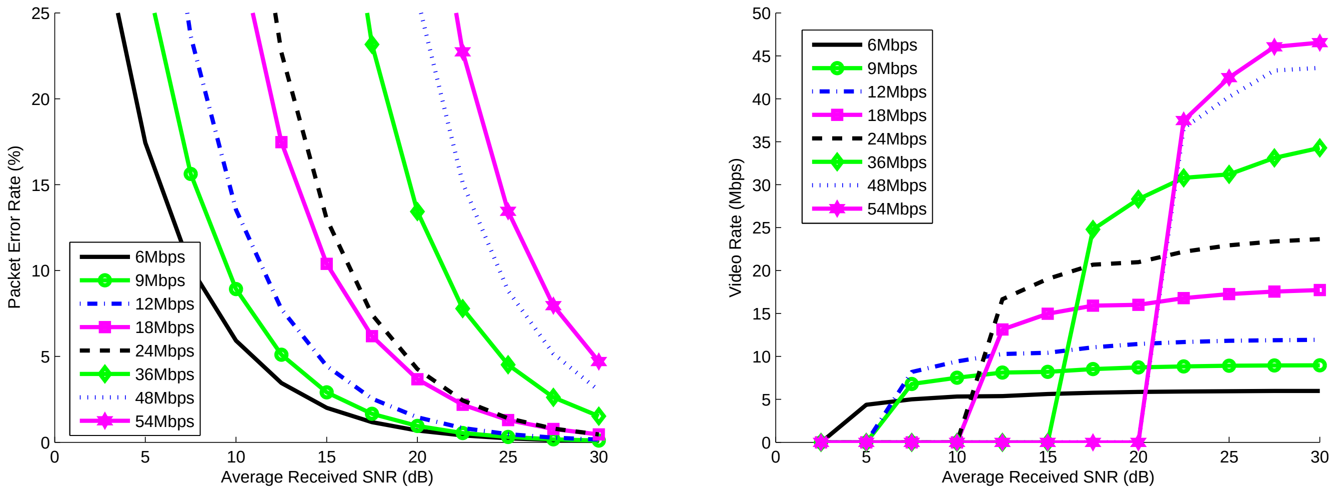
The *rate* of a perfect code, γ is the ratio of the number of source packets to the total number of packets, that is $\gamma = s/(s+p)$. The FEC decoding failure probability is the probability that at least $p+1$ packets are in error. While evaluating the performance of the system, for given s and average PER, we numerically determine γ so that FEC decoding failure probability is below $\tau = 0.5\%$. We observe that when using an error-resilient video decoder, typically there is no noticeable quality degradation when FEC decoding failure probability is below this threshold.

Suppose that at a direct transmission rate of R_d bits/sec, the maximum PER among all nodes in the desired coverage radius r_d is ϵ_{max}. Note that $\epsilon_{max}(R_d)$ depends on the transmission rate. Hence, the packet level FEC rate $\gamma_d(R_d)$ also depends on R_d. In a wireless network, multicast service usually uses a portion of the total available bandwidth. We define the effective data ratio, β, as the ratio of the bit rate used to transmit multicast payload data (e.g. video data including FEC parity packets) to the total transmission rate. Then, with direct transmission for a given β, all the nodes receive video at the same rate of:

$$R_{v_d}(R_d|\beta) = \beta\gamma_d(R_d)R_d \tag{10}$$

In conventional multicast systems (referred as *Direct*), all packets are transmitted at the base rate of the underlying network (e.g. 6Mbps for IEEE 802.11g) with a packet level FEC at fixed rate γ_d that is chosen based on this average PER such that the FEC decoding failure probability is smaller than τ. Note that, although in conventional multicast, the transmission rate and FEC rate is fixed, one can adapt the transmission rate and FEC rate based on the channel conditions to maximize the video rate in (10).

Since the transmission rate affects the FEC rate through the corresponding PER, we ran preliminary simulations using the single link packet error formulation in Section III-A, to observe the PER variation for different transmission rates and different average channel qualities between the transmitter and the



(a) Packet Error Rate

(b) Video Rate

Fig. 3. PER and Video Rates vs different received SNR's for IEEE 802.11g with $\beta = 1$.

receiver. In Table II, we list the physical layer transmission rates of IEEE 802.11g and their corresponding modulation and convolutional channel coding rates [30]. In Figure 3(a), we illustrate the PER as a function of average received SNR between the transmitter and its receiver for different transmission rates. Here, we only present the results up to a PER of 25%, since for higher PER, the channel will be highly unreliable. For a fixed received SNR, we define sustainable transmission rate as the rate at which the average PER is less than 25%. Note that at a particular received SNR, among all sustainable transmission rates, the higher the transmission rate is, the higher the PER and therefore the more FEC parity packets should be transmitted. On the other hand, as the transmission rate increases, the more efficient the use of the spectrum becomes, allowing more room for extra FEC parity packets. In order to find the best transmission rate to maximize the overall video rate, we utilize the above obtained PER values along with equation (10), and depict the video rates in Figure 3(b). Since we only consider the PER up to 25%, for each transmission rate, we can not sustain received SNR below a threshold.

We observe that as the average received SNR increases, a higher transmission rate together with stronger FEC is more efficient than using a lower transmission rate with weaker FEC. Motivated by this observation, we also consider rate adaptation for direct transmission (*Direct-adaptive*) [3]. For *Direct-adaptive*, the transmission rates and FEC rates are dynamically adjusted according to node channel conditions to maximize the video quality.

V. Problem Formulation for Cooperative Multicast

In this section, we derive a formulation for the video rate of cooperative multicast. In the most general setup, we assume two-hop cooperative multicast where at each hop, we consider the transmission of base

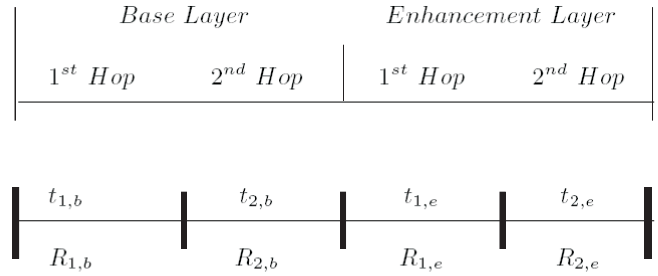


Fig. 4. Time scheduling and transmission rates for base and enhancement layers at first and second hop.

and enhancement layer packets. For this setup, we divide a video into segments of duration of T seconds. The time T is shared between the first and second hops. The base layer is transmitted over $t_{1,b}$ and $t_{2,b}$ fractions of each time interval for the first and second hop respectively, where

$$t_b = t_{1,b} + t_{2,b}. \tag{11}$$

Similarly, the enhancement layer is transmitted over $t_{1,e}$ and $t_{2,e}$ fractions of each time interval for the first and second hop respectively, where

$$t_e = t_{1,e} + t_{2,e}. \tag{12}$$

This leads to

$$t_b + t_e = t_{1,b} + t_{1,e} + t_{2,b} + t_{2,e} = 1. \tag{13}$$

The time scheduling of the base and enhancement layers along with the transmission rates are illustrated in Figure 4.

Following (10), the video rates for the base layer at Hop-1 and Hop-2, $R_{v_{1,b}}$ and $R_{v_{2,b}}$, can be expressed as:

$$R_{v_{1,b}} = \gamma_b \beta R_{1,b} t_{1,b} \quad , \quad R_{v_{2,b}} = \gamma_b \beta R_{2,b} t_{2,b} \tag{14}$$

where γ_b is the FEC rate for the base layer.

Similarly, the video rates for the enhancement layer at Hop-1 and Hop-2, $R_{v_{1,e}}$ and $R_{v_{2,e}}$, are:

$$R_{v_{1,e}} = \gamma_e \beta R_{1,e} t_{1,e} \quad , \quad R_{v_{2,e}} = \gamma_e \beta R_{2,e} t_{2,e} \tag{15}$$

where γ_e is the FEC rate for the enhancement layer.

Below we formulate the single layer and layered randomized cooperative multicast. We will discuss different transmission schemes and the selection of the system operating parameters based on the available channel information in Section VI.

A. *Single layer Cooperation (*RDSTC*)*

For single layer cooperation (*RDSTC*), we set $t_{1,e} = t_{2,e} = 0$ in (12), hence, we have $t_e = 0$ and $t_b = t_{1,b} + t_{2,b} = 1$. The first and second hop transmission rates are $R_1 = R_{1,b}$ and $R_2 = R_{2,b}$. The FEC rate $\gamma_c = \gamma_b$ depends on the maximum PER among all nodes after two hop transmission. Since we consider end-to-end packet level FEC, we compute the PER experienced by each node in the multicast group using the formulation in Section III. Note that the maximum PER, hence γ_c, depends on the transmission rates of both hops, R_1 and R_2 and the corresponding R-DSTC dimension L.

Since we would like Hop-1 and Hop-2 nodes to receive the same video rate, the transmission parameters should be chosen such that $R_{v_1,b} = R_{v_2,b}$. This yields $t_{1,b} = R_2/(R_1 + R_2)$, and given β, the the corresponding video rate for *RDSTC* can be expressed as:

$$R_{v_c}(R_1, R_2|\beta) = \gamma_c(R_1, R_2)\beta\tfrac{R_1 R_2}{R_1+R_2} \tag{16}$$

B. *Layered Cooperation (*RDSTC-layered*)*

In order to provide nodes differentiated quality based on their channel conditions, we consider two layers: Base and enhancement layer. For layered cooperation (*RDSTC-layered*), since we want all nodes receive the base layer at the same video rate, we have $R_{v_b} = R_{v_1,b} = R_{v_2,b}$. This yields $t_{1,b} = R_{2,b}t_b/(R_{1,b} + R_{2,b})$. Then, the corresponding video rate for the base layer can be expressed as:

$$R_{v_b}(R_{1,b}, R_{2,b}, t_b|\beta) = \gamma_b(R_{1,b}, R_{2,b})\beta\frac{R_{1,b}R_{2,b}}{R_{1,b} + R_{2,b}}t_b \tag{17}$$

where γ_b is the FEC rate for the base layer and is determined by the maximum PER after two hop transmission, $\epsilon_{max}(R_{1,b}, R_{2,b})$.

For the enhancement layer, we consider two options: The relays either forward all the enhancement layer packets or not forward any enhancement packets at all. In both options, we require that a certain percentage of nodes μ, receive the enhancement layer. By choosing the enhancement layer FEC rate γ_e, we can adjust the percentage of nodes that receive the enhancement layer with a FEC decoding failure probability below the threshold τ. Therefore, in the first option, γ_e depends on the target μ as well as $(R_{1,e}, R_{2,e}, L_e)$. Furthermore, since all enhancement layer packets are forwarded, we choose the transmission time such that $R_{v_1,e} = R_{v_2,e}$. This yields $t_{1,e} = R_{2,e}t_e/(R_{1,e} + R_{2,e})$. Since $t_e + t_b = 1$, the video rate for the enhancement layer can be expressed as:

$$R_{v_e}(R_{1,e}, R_{2,e}, t_b, \beta, \mu) = \gamma_e(R_{1,e}, R_{2,e}|\mu)\beta\frac{R_{1,e}R_{2,e}}{R_{1,e} + R_{2,e}}(1 - t_b). \tag{18}$$

Alternatively, the enhancement layer packets can go through only one hop transmission as in [28], and the source station chooses $R_{1,e}$ and γ_e so that μ percentage of nodes successfully receive the enhancement layer packets in the first hop. Since the enhancement layer packets are not forwarded, the FEC rate only depends on the first hop transmission rate, $R_{1,e}$ as well as μ. In this case, $t_{2,e} = 0$, hence, $t_e = t_{1,e}$. Then the video rate for the enhancement layer is:

$$R_{v_e}(R_{1,e}, t_b|\beta, \mu) = \gamma_e(R_{1,e}|\mu)\beta R_{1,e}(1 - t_b) \tag{19}$$

VI. Impact of Available Channel Information on multicast R-DSTC

In this section, we introduce different levels for channel information and discuss the selection of the system operating parameters that maximizes the video rates derived in Section V. We will describe the simulation setup and compare the performance of these schemes in Section VII.

We consider different levels for channel information. First, we assume that the source knows all the average channel qualities between itself and all the nodes, as well as among the nodes. This scheme is referred as *full-channel*. In order for the source station to know the average channel quality among the nodes, the nodes could exchange control signals among themselves for measuring the average SNR, and then transmit this information back to the source station. Although having full channel information provides the best results, we recognize that such computation of the transmission parameters may be too complex to be done in real time. Therefore, *full-channel* information will be used as a benchmark for more practical schemes with partial channel information. For partial channel information, we consider two different scenarios: *limited-channel* and *node-count*. For the *limited-channel* case, we assume the source station knows the average channel quality between itself and every node in the target coverage area. This requires channel feedback from the nodes; however in this case, inter-node channel qualities are not needed. For the *node-count* case, the only information the source station has is the number of nodes in the multicast coverage range.

Next, we will discuss the selection of system operating parameters for randomized cooperation based on these different levels of channel information.

A. *R-DSTC with full-channel information (*RDSTC*)*

For single layer cooperation, R_1, R_2 and the corresponding L, γ_s are chosen through an exhaustive search procedure in our current study. For each candidate (R_1, R_2), we first determine the average number of nodes (averaged over different node placements), N_{avg} that can successfully decode the first hop transmission. Among available STC dimensions, L is chosen to be equal or lower than N_{avg} to maximize the diversity gain. Hence in (16), we only indicate the dependence of the video rate and the FEC rate on (R_1, R_2). Then for this set of R_1, R_2, L we determine maximum end-to-end average PER (averaged over fading) among all nodes. We determine the suitable FEC of rate γ_c to ensure FEC decoding failure probability is less than τ. We search over all sustainable (R_1, R_2) through an exhaustive search to choose (R_1, R_2), and the corresponding L, γ_c that maximizes the video rate in (16).

In order to find the system operating parameters for layered cooperation, we set the video rate of the base layer to a target bit rate R_{v_b}. Then, for a given $R_{1,b}, R_{2,b}$, we determine L_b, γ_b to maximize $\gamma_b \frac{R_{1,b}R_{2,b}}{R_{1,b}+R_{2,b}}$ similar to single layer case. Next, we compute t_b using the selected $R_{1,b}, R_{2,b}, \gamma_b, L_b$ such that (17) is met for the target base layer video rate R_{v_b}. Note that since we want to maximize R_{v_e}, this results in the lowest t_b, and therefore the largest t_e. For the enhancement layer for the two-hop case, we find all feasible $R_{1,e}, R_{2,e}$ and the corresponding L_e, γ_e that guarantees the reception at μ percent of the nodes. Then, the source station chooses $R_{1,e}, R_{2,e}$ and the corresponding L_e, γ_e that maximizes, R_{v_e} by exhaustive search. For the one-hop case, after identifying all feasible $R_{1,e}$ and the corresponding γ_e, the system operating parameters are chosen to obtain the maximum R_{v_e} for a target R_{v_b} and μ.

For all the remaining channel information levels, we only consider the single layer case, however, the parameters for the layered case can be selected in a similar manner.

*B. R-DSTC with limited-channel information (*RDSTC-limited*)*

In order to compute the transmisison parameters, for a given set of average channel conditions between the source station and the nodes, we generate multiple node placements which have same source-node average channel qualities, but different inter-node average channel qualities. Since some node placements can be very unfavorable to cooperation, we only consider the majority of the node placements for a given set of source-node average channel conditions and choose the system operating parameters based on 95% of the node placements, by not considering those 5% of node placements with the highest PER. However, when we report the system performance, we evaluate the performance for the worst 5% of the node placements as well. The system operating parameters is pre-computed only once over a large set of node placements. Note that one can choose to drop a different percentage of nodes to compute the system operating parameters, but there is a tradeoff between the percentage of node placements dropped and the received video rate. As the percentage of node placements dropped increases, since the remaining node placements are more favorable, the received video rate increases, however, the percentage of nodes who receive all the packets decreases.

Specifically, for each candidate R_1, R_2 and the corresponding L, among all node placements with the same source-node average channel qualities, we remove the worst 5% of node placements in terms of PER, and find the maximum PER among the remaining 95%, and set γ_c in (16) based on this PER. Since the system computes ϵ_{max} considering the majority of the node placements, for a given (R_1, R_2) partial channel information mainly effects ϵ_{max} and hence the FEC rate γ_c. The choice of L for a given R_1 can be carried out as in Section V-A. Then, among all candidates, we choose (R_1, R_2) and the corresponding L, γ_c that maximize the video rate in (16). In practice, a table of the system operating parameters (R_1, R_2, γ_c and L) for different channel conditions between the source station and the nodes, can be pre-computed and stored at the source station.

*C. R-DSTC with node-count information (*RDSTC-nodecount*)*

In order to compute the transmission parameters, for a given node count, we generate different node placements. Different from the *RDSTC-limited* scheme, here we have different source-node distances as well as different inter-node distances for a given node count. In a manner similar to *RDSTC-limited* scheme, we only consider the majority of the node placements (i.e. 95% best node placements). We first find the maximum PER among all node placements with the same node count (except for the worst 5% placements) and compute γ_c based on this PER. Then we choose (R_1, R_2) and the corresponding L, γ_c to maximize the video rate in (16). In practice, a table of the system operating parameters (R_1, R_2, L and γ_c) for different number of nodes can be pre-computed and stored at the source station.

VII. Simulation Setup and Performance Evaluation

To evaluate and compare the performances of different transmission schemes, we study an IEEE 802.11g based network. Since we are considering physical layer cooperation, we conducted the simulations in Matlab7.1 and use the modulation and channel coding rates of IEEE 802.11g as listed in Table II. In our simulations, we consider different total number of nodes, N_T, corresponding to different density networks and for each node density, we generate 200 different node placements. The nodes are randomly uniformly distributed in a coverage area with a radius of $r_d = 100m$, where the access point is at the center of the network. We assume each packet whose length is typically around 1400 bytes, sees an independent and constant fading. For video, we use the slice mode of H.264/SVC [23] encoder with a maximum packet size of 1400 Bytes. To compute the PER at each node, we generate 2000 different independent fading levels for all node pairs (including source station to node). We use a block size $s = 128$ packets for FEC encoding. For R-DSTC, we choose among orthogonal STC dimensions of $L = 2, 4, 8$. For these STC dimensions, there exist real orthogonal designs which provide full rate for square constellations [33].

We choose the transmission power of the source station such that with direct transmission at the base transmission rate $R_d = 6Mbps$, and the nodes at the edge of the coverage range experience an average PER of 5% (before FEC), which is a typical PER assumption for wireless networks. For the same node count, the transmission parameters and hence achievable video rates for *RDSTC*, *RDSTC-limited* and

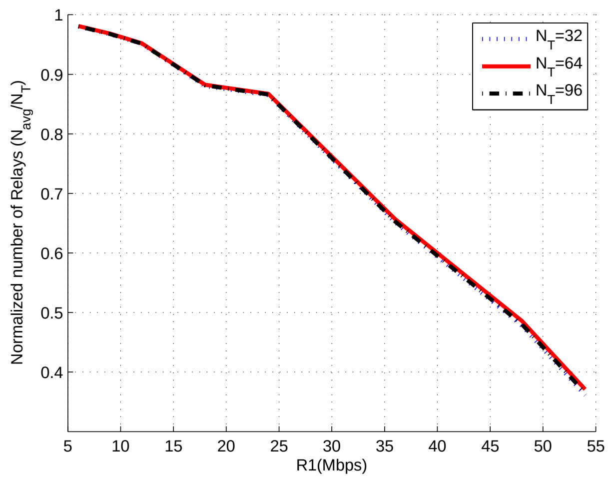


Fig. 5. N_{avg}/N_T vs R_1

Direct-adaptive depend on the actual node placements. In the performance curves presented below, for the same node count, we report the average video rates that are averaged over all node placements.

In order to have comparable power consumption with direct transmission, we would ideally like to choose the total relay transmission power to be equal to the source station transmission power. However, this requires the knowledge of the number of Hop-1 nodes, which varies from packet to packet. In order to avoid the feedback needed to acquire such information, we set the relay energy per symbol for the relays in the R-DSTC system to $E_{s,r} = E_{s,s}/N_{avg}$ where $E_{s,s}$ is the symbol energy of the source station and N_{avg} is the average number of Hop-1 nodes that receive each packet. Note that N_{avg} depends on the total number of nodes, N_T and first hop transmission rate, R_1. Since the symbol rate is same for all different physical transmission rates, by setting the symbol energy as above, the average power consumed by R-DSTC scheme is on the average equal to direct transmission. In Figure 5, we illustrate N_{avg}/N_T versus different first hop transmission rates for different N_T (averaged over node placements and fading levels). We observe that the ratio is almost constant for different number of nodes N_T. Therefore we use this constant ratio (depending on R_1) to normalize each relay's transmission power in all three R-DSTC schemes. Note that even at the highest transmission rate, this ratio is quite large and above 0.3.

In our simulations, for *Direct*, we choose the symbol energy of the source station such that with direct transmission at the base transmission rate $R_d = 6Mbps$, the nodes at the edge of the coverage range experience a certain average PER 5%. We apply a FEC rate of $\gamma_d = 0.905$ such that FEC decoding failure probability is below $\tau = 0.5\%$. For *Direct-adaptive*, given the node placement, we choose R_d and corresponding γ_d that lead to the highest video rate in (10) by exhaustive search [3]. The system operating parameters for all cooperative schemes are chosen as described in Section VI.

In Figure 6, we illustrate the achievable average video rates for different single layer schemes as a

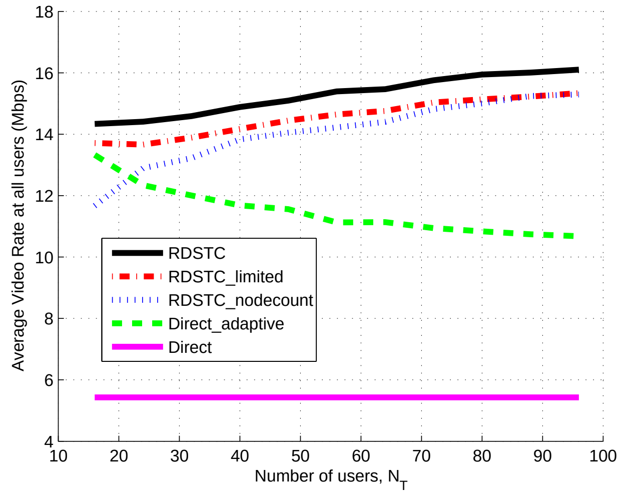
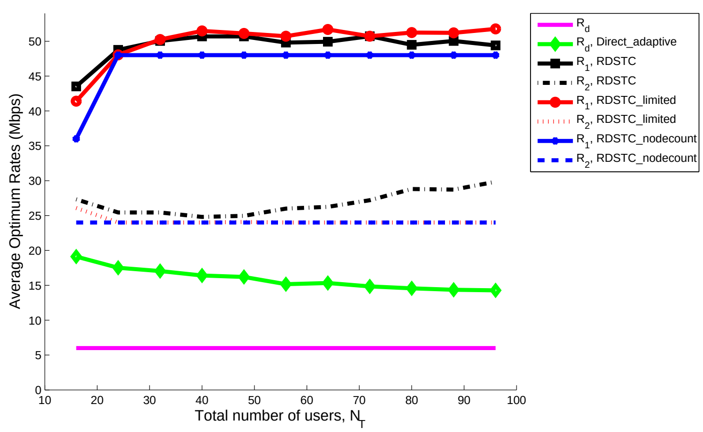
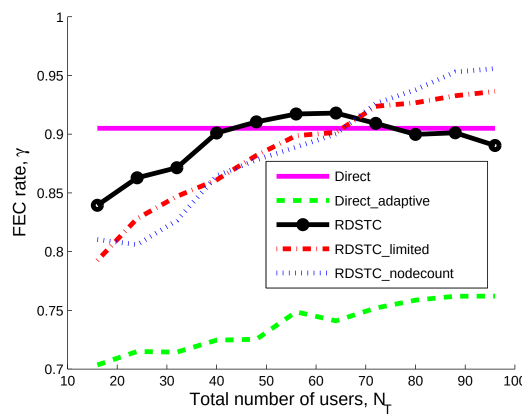


Fig. 6. Average video rates vs number of nodes for single layer systems ($\beta = 1$).



(a) Average transmission rates



(b) Average FEC rates

Fig. 7. Transmission rates and FEC rates for single layer systems

function of the number of nodes. For *Direct*, the video rate does not change with number of nodes as transmission and FEC rates are fixed. For *Direct-adaptive*, since the transmission and FEC rates are chosen based on the node with the worst average channel condition, for a large number of nodes, there is a higher chance that there will be some node at the edge of the coverage range; hence the video rate reduces as the number of nodes increases. For the cooperative multicast systems, as the number of nodes increases, more relays participate in the transmission, resulting in higher video rates. As illustrated in the figure, the proposed schemes outperform both direct transmission and rate-adaptive direct transmission. Our results show that the performance of *RDSTC-limited* and *RDSTC-nodecount* converge as the number of nodes increases, which suggests that knowing only the node count is almost as good as knowing the average channel conditions between the source station and nodes, when the node density is large. Note

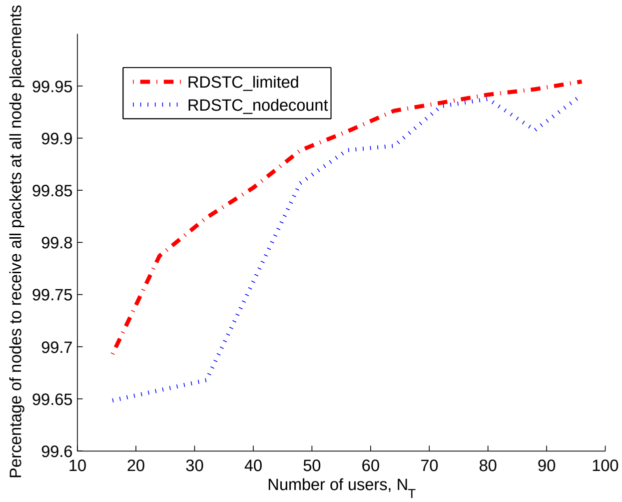


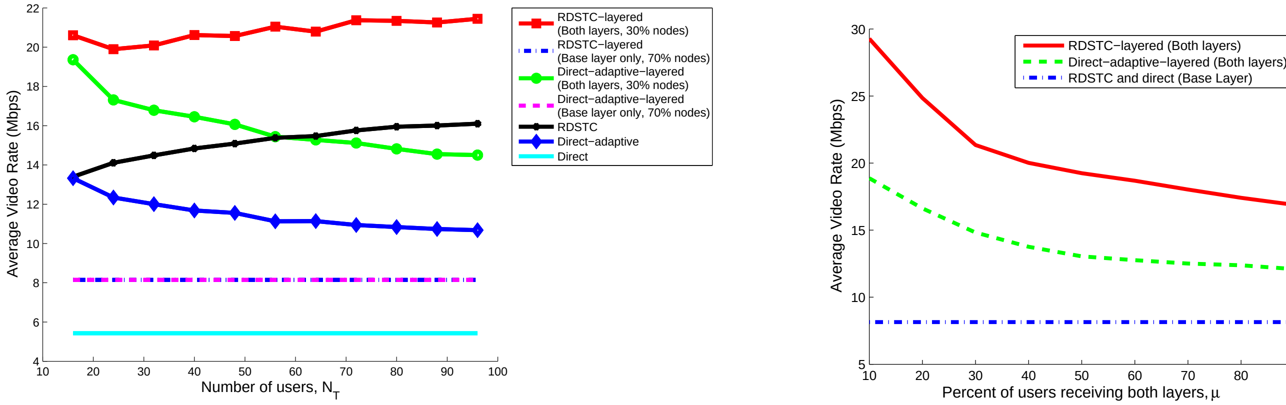
Fig. 8. Percentage of nodes to receive all packets at all node placements versus number of nodes, N_T

that the average video rates reported for *RDSTC-limited* and *RDSTC-nodecount* only include the best 95% node placements. We discuss the performance in the remaining 5% node placements below. Furthermore, the achievable video rates by both *RDSTC-limited* and *RDSTC-nodecount* are only up to 10% lower than that of the *RDSTC* requiring full channel information. This demonstrates that cooperation using R-DSTC is indeed very robust and capable of near optimal performance even without full channel information.

In Figure 7, for different node counts, we present the operating transmission rates (R_1, R_2) and the corresponding FEC rates γ. Note that for all schemes except for *Direct* and *RDSTC-nodecount*, the transmission rates and corresponding FEC rates depend on the actual node placement for a given node count. The curves in this figure show the average over all node placements. We observe that the average first hop transmission rates for the RDSTC schemes are between 48Mbps and 54Mbps. In this transmission rate range, the N_{avg}/N_T ratio is around 0.45 (see Figure 5). This means for each packet, almost half of the nodes receive the packet correctly and participate in the second hop transmission. Furthermore, we show that even when the system operating parameters are chosen with partial channel information, they are close to those of R-DSTC with full-channel information.

Recall that in *RDSTC-limited* and *RDSTC-nodecount*, the system operating parameters are chosen based on the best 95% of the node placements. All nodes in these placements receive video packets with a FEC decoding failure probability of less than $\tau = 0.5\%$. In Figure 8, we consider all the node placements (including the worst 5% of node placements) and present the percentage of nodes that receive all the packets with a FEC decoding failure probability of less than $\tau = 0.5\%$. We observe that even though the system operating parameters were not particularly chosen for these node placements, for a high density network, almost all the nodes in these node placements receive all the packets.

For layered cooperation, we only evaluate the performance of layered R-DSTC under full channel



(a) Video rates vs number of nodes for $\mu = 30\%$ (b) Video rates vs μ for $N_T = 80$

Fig. 9. Average video rates for layered cooperation for different N_T and μ.

	Direct	*Direct-Adaptive*	*RDSTC*	*RDSTC-layered* **(Both Layers)**	*RDSTC-layered* **(Base Layer)**
Harbor	26.54 dB	29.31 dB	31.76 dB	32.87 dB	28.19 dB
Terrace	29.17 dB	34.78 dB	37.27 dB	38.18 dB	33.13 dB

TABLE III

VIDEO QUALITY FOR DIFFERENT TRANSMISSION SCHEMES ($\beta = 0.1, N_T = 80, \mu = 10\%$)

information (*RDSTC-layered*), but the results can be extended to other schemes easily. In Figure 9(a), we illustrate the average video rates, for *RDSTC-layered* and *Direct-Adaptive-layered*, and compare with *RDSTC* as well as direct transmission schemes for $\mu = 30$ percent. Here we set the base layer rate to $R_{v_b} = 1.5R_{v,d}$ where $R_{v,d}$ is the video rate for direct transmission and evaluate the video rate of the enhancement layer, R_{v_e}. With layered randomized cooperation, $\mu = 30$ percent of the nodes observe significant improvement on the video rate compared to single layered randomized cooperation while the remaining nodes still experience a much better video quality than direct transmission. Furthermore, layered randomized cooperation outperforms layered direct transmission. In Figure 9(b), for a fixed number of nodes, we present the achievable total video rates ($R_{v_b} + R_{v_e}$) as a function of μ for the same base layer rate above. Recall that μ is the percentage of nodes receiving both layers, while $100 - \mu$ is the percentage of nodes receiving only base layer, hence as we increase μ, the total achievable video rate reduces, as we provide this rate to more nodes.

We also consider the quality of the receivers in terms of average PSNR values for the Harbor and Terrace video sequences. We assume that as long as the FEC decoding failure probability is below the threshold, the decoded video quality is almost equal to the encoded video quality and depends on the video rate. We use a H.264/SVC [23] codec with SNR scalability and encode SD resolution (704x576) video sequences. Considering the range of SD video rate, we choose $\beta = 0.1$. We compute the average PSNR that can be supported by different transmission schemes for a dense network (N_T=80). We present the performance of different transmission schemes in Table III. For Terrace sequences, single layer cooperative multicast achieves 8.1dB and 2.49dB improvement compared to direct transmission and rate adaptive direct transmission, respectively. Layered cooperation provides further PSNR gains of up to 9.01dB for nodes with good channel quality whereas the nodes with bad channel conditions experience a PSNR improvement of 3.96dB compared to direct transmission. Such gains in PSNR lead to significant visual improvement.

Finally, we discuss the delay introduced by FEC into the direct transmission and cooperative multicast system. In a system that adds m parity packets to each block of s source packets, the receiver must wait for $n = s+m$ packet transmission times before FEC decoding. Therefore the delay due to FEC decoding is the time needed to transmit n packets. Since the received video rate already considers the parity packets and β, the delay is $D = Ls/R_v$, where L is the packet size and R_v is the received video rate. In our case, for $\beta = 0.1$, we use $s = 128$ packets and $L = 1400$ Bytes. For direct transmission schemes, the delay due to the block transmission can be computed using $D_d = Lk/R_{v_d}$. The delay is around 0.330 and 0.130 seconds per FEC block for *Direct* and *Direct-Adaptive*, respectively. For cooperative multicast schemes, delay can be computed similarly as $D_c = Lk/R_{v_c}$ and it is 0.092, 0.096 and 0.097 seconds for *RDSTC*, *RDSTC-limited* and *RDSTC-nodecount*, respectively. Note that for the cooperative multicast, even though the relays introduce additional delay for the FEC block, since the throughput is also higher, the total delay is still smaller compared to the direct transmission. Also note that this delay only causes initial play-out delay, which is acceptable for multicast applications. The previous discussion is for single layer cooperative multicast and similar computations can be carried out for the layered case.

VIII. Conclusion

In this paper, we propose a cooperative layered video multicasting scheme using R-DSTC along with packet level FEC to enable error resilient video delivery. We choose the transmission rates of the first and second hops, STC dimension and FEC rate to maximize the achievable video rate at all nodes in the single layer system. In the layered case, we maximize the video rate of the enhancement layer given a target base layer video rate R_{v_b} and a percentage of nodes μ that receive both base and enhancement layers. We further discuss the impact of the available channel information, and propose three different schemes to choose the system operating parameters based on the available network state information for the R-DSTC scheme. Our results show that rate adaptive direct transmission provides more than two times higher video rates as compared to conventional multicast. For single layer cooperation with full channel information, each node experiences the same video rate which is up to three times higher than conventional multicast. For the layered case with full channel information, closer nodes experience up to six times higher video rates, depending on μ, while the distant nodes still experience much better video rates compared with the direct transmission. We observe that R-DSTC with limited channel information and R-DSTC with node count perform similarly when there are a large number of nodes in the network. We show that even when the transmission parameters are chosen with partial channel information (for example, only based on node count), the robustness of R-DSTC ensures that the performance loss is negligible compared to R-DSTC with full channel information.

With the proposed scheme in this paper, the relays forward all the packets without differentiating between the source and parity packets. Furthermore, the parity packets are only generated at the source station, and even when the nodes receive all k source packets, they do not generate parity packets. A future research direction considers enabling FEC encoding at the relays to forego first hop transmission of parity packets in order to improve the overall multicast performance. With such a design, parity packets are generated by the nodes who receive the source packets correctly, and these parity packets are only transmitted in the second hop using R-DSTC.

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