Layered Wireless Video Multicast Using Relays

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***Abstract*—Wireless video multicast enables delivery of popular events to many mobile users in a bandwidth efficient manner. However, providing good and stable video quality to a large number of users with varying channel conditions remains elusive. In this paper, an integration of layered video coding, packet level forward error correction, and two-hop relaying is proposed to enable efficient and robust video multicast in infrastructure-based wireless networks. First, transmission with conventional omni-directional antennas is considered where relays have to transmit in non-overlapping time slots in order to avoid collision. In order to improve system efficiency, we next investigate a system in which relays transmit simultaneously using directional antennas. In both systems, we consider a non-layered configuration, where the relays forward all received video packets and all users receive the same video quality, as well as a layered setup, where the relays forward only the base-layer video. For each system setup, we consider optimization of the relay placement, user partition, transmission rates of each hop, and time scheduling between source and relay transmissions. Our analysis shows that the non-layered system can provide better video quality to all users than the conventional direct transmission system, and the layered system enables some users to enjoy significantly better quality, while guaranteeing other users the same or better quality than direct transmission. The directional relay system can provide substantial improvements over the omni-directional relay system. To support our results, a prototype is implemented using open source drivers and socket programming, and the system performance is validated with real-world experiments.**

***Index Terms*—Directional relays, forward error correction, layered video coding, omni-directional relays, video multicast, wireless networks.**

I. Introduction

In RECENT years, the demand for video applications over wireless networks has been on the rise due to the significant increase in both the bandwidth of wireless channels and the computational power of mobile devices. To provide efficient delivery among a group of users simultaneously, multicast has been used as an effective solution as it saves network resources by sharing a data stream across multiple receivers. However, a higher packet loss ratio and variation of the wireless channels, along with heterogeneity of the users, make video multicast over wireless networks a challenging problem.

In this paper, we consider multicast in the coverage area of an access point (AP) in a wireless local area network (WLAN). The same principle can be applied to the coverage area of a base station (BS) in a cellular network. The contribution of this paper is the integration of layered video coding, two-hop relaying, and packet level forward error correction (FEC) to enable efficient and robust video multicast. In conventional multicast design for infrastructure networks, the sender adjusts its transmission rate according to the worst channel quality among all users, therefore the receivers with a good channel unnecessarily suffer and experience a lower quality video than they would have if the system was targeted for them. The basic idea behind multicast using relays is the division of all the receivers into two groups in a way that receivers in Group 1 have better average channel quality than those of Group 2. In such a system, we let the sender choose its transmission rate based on the worst channel quality of Group 1. Then, the relays (either selected among Group 1 receivers or placed at fixed locations) forward the received information to Group 2 users. Such a scheme not only allows receivers in Group 1 to have a higher quality signal, but also provides quality gains for the users in Group 2. Although the same principle can be extended to use more than two hops, our results show that two hop transmission is sufficient for providing good quality video multicast within the same coverage area of an AP.

Multi-hop communications have been studied for different types of networks, such as cellular networks, ad hoc networks, and mesh networks. For multi-hop cellular networks, authors of [1] and [2] studied unicast applications. To the best of our knowledge, multicast has not been considered specifically in the context of multi-hop cellular networks. In [3] and [4], multicast routing protocols have been discussed for ad hoc networks. The authors of [5] and [6] also considered video multicast over ad hoc networks, where the use of multiple description video is proposed to overcome the unreliability of wireless links. In this paper, we consider an infrastructure-based network, rather than a self-organizing network such as ad hoc networks. Studies on multicast in mesh networks in general consider building an efficient multicast tree. Chou *et al.* [7] considered video multicast for multi-rate wireless mesh networks where the construction of the multicast tree along with scheduling for low latency multicast was explored. Methods that enhance the performance of the tree-based mul-

Manuscript received February 16, 2009; revised August 20, 2009 and January 8, 2010. Date of publication July 1, 2010; date of current version August 4, 2010. This work was supported in part by the National Science Foundation (NSF) under Awards 0 430 885, 0 722 868, 0 708 989, 0 905 446, by the New York State Center for Advanced Technology in Telecommunications, and by the Wireless Internet Center for Advanced Technology, an NSF Industry/University Research Center at the Polytechnic Institute of New York University. This paper was recommended by Associate Editor T. Nguyen.

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Digital Object Identifier 10.1109/TCSVT.2010.2056951

ticast have also been investigated [8], [9]. In order to address the heterogeneity of users, scalable (layered) video coding is widely used. Layered video multicast has been studied in infrastructure-based wireless networks [12]–[22], as well as in mesh networks [13]. The approach proposed in this paper has a fundamental difference compared to approaches proposed in prior work for multicast in mesh networks. Our work defines a medium access control mechanism from the AP and the relays. By scheduling the relay transmissions at the medium access control (MAC) layer, the relays cooperatively access the channel instead of contending for the channel by following the regular carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Such a scheme cannot be implemented in mesh networks since the forwarding in mesh networks operates in layer 3 (network layer), hence, there is neither a guarantee on any timing constraints nor control on the relays' access to the channel. Finally, while the forwarding decisions in mesh networks are based on an efficient setup of the multicast tree in order to meet objectives such as minimizing maximum delay or traffic congestion, the proposed method takes the channel conditions into account to determine relay positions that lead to higher transmission rates in both hops and hence higher video quality.

The main focus of this paper is to formulate and compute the optimum system parameters, including relay placement, user partition, transmission rates, and FEC rates of each hop and transmission time scheduling, which maximize a chosen multicast performance criterion. Our optimization considers all possible user locations in the target coverage region, rather than a particular user distribution. Note that optimum relay placement can be accomplished in two ways. First, if the network is dense, the relays can be selected among the intended receivers. Here, dense network ensures that there exist receivers at optimum relay locations. An example for a dense network is an urban environment, where a large number of devices access the channel at the same time. Alternatively, optimized relay positions can be used for optimal relay placement in an infrastructure based network where fixed relay nodes are introduced to the system. With fixed relays, the system will work regardless of the distribution of the receiver nodes. The literature on optimum relay placement is mostly for unicast communication. For example, in [14], optimum placement for a single relay is discussed to maximize the capacity in IEEE.802.16j networks. [14] is extended in [16] to study the optimum relay station placement and the corresponding bandwidth and power allocation for cooperative relaying. A more theoretical work on relay selection in sensor networks is [15] where the minimization of the average probability of error is studied. The relay placement algorithm described in this paper on the other hand considers a multicast scenario.

We first consider omni-directional relay transmission [17], where each relay targets a subgroup of Group 2 users and transmits in a different time slot sequentially to avoid collision. A deficiency of this system is that the relays cannot send simultaneously, which limits the supportable video rates. To circumvent this problem, we also investigate using directional antennas for relay transmission [18]. In this case, we assume the relay stations are equipped with directional antennas, and directionally transmit the relayed data to their targeted subgroups using non-overlapping beams. Although the current cost of directional antennas may be high, the significant potential performance gain motivates their use.

In order to handle packet losses at each hop, we further employ packet level FEC, which is a promising solution for error control in video multicast over wireless networks [19]–[22]. 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.

Along with numerical evaluation, in order to validate our research in a practical environment, we implement a prototype of the proposed system using omni-directional relays and conduct extensive experiments. The implementation is carried out in the MAC layer as well as in the application layer, using open source drivers and socket programming, along with a packet level FEC. We show that the implementation results are close to our numerical analysis.

This paper is organized as follows. In Section II, we introduce the system model and discuss multicast performance metric. We discuss the packet level FEC in Section III. In Sections IV and V, we formulate the optimum user partition and time scheduling for omni-directional and directional relay transmission, respectively. Section VI analyzes the obtained numerical results. Section VII summarizes our implementation efforts. We conclude this paper in Section VIII.

II. Overview of Proposed System Architecture

A. Multicast Using Relays: System Model

We study an infrastructure-based wireless network (such as WLAN, 3G, or WiMAX), and assume that a sender (BS or AP) multicasts video to the receivers within a coverage area of a certain radius. Our system is based on a path loss model with a path loss exponent of PLE, which solely depends on the distance between a transmitter and its receiver. In other words, the receivers closer to the transmitter have better channel qualities and hence can experience lower packet loss rates than the far away receivers. Relaying can also be used to overcome the shadowing effects in wireless networks; however in this paper, in order to have a fair comparison with direct transmission, we assume all the users are in line-of-sight.

We consider optimized system parameters within a target coverage area. We divide the entire coverage area into two groups, so that receivers in Group 1 have better channel quality than receivers in Group 2. We let the sender choose its transmission rate and packet level FEC rate based on the worst channel quality in Group 1. For a chosen transmission rate and corresponding packet loss rate in a given coverage area, we apply sufficient amount of packet level FEC so that the FEC decoding failure rate is negligible. This will be further discussed in Section III. Then, the relays (either selected among Group 1 receivers or placed at fixed locations) will forward all or selected received packets from the sender to Group 2 receivers with the transmission rate and FEC rate chosen based on the worst channel quality of relays to Group 2 receivers.

TABLE I
NOTATION

R_d	Direct transmission rate (Mb/s)
R_1	First hop transmission rate (Mb/s)
R_2	Second hop transmission rate (Mb/s)
r_d	Direct transmission coverage range (m)
r_1	First hop coverage range (m)
r_2	Second hop coverage range (omni-directional) (m)
r'_2	Second hop coverage range (directional) (m)
$r_{s,r}$	Distance between source and relay (m)
r_{omni}	Coverage range with omni-directional antennas (m)
r_{dir}	Coverage range with directional antennas (m)
t_1	First hop transmission time fraction
t_2	Second hop transmission time fraction
R_{vd}	Received video rate for direct transmission (kb/s)
R_{v1}	Received video rate for Group-1 nodes (kb/s)
R_{v2}	Received video rate for Group-2 nodes (kb/s)
Q_d	Video quality for direct transmission (PSNR)
Q_1	Video quality of Group-1 nodes (PSNR)
Q_2	Video quality of Group-2 nodes (PSNR)
β	Effective data ratio
α	Separation angle of the relays
γ	FEC rate with omni-directional antennas
γ'	FEC rate with directional antennas
γ_d	FEC rate for direct transmission
γ_1	FEC rate for first hop transmission
γ_2	FEC rate for second hop transmission
θ	Directional antenna angle
P_E	Packet error rate
N	Number of relays
M	Number of beams for directional antennas

The two-hop relaying strategy enables both the sender-to-Group 1 receivers' links and relay-to-Group 2 receivers' links to have better quality and hence lower packet loss rates than the sender to the worst user in the entire coverage area. By improving the channel quality we boost the transmission rates for both transmission hops. In general, Group 2 receivers can combine the received information from the sender and the relays, but in this paper, we consider the simple case where Group 2 receivers only listen to their designated relay. We show that even with such a two-hop relay strategy, substantial improvement in performance is possible.

Before describing the details of the proposed system, we summarize the notation we used in this paper in Table I. For the baseline direct transmission system, we assume that the sender uses a transmission rate of R_d Mb/s and a FEC rate of $\gamma_d = \gamma(R_d, r_d)$ to cover users in a radius of r_d meters (m). Here, γ is the FEC rate with omni-directional antennas and is chosen so that the FEC decoding failure rate at all receivers is negligible. This implies that the FEC rate is chosen based on the packet error rate (PER) at the farthest users in the coverage region, which depends on R_d and r_d. The details of FEC are provided in Section III.

For the proposed multicast system using omni-directional relays, each relay transmits to a subset of Group 2 users in a separate time slot. A Group 2 user only listens to its designated relay as illustrated in Fig. 1(a). In Group 1, we assume a transmission rate of R_1 Mb/s and a FEC rate of $\gamma_1 = \gamma(R_1, r_1)$ that can cover users within a radius of r_1 meters with a negligible FEC decoding failure rate. Similarly, in the second hop transmission, the relays transmit at a rate R_2 Mb/s, and a FEC rate of $\gamma_2 = \gamma(R_2, r_2)$ is chosen to cover users at a distance r_2 meters from the relay. We assume that the video data is sent in intervals of T seconds, and the sender and the relays use T_1 and T_2 seconds for their transmissions, respectively, such that $T = T_1 + NT_2$ where N stands for the number of relays. In other words, the sender transmits during a fraction $t_1 = T_1/T$ of each transmission interval, and each relay transmits during a fraction $t_2 = T_2/T$. With this setup, we cover an area of a radius r_{omni} meters such that $r_{\text{omni}} \geq r_d$.

For the proposed system with directional relays, we assume each relay directionally transmits the data in the second hop to its targeted subgroup as depicted in Fig. 1(b). In this figure, as an example, four relays are responsible for transmitting in the second hop. Each relay station uses three beams and transmits the relayed packet three times, one after the other, scanning the area around it. By scheduling simultaneous transmissions clockwise for each relay (e.g., all relays transmit simultaneously using beam 1, then beam 2, and so on), we achieve efficient spatial reuse. With directional antennas, the first hop parameters are the same as in the omni-directional case. In the second hop, the relays transmit at a rate R_2, and a FEC rate $\gamma_2 = \gamma'(R_2, r'_2, \theta)$, where each beam has an angle θ with a coverage range of r'_2 from the relay. Here, γ' is the FEC rate with directional antennas and is chosen so that the FEC decoding failure rate at all receivers is negligible. The sender uses T_1 seconds for its transmission and the relays use T_2 seconds for each beam, such that $T = T_1 + MT_2$, where M is the number of beams. Here, we cover an area of radius r_{dir} meters such that $r_{\text{dir}} \geq r_d$. The criteria to optimize the parameters both in the omni-directional and the directional case will be described next.

B. Multicast Performance Criteria

The optimum user partition and relay scheduling depends on the chosen performance metric. In order to have a fair comparison with direct transmission, we only consider the receivers within the coverage range of direct transmission r_d. For a fixed energy consumption by the sender and coverage range, our main focus is to improve the video quality for all possible user locations in the coverage area. In general, coverage range and energy consumption of the system can also be considered as a design parameter as discussed in [23].

We define $Q_d(R_d, r_d)$ as the average quality among all users with direct transmission, $Q_1(R_1, r_1, t_1)$ as the average quality of Group 1 receivers, and $Q_2(R_2, r_2, t_2)$ as the average quality for Group 2 receivers. Recall that, for a given transmission rate R_i ($i = 1, 2$) and coverage distance r_i, we assume that the FEC rate $\gamma(R_i, r_i)$ is chosen such that all receivers in Group i have negligible FEC decoding failure rate (to be discussed further in Section III). We define the video rate $R_{v_i}(R_i, r_i, t_i)$ as the rate at which video bits are delivered, which depends on the transmission rate, the FEC rate, and the transmission time scheduling. Since the FEC rate is chosen so that video can be received with negligible packet losses in all receivers in the same group, we assume the video quality in Group i only depends on the video rate of Group i, i.e., $Q_i(R_i, r_i, t_i) = Q(R_{v_i}(R_i, r_i, t_i))$, where $Q(R_v)$ indicates the quality-rate function for a given video. Note that, for a given r_i and r_d, there is a corresponding N and M for omni-directional

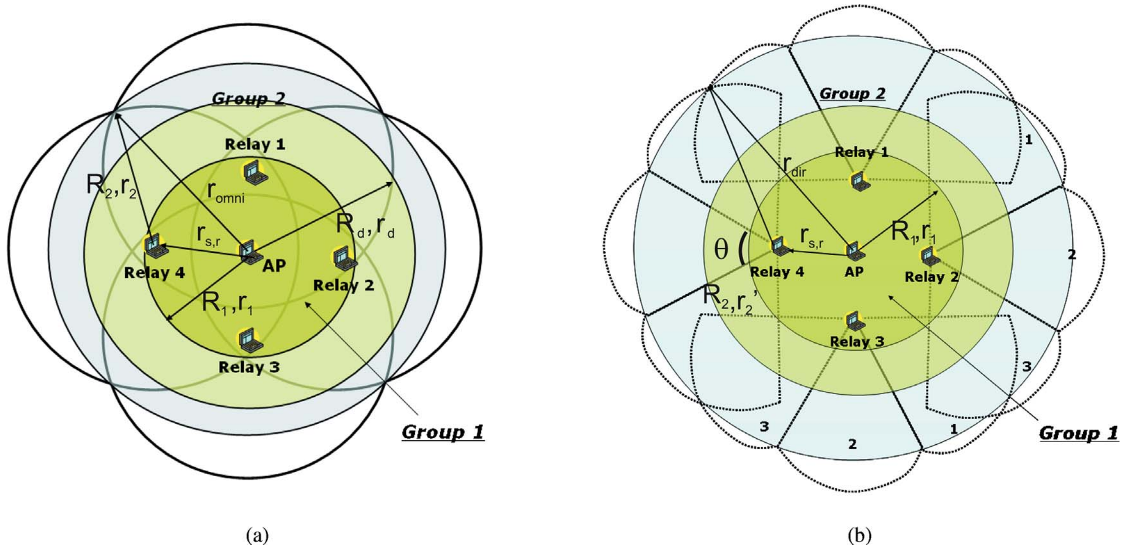

Fig. 1. System setup. (a) Omni-directional relays. (b) Directional relays.

and directional relay transmission, respectively, which along with R_i and R_d, determines the dependence of t_is. Therefore, Q_is also depend on N and M.

We consider two different performance metrics as our multicast performance criteria.

1) *Same Quality at All Users (Non-Layered):* From the service provider's point of view, sometimes it is better to guarantee that all the users in a multicast session see the same video quality. This can be accomplished by choosing the system parameters so that $Q_1(R_1, r_1, t_1) = Q_2(R_2, r_2, t_2) = Q_{\text{eq}}(R1, R2, r1, r2, t1, t2)$, and let the relays forward all the received video packets to Group 2. In this setup, we want to choose the system parameters to maximize Q_{eq}. In other words, we determine the optimum parameters that maximize $Q_{\text{eq}} = Q_1(R_1, r_1, t_1) = Q_2(R_2, r_2, t_2)$. Note that this is equivalent to maximizing the rate $R_{\text{eq}} = R_{v_1} = R_{v_2}$.

2) *Better Quality at Group* 1 *Users (Layered):* We also investigate layered relay transmission where the system favors Group 1 receivers. Here, we maximize $Q_1(R_1, r_1, t_1)$ while providing Group 2 users with the same or better quality as in direct transmission. In this case, we find the optimum parameters that maximize $Q_1(R_1, r_1, t_1)$ while guaranteeing $Q_2(R_2, r_2, t_2) = Q_{\min} \geq Q_d(R_d, r_d)$. Note that this is equivalent to maximizing R_{v_1} while having $R_{v_2} \geq R_{v_d}$.

III. Packet Level FEC

Forward error correction (FEC) at the application layer is used to handle packet losses in multicast services. The basic idea of 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. 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 VI. Despite additional overhead and delay, considering the benefits for error recovery, such a scheme is widely used in a multicast environment.

In this section, we will discuss the overhead and the useful rate which is used to deliver video, considering the overhead due to FEC and other factors in the network.

A. FEC Rate

We assume that by using CRC at the link layer, each receiver is able to decide whether a packet is correctly received or not. For every k source packets, we add m parity packets for a total number of packets of $n = m + k$. For Reed-Solomon code [24] and PER of P_E, the FEC decoding failure rate is the probability that at least $m + 1$ packets are in error. For given k and P_E, we determine m so that the FEC decoding failure rate is less than or equal to 0.5%. We observe that using an error-resilient video decoder, there is no observable quality degradation when the loss rate is equal or below this threshold.

In wireless networks, for a fixed transmission rate R, we observe different PER values at different distances, r, due to path loss. Generally, for fixed transmission power, we can express P_E as a function of R and r, $P_E(r, R)$. Note that since P_E is a function of r and R, the FEC rate γ is also a function of r and R, and can be written as $\gamma(r, R)$.

The above formulation for the FEC overhead considers single link transmission. For multicast transmission with relays, this formulation can be used to determine the FEC rate for both hops. We assume the source FEC rate is chosen based on the PER of the first hop. Upon reception of the packets, the relays decode the FEC block and regenerate parity packets based on the PER of the second hop. They transmit the parity packets along with the source packets.

B. Useful Rate

While computing the useful rate, we also consider other overheads (such as headers) in the system. We define the effective data ratio, β, as the ratio of the time spent in transmitting the actual payload data (including the parity packets) to the total transmission time. Specifically, β has two components $\beta = \beta_t \beta_{\text{header}}$ where β_t is the proportion of the time used to transmit a given stream and β_{header} is the ratio of the time used to transmit the payload data to the time spent to transmit the payload data and the headers. For IEEE802.11, MAC and IP headers are sent at the selected transmission rate, whereas the physical layer header is always sent at the base transmission rate. Hence, β_{header} depends on the transmission rate, and as the transmission rate increases, β_{header} decreases. Typical β values will be presented in Section VI.

Based on the discussion above, the useful rate R_{useful} at which the video is transmitted can be computed as follows:

$$R_{\text{useful}}(r, R) = \gamma(r, R)\beta(R)R. \tag{1}$$

Note that the useful rate depends on the transmission rate and the coverage radius. Here we assume a fixed bandwidth 802.11 system with different transmission rates by changing the corresponding modulation schemes. Hence, for this system, the higher the transmission rate, the higher the PER value as will be illustrated in Fig. 4. In this case, since the PER is higher, we need more parity packets to correct the errors, hence γ decreases. Furthermore, as the transmission rate increases the header overhead also increases, so that $\beta(R)$ decreases as will be illustrated in Table II. On the other hand, as the transmission rate increases, the number of bits we can transmit increases, allowing more room for extra FEC parity packets. Therefore, in the system design, for a fixed distance, there is an optimum transmission rate that maximizes R_{useful}.

The above analysis only considers a single link. For instance, for direct transmission at rate R_d to an area of radius r_d, all users will experience the same useful rate and hence, the same video rate of $R_{v_d} = R_{\text{useful}}(r_d, R_d) = \gamma(r_d, R_d)\beta(R_d)R_d$ kb/s. On the other hand, for the two-hop multicast system, along with the transmission rates, relay selection and relay scheduling also affect the useful rate. Specifically, when the sender transmits over a fraction $t_1 = T_1/T$ of each transmission interval, and each relay transmits over a fraction $t_2 = T_2/T$, the rates at which video can be delivered to Group 1 and Group 2 users are $R_{v_1}(R_1, r_1, t_1) = t_1\gamma(r_1, R_1)\beta(R_1)R_1$ kb/s and $R_{v_2}(R_2, r_2, t_2) = t_2\gamma(r_2, R_2)\beta(R_2)R_2$ kb/s, respectively.

In general, video rates for Group 1 and Group 2 can be different using a scalable video. We can code a video signal into multiple layers so that reception of more layers leads to better quality but even just one layer (the base layer) can provide acceptable quality. We can choose the system parameters t_i, r_i, R_i so that $R_{v_1} = R_{v_2}$, in order for all the users to experience the same video quality. Alternatively, using layered coding, we can make $R_{v_1} \geq R_{v_2} \geq R_{v_d}$, so that users in Group 1 get much better quality than that experienced in direct transmission, whereas users in Group 2 get video quality better than or similar to the direct transmission.

In Sections IV and V, we will discuss the relay selection and relay scheduling in detail for omni-directional and directional relay transmission, respectively.

IV. Optimum User Partition and Time Scheduling Using Omni-Directional Relays

In this section, we will first describe the time scheduling of the relays and formulate the corresponding video rates at both hops. Note that scheduling, and hence the received video rates, depend on the number of relays, N. We will derive the optimal solutions for the number of relays and their locations (i.e., user partition) using omni-directional relays following a geometric approach, so that all possible user locations with the target circular region can be covered.

For omni-directional relays, recall that the sender and the relays transmit over fractions t_1 and t_2 of the time, where $t_1 + Nt_2 = 1$. We can express the received video rates for Group 1 and Group 2, R_{v_1} and R_{v_2}, as

$$R_{v_1} = t_1 R_{\text{useful1}} = t_1\gamma(r_1, R_1)\beta(R_1)R_1 \tag{2}$$

$$R_{v_2} = t_2 R_{\text{useful2}} = t_2\gamma(r_2, R_2)\beta(R_2)R_2 \tag{3}$$

where R_1 and R_2 stand for the transmission rates for Group 1 and Group 2, and r_1 and r_2 are the coverage ranges for Group 1 and Group 2, respectively. By applying a sufficient amount of FEC, we assume that the FEC decoding failure rate is negligible as discussed before. Therefore the video qualities in Group 1, $Q_1(R_{v_1})$, and Group 2, $Q_2(R_{v_2})$, depend entirely on the video rates R_{v_1} and R_{v_2}, respectively.

In the above formulation, note that for a fixed t_1, since the relays cannot transmit simultaneously due to collisions, the time interval that each relay can transmit t_2 decreases as N increases. On the other hand, for a fixed r_1, as N increases, each relay only needs to cover a smaller subgroup to have the same coverage as in direct transmission and hence, a smaller r_2 will be sufficient. For a fixed transmission rate, as the coverage range for the relay r_2 decreases, the PER also decreases due to a better average channel, hence less error protection is needed leading to a higher FEC rate $\gamma(r_2, R_2)$. Therefore, while optimizing the system for a given performance criterion, we need to consider all parameters $(R_1, R_2, r_1, r_2, t_1, t_2, N)$ jointly.

We determine the optimum values of R_1, R_2, r_1, r_2, t_1, t_2, and N using one of the multicast performance criteria in Section II-B. This is accomplished using a two-step approach. For fixed r_1 and r_2, there may be different user partitions with different number of relays which satisfy $r_{\text{omni}} \geq r_d$ where r_{omni} is the radius of the coverage area of the omni-directional relay system. Note that, for fixed r_1 and r_2, the time each relay can transmit decreases as the number of relays increases. Hence, among the user partitions, we choose the one with minimum number of relays. Then, for this user partition, we find the optimum R_1, R_2, and t_1 that maximizes the system performance index. Recall that $t_1 + Nt_2 = 1$. By repeating the above procedure for all possible (r_1, r_2), we find the optimum user partition and time scheduling that maximizes the performance.

For fixed r_1 and r_2, we find the minimum number of relays that cover all the receivers within the coverage range of direct transmission, r_d, following a geometric approach. We define $r_{s,r}$ as the distance between the AP and the relays (equal for all the relays), and r_{omni} as the radius of the coverage area of the omni-directional relay system, as illustrated in Fig. 2.

User partition is defined by r_1, r_2 and the separation angle α (see Fig. 2). The total angle between two relays is defined to be 2α and is related to the number of relays by the equation

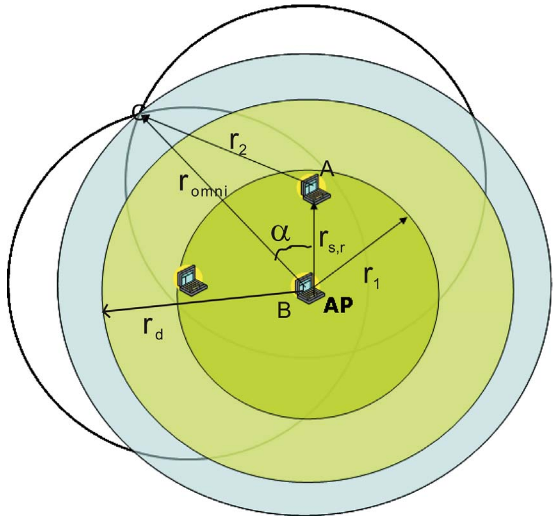

Fig. 2. Geometric model for the omni-directional relay transmission.

$N = \frac{2\pi}{2\alpha}$. We define $\alpha_{\max}$ as the maximum angle which satisfies the constraints

$$r_{s,r} \leq r_1 \tag{4}$$

$$r_{\text{omni}} \geq r_d. \tag{5}$$

More specifically, (4) states that the relay is selected from the Group 1 receivers and (5) guarantees that all the receivers in Group 2 are covered. The separation angle will be maximum (hence the number of relays will be minimum) when $r_{s,r} = r_1$ and $r_{\text{omni}} = r_d$. Note that, the triangle, ABC, in Fig. 2 has sides r_1, r_d and r_2. Applying the cosine theorem, we can compute $\alpha_{\max}$ as

$$\alpha_{\max} = \arccos \frac{r_1^2 + r_d^2 - r_2^2}{2r_1 r_d}. \tag{6}$$

Then the minimum number of relays can be calculated as

$$N = \lceil \frac{2\pi}{2\alpha_{\max}} \rceil. \tag{7}$$

After calculating the minimum number of relays, we consider that the relays are equally spaced at an angle $2\alpha = \frac{2\pi}{N}$, and $r_{s,r} = r_1$. Note that since the number of relays needs to be an integer, the actual separation angle α is generally smaller than $\alpha_{\max}$, hence, the coverage area, r_{omni}, is generally greater than the coverage area of direct transmission, r_d. We calculate r_{omni} using the cosine theorem on the triangle ABC by solving for the roots of the following second order equation:

$$r_{\text{omni}}^2 - 2r_1 \cos\alpha \; r_{\text{omni}} + r_1^2 - r_2^2 = 0. \tag{8}$$

After computing the user partition (i.e., r_1, r_2, N), we use an exhaustive search over a discretized space of feasible R_1, R_2, t_1 and $t_2 = (1 - t_1)/N$, and find the optimum solution for one of the multicast performance criteria in Section II-B. Note that for a chosen practical network such as IEEE802.11b, there are only a few possible transmission rates R_1 and R_2 and the corresponding r_1 and r_2. Numerical results for optimum parameters and achievable performances will be provided in Section VI.

V. Optimum User Partition and Time Scheduling Using Directional Relays

Directional antennas can significantly increase the performance of a wireless network due to their ability to point the transmission (or the reception) of an electromagnetic signal toward a specific direction. The targeted nature of the transmission results in spatial reuse, as there can be multiple transmissions in the same neighborhood without any collision. Additionally, directional transmission increases the signal energy toward the direction of the receiver. Directional antennas are becoming practical both in terms of size and usage, for example, there are directional antenna systems for laptops. Furthermore, for the dedicated relay model, it is quite reasonable for the relays to use directional antennas. One of the challenges of using directional antennas is adjusting the direction of the antennas to the target nodes, especially for relay networks. However, there are several MAC layer protocols for unicast in the literature discussing the location awareness and directionality in ad hoc networks [25], [26]. Similar approaches can be used for our MAC protocol for multicast.

When directional antennas are used, we can achieve a higher transmission rate for the same coverage range with a certain PER and the same transmission power. Alternatively, for the same transmission rate R and the same transmission power, we can achieve a larger coverage range r', compared to omni-directional antennas, which can be computed as

$$r' = \sqrt[PLE]{\frac{2\pi}{\theta}}\, r \tag{9}$$

where r is the coverage range with omni-directional antennas, PLE is the path loss exponent and θ is the beam angle. Note that as θ increases, r' decreases.

Using directional relays, we can have all the relays transmit simultaneously by scheduling each relay to transmit sequentially using different beams at different time slots. For example, in Fig. 1(b) four relays transmit simultaneously, each with three beams. In the first time slot, the relays transmit using their first beams, then in the second time slot their second beams are used for the transmission, etc. Recall that the sender and each beam of the relays transmit over t_1 and t_2 fraction of the time where $t_1 + Mt_2 = 1$.

For the directional relay system, the received video rates for Group 1 is the same as in the omni-directional relay system, given in (2). On the other hand, the received video rate for Group 2, R_{v_2}, is different from the omni-directional relay system and can be expressed as

$$R_{v2} = t_2 R_{\text{useful2}} = t_2 \gamma'(r_2', \theta, R_2)\beta(R_2)R_2 \tag{10}$$

where γ' is the FEC rate and $r_2{}'$ is the coverage range for directional relay transmission. While computing γ', we assume that the PER at r_2' with directional transmission is the same as the one at r_2 with omni-directional, where r_2' and r_2 are related via (9). Therefore, for the directional relay system, the PER is a function of r' and R, by $P_E'(r', R) = P_E(r'/\sqrt[PLE]{\frac{2\pi}{\theta}}, R)$, and the FEC rate for the directional relay transmission is

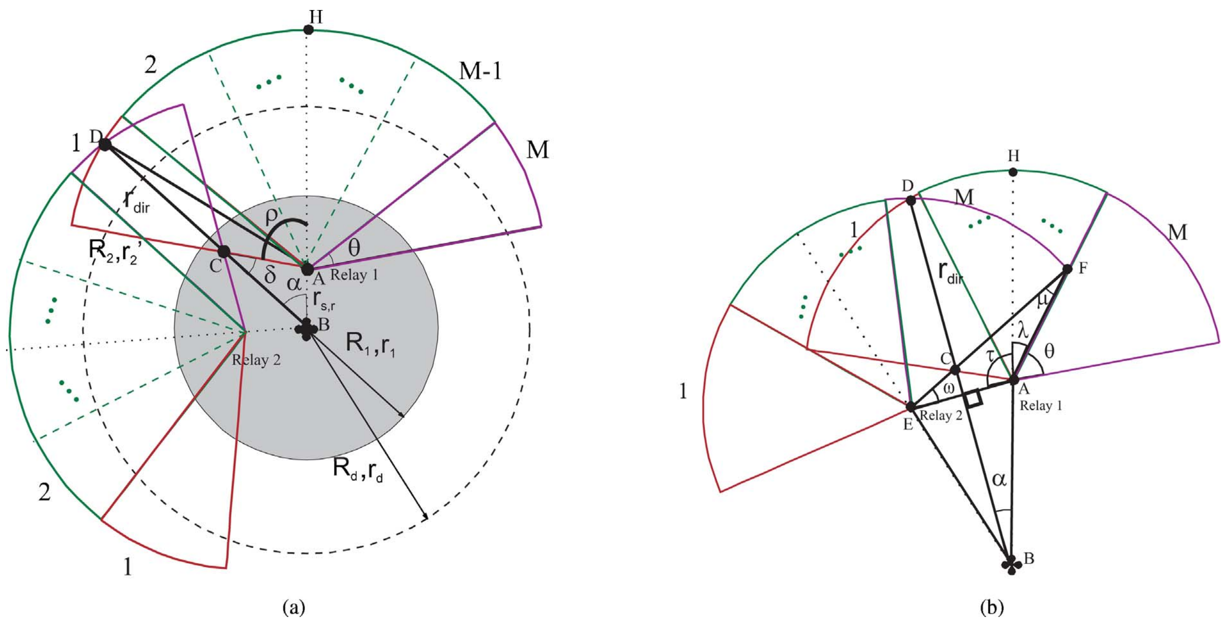

Fig. 3. Directional relay transmission. (a) Geometric model for the directional relays. (b) Boundary condition to avoid overlap among relay beams.

related to that of the omni-directional relay transmission by $\gamma'(r_2', \theta, R_2) = \gamma(r_2' / \sqrt[PLE]{\frac{2\pi}{\theta}}, R_2)$.

Note that for a fixed t_1, the number of relays does not affect the time interval that each beam can transmit, t_2, and hence R_{v_2}. However, we do not want to consume the system resources by using more relays than necessary, so we restrict the system to use the minimum number of relays required to cover all the users. Note that the area covered by each relay is determined by θ and M. For a fixed θ, as we increase M, each relay can cover a larger area, hence, we need less relays to cover all the users. On the other hand, for a fixed t_1, as we increase M, the time interval that each beam can transmit, t_2, decreases and so does R_{v_2}. Also, note that for a fixed M, as we decrease θ, we need more relays in order to cover all users. However, small θ results in larger r_2', hence, the coverage area increases.

In order to find the configuration that optimizes one of the multicast performance criteria in Section II-B in the case of directional relays, we determine the optimum R_1, R_2, r_1, r_2, $r_{s,r}$, t_1, t_2, θ, M and N in two steps. For fixed r_1, r_2, θ and M, we first determine the user partition with a minimum number of relays. Then, for this user partition, we find the optimum R_1, R_2, t_1 and t_2 that maximizes the system performance index. Note that t_1 and t_2 are not independent design parameters and for a particular M and t_1, the corresponding t_2 is $t_2 = (1 - t_1)/M$. By repeating the above procedure for all possible r_1, r_2, θ and M, we find the optimum user partition and time scheduling that maximizes the performance.

To find the minimum number of relays, N, for a fixed r_1, r_2, θ and M, we first compute r_2' using r_2 and θ as in (9). Then using a geometric approach, we find $r_{s,r}$ and N such that relays not only cover all the users within the coverage range of direct transmission, r_d, but also overlap among simultaneously transmitted beams of different relays are avoided. As illustrated in Fig. 3(a), r_{dir} denotes the radius of the coverage area with directional relay transmission.

Similar to the omni-directional case, the relays are equally spaced at an angle $2\alpha = \frac{2\pi}{N}$. We want to find the maximum α, hence, the minimum number of relays satisfying the constraints below

$$r_{s,r} \leq r_1 \tag{11}$$

$$r_{\text{dir}} \geq r_d \tag{12}$$

$$|BC| \leq r_1. \tag{13}$$

More specifically, (11) states that the relay is selected among the Group 1 receivers. In order to cover all the users, (12) states that the coverage area of directional transmission should be greater than the direct transmission coverage range. We define the point C in Fig. 3(a) as the intersection of one relay's first beam and the neighbor relay's last beam. $|BC|$ is the distance between this intersection and the access point. Note that if $|BC|$ is greater than the coverage range of Group 1, there will be some users in Group 2 that are not covered. This is why we need to have the constraint given in (13). We can calculate $|BC|$ by applying the sine theorem on the triangle ABC as

$$|BC| = \frac{r_{s,r} \sin(\pi - \rho)}{\sin \delta} \tag{14}$$

where $\delta = \rho - \alpha$. Here, due to symmetric structure we use, the line BH passes through the center of Relay-1's beams, hence, on each side of this line Relay-1 spans an angle of $\rho = \frac{M}{2}\theta$. Inserting the angle values in (14), for a fixed $r_{s,r}$, θ, M, and N, the constraint given in (13) can be expressed as

$$|BC| = \frac{r_{s,r} \sin(\pi - \frac{M}{2}\theta)}{\sin(\frac{M}{2}\theta - \frac{\pi}{N})} \leq r_1. \tag{15}$$

Along with covering all the users within the coverage range of direct transmission, we also want to avoid overlap among simultaneously transmitted beams of different relays. In Fig. 3(b), we illustrate the minimum distance between the relays and the access point that avoid this. Note that if we

TABLE II
β VALUES WITH $\beta_t = 0.2$ FOR PACKET SIZE OF 1470 B

Transmission Rate (Mb/s)	11	5.5	2	1
β	0.172	0.182	0.188	0.190

place relays closer to the access point, relay-2's Mth beam will overlap with relay-1's Mth beam. Using the sine theorem on the AEF triangle in the figure, we have

$$\frac{|AE|}{\sin(\mu)} = \frac{r'_2}{\sin(\widehat{EAF})} \tag{16}$$

where $|AE| = 2r_{s,r}\sin(\alpha)$. Then, we can express the constraint on $r_{s,r}$ as

$$r_{s,r} \geq \frac{r'_2 \sin(\mu)}{2\sin(\alpha)\sin(\widehat{EAF})} \tag{17}$$

where $\mu = \theta - 2\alpha$, $\widehat{EAF} = \tau + \lambda$, $\tau = \pi/2 + \alpha$, and $\rho = \lambda + \theta$. μ can be computed using the triangle AEF. Note that the sum of all inner angles of triangle AEF is equivalent to $\omega + \tau + \lambda + \mu = \pi$ where $\omega = \tau - \lambda - \theta$. Inserting the angle values and $|AE|$ in (17), for a fixed r'_2, θ, M, and N, the constraint on $r_{s,r}$ can be expressed as

$$r_{s,r} \geq \frac{r'_2 \sin(\theta - 2\frac{\pi}{N})}{2\sin(\frac{\pi}{N})\sin(\pi/2 + \frac{\pi}{N} + \frac{M}{2}\theta - \theta)}. \tag{18}$$

We check various N values for a fixed r'_2, r_1, θ, and M, and find the minimum N that satisfies the above constraints. Then we calculate r_{dir} using the cosine theorem on the triangle ABD and we solve for the roots of the following second order equation:

$$r_{\text{dir}}^2 - 2\cos\alpha r_{s,r} r_{\text{dir}} + r_{s,r}^2 - r'^2_2 = 0. \tag{19}$$

After computing the user partition, we use an exhaustive search over a discretized space of feasible R_1, R_2, t_1 and t_2, and find the optimum solution for a multicast performance index.

VI. Numerical Studies Based on PER Measurements

In order to study the behavior of the proposed multicast strategies in a real environment, we first conducted outdoor experiments for an IEEE802.11b based WLAN and obtained PER values for different transmission rates and various locations. Then, based on these PER measurements, we computed the amount of FEC as described in Section III. Finally, as outlined in Sections IV and V, we numerically calculated the optimum user partition and time scheduling, and determined the achievable system performances. In this section, we first describe the PER measurement study, and then report the achievable system performances of different systems.

A. PER Measurement and Typical β Values for IEEE802.11b

We measured PER using Iperf [27], which is a powerful tool for traffic generation and measurement. In our measurement setup, one of the stations runs an Iperf client to generate user datagram protocol (UDP) traffic streams, while the other runs an Iperf server which receives the traffic and collects the statistics (e.g., PER). To remove any random effects and short-term fluctuations, we ran each experiment ten times with each run lasting 1 min. We then averaged the results. The experiments were conducted in Columbus Park, Brooklyn, NY.

During the PER measurements, we are mainly interested in the packet losses due to channel conditions rather than the traffic contention in the channel. In our experiments, we only use $\beta_t = 20\%$ of the total air time in order to keep the traffic level low. We ran several experiments for different distances between the access point and the receiver. Fig. 4 illustrates the PER results for different distances and data rates in the broadcast mode. In this figure, the data points are the average error rates derived from the experimental results, whereas the curves show the exponentials fitted to these results. We reported a more detailed description of the experiments in [28].

We also consider the overhead introduced by MAC, IP and physical layer headers, β_{header} (see [28] for details). We performed preliminary experiments to investigate the effect of the packet size on the useful rate and observe that for higher packet sizes, even though we have a higher PER, the useful rate is also higher. Hence, in order to minimize the header overheads, all the results reported in the remainder of this section are obtained for a packet size of 1470 B. We

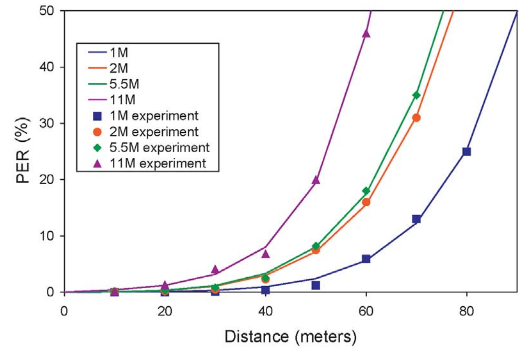

Fig. 4. PER vs. coverage distance at a packet size of 1470 B.

TABLE III
NUMBER OF PARITY PACKETS NEEDED FOR $k = 64$ SOURCE PACKETS
(PACKET SIZE IS 1470 B)

	10m	20m	30m	40m	50m	60m	70m	80m
1 Mb/s	1	1	1	2	4	10	15	31
2 Mb/s	1	1	3	7	16	24	48	–
5.5 Mb/s	1	1	3	7	18	28	57	–
11 Mb/s	1	3	7	18	31	89	–	–

TABLE IV
USEFUL RATE IN KB/S (PACKET SIZE IS 1470 B)

	10m	20m	30m	40m	50m	60m	70m	80m
1 Mb/s	187	187	187	184	179	164	154	128
2 Mb/s	370	370	359	339	301	273	215	–
5.5 Mb/s	986	986	956	902	781	696	529	–
11 Mb/s	1863	1807	1705	1477	1275	791	–	–

TABLE V
OPTIMAL SYSTEM CONFIGURATION WITH OMNI-DIRECTIONAL AND DIRECTIONAL RELAYS

	Optimal System Configuration		Non-Layered	Layered
Omni	$R_1 = R_2 = 11$ Mb/s $r_1 = r_2 = 50$ m $N = 5$ $r_{\text{omni}} = 80.9$ m	*Opt.* t_1	1/6	6/11
		Opt. t_2	1/6	1/11
		R_{v_1} (kb/s)	213	635
		R_{v_2} (kb/s)	213	128
Directional	$R_1 = R_2 = 11$ Mb/s $r_1 = r_2 = 40$ m $r_2' = 62.6, \theta = \pi/3$ $N = 6, M = 2$ $r_{\text{dir}} = 81.45$ m $r_{s,r} = 23$ m	*Opt.* t_1	1/3	0.82
		Opt. t_2	1/3	0.09
		R_{v_1} (kb/s)	492	1221
		R_{v_2} (kb/s)	492	128

summarize the practical β values in Table II for different transmission rates for this packet size.

B. Results for Numerical Analysis

Based on the PERs obtained, we compute the number of parity packets for $k = 64$ source packets that gives FEC decoding failure rate of less than or equal to 0.5%. Note that, as we increase k, the delay introduced into the system also increases. On the other hand, we cannot use very small k since the measured average P_E will vary a lot from block to block. In that case, there may be many instances when the number of lost packets exceeds the correction capability of the FEC code designed based on P_E. In Table III, we specify the required number of parity packets for different distances. As seen in the table, for a fixed target distance, as we increase the transmission rate, we need to send more parity packets due to higher PER. However, the overall useful rate calculated from (1) increases with transmission rate as tabulated in Table IV.

The packet video streams in our analysis are created by encoding three different video clips (*Soccer*, *Foreman*, *Bus*) with an H.264/SVC encoder using the JSVM software [33]. These videos are chosen since they possess a good variety of motion and texture characteristics. The videos are coded at fixed spatial (352 × 288) and temporal resolution (30 frames/s) with medium grained scalability (MGS) where the base rate is set to 110 kb/s. We use the average of peak signal to noise ratio (PSNR) over all frames in the decoded video as the quality measure, $Q(R)$.

In order to cover a radius of 80 m with direct transmission, we need $R_d = 1$ Mb/s and the optimal FEC rate is 0.674 (31 parity packets for 64 source packets). The resulting useful video rate from Table IV is 128 kb/s. In the rest of this section, we numerically calculate and describe the optimal configurations using omni-directional and directional relay transmission under different performance metrics and their respective gains over direct transmission.

In Table V, we compare the optimum configurations for omni-directional and directional transmission for the performance metrics discussed in Section II-B. The optimal parameters are the same for both performance metrics and given in Table V for omni-directional and directional relay transmission.

We present the average PSNR values under these optimal configurations for different videos for both omni-directional and directional relays in Table VI. For example, with omni-directional relays, for *Foreman* sequence, when we have equal quality at all users, we achieve a quality improvement of 1.57 dB at all receivers. When we favor Group 1 users, we achieve a quality improvement of 6.98 dB for Group 1 receivers compared to direct transmission, while keeping the quality of Group 2 receivers the same as in direct transmission.

Similarly, with directional relays, for *Foreman* sequence, when we have the same quality at all users, the improvement is 5.55 dB at all receivers, compared to direct transmission. Furthermore, compared to omni-directional relay transmission, the quality improvement is 3.98 dB. When we favor Group 1 users, while keeping the quality of Group 2 receivers the same as in direct transmission, we achieve a quality improvement of 10.15 dB for Group 1 receivers compared to direct transmission, and an improvement of 3.17 dB compared to omni-directional relay transmission.

In Fig. 5, we compare the visual quality at the receivers using different multicast metrics for Soccer video sequence. Two-hop multicast with omni-directional relays improves the visual quality of all users [see Fig. 5(b)] compared to direct transmission [see Fig. 5(a)]. Furthermore, when we favor Group 1 receivers, we significantly improve the quality of Group 1 receivers [see Fig. 5(c)] compared to direct transmission while Group 2 receivers experience the same quality

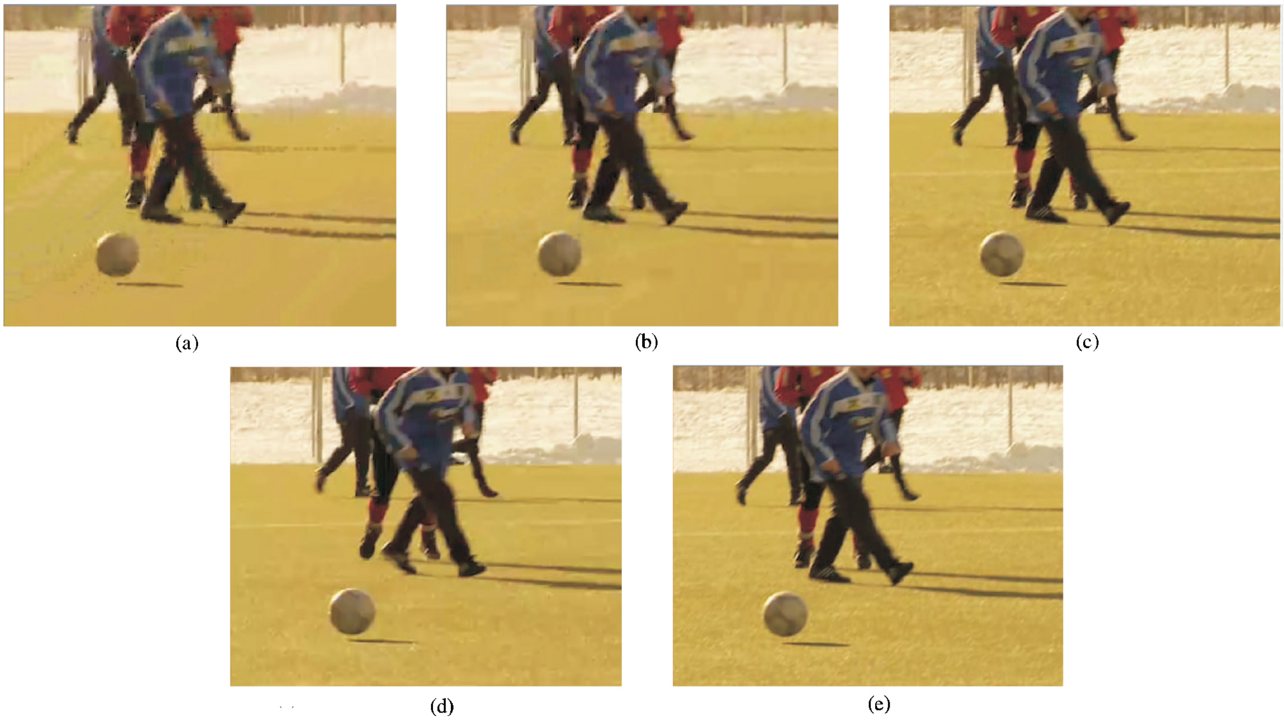

Fig. 5. Visual quality comparison of two-hop layered multicast with omni-directional relays, directional relays, and direct transmission. (a) Direct transmission. (b) Equal quality (omni). (c) Better quality in Group 1 (omni). (d) Equal quality (directional). (e) Better quality in Group 1 (directional).

TABLE VI

ACHIEVABLE PSNRS (DB) WITH OMNI-DIRECTIONAL AND DIRECTIONAL RELAYS FOR THREE DIFFERENT VIDEO SEQUENCES

	Omni		Directional	
Sequence	Non-Layered	Layered	Non-Layered	Layered
Soccer	29.68	34.61, 28.42	33.18	38.51, 28.42
Foreman	31.54	36.95, 29.97	35.52	40.13, 29.97
Bus	24.57	29.71, 23.28	28.21	33.78, 23.28

PSNRs achievable with direct transmission are 28.42 dB, 29.97 dB, 23.28 dB for *Soccer*, *Foreman*, and *Bus*, respectively.

with direct transmission. Two-hop multicast with directional relays can either significantly improve the quality of all users [see Fig. 5(d)] compared to direct transmission [see Fig. 5(a)] or substantially improve the quality of Group 1 receivers [see Fig. 5(e)] compared to direct transmission while Group 2 receivers experience the same quality with direct transmission. Furthermore, compared to omni-directional relay transmission, we achieve a higher quality for both equal quality at all users and best quality at Group 1 receivers.

Finally, we discuss the delay introduced by FEC into the direct transmission and two-hop multicast system. In a system that adds m parity packets to each block of k source packets, the receiver must wait for $n = k+m$ packet transmission times before FEC decoding. Therefore the delay due to FEC decoding is the time needed to transmit n packets, i.e., $D = Ln/R$, where L is the packet size and R is the transmission rate. In our case, we use $k = 64$ packets and $L = 1470$ B. For direct transmission, $n = 95$, the delay due to the block transmission can be computed using $D_d = Ln/R_d$ which is around 0.139 s per FEC block. For non-layered two-hop multicast using omni-directional relays, delay after first hop and the second hop can be computed using $D_1 = Ln/R_1$ and $D_2 = Ln/R_2$, respectively. The total delay after two hop transmission is $D_{\text{omni}} = D_1 + ND_2$. With $n = 95$, $N = 5$, and $R_1 = R_2 = 11$ Mb/s, $D_{\text{omni}} = 0.077$ s. Note that for the two-hop 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 non-layered two-hop multicast using omni-directional antennas. Similar computations can be carried out for the other cases.

VII. IMPLEMENTATION EFFORTS AND EXPERIMENTAL RESULTS

In Section VI, we discussed the performance of proposed two-hop multicast strategies obtained by numerical analysis that is based on experimental PER measurements. In order to gain more insights into the system performance in a real environment, we implemented two-hop multicast with omni-directional relays in our experimental testbed [29].

Before going into the details of our implementation, we discuss the assumptions we made during our experiments. We assume that the number of relays and their MAC addresses are already known at the transmitter or AP. Due to our inability to access the MAC layer firmware in a real system (the higher MAC layer functionality is implemented in the driver while the lower level time sensitive functions are implemented in the wireless card), the forwarding of data at the relay node was done as an independent transmission [30].

A. Driver Implementation and Socket Programming

We implemented the MAC layer using the open source driver Madwifi 0.9.2 [31]. The implementation details of each module are summarized as follows.

1) In each packet, we added a new header between the 802.11 header and the payload that we call CoopHeader. The CoopHeader consists of the following fields: *Destination Address*, *Source Address*, *Relays Addresses*, and *number of relays*. Since we are broadcasting the data, the broadcast MAC address is the destination address. The AP defines the relays for a particular broadcast, and adds their MAC addresses in the *Relays Addresses* field.
2) Each station that receives a packet checks whether it is selected by the AP as a potential relay. In order to do so, it checks the *Relays Addresses* field in the CoopHeader. If one of the MAC addresses indicated in this field is equal to its address, it realizes that it is a relay and forwards the packet to the FEC module in the application layer.
3) A Group 1 receiver only receives packets from the AP.
4) A Group 2 receiver only receives packets from its dedicated relay and discards all other packets.

In order to implement video streaming, we built a video client/server application using UDP/IP socket programming along with FEC encoding/decoding.

In the transmitter, we run a server program that reads a FEC encoded, RTP packetized video file, and transmits the packets accordingly. At the relays, we run a program which receives packets and stores them in a file. Furthermore, we implemented a FEC module which buffers all the packets of the same block. For the second-hop transmission, we generate new parity packets and transmit them along with the source packets. At the receivers, we run a client program which receives packets and stores them in a file.

As mentioned in the beginning of this section, the forwarding of the block of packets by the relays is done sequentially. Specifically, we implement the scheduling among the relays by adding different delays before the transmission of each relay. The AP sends guard packets after the transmission of each block in order to inform the relays that the transmission of one block is completed. Upon reception of the guard packets the first relay, Relay 1, starts to transmit the block of packets immediately. On the other hand, Relay 2 waits for a fixed period of time which is equal to the time needed to transmit 64 source packets and m parity packets for a particular transmission rate. After this period, Relay 2 transmits its block of packets. Rest of the relays continue the transmission in the same manner.

The relays have the ability to forward all the received packets or to filter the transmission in the second hop by transmitting only a particular video layer. This can be defined before the experiment based on a GUI designed for this purpose. Using this GUI, we are able to choose packet transmission in one of the two modes.

1) *Non-layered two-hop multicast:* The relays forward all the received packets.
2) *Layered two-hop multicast:* The relays check the header of the video packet to see whether it belongs to the base layer or the enhancement layer. A packet is forwarded only if it belongs to the base layer. This mode results in differentiated video qualities among Group 1 and Group 2 receivers.

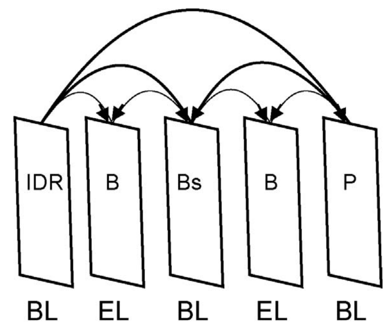

Fig. 6. H.264 temporal scalability coding structure.

The stored files at the relays and receivers are first FEC decoded to recover the video file. Then, we decode these files using a video decoder. Recall that for our theoretical analysis and numerical results, we assume that the chosen FEC rate based on the PER is sufficient to recover all but a few packet losses so that the video quality is completely determined by the video rate. However, in our experimental study, the applied parity packets are sometimes insufficient to correct all packet losses. In that case, only the correctly received video packets are fed into the video decoder. The decoder uses *frame copy* as the error concealment method to recover areas affected by lost packets. The video quality at each receiver for a particular experiment is determined by the average PSNRs of all the decoded frames of the video.

Note that the estimation of PER is important while determining the FEC rate. In the implementation part, we placed the nodes at particular distances, and use the PER values in Fig. 4. In a real system, the PERs at the farthest distance of the Group 1 and Group 2, can be pre-measured for the optimal user partition and the expected deployment environment.

B. Layered Video Architecture

Our two-hop multicast framework can in principle work with other layered coding methods, but we choose to employ H.264/AVC [32] with temporal scalability for our testbed implementation since H.264/SVC currently has no slice structure support which makes error handling difficult. In our experiments, we generate temporal scalable video bit streams with slice mode to create slices which are packetized into a packet. Specifically, we use H.264 Main Profile to encode a video sequence with the coding structure shown in Fig. 6. The base layer (BL) consists of the slices of instantaneous decoder refresh (IDR) type, P type and reference B type (Bs), and the enhancement layer (EL) consists of the slices of non-reference B types (B). The arrows in the figure indicate the reference dependencies during encoding, which forms a hierarchial motion prediction structure. From the figure, BL is independently decodable, while EL relies on BL for correct decoding. Note that a lost I or P picture from BL can affect all the following pictures in both BL and EL until the next IDR

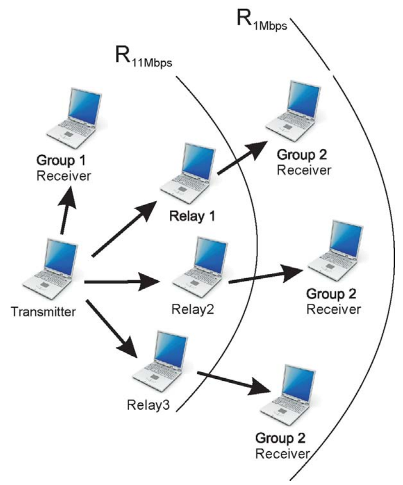

Fig. 7. Experimental setup.

picture. A lost Bs picture in BL, although not affecting other pictures in the BL, affects decoding of the EL. On the other hand, the loss of any picture in the EL does not affect decoding of any other picture. For the encoding of the videos, we use the H.264 reference software JM11 and, for the decoding of the received streams, we modified the JM11 decoder so that it can support slice level errors.

The packet video streams in our experiments are created by encoding a video clip (*Soccer*, 352 × 288, 30 frames/s, 240 frames) at a variety of bit rates. We create slices of size 1470 Bytes or less and packetized each slice into an RTP packet.

C. Results

In our experiments, we use one transmitter, three relays that are also Group 1 receivers, one Group 1 receiver that is not a relay and three Group 2 receivers. Although our theoretical analysis shows that to cover the 80 m radius we need five relays, we only used three relays in the testbed to illustrate the basic idea. The experimental setup is depicted in Fig. 7. All stations share channel 11 (2.462 GHz) under IEEE802.11b ad hoc mode. In our numerical analysis, we showed that the optimum solution is achieved when we use the maximum transmission rate of the IEEE 802.11b system in each hop. Hence, in the experiments, we compare a two-hop system (with a transmission rate of 11 Mb/s at each hop) with the conventional multicast system (direct transmission at 1 Mb/s). Based on our numerical analysis, we place a Group 1 non-relay receiver and all three relays at a distance of 50m from the access point, and the Group 2 receivers are 50 m apart from the relays. We arrange the three relays at the same distance of r_1 from the AP as the numerical analysis and have them positioned to cover more than half a circle (216deg) of radius 80 m. Note that increasing the number of relays (to cover the entire circle) will lower the video quality at each receiver as the transmission time available for the AP and each relay will be reduced.

We first ran experiments and analyzed the conventional multicast system. Then, we conducted two sets of experiments: non-layered two-hop multicast and layered two-hop multicast. In order to remove any random effect and short-term fluctuations, we ran each experiment with the same setting ten times and averaged the results. The Group 2 results of two-hop multicast presented below are obtained by averaging the quality of all Group 2 receivers. Similarly, the Group 1 results are obtained by averaging all Group 1 receivers (including the three relays). For the direct transmission case, we averaged the results of Group 2 receivers. Note that with this setup, the reported quality for each group in the two-hop system indicates the achievable average quality at farthest receiver in each group, and likewise, the reported quality for the direct transmission system represents the achievable quality at the farthest receiver in its coverage area.

Instead of using the theoretically derived useful rate as the video rate, we vary the video rates over a large range and see at what rate we get the best video quality. In our experiments, for each block of 64 source packets, we compute the number of parity packets using $m = \lambda k P_E/(1 - P_E)$, with $\lambda = 1.2$, and P_E determined from our measurement study. For direct transmission, this leads to a FEC rate of 0.703. For the two-hop system, the FEC rate is 0.762 in both hops. Note that this FEC rate is slightly higher than what we derived in Section III. In the decoder, missing regions of a frame due to unrecoverable packet losses are recovered by using frame copy. With H.264/AVC slice structure, we found that this setting provides negligible FEC decoding failure rate. Note that, in our numerical results, we only used $\beta_t = 20\%$ of the total air time in order to avoid congestion-caused losses. This leads to a low effective data ratio, $\beta \leq 20\%$. In the implementation, we not only observe the channel effect but also the congestion that is generated as we increase the video rate. Note that as we increase the video rate, β also increases. Fig. 8(a) compares the results obtained for direct transmission and non-layered two-hop multicast, both with and without FEC. At a low video rate, most receivers can recover all lost packets. Therefore, the video quality initially increases as the video rate increases. However, as we increase the rate beyond a certain point, due to the contention in the channel, there is not enough time for the transmission of all the packets, hence, the decoded video quality starts to drop. The results show that, the use of FEC significantly improves the video quality for both direct transmission and two-hop multicast. Note that, even at 1 Mb/s, there are significant packet losses at Group 2 receivers, so that direct transmission without FEC yields poor average quality. Non-layered two-hop multicast with FEC can sustain up to 1.2 Mb/s video rate. Above this rate, due to congestion, the video quality drops sharply. Compared to the direct transmission with FEC, where we can only sustain a video rate of 0.5 Mb/s, we observe that two-hop multicast significantly improves the performance. Two-hop multicast system improves the maximum achievable average PSNR to 38.89dB and 37.31dB for Group 1 and Group 2 users, respectively, compared to 33.76 dB for all users with direct transmission. We observe that these PSNR numbers are very close to the encoding PSNRs at the respective video rates, suggesting that the applied FEC parity packets are able to correct almost all the lost packets at these video rates. In theory, for non-layered two-hop multicast, Group 1 and

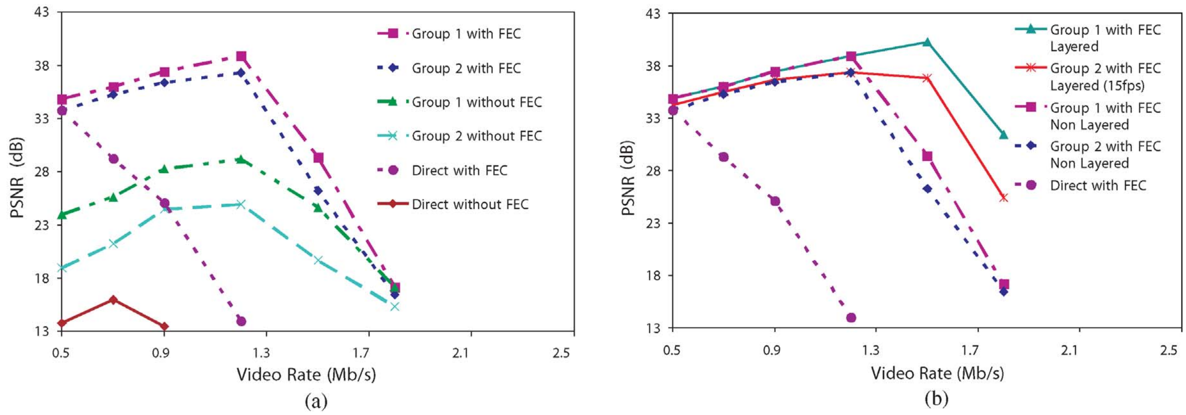

Fig. 8. Experimental results for omni-directional relay transmission. (a) Comparison of non-layered two-hop multicast with direct transmission with and without FEC (averaged over ten experiments). (b) Comparison of layered two-hop multicast with non-layered two-hop multicast and direct transmission with FEC (averaged over ten experiments).

TABLE VII
COMPARISON OF MAXIMUM SUSTAINABLE VIDEO RATES BASED ON NUMERICAL ANALYSIS AND IMPLEMENTATION RESULTS

	Direct Transmission	Non-Layered Relaying	Layered Relaying
Numerical analysis	0.60 Mb/s	1.36 Mb/s	1.60 Mb/s
Experimental results	0.5 Mb/s	1.2 Mb/s	1.5 Mb/s

Group 2 receivers should see the same quality. However, in our experiments, we observe that Group 1 receivers have slightly better quality than Group 2 receivers. This is due to the fact that if a relay does not receive all the video packets in a block in the first hop, it cannot relay all the packets to its Group 2 receivers. Moreover, there may be some additional losses in the second hop transmission.

For the layered two-hop multicast experiment, the sender transmits the base and the enhancement layer, and the relays only forward the base layer. Therefore, while Group 1 receivers experience a full frame rate of 30 frames/s, Group 2 receivers experience a frame rate of 15 frames/s. In Fig. 8(b), we present the layered two-hop multicast results and compare with direct transmission and non-layered two-hop multicast, all with FEC. The reported video rate for the layered two-hop multicast is the sum of base layer and enhancement layer rates and as the video rate increases, both the base and enhancement layer rate also increase. In our videos, the BL rate to EL rate ratio is approximately 4 (i.e., 80% of the overall video rate is BL and 20% of the overall rate is EL). Group 1 receives both BL and EL, whereas Group 2 only receives BL. Hence, $R_{v_2} = 4R_{v_1}/5$. Since sender transmits both BL and EL, and since we have three relays transmitting only the BL sequentially, $t_1 = 0.294, t_2 = 0.235$. When we use layered video, since the relays do not need to forward all the packets, the sender has more time to transmit ($t_1 = 0.294$ in the layered case vs. $t_1 = 0.25$ in the non-layered case). Therefore, the video rate at the sender can be increased to yield a higher video quality for Group 1 receivers. Note that, even though the PSNR of Group 2 receivers is slightly lower than the PSNR of Group 1 receivers, Group 2 receivers experience a frame rate of 15 frames/s rather than 30 frames/s . Compared to non-layered two-hop multicast, layered system was able to increase the sustainable video rate from 1.2 Mb/s to 1.5 Mb/s with a corresponding gain of PSNR from 38.89 dB to 40.21 dB at Group 1, while keeping the PSNR at Group 2 about the same, but at half of the frame rate (from 37.31 dB at 30 frames/s to 36.80 dB at 15 frames/s).

Note that the results for direct transmission, non-layered and layered two-hop multicast are not directly comparable in terms of video quality (i.e., PSNR) in numerical and implementation sections due to the use of different number of relays and different video codecs. To facilitate a fair comparison, we compute the maximum supportable video rates by the experimental system with three relays using the same numerical analysis method of Section IV. Since we did not try to limit the air time to 20%, we cannot use the β assumed in our numerical analysis. In [34], the authors show that for different transmission rates, due to collisions and idle times as well as the headers, the effective throughput hence the β value for 1 Mb/s and 11 Mb/s is approximately 85% and 65%, respectively. Using these β's and the actual FEC rates used in the experiments, we derive the maximum video rates supportable by different systems. In Table VII, we compare the numerical analysis with the experimental results. We show that the experimental results are very close to the numerical analysis.

VIII. CONCLUSION

In this paper, we proposed the integration of layered video coding, packet level FEC and two-hop relaying to enable efficient and robust video multicast in infrastructure-based wireless networks. We determined the user partition, transmission time scheduling and FEC that can optimize a multicast performance criterion. We showed that the use of omni-directional relays can substantially improve multicast system performance by providing better quality links (both for sender and relay) and hence, higher sustainable transmission rates. Using directional relays further improves the multicast system performance as compared to omni-directional relays. To supplement our numerical results, we further implemented a prototype using open source drivers and socket programming and validated the system performance with real-world experiments. Experimental results confirm the efficiency of our schemes and show that such an integrated system infrastructure presents a promising design for future realistic wireless multimedia multicasting networks.

There are many possible avenues for further research. The proposed system is designed so that we optimize the video quality while guaranteeing $r_{\text{omni}} \geq r_d$ and $r_{\text{dir}} \geq r_d$ for omni-directional relays and directional relays, respectively. However, coverage range or the total energy consumption can be also used as a performance metric. In the numerical analysis of this paper, assuming only path loss, we perform optimum relay selection and compute the maximum achievable performances with both omni-directional and directional relay transmissions. Our results are either applicable to dense networks or non-dense networks with fixed, dedicated relays. In the implementation, the relays are located at pre-computed optimum positions. In a realistic environment, user distribution may not be dense and is likely to change over time. Furthermore, channel conditions are affected by both path loss and fading. Protocols that give a good estimate of the channel conditions for all receivers through an efficient feedback mechanism for multicast such as RTCP exist, however, how to dynamically adapt user partition and relays selection based on such estimate is a challenging problem. In this paper, we find the optimum parameters that maximize the video quality of multicast users in a single cell. More generally, one should optimize the system parameters while considering the interference to the neighboring cells. These are challenging issues and subjects of our ongoing research.

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