Layered Wireless Video Multicast using Directional Relays

Özgü Alay, Thanasis Korakis, Yao Wang and Shivendra Panwar
Department of Electrical and Computer Engineering, Polytechnic University, Brooklyn, New York
E-mails: ozgu@vision.poly.edu, {korakis,yao}@poly.edu, panwar@catt.poly.edu

***Abstract*— In this paper, we explore the use of directional antennas in relay transmission to improve the performance of video multicast with omni-directional relays in infrastructure-based wireless networks. We describe the system setup with directional relays and determine the user partition along with transmission time scheduling that can optimize a multicast performance criterion. We demonstrate that directional relays significantly improve the multicast system performance compared to omni-directional relays. Furthermore, it also provides larger coverage area.**

Index Terms: layered video coding, directional antennas, relays, wireless video multicast

I. Introduction

Wireless video multicast enables delivery of popular events to many wireless 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 due to the high packet loss ratio and bandwidth variations of wireless channels. Generally, receivers may have very different channel qualities, with ones closer to the sender having better quality on average and far away receivers having poor quality. In a conventional multicast system, the sender adjusts its transmission rate to accommodate the user with the worst channel conditions. With this design, the users with good channel conditions unnecessarily suffer.

In our previous work, we integrated layered video coding with cooperative multi-hop transmission to enable efficient and robust video multicast in infrastructure-based wireless networks [1]. The basic idea behind the cooperative multicast system is that we divide all the receivers into two groups such that receivers in Group 1 have better average channel quality than Group 2, and we let the sender choose its transmission rate based on the average channel quality of Group 1. Then, selected receivers in Group 1 will relay the received information to Group 2 users. We considered omni-directional relay transmission, where each relay targets a subgroup of Group 2 users and transmits at a different time slot, and that a Group 2 user only listens to its designated relay. We showed that cooperative multicast with omni-directional relays improves the multicast system performance by providing better quality links (both for sender and relay) and hence higher sustainable transmission rates. Furthermore, with the same sender transmission power, we achieved a larger coverage area.

One deficiency with omni-directional setup is that the relays cannot transmit simultaneously in time. In this paper, we circumvent this problem by using directional antennas in relay transmission. We assume the relay stations are equipped with directional antennas, and directionally transmit the relayed data to its targeted subgroup. Relay stations transmit relayed packet using non-overlapping beams. By scheduling simultaneous transmissions from non-overlapping beams, we achieve efficient spatial reuse. Additionally, we further extend the coverage area since directional transmission increases the signal energy towards the direction of the receiver. Although directional antennas are more expensive to operate at present, we believe the potential performance gain is significant, and worth pursuing.

This paper is organized as follows. We introduce the system model in Section II. We formulate the optimum user partition and discuss time scheduling along with the multicast performance metric in Section III. Section IV analyzes the obtained results. We conclude the paper in Section V.

II. System Model

In this paper we study an infrastructure-based wireless network (such as WLAN, 3G or WiMAX networks), and assume a sender (a base station or access point) is multicasting a video to uniformly distributed receivers within its coverage area. We consider a path loss channel model where the channel condition solely depends on the distance between the sender and receiver. In other words, the receivers closer to the sender have better channels and hence can support higher transmission rates than the far away receivers. We assume a dense, low mobility network and divide all the receivers into two groups such that Group 1 receivers have better average channel quality than Group 2 receivers, and let the sender choose its transmission rate based on the average channel quality of Group 1. Selected receivers in Group 1 (to be called relays) will relay all or selected received packets from the sender to Group 2 receivers, with the modulation and channel coding schemes chosen based on the average channel quality of relays to Group 2 receivers. In general, Group 2 receivers can combine the received information from 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 multi-hop strategy substantial gains in signal quality is achievable.

In our previous work [1], we considered the transmission with omni-directional antennas where each relay transmits at a different time slot which reduces the system efficiency. To circumvent this problem, we explore the use of directional antennas in relay transmission. We use a directional antenna model that assumes the area around the node is covered by K non-overlapping beams. For our multicasting scheme, we use M out of K available beams as described later. Although this model simplifies the physical layer representation of directional transmission by considering 'perfect' beamforming without overlapping, it is a standard model that is used in

[1]This work is supported in part by National Science Foundation (NSF) under award 0520054 and 0430885. The work is also supported by the Joint Research Fund for Overseas Chinese Young Scholars of National Natural Science Foundation of China under grant No. 60528004.

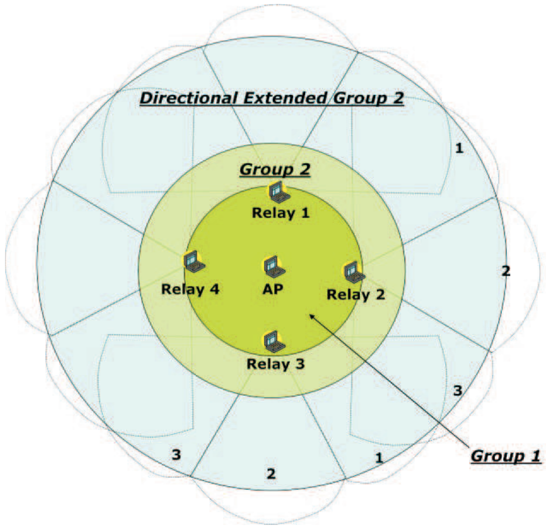

Fig. 1. Directional set up

most of the papers that study MAC issues in the presence of directional antennas [2]-[4].

In the proposed system, relay stations are equipped with directional antennas and directionally transmit the relayed data in the second hop to its targeted subgroup as depicted in Figure 1. In this figure, 4 relays are responsible for transmitting the video in the second hop. Each relay station uses three beams ($M = 3$) and transmits each 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 their beam 1, then beam 2, etc.), we achieve efficient spatial reuse. Furthermore, directional transmission increases the signal energy in the direction of the receiver resulting in a further increase of the coverage area which we call Directional Extended Group 2.

The proposed system configurations are applicable to the multicast of both data and video (or more generally audio-visual signals). A difference between data and video is that video data does not need to be completely delivered to be useful. A video can be coded into multiple layers so that receiving more layers leads to better quality, but even just one layer (the base layer) can provide acceptable quality. Also occasional packet loss in a delivered layer may be tolerable. On the other hand, delivered video segment must be in time before its scheduled playback time. We exploit the advantage provided by layered coding in two ways. Firstly, the number of layers to be delivered by the sender should be adjusted based on the channel conditions of the sender-to-Group 1 links. Secondly, the relay nodes may forward only a subset of layers that they receive. This way, we can make users in Group 1 get much better quality than that offered by direct transmission, whereas users in Group 2 get video quality better than or similar to direct transmission. Considering that relays are spending their own resources to help others, we think this differentiated quality of service may be justified. In general, a user may move from one location (Group 1) to another (Group 2) at different times. Hence, on average, every user in the system consumes an equal amount of power while getting better video quality.

III. Optimum User Partition and Time Scheduling

Directional antennas is a technology that can significantly increase the performance of a wireless network due to its ability to point the transmission or the reception of an electromagnetic signal towards a specific direction. The targeted nature of the transmission results in spatial reuse, as there can be multiple transmissions in the same neighborhood without causing a collision. Directional transmission also increases the signal energy towards the direction of the receiver. With directional antennas, for the same coverage area and the transmission power, we can achieve higher transmission rate. Alternatively, for the same transmission rate, R, and the transmission power, we can achieve an extended coverage range, r', which can be computed as

$$r' = \sqrt[PLE]{\frac{360}{\theta}}\, r \tag{1}$$

where r is the coverage range with omni-directional antennas, PLE is the path loss exponent and θ is the beam angle.

Using directional relays, we can have all the relays transmitting simultaneously but each relay transmits sequentially using different beams on different time slots. We assume that the video data is sent in intervals of T seconds. The sender uses T_1 seconds for its transmission and for each beam the relays use T_2 seconds such that,

$$T = T_1 + MT_2 \tag{2}$$

where M is the number of beams for each relay. Note that, with such a setup, the rate observed by the receivers (to be called the received video rate) will be different from the physical layer transmission rate. Let R_1 and R_2 denote the physical layer transmission rates for Group 1 and Group 2, respectively. We can express the received video rates for Group 1 and Group 2, Rv_1 and Rv_2, as

$$Rv_1 = \beta R_1 \tfrac{T_1}{T}\ ,\ Rv_2 = \beta R_2 \tfrac{T_2}{T} \tag{3}$$

where β, $0 < \beta < 1$, is the effective payload ratio (i.e., it is the ratio of the payload data to the physical layer transmission which includes additional headers, FEC bits, signalling bits, and possibly other traffic). Note that, for given physical layer parameters, path loss model and target BER (Bit Error Rate), we can compute the coverage ranges (r_1, r_2) for the corresponding transmission rates (R_1, R_2) for the omnidirectional antennas. Then using Equation 1, for a given r_2 and θ, we can compute the coverage range for directional transmission, $r_2{}'$.

In the above formulation, we can have multiple simultaneous relay transmissions. Note that due to this spatial reuse, for a fixed T_1, the number of relays does not affect the time interval that each beam can transmit, T_2, and hence Rv_2. In general, as M increases, the achievable transmission rate also increases. But with 802.11b network, we found that even with $M = 2$, we can use the maximum possible transmission rate to reach the desired coverage area, hence using higher M does not lead to higher transmission rate. Hence we use two beams ($M = 2$) for each relay as seen in Figure 2. We also do not want to consume the system sources by using more relays than necessary, so we want to use the minimum number of relays required to cover all the users.

In order to find the configuration that optimizes a multicast performance criterion, we search in the space of $(R_1,\ R_2,\ \theta)$.

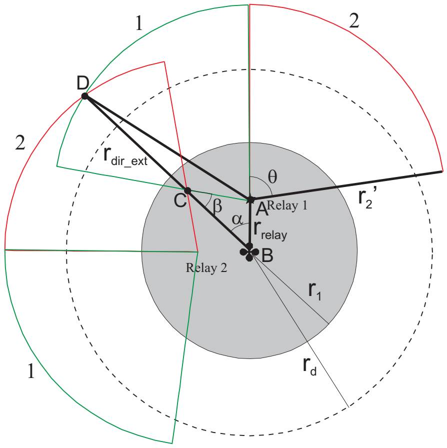

Fig. 2. Optimization for the directional antennas

For a particular R_1, R_2 and θ, we first determine the user partition with a minimum number of relays that will cover all users in a target coverage area and determine the corresponding extended coverage area. Then for each feasible user partition found in Step 1, we find the optimum T_1 and T_2 that maximizes the system performance index (to be discussed in Section III-B). By repeating the above procedure for all possible (R_1, R_2, θ) we find the optimum user partition and time scheduling that maximizes the performance. In the following subsections we will first formulate the user partition using a geometric approach and then discuss time scheduling along with the multicast performance criterion.

A. User partition

For fixed R_1, R_2 and θ, we first compute r_1 and $r_2^{'}$, then we find the minimum number of relays, N, that not only cover all the users within coverage range of direct transmission, r_d, but also avoids an overlap among simultaneously transmitting antennas of different relays following a geometric based approach. We define r_{relay} as the distance between the base station and the relay, and r_{dir_ext} as the radius of the Directional Extended Group 2 as illustrated in Figure 2.

We assume a symmetric structure where 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, which satisfies the constraints below,

$$r_{relay} \leq r_1 \tag{4}$$

$$r_{dir\_ext} \geq r_d \;,\; |BC| \leq r_1 \tag{5}$$

More specifically, Equation (4) states that the relay is selected among the Group 1 receivers and Equation (5) states that all the receivers in Group 2 are guaranteed to be covered. Note that, we also need to avoid overlap among simultaneously transmitting antennas of different relays. In Figure 3, we illustrate the minimum distance between the relays and the access point that avoids overlap. In this figure, note that if we place relays closer to the access point, relay 2's second beam will overlap with relay 1's second beam. We can express the constraint on r_{relay} using the sinus theorem on the highlighted triangle in Figure 3.

$$r_{relay} \geq \frac{r_2'}{\sin(2\alpha)} \sin(\theta - 2\alpha) \tag{6}$$

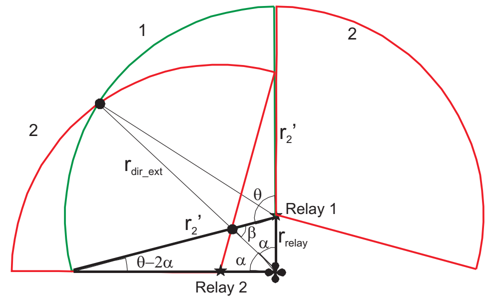

Fig. 3. Boundary condition to avoid overlap

In order to find N, we check various N values and find the minimum N that satisfies the above constraints. For a particular number of relays, N, we can write $\alpha = \frac{360}{2N}$ and $\beta = \theta - \alpha$.

Applying the sinus theorem on the triangle ABC for a given r_{relay}, we can calculate the distance $|BC|$ as

$$|BC| = \frac{r_{relay} \sin(180 - \theta)}{\sin \beta} \tag{7}$$

Then we calculate r_{dir_ext}, using the cosine theorem on the triangle ABD and solving for the roots of the following second order equation,

$$r_{dir\_ext}^2 - 2\cos\alpha\, r_{relay} r_{dir\_ext} + r_{relay}^2 - r_2'^2 = 0 \tag{8}$$

B. Time Scheduling and Performance Metric

We define $D_1(Rv_1)$ as the distortion of Group 1 receivers and $D_2(Rv_2)$ as the distortion for Group 2 receivers. Note that D_1 is a function of the received video rate, Rv_1 and for a given video file if we know Rv_1, we can compute D_1. For each feasible set of R_1 and R_2 determined from Section III-A, we use exhaustive search over a discretizied space of feasible T_1 and T_2, satisfying the constraint given in Equation 2 (as described earlier we only consider M=2). For each candidate T_1 and T_2, we determine Rv_1 and Rv_2 and correspondingly, D_1 and D_2 that optimizes a chosen multicast performance criterion.

We consider three different performance metrics. First we will discuss the minimum average distortion criterion. The average distortion can be computed as,

$$D_{avg} = \frac{N_1 D_1(Rv_1) + N_2 D_2(Rv_2)}{N_1 + N_2} \tag{9}$$

where N_1 and N_2 are the number of users in Group 1 and Group 2, respectively. We assume that the users are uniformly distributed around the sender so that $N_1 \sim r_1^2$ and $N_2 \sim (r_d^2 - r_1^2)$. Here, in order to have a fair comparison with direct transmission, we only consider the receivers in the coverage range of direct transmission, r_d.

The minimum average distortion is not always a good metric to evaluate the system performance. Thus, we also consider the case where we require all the receivers have the same distortion. In other words, we find the optimum user partition and time scheduling that leads to maximum $Rv_1 = Rv_2$.

Furthermore, considering that relays are spending their own resources to help others, we also investigate the case where the system favors the Group 1 receivers. Here, we minimize $D_1(Rv_1)$ while providing Group 2 users the same quality as with direct transmission. So in this case, we find the optimum user partition and time scheduling that minimizes $D_1(Rv_1)$ while guaranteeing $Rv_2 = \beta R_d$.

IV. RESULTS

We utilize an IEEE 802.11b based WLAN. Table I illustrates the coverage range for each transmission rate of 802.11b [1]. Here, we assume a channel model where the signal propagated from the transmitter is only subject to path loss and Gaussian noise, and the base rate of 802.11b ($1Mbps$) can be supported up to 100 meters.

Sustainable Rate(Mbps)	11	5.5	2	1
Distance (m)	61	72	88	100

TABLE I
SUSTAINABLE RATES VS. DISTANCE WITH IEEE 802.11B

We consider a coverage range of 100m radius, $r_d = 100m$, where the sustainable rate with direct transmission to all users is $R_d = 1Mbps$. Based on our experiments, we assume $\beta = 0.25$, so at $1Mbps$ transmission, the payload rate is $250kbps$. We used H.264/SVC codec since for different performance metrics, we transmit different layers at different hops. We encode 240 frames of the (352x288) Soccer video. The PSNR value of the video with direct transmission is $29.55\ dB$.

We first compute the feasible user partition for various beam angles. In Table II, we illustrate the results for $R_1 = R_2 = 11Mbps$ for different θ values. Note that, as we decrease the angle, in order to cover all the users we need to have more relays but on the other hand, by decreasing the angle you also increase the directional antennas strength which expands the overall system coverage area. We enlarge our coverage area for similar N compared to the omni-directional case where we cover an area of radius $105.7m$ with $N = 6$ relays [1].

θ	**N**	$r_{dir\_ext}(m)$	$r_{relay}(m)$
15	13	139	4
30	7	122	9
45	5	113	13
60	4	107	18

TABLE II
FEASIBLE USER PARTITION (WITH $R_1 = R_2 = 11Mbps$)

Note that based on Equation 1, for fixed M, the distortion performance depends only on R_1, R_2, T_1, T_2, but not on θ and N. For all three metrics, we found that the optimal performance is achieved when R_1 and R_2 are the largest possible rates, i.e., $R_1 = R_2 = 11Mbps$. Hence, all four user partitions given in Table II are optimal user partitions, and they all lead to the same performances given in Table III. In practice, which configuration in Table II should be chosen depends on the desired tradeoff between the coverage area and the number of relays.

In Table III, we compare optimum time scheduling and achievable performance for three different performance metrics discussed in Section III-B. Note that when we favor Group 1 users, we achieve a quality improvement of $\triangle_1 = 12.43$ dB for Group 1 receivers compared to direct transmission, and $\triangle_2 = 3.32$ dB compared to omni-directional relay transmission while keeping the quality of Group 2 receivers the same as direct transmission. We can alternatively have equal quality at all users in which case we achieve a quality improvement of

	Minimum average distortion	*Equal distortion at all users*	*Best quality in Group 1*
Optimum T_1/T	3.83/11	1/3	9/11
Optimum T_2/T	3.59/11	1/3	1/11
$Rv_1(Mbps)$	0.96 ($\triangle_1 = 0.71$) ($\triangle_2 = 0.35$)	0.92 ($\triangle_1 = 0.67$) ($\triangle_2 = 0.52$)	2.25 ($\triangle_1 = 2.00$) ($\triangle_2 = 1.00$)
$Rv_2(Mbps)$	0.90 ($\triangle_1 = 0.65$) ($\triangle_2 = 0.54$)	0.92 ($\triangle_1 = 0.65$) ($\triangle_2 = 0.52$)	0.25 ($\triangle_1 = 0.00$) ($\triangle_2 = 0.00$)
$PSNR_1(dB)$	37.15 ($\triangle_1 = 7.59$) ($\triangle_2 = 2.57$)	36.90 ($\triangle_1 = 7.35$) ($\triangle_2 = 4.79$)	41.98 ($\triangle_1 = 12.43$) ($\triangle_2 = 3.32$)
$PSNR_2(dB)$	36.78 ($\triangle_1 = 7.23$) ($\triangle_2 = 5.21$)	36.90 ($\triangle_1 = 7.35$) ($\triangle_2 = 4.79$)	29.55 ($\triangle_1 = 0.00$) ($\triangle_2 = 0.00$)
$PSNR_{avg}(dB)$	36.91 ($\triangle_1 = 7.36$) ($\triangle_2 = 4.45$)	36.90 ($\triangle_1 = 7.35$) ($\triangle_2 = 4.79$)	31.43 ($\triangle_1 = 1.88$) ($\triangle_2 = 0.16$)

TABLE III
COMPARISON OF DIFFERENT PERFORMANCE CRITERIA (WITH $R_1 = R_2 = 11Mbps$ FOR ALL THREE CASES. $\triangle_1$ IS THE DIFFERENCE FROM THE DIRECT TRANSMISSION AND $\triangle_2$ IS THE DIFFERENCE FROM THE TRANSMISSION WITH OMNI-DIRECTIONAL RELAYS [1].)

$\triangle_1 = 7.35$ dB at all receivers compared to direct transmission, and $\triangle_2 = 4.79$ dB at all receivers compared to omni-directional relay transmission. Finally, when we minimize the average distortion, compared to the omni-directional case, we improve the quality $\triangle_2 = 4.45$ dB and compared to direct transmission we achieve a quality improvement of $\triangle_1 = 7.36$ dB.

In light of above discussion, compared to omni-directional case, for a similar number of relays, we not only significantly improve the video quality but also extend the coverage area of the multicast system.

V. CONCLUSION

In this paper, we explore the use of directional antennas in relay transmission to enable efficient and robust video multicast in infrastructure-based wireless networks. We determine the user partition and transmission time scheduling that can optimize a multicast performance criterion. We argue that cooperative communication with directional relays further improves the multicast system performance compared to omni-directional relays while providing a larger coverage area. Although directional antennas are expensive, we believe the potential performance gain is significant.

REFERENCES

[1] O. Alay, T. Korakis, Y. Wang, E. Erkip, S. Panwar, "Layered Wireless Video Multicast using Omni-directional Relays", in *Proceedings of IEEE ICASSP*, 2008, available at http://vision.poly.edu/∼ozgu/icassp08

[2] T. Korakis, G. Jakllari, L. Tassiulas, "A MAC protocol for full exploitation of Directional Antennas in Ad-hoc Wireless Networks", in *Proceedings of the ACM MOBIHOC*, 2003.

[3] Z. Tao, T. Korakis, Y. Slutskiy, S. Panwar, L. Tassiulas, "Cooperation and Directionality: A Co-opdirectional MAC for Wireless Ad Hoc Networks",in *Proceedings of WiOpt*, 2007.

[4] R. R. Choudhury, X. Yang, R. Ramanathan, and N. Vaidya, "Using Directional Antennas for Medium Access Control in Ad Hoc Networks", in *Proceedings of ACM MobiCom*, 2002.