Reliable Video Multicast over Wi-Fi Networks with Coordinated Multiple APs

Munhwan Choi
Samsung Electronics Co., Ltd.
Suwon, 443-803, Korea
mhchoi@mwnl.snu.ac.kr

Weiping Sun, Jonghoe Koo, Sunghyun Choi
Department of ECE and INMC
Seoul National University
Seoul, 151–744, Korea
{weiping, jhkoo}@mwnl.snu.ac.kr, schoi@snu.ac.kr

Kang G. Shin
Department of EECS
The University of Michigan
Ann Arbor, MI 48109–2121, U.S.A.
kgshin@eecs.umich.edu

Abstract—**Forward Error Correction (FEC) can be exploited to realize reliable video multicast over Wi-Fi with high video quality. We propose reliable video multicast over Wi-Fi networks with coordinated multiple Access Points (APs) to enhance video quality. By coordinating multiple APs, each AP can transmit entirely or partially different FEC-encoded packets so that a multicast receiver can benefit from both spatial and time diversities. The proposed schemes can enlarge the satisfactory video multicast region by exploiting the AP diversity, thus serving more multicast receivers located at cell edge with satisfactory video quality. We propose a resource-allocation algorithm for FEC-code rate adaptation, utilizing the limited wireless resource more efficiently while enhancing video quality. We also introduce the method for estimating the video packet delivery ratio after FEC decoding. The effectiveness of the proposed schemes is comparatively evaluated via extensive simulation and experimentation. The proposed schemes are observed to enhance the ratio of satisfied users by up to 37.1% compared to the conventional single AP multicast scheme.**

I. INTRODUCTION

There have been increasing R&D efforts on smartphones' Wi-Fi as smartphone user population and applications rapidly expand. In particular, the emergence of high-speed Wi-Fi, such as IEEE 802.11n [1] and IEEE 802.11ac [2], has enabled high-quality and bandwidth-hungry applications such as video streaming to/from smartphones. Moreover, there exist applications, e.g., screen-sharing in smart classroom and game broadcast in sports stadium, in which multiple users need the same video. In such applications, multicast that transmits the data to multiple receivers only once is more efficient than unicasting the same data to each receiver individually. The IEEE 802.11 [1] standard has already defined the multicast transmission, in which a transmitter sends a packet to multiple receivers with a single transmission, utilizing the broadcast nature of wireless medium. This efficiency of multicast triggered extensive investigation of video multicast in Wi-Fi systems, in which the video data is delivered to multiple receivers via multicast transmissions.

However, error control with Automatic Repeat reQuest (ARQ) is not feasible in multicast, since there is no acknowledgement or request of packet-retransmission. Therefore, multicast is inherently vulnerable to the transmission failures caused by wireless channel errors. To overcome this deficiency, application-layer packet-level Forward Error Correction (AL-FEC) has been proposed [3]–[5]. In AL-FEC, the FEC encoding and decoding are performed in the application layer, which can help the receiver recover the erased data packets by exploiting the additional parity packets that are generated from data packets by FEC encoder. AL-FEC is helpful, especially in multicast scenarios, since the additional parity packets can compensate the unreliable nature of multicast. Moreover, in most cases, although the lost packets of different users could be different, by utilizing AL-FEC, all such different lost packets can be recovered by the same parity packets.

The existing research on video multicast using AL-FEC only considers a single AP environment. In this paper, we propose video multicast schemes, in which a video multicast user can be served by multiple coordinated neighboring APs to improve the reliability of video multicast. In hot-spot or enterprise networks where multiple APs are scattered, even though each AP transmits a large number of video packets using AL-FEC to serve its associated users, the users located at cell boundaries might be served with poor quality. In order to enhance the performance of video streaming, especially for users at cell edges, we propose to let them (over)hear the packets from neighboring APs.

With the help of both AL-FEC and the coordination of multiple surrounding APs, in the proposed schemes, each AP can transmit entirely or partially different FEC-encoded packets. The users will receive more FEC-encoded packets by (over)hearing the packets transmitted by surrounding APs, thus increasing the video packets decoding probability. Especially, the *partially overlapped* scheme, by making each AP transmit entirely different parity packets in addition to the video packets, provides balanced video quality to the users regardless whether they are served by multiple APs or a single AP.

In order to efficiently utilize limited wireless resource, we propose a resource-allocation algorithm for FEC-code rate adaptation. Typically, with a more robust FEC code rate (i.e., more parity packets are generated based on a given number of video packets), we can enhance the reliability of the video multicast at the expense of more wireless resources for transmitting more parity packets. In a limited wireless resource environment,

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increasing the amount of resource allocated to a certain AP will decrease other APs' resource. The initial goal of the proposed FEC-code rate adaptation algorithm is to increase the number of satisfactory video service users by adjusting each AP's FEC-code rate in a given multi-AP environment. If the initial goal is met, or if all users are served with satisfactory video quality and there is still some remaining wireless resource, the subsequent objective is to improve the users' perceived video quality beyond the satisfaction level. To correctly evaluate the impact of both the video and parity packets reception on the FEC decoding probability, we investigate how to estimate the video packet delivery ratio and use it to evaluate the proposed schemes.

The contributions of this paper are summarized as follows.

1) To best of our knowledge, this is the first to extend AL-FEC-based reliable video multicast to multiple AP environments, thus exploiting spatial and time diversities.
2) By coordinating multiple APs' transmissions of FEC-encoded packets, we further enhance the diversity gain.
3) We propose an FEC-code rate adaptation algorithm by which more multicast users are served with satisfactory video quality.
4) An estimation method of video packet delivery ratio after FEC decoding is developed.
5) The performance of the proposed multicast schemes is investigated extensively using both simulation and experimentation.

The rest of this paper is organized as follows. Section II describes the system environment under consideration. Section III presents a new reliable video multicast protocol with coordinated multiple APs, and introduces its detailed procedure with AL-FEC. An FEC-code rate adaptation algorithm is described in Section IV. Section V evaluates the performance of the proposed video multicast protocol while Section VI discusses the related work. Finally, the paper concludes with Section VII.

II. SYSTEM ENVIRONMENTS

A. Multi-AP Environment

In the multi-AP environment under consideration, we must ensure that users can utilize the packets from neighboring APs. This can be achieved by letting the users overhear other APs' packets while maintaining a single association with a certain AP. Another candidate solution is to allocate a common Basic Service Set IDentification (BSSID) (as implemented in [6]) to all the APs so that the users can communicate with multiple APs with a single association.

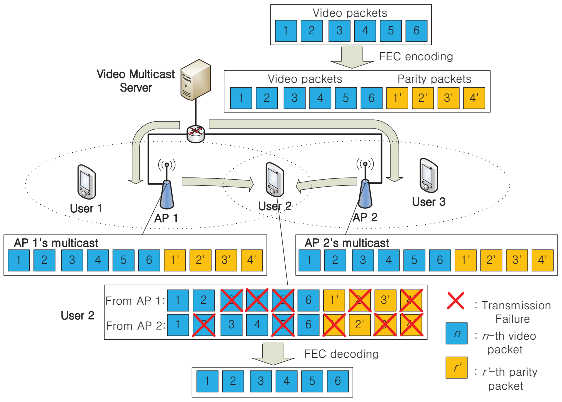
How to determine the operating channel of each AP is also an important issue. In order to enable the users to overhear packets from all the neighboring APs, one simple solution is to make all the APs operate on a common channel. In such a case, the signal interference among the APs and the traffic generated from other types of application can limit the availability of wireless resource for the video traffic. To reduce the negative impact of signal interference generated from video multicast traffic, we can intentionally spread multiple APs' video packet transmission time so that the video multicast can be done exclusively among multiple APs. Although the exclusivity of the video multicast might not be achieved by simply spreading the transmission time due to the interference generated from other types of traffic, IEEE 802.11 devices basically use Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) channel-access mechanisms by which traffic coordination can be achieved. So, the collision between the multicast packets from different APs rarely occurs.

Another candidate solution is to make multiple APs work on different channels. When the user devices are equipped with multiple Network Interface Cards (NICs), they can operate on multiple channels simultaneously so that the video packets transmitted on different channels may be exploited irrespective of the video multicast time. In such a case, the maximum number of simultaneously accessible channels is limited by the number of network interfaces. When the user devices are equipped with only a single NIC, they can hop to each AP's operating channel at a predefined time to receive multiple APs' video multicast packets if the multiple APs' multicast transmissions can be made non-overlapping in time. However, this is unrealistic since the time of multicast cannot be perfectly controlled in a CSMA/CA-based Wi-Fi environment.

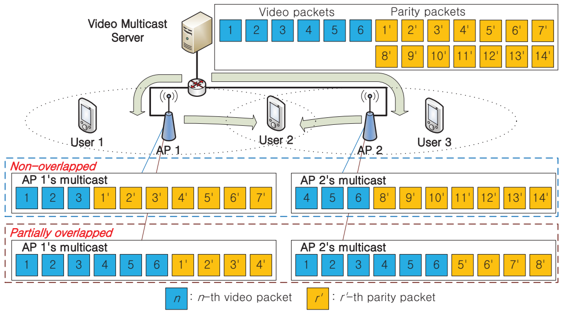
In both candidate solutions, the wireless resource for the video multicast with FEC should be limited since the wireless resource is shared with other types of traffic. Even though the video source rate is fixed in case of Constant Bit Rate (CBR) video traffic, the amount of multicast data can vary depending on the FEC code rate. Therefore, we can control each AP's transmission time for the video multicast by adapting the adopted FEC code rate. That is, each AP periodically transmits the multicast packets within its allocated time duration, and the remaining time is made available to other types of traffic. Since an AP can perform video multicast with higher priority than non-AP stations (STAs) using the prioritized channel access of Enhanced Distributed Channel Access (EDCA) in IEEE 802.11, the transmissions of multicast packets are rarely interfered with.

B. FEC Coding Scheme

For AL-FEC, we employ Raptor code [7], which has been introduced as a rateless fountain erasure-correction code, being capable of producing an unlimited sequence of parity symbols from a block of data symbols—typically non-binary symbols. It is designed and optimized as an erasure-correction code and provides large degrees of freedom in parameter choices. A receiver can recover all the N_O data symbols from a number of data and parity symbols as long as the number of received symbols is slightly larger than N_O. In this work, we use the systematic Raptor code, which includes the original data symbols in the encoded symbols because the systematic Raptor codes generally outperform the non-systematic counterpart.



(a) Totally overlapped video multicast



(b) Non-overlapped & partially overlapped video multicast

Fig. 1. Illustration of the proposed reliable video multicast schemes.

III. RELIABLE VIDEO MULTICAST WITH COORDINATED MULTIPLE APS

A. The Proposed Video Multicast

We propose reliable video multicast by exploiting both AL-FEC and coordination of multiple APs as illustrated in Fig. 1. The server packetizes the video data and generates parity packets using the FEC encoder. Both video and parity packets are delivered to all APs that provide video multicast service, and each AP then multicasts video and parity packets using one of the three proposed schemes.

Fig. 1(a) illustrates *totally overlapped* video multicast in which APs multicast the same set of packets to multicast receivers, given that they are allocated the same amount of time for transmission. When User 2 in Fig. 1(a) is being served by multiple APs, he can receive part of the video and parity packets from both AP 1 and AP 2. Even when his link to one AP becomes bad due to deep fading, User 2 can still receive packets from the other AP, thus exploiting spatial diversity. However, the user might receive the same packet multiple times from multiple APs.

Fig. 1(b) illustrates the other two proposed multicast schemes. Thanks to the characteristic of rateless Raptor FEC coding, the video server can generate as many parity packets as needed. With help from multiple coordinated APs, each AP can transmit entirely or partially different FEC-encoded packets.

In *non-overlapped* video multicast, each AP transmits entirely different video and parity packets based on the allocated amount of time. Compared to Fig. 1(a), each AP transmits fewer video packets but more parity packets. If the users served by a single AP (i.e., User 1 and User 3) receive a sufficiently large number of video and parity packets from their serving AP, they can recover the unsent/lost video packets by utilizing the received parity packets. On the other hand, the user served by multiple APs (i.e., User 2) can receive more packets than the case of Fig. 1(a), as a result of non-overlapped transmissions from multiple APs. Therefore, all video packets can be recovered with a high probability. However, the users in this scheme are likely to receive relatively fewer video packets because the total video packets are divided and allocated to multiple APs for non-overlapped transmissions. In a systematic Raptor FEC, a successful reception of a video packet can be more useful than that of a parity packet in terms of packet recovery, and hence, the reduction of the received video packets could decrease the probability of successful FEC decoding. This characteristic of the systematic Raptor FEC is explained in Section V-A. Consequently, User 1 and User 3 require reception of more parity packets for successful decoding. Similarly, when FEC decoding fails, the user will encounter more video packet losses.

To overcome the deficiency of the non-overlapped multicast scheme, we propose a hybrid scheme called *partially overlapped* video multicast. Unlike the previous cases, each AP transmits all the video packets identically and is allocated entirely different parity packets to transmit. Since the AP transmits all the video packets, the users served by only one AP can receive more video packets than the non-overlapped scheme, and can also recover missing video packets by FEC decoding. In addition, the users who can be served by multiple APs (i.e., User 2) can receive more video packets, while fewer parity packets are likely to be utilized in FEC decoding compared to the non-overlapped scheme. Compared to the totally overlapped scheme, since the partially overlapped scheme makes the users receive an equal or greater number of parity packets regardless whether they are served by single AP or multiple APs, the users can recover the lost video packets with higher probability. The partially overlapped scheme is supposed to provide more balanced video quality than the non-overlapped and totally overlapped schemes, because the effectiveness of the video packet and that of the parity packet are properly utilized. Therefore, in this paper, we propose the partially overlapped video multicast scheme as our main scheme.

B. Video Multicast Procedure

Fig. 2 shows the procedure of the proposed video multicast schemes. This procedure is repeated at every fixed interval, e.g., Group of Pictures (GoP) interval. Each step as numbered in the figure works as follows.

1) The video server performs packetization that divides the video data (corresponding to GoP) into video symbols, which are the input to the FEC encoder. We assume that the video data is generated as CBR traffic and the video data are divided into N_O video symbols.

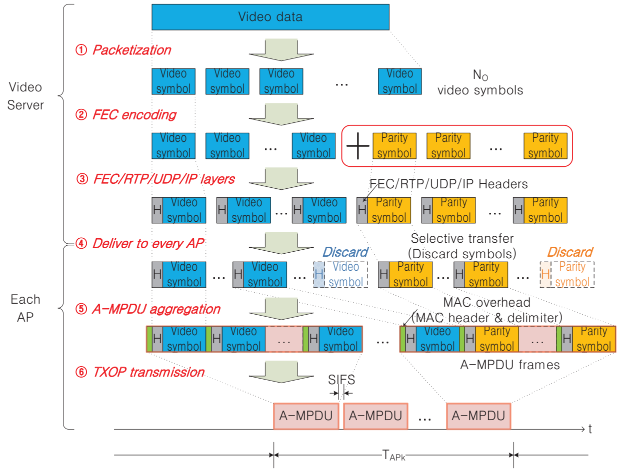


Fig. 2. The procedure of the proposed video multicast.

2) In the application layer, the FEC encoder generates as many parity symbols as needed from these N_O video symbols, where the number of generated parity symbols is determined by the adopted video multicast scheme.

3) These video symbols and parity symbols are then appended by some protocol headers, i.e., FEC, RTP, UDP, and IP headers, to make video and parity packets, respectively.

4) These video packets and parity packets are then delivered to multiple APs over the wireline network and the number of video multicast packets transmitted by each AP is determined by a coordinator,[1] which is responsible for letting each AP know when to start the transmission and which packets to be transmitted over the wireless medium based on the proposed video multicast schemes.

5) Each AP discards the video packets and/or some parity packets that are not transmitted over the air as informed by the coordinator. The remaining packets are aggregated into one or more Aggregation MAC Protocol Data Units (A-MPDUs) [1] to reduce the overheads of the MAC layer according to the maximum A-MPDU length (64 kbytes) and duration (10 msec).

6) Each AP transmits A-MPDU frame(s) during the allocated time. To reduce the overheads in channel access, Transmission Opportunity (TXOP) [1]—which allows consecutive transmission of multiple frames—is used for the efficient video multicast.

The duration of allocated time for each AP is also decided by the coordinator, considering the number of APs, the minimum time of transmitting N_O video packets, and the airtime for the other traffic, etc., as presented in Section IV-B. The number, $N^{(k)}$, of packets transmitted by AP k that each AP was informed of in Step 4, is also decided by the coordinator by considering the duration, T_{AP_k}, of allocated time of AP k, N_O, the length of each packet, and other protocol overheads. The total time, $T(N^{(k)})$, for transmitting $N^{(k)}$ packets should be smaller than T_{AP_k}. Since all A-MPDUs are transmitted in a bursty manner according to the TXOP operation, $T(N^{(k)})$ is equal to the sum of transmission times of A-MPDUs and the transmission time of each A-MPDU is determined by the number of aggregated packets and the Modulation and Coding Scheme (MCS).

Upon reception of video and parity packets, each video multicast user tries to recover the video symbols via FEC decoding.

IV. FEC CODE RATE ADAPTATION

We assume the aggregate transmission time of all the APs for the video multicast is limited, i.e., $T_{sum\_limit} \geq \sum_k T_{AP_k}$, where T_{sum_limit} is the maximum transmission time for the video multicast in a given (e.g., GoP) interval. For efficient adaptation, here we assume that the duration of the time, T_{AP_k}, allocated to AP k is set to $T(N^{(k)})$. Video multicast with the robust FEC code rate can enlarge an AP's coverage, while requiring larger T_{AP_k}, since the AP transmits more parity packets for the same video. Properly adapting the FEC code rate of APs can eliminate service coverage holes. For example, if an AP is located relatively far from the other APs, decreasing the FEC code rate of this AP is likely to enlarge the video multicast region. On the other hand, the FEC code rate of the AP, whose coverage greatly overlaps with other neighboring APs', may not affect the size of the overall multicast service region. Moreover, by making a specific AP serving many users transmit more parity packets at the expense of increasing the FEC code rate of other APs serving fewer users, we can satisfy a larger number of users in the network. We therefore propose an FEC code rate adaptation algorithm for enlarging the video multicast service region.

Here our scope is limited to *partially overlapped* video multicast, which is found to perform best overall as shown in Section V. To determine the FEC code rate of each AP, we utilize channel measurement results from multiple measurement locations. At each measurement location, a user collects the channel information (e.g., Signal-to-Noise Ratio (SNR) value and packet error probability) from all the neighboring APs, and feeds it back to the central coordinator, which then decides the FEC code rate of each AP. The measurement locations should be determined by considering where many users are likely to be. Since the APs' locations usually do not change, the thus-collected information can be used for a long period of time. For each measurement location i and AP k, we assume that the probability $p_{i,k}$ of erroneously receiving a packet from AP k has been fed back to the coordinator in advance so that link-status information required to conduct the proposed scheme is available to the coordinator. On-line measurements and reports to the coordinator might be also feasible, but they are outside the scope of this paper.

A. Estimation of Delivery Ratio

We now present a method for estimating the video packet delivery ratio, which will be used by the FEC-code rate adaptation algorithm. In a systematic Raptor code, successful reception of video packets can be more effective for decoding than reception of parity packets. Therefore, we need to consider separate reception probabilities of video and parity packets.

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[1] It can be a separate entity or can be located inside the server or an AP.

$$\Pr(r_i = r) = \\ \sum_{a_1=0}^{r} \left(f\left(a_1, N_R^{(1)}, p_{i,1}\right) \sum_{a_2=0}^{r-a_1} \left(f\left(a_2, N_R^{(2)}, p_{i,2}\right) \cdots \left(\sum_{a_{N_{ap}-1}=0}^{r-a_1-\ldots-a_{N_{ap}-2}} f\left(a_{N_{ap}-1}, N_R^{(N_{ap}-1)}, p_{i,N_{ap}-1}\right) f\left(r - \sum_{j=1}^{N_{ap}-1} a_j, N_R^{(N_{ap})}, p_{i,N_{ap}}\right) \right) \cdots \right) \right). \tag{1}$$

Algorithm I FEC code rate adaptation

```
***Initialization***
  $\Delta n_r \leftarrow 1, \quad p_{\text{thrs}} \leftarrow p_{\text{thrs}_{\text{init}}}$
  $S_{\text{unsat}} \leftarrow \{s_1, s_2, ..., s_{N_{\text{MP}}}\}, \quad S_{\text{fail}} \leftarrow \emptyset$
  for $k \in S_{AP}$ do
      $N^{(k)} \leftarrow N_O$
  end for
  $S_{\text{unsat}} \leftarrow S_{\text{unsat}} - \text{satisfy}(0, 0, S_{\text{unsat}}, p_{\text{thrs}})$
***Greedy algorithm***
  while $T_{sum\_limit} \geq \sum_k T(N^{(k)})$ do
      $k' := \arg\max_{k \in S_{AP}} \left( \frac{|\text{satisfy}(k, \Delta n_r, S_{\text{unsat}}, p_{\text{thrs}})|}{T(N^{(k)} + \Delta n_r) - T(N^{(k)})} \right)$
      if $T_{sum\_limit} \geq T(N^{(k')} + \Delta n_r) + \sum_{k \neq k'} T(N^{(k)})$ then
          if $\text{satisfy}(k', \Delta n_r, S_{\text{unsat}}, p_{\text{thrs}}) \neq \emptyset$ then
              $N^{(k')} \leftarrow N^{(k')} + \Delta n_r$
              $S_{\text{unsat}} \leftarrow S_{\text{unsat}} - \text{satisfy}(k', \Delta n_r, S_{\text{unsat}}, p_{\text{thrs}})$
              $\Delta n_r \leftarrow 1$
          else
              $\Delta n_r \leftarrow \Delta n_r + 1$
          end if
      else
          if $p_{\text{thrs}} \neq p_{\text{thrs}_{\text{max}}}$ then
              $\Delta n_r \leftarrow 1, \quad p_{\text{thrs}} \leftarrow p_{\text{thrs}_{\text{next}}}$
              $S_{\text{fail}} \leftarrow S_{\text{fail}} \cup S_{\text{unsat}}$
              $S_{\text{unsat}} \leftarrow \{s_1, s_2, ..., s_{N_{\text{MP}}}\} - S_{\text{fail}}$
          else
              break
          end if
      end if
  end while
proc satisfy$(k, n, S, p)$
  $S_{sat} \leftarrow \emptyset$
  for $s_i \in S$ do
      if $P_i(N^{(1)}, ..., N^{(k)} + n, ..., N^{(N_{ap})}) \geq p$ then
          $S_{sat} \leftarrow S_{sat} \cup \{s_i\}$
      end if
  end for
  return $S_{sat}$
end proc
```

When AP k transmits $N^{(k)}$ packets, the number of parity packets, $N_R^{(k)}$, of $N^{(k)}$ is determined by $N_R^{(k)} = N^{(k)} - N_O$. Since all the APs multicast the same video packets in *partially overlapped* multicast, the probability $\Pr(n_i = n)$ that the number of received video packets is equal to n $(0 \leq n \leq N_O)$ is derived as:

$$\Pr(n_i = n) = f\left(n, N_O, \prod_{k=1}^{N_{ap}} p_{i,k}\right), \tag{2}$$

where n_i and N_{ap} are the numbers of received video packets and APs in the network, respectively, and the function $f(a, b, e)$ is the probability mass function of the binomial distribution representing the probability of a successes out of b trials with the failure probability of e:

$$f(a, b, e) = \begin{pmatrix} b \\ a \end{pmatrix} (e)^{b-a} (1-e)^a. \tag{3}$$

On the other hand, we use Eq. (1) to derive the probability $\Pr(r_i = r)$ that the number r_i of received parity packets is equal to r $(0 \leq r \leq \sum_{k=1}^{N_{ap}} N_R^{(k)})$. Since each AP transmits entirely different parity packets, the number of received parity packets is the sum of the numbers of received parity packets from all APs.

For the estimation of the delivery ratio, we define a function, $P(n, r)$, that represents the delivery ratio after Raptor decoding when the numbers of received video packets and received parity packets are equal to n and r, respectively. $P(n, r)$ can be derived by using simulation as explained in Section V-A and as shown in Fig. 3. We derive the estimated delivery ratio $P_i\left(N^{(1)}, \ldots, N^{(k)}, \ldots, N^{(N_{ap})}\right)$ at the measurement location i, when AP k transmits $N^{(k)}$ packets:

$$P_i\left(N^{(1)}, \ldots, N^{(N_{ap})}\right) = \sum_n \sum_r \Pr(n_i = n) \cdot \Pr(r_i = r) \cdot P(n, r). \tag{4}$$

B. Greedy FEC-Code Rate Adaptation

The goal of the FEC-code rate adaptation is to maximize the number of satisfied measurement locations. By definition, at a *satisfied* measurement location, the estimated video packet delivery ratio $P_i(\cdot)$ should be above a given *satisfaction threshold*. Since finding the optimal combination of FEC-code rates for all APs is too complicated to obtain, we propose a greedy algorithm, which incrementally decreases the AP's FEC-code rate while satisfying the most measurement locations. If no more measurement locations can be satisfied with the remaining resource, we increase the current threshold to a higher one, and the goal of the proposed algorithm is altered to utilize the remaining resource to further enhance the reliability of the already satisfied measurement locations. The algorithm terminates if the threshold reaches its maximum value or there is no more resource left to allocate.

Algorithm I shows the pseudo code of the proposed greedy algorithm for the FEC-code rate adaptation, where (1) Δn_r is the number of additionally allocated parity packets, (2) p_{thrs}, $p_{\text{thrs}_{\text{init}}}$, $p_{\text{thrs}_{\text{next}}}$, and $p_{\text{thrs}_{\text{max}}}$ are the current, initial, next, and maximum satisfaction threshold, respectively, (3) S_{AP} is the set of APs in the network, (4) S_{unsat} is the set of unsatisfied measurement locations which might become satisfied by the algorithm, (5) S_{fail} is the set of measurement locations which cannot be satisfied with the current satisfaction threshold, (6) N_{MP} is the total number of measurement locations in the network, and (7) satisfy(k, n, S, p) is the function which returns the set of the satisfied measurement locations out of the set of measurement locations, S, when the number of multicast packets of AP k, $N^{(k)}$, is changed to $N^{(k)} + n$ and the satisfaction threshold is p, respectively.

In this algorithm, AP k', which can satisfy more measurement locations with fewer additional parity packets, i.e., AP k' with the maximum value of $\frac{|\text{satisfy}(k, \Delta n_r, S_{\text{unsat}}, p_{\text{thrs}})|}{T(N^{(k)} + \Delta n_r) - T(N^{(k)})}$, is selected to increase its $N^{(k')}$ preferentially. This procedure is repeated

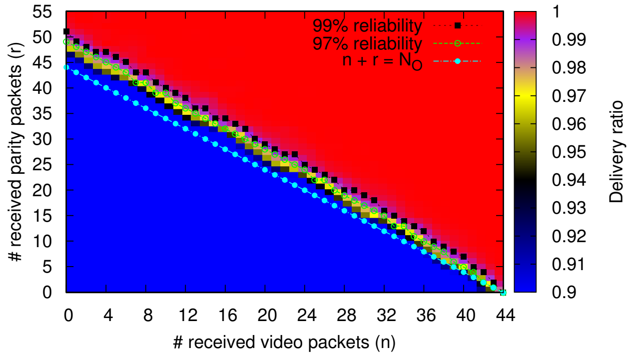


Fig. 3. Video packet delivery ratio $P(n, r)$ with Raptor code ($N_O = 44$).

until the total transmission time of all APs reaches the limit, T_{sum_limit}. If no newly satisfied measurement location is found for all APs with large Δn_r, satisfying more measurement locations is abandoned, and the satisfaction threshold is updated to the next-higher value to further enhance the video quality at the already satisfied measurement locations.

V. PERFORMANCE EVALUATION

We now comparatively evaluate the performance of the proposed reliable video multicast protocol using an H.264 CBR video clip of 500 kbps. The number, N_O, of video packets per GoP (corresponding to 0.5 second) and the number, N, of encoded packets (when code rate adaptation is not used) are assumed to be 44 and 50, respectively. Our evaluation is done with Peak Signal-to-Noise Ratio (PSNR), which is a widely-accepted measure of video quality.

We use the NS-3 network simulator [8] integrated with real Raptor encoder and decoder. IEEE 802.11n PHY and MAC models are used, and Jake's fading model with pathloss exponent of 3.5 and Doppler speed of 1.0 m/s is used unless specified otherwise. All the multicast packets are transmitted via MCS 0 of 802.11n, i.e., 6.5 Mbps, using A-MPDU. Therefore, when $N = 50$, an AP consumes about 15 % of the wireless resource for video multicast.

A. Raptor Code Performance

We first evaluate the performance of the employed Raptor code. Fig. 3 shows the average video packet delivery ratio, $P(n, r)$ used in Eq. (4), while varying the numbers of received video and parity packets. The delivery ratios are obtained via simulation using a software implementation of Raptor encoder and decoder. Whether or not a decoding succeeds for a given (n, r) is not deterministic, but actually depends on which of video and parity packets are received. For a given (n, r), we randomly select n video packets and r parity packets, and run the decoder to determine the number of successfully delivered video packets. If the decoding is successful, all N_O video packets are delivered, thus making the delivery ratio 1 or 100%. However, if the decoding fails, only n video packets are assumed to have been delivered, thus making the delivery ratio n/N_O. We obtain the delivery ratio $P(n, r)$ by averaging the results from 1,000 randomly-chosen combinations of n and r.

TABLE I
SATISFIED USERS AND AVERAGE PSNR

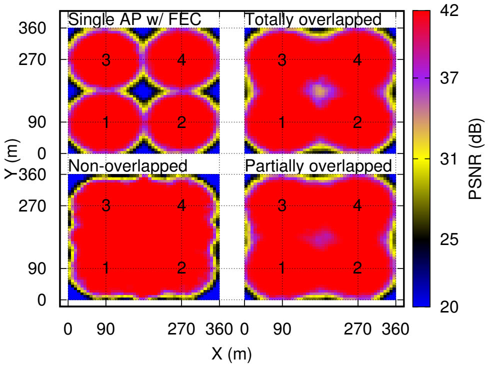
	Results in Fig. 4(b)		Results in Fig. 6	
	Satisfied users (%)	Average PSNR (dB)	Satisfied users (%)	Average PSNR (dB)
Single AP w/o FEC	68.25	34.5	67.86	33.89
Single AP w/ FEC	84.1	38.19	78.52	36.86
Totally overlapped	92.4	39.91	85.26	38.51
Non-overlapped	86.5	39.00	83.66	38.02
Partially overlapped	93.6	40.23	86.42	38.82
Partially overlapped w/ FEC adaptation			88.02	39.15

Fig. 3 shows that the delivery ratio increases as the sum of the numbers of received video and parity packets increases. The figure also shows the minimum number of r received parity packets for a given n received video packets to achieve two target video packet delivery ratios, namely, 99% and 97%. A line representing $n + r = N_O$ $(= 44)$ is also drawn as a reference. We first observe that the required sum of n and r to achieve a target delivery ratio is larger for a larger target ratio. Moreover, for the considered target values, the required sum is slightly larger than N_O, meaning that we need more than one parity packet to recover one video packet in an average sense. We also observe that the required sum of n and r to achieve a target delivery ratio decreases as n increases, because the number of video packets to be recovered by the decoding decreases as n increases. Consequently, a successful reception of a video packet can be more useful than that of a parity packet in terms of packet recovery.

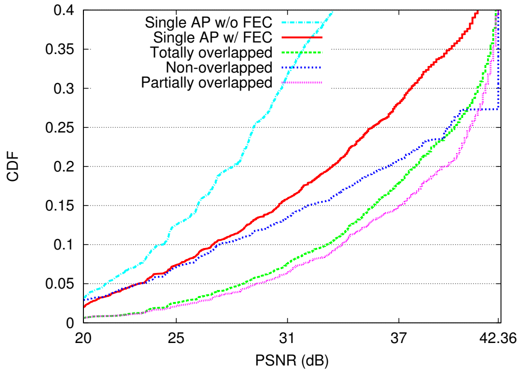
B. Simulation Results: Fading Channel

Apparently, video quality and packet losses are tightly coupled. The PSNR value of the used H.264 video clip without damage is about 42 dB, and the PSNR value rapidly decreases as the delivery ratio decreases in large delivery ratio region. Based on the relationship between PSNR and Mean Opinion Score (MOS) [9], and assuming MOS of 4 (i.e., Good) as the satisfactory video quality, the delivery ratio over 0.97 is acceptable for the good video quality of this video clip.

Fig. 4 shows the PSNR distribution when there are four equally apart APs and 2,000 users are randomly spread in 360 m × 360 m area. Fig. 4(a) shows the PSNR as a function of the positions of the users and Fig. 4(b) shows empirical Cumulative Distribution Function (CDF) of PSNR observed by 2,000 users. Table I shows the ratio of satisfied users and the average PSNR based on Fig. 4(b). We observe that the *partially overlapped* scheme achieves the best performance in terms of both metrics. Compared to *single AP* w/o and w/ FEC, the *partially overlapped* scheme enhances the satisfied user ratio by 37.1% and 11.3%, respectively. The *non-overlapped* scheme is the best in reducing the size of coverage hole in the middle of APs. However, since the users served by only one AP in the area's boundary experience the worst performance, the overall performance of the *non-overlapped* scheme is worse



(a) PSNR



(b) CDF of PSNR

Fig. 4. Four APs at (90,90), (270,90), (90,270), (270,270), and 2,000 users.

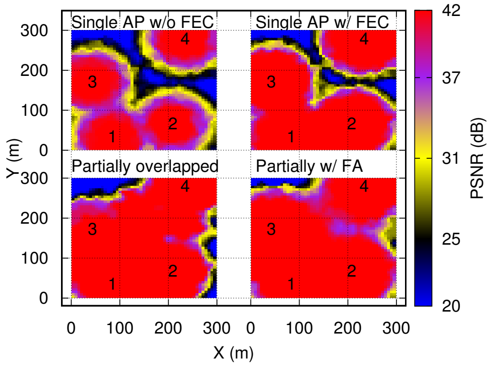


Fig. 5. Four APs at random locations and 500 users.

than the other proposed schemes. Based on these observations, we conclude that *partially overlapped* video multicast is the best for the reliable video multicast service.

C. Simulation Results: Code Rate Adaptation

Fig. 5 shows PSNR values of 500 randomly placed users when four APs are randomly located. Note that the proposed FEC code rate adaptation is expected to be effective when the APs and/or users are unevenly distributed. In this evaluation, we assume that each user is located at a measurement location so that the channel information of all the users is available at the coordinator to maximize the performance of the proposed FEC code rate adaptation algorithm. Inter-AP distances are not fixed, and the number of serving APs for a user can vary depending on his location. For the proposed FEC adaptation algorithm, the initial satisfaction threshold, i.e., $p_{\text{thrs}_{\text{init}}}$, is set to 0.97 for the satisfactory video quality. Based on the proposed FEC rate adaptation algorithm, AP 1, whose coverage overlaps with neighboring APs' coverage, increases its code rate (i.e., decreases $N^{(1)}$) so that other APs (AP 2 and AP 3) can transmit more parity packets, i.e.,

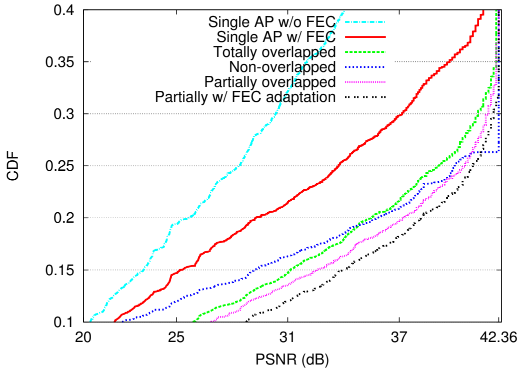


Fig. 6. Four APs and 500 users at the random locations in a 300 m × 300 m area.

$$(N^{(1)}, N^{(2)}, N^{(3)}, N^{(4)}, N_O) = (46, 52, 56, 49, 44).$$

Fig. 6 shows the empirical CDF of PSNR values of 500 users when 4 APs and 500 users are placed at random locations. Ten simulations with different topologies are performed and the results are averaged. Table I also shows the ratio of satisfied users and the average PSNR based on Fig. 6. Since many users are served by only one AP, *non-overlapped* video multicast performs very badly, while *partially overlapped* video multicast achieves the best performance. Moreover, using the proposed FEC adaptation algorithm, the overall video quality is further enhanced and more users are satisfied with good video quality. Compared to *single AP* w/o and w/ FEC, *partially overlapped* w/ FEC adaptation enhances the satisfied user ratio by 29.7% and 12.1%, respectively.

D. Trace-Based Evaluation

Fig. 7 shows the experimental setup in our building, where 4 APs perform video multicast. All APs are connected to a video streaming server via Ethernet. Each AP periodically transmits N FEC-encoded packets, which are generated by the video server, by taking turns in a round robin fashion. The experiments are done at a 5 GHz channel with virtually no interference and all the packets are transmitted using 6 Mbps PHY rate of 802.11a. Each user records the trace of packet receptions from the APs. The trace results indicate which packets are correctly received and which are lost. The Raptor decoder is used to recover the lost packets, and then, the portions of the video clip corresponding to the unrecovered lost packets are eliminated. Finally, the PSNR is determined by comparing the original and decoded video clips. This trace-based performance evaluation is useful for a fair comparison since the same trace is used for each scheme.

Fig. 8 shows the video multicast performance at various locations. In the case of users 1, 2, 3, and 10, they can receive

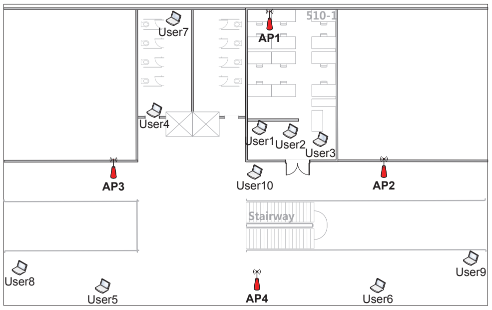


Fig. 7. Experimental environment.

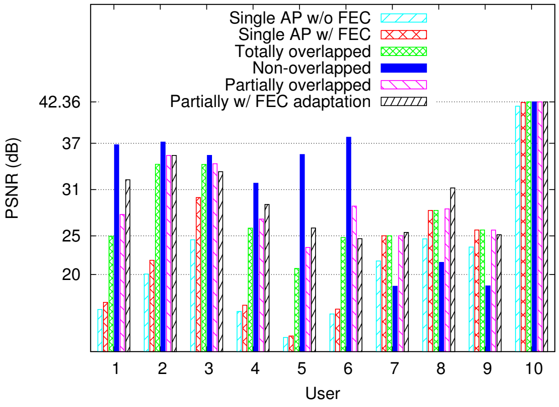


Fig. 8. Experimental results ($N_O = 44$).

the packets from 4 APs with some errors. On the other hand, users 4, 5, and 6 can receive the packets from only 2 APs among 4 APs, while users 7, 8, and 9 can receive the packets from only one closest AP. Therefore, in the case of the users who can receive the packets from multiple APs, utilizing the proposed multi-AP video multicast schemes, especially, the *non-overlapped* scheme, the users can achieve better video performance. However, if the user can be served by only one AP, e.g., users 7, 8, and 9, the *non-overlapped* scheme performs worst, while the other schemes with AL-FEC perform almost the same. Based on the proposed FEC rate adaptation algorithm, the values of $N^{(k)}$ for AP k are:

$$(N^{(1)}, N^{(2)}, N^{(3)}, N^{(4)}, N_O) = (51, 49, 56, 47, 44)$$

by allocating the most parity packets to AP 3 with most associated users. It should be noted that with the partially overlapped scheme with code rate adaptation, we have five satisfied users (i.e., PSNR over 31 dB) while there are only 3 satisfied users without code rate adaptation, thus empirically demonstrating the utility of the code rate adaptation algorithm. It is also shown that our proposed multi-AP video multicast schemes outperform the conventional single AP schemes.

E. Prototype Implementation

We have also prototyped the proposed video multicast protocols in real video streaming environments. We use VLC media player [10], which is a popular open-source media player supporting video streaming over networks. In general, the VLC streamer sends video stream to a specific destination IP address with a specific port number, and the VLC player in the receiver waits for the video stream with the specific port number. Our implementation is based on the socket programming and software-based Raptor FEC en/decoder. The FEC encoder and decoder work at the application layer of the video server and receivers, respectively. The VLC streamer, instead of sending the video stream to the destination, sends the video stream to the FEC encoder process running in the same video server machine. The FEC encoder, after generating N FEC-encoded packets from the N_O video packets, sends encoded packets to APs for multicast. The code rate is set to $10/15$, i.e., $N_O = 10$ and $N = 15$, for fixed rate schemes. These FEC-encoded packets are transmitted with the destination port number equal to the port number of FEC decoder, not the VLC player's. Upon reception of the multicast packets from one or multiple APs, the FEC decoder process decodes and forwards the decoded video packets to the VLC player. The advantage of this structure is that it does not require any change of the legacy video streaming software for the FEC en/decoding because the communication between streamer (player) and encoder (decoder) is done via the conventional socket interface.

Fig. 9. A snapshot of the demonstration.

Fig. 9 shows a snapshot of the video multicast demonstration. Three tablet PCs work as the receivers. In this experiment, the receivers are away from the APs insomuch as the channel error occurs frequently. The first receives video packets without FEC from one AP (i.e., *w/o FEC*), the second receives and decodes FEC-encoded packets from one AP (i.e., *w/ FEC*), and the third receives FEC-encoded packets from 2 APs based on the proposed *partially overlapped* video multicast protocol. All the receivers have an embedded Wi-Fi Network Interface Card (WNIC), and an additional WNIC is used for receiving packets from 2 APs. The average PSNR values of *w/o FEC*, *w/ FEC*, and *Partially overlapped* are 21.83 dB, 26.04 dB, and 37.12 dB during 5 minutes long video clip streaming, respectively. As shown in the snapshot, *partially overlapped* scheme achieves the best video quality and *w/ FEC* achieves the better video quality than *w/o FEC*.

VI. RELATED WORK

The existing research efforts on improving the performance of video transmission over IEEE 802.11 WLAN focused on single AP environments. The authors of [11] proposed an adaptive cross-layer protection strategy for enhancing the robustness and efficiency of scalable video unicast transmission in a single AP environment, in which various protection strategies in the protocol stack, such as AL-FEC, maximum MAC retransmission limit, and packet size adaptation, are jointly optimized for a given channel condition. Raptor code-based schemes for video multicast were presented in [3]. In order to achieve the reliability and efficiency of video multicast, Raptor code rate was dynamically determined based on the given channel condition in a single AP environment.

M. Santos *et al.* [12] introduced a novel Quality of Experience (QoE)-aware multicast mechanism for video transmission. It integrates a structured set of collision prevention, feedback and rate adaptation control mechanisms without FEC in a single AP environment. To enhance the reliability of video multicast, the authors of [13] proposed a Wi-Fi multicast system called *DirCast*, in which an AP converts multicast packets to targeted unicast transmissions and most of the stations operate in promiscuous mode to overhear the unicast transmissions. To minimize the amount of consumed air time, DirCast uses greedy algorithm-based destination and association control, which was applied to a single AP environment without FEC. Another MAC-level video multicast protocol named *REMP* was proposed in [14], where the AP selectively retransmits erroneous multicast frames and adjusts MCS under varying channel conditions. This scheme was also for a single AP environment without FEC.

On the other hand, there have been some efforts exploiting multi-AP diversity. Zhu *et al.* [15] propose a multi-AP architecture and compared its performance with the traditional WLANs in terms of throughput from a network perspective. There multi-AP meant that each user is capable of maintaining multiple associations. However, they considered performance improvements of uplink only and did not incorporate FEC scheme across multiple associations. Vella *et al.* [16] proposed a multi-AP infrastructure that multiple transmit sources, such as APs, can be placed at the edge of a coverage area so as to aid the stations which are suffering from severe signal attenuation. They call the AP placed at the edge a *slave AP* and the AP placed at the center of the coverage area the *master AP*. The slave and master APs share a common frequency channel and transmit during non-overlapping time intervals so that stations can receive video multicast packets from both slave and master APs. They only considered packet repetition between master and slave APs as a diversity scheme without considering other FEC schemes.

VII. CONCLUDING REMARKS

In this paper, we have proposed new reliable video multicast schemes in which using AL-FEC and the coordination between multiple APs, each AP transmits entirely or partially different FEC-encoded packets for reliable video multicast. These schemes extend the video multicast coverage by improving the video quality of cell-edge users. We have also proposed a resource-allocation algorithm for the FEC-code rate adaptation of each AP to the limited availability of wireless resource. This FEC-code rate adaptation satisfies more users and enhances the video quality of the satisfied users. We have also developed a way of estimating the delivery ratio after FEC decoding. Our extensive evaluation using simulation and experimentation has demonstrated that the proposed schemes can enhance overall video quality in video multicast systems.

In future, we would like to expand the video multicast service area and explore ways of utilizing spatial reuse for video multicast. We will also study combined cross-layer FEC-code and PHY rate adaptation to improve resource efficiency and video quality further. The proposed video multicast schemes have wide applicability. For example, they can be used for more reliable video streaming in smartphones with connections to both cellular and Wi-Fi networks.

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