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Harkirat Singh
*Samsung Electronics*

Huaning Niu
*Samsung Electronics*

Xiangping Qin
xqin@siu.edu

Huai-rong Shao
*Samsung Electronics*

ChangYeul Kwon
*Samsung Electronics*

*See next page for additional authors*



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**Authors**
Harkirat Singh, Huaning Niu, Xiangping Qin, Huai-rong Shao, ChangYeul Kwon, Guoping Fan, Seong Soo Kim, and Chiu Ngo

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# Supporting Uncompressed HD Video Streaming without retransmissions over 60GHz Wireless Networks

Harkirat Singh*, Huaning Niu*, Xiangping Qin*, Huai-rong Shao*, ChangYeul Kwon†, Guoping Fan†, Seong Soo Kim† and Chiu Ngo*

Samsung Electronics
* 75 W Plumeria Dr., San Jose, CA 95134, USA
† 416 Maetan-3Dong, Youngtong-Gu, Suwon-Shi, Gyungki-Do 443-742, Korea

*Email:*{har.singh, huaning.niu, x.qin, hr.shao, cy.kwon, guoping.fan, seongsoo1.kim, chiu.ngo}@samsung.com

***Abstract*—Uncompressed HD (high-definition) video delivery over wireless personal area networks (WPANs) is a challenging problem because of the limited bandwidth and variations in channel. The most straight forward technique to recover from channel errors is to retransmit corrupted packets. However, retransmissions introduce significant delay/jitter and require additional bandwidth. Therefore, retransmissions may be unsuitable for uncompressed video streaming.**

**In this paper, we develop, simulate, and evaluate an millimeter-wave (mmWave) system for supporting uncompressed video streams up to 3-Gbps without any retransmissions. New features of the mmWave system incorporates: (i) *UEP* (unequal error protection) where different video bits (MSBs and LSBs) are protected differently, (ii) a *multiple-CRC* to determine whether MSB or/and LSB portions are in error, (iii) *RS code swapping (RSS)*, an error concealment scheme which can conceal some errors in video pixels. Simulations using real uncompressed HD images indicate that the proposed mmWave system can maintain good average PSNR (peak-signal-to-noise-ratio) under poor channel conditions, achieving what is generally accepted as a good picture quality with PSNR values greater than 40dB. Moreover, the proposed system results in less fluctuating PSNR values.**

***Index Terms*—Uncompressed high-definition video, Gigabit WPAN, 60GHz, millimeter-wave, PSNR.**

## I. Introduction

Transmission of uncompressed video can do away with video codecs, which may not be suitable for some delay sensitive applications such as interactive gaming. In addition, uncompressed video brings enhanced picture quality by avoiding compression and decompression, which can reduce the video quality. Therefore, the need for supporting uncompressed video is obvious. The High-Definition Multimedia Interface (HDMI) allows transfer of uncompressed HD signals between devices via a cable. A wireless interface can provide flexible setup without tangled wires. The current wireless technologies such as MBOA-UWB [1], IEEE 802.11n [2], etc. can support less than 1Gbps (gigabit per second) data rate. Therefore, it is not feasible to transmit uncompressed HD video over existing wireless networks. Instead, a multi-gigabit wireless solution is required.

The 60GHz millimeter-wave (mmWave) band has recently drawn much interest because of the huge bandwidth that it can provide from 57-64 GHz unlicensed spectrum available in the US. This huge bandwidth coupled with very sharp signal attenuation beyond a few meters make the 60GHz mmWave band a suitable candidate for supporting short-range applications such as uncompressed HD video streaming. For instance, a user can stream uncompressed HD video from a handheld device or a personal video recorder (PVR) to a high-definition television (HDTV). The application data rate of a single uncompressed HD (1080p) stream with a color depth of 8-bits is 3.0Gbps. In the near future, 12- and 16-bit color would become available, thus increasing the data rate even further to 4.5 and 6.0 Gbps. *Therefore, supporting uncompressed HD video wirelessly without any retransmissions is still a very challenging task.*

In data communication all bits are equally important, hence must be reliably delivered. In contrast, in uncompressed video streams some bits are more important than other bits. For instance, in comparison to the least significant bit (LSB), the most significant bit (MSB) of a color pixel has the maximum impact on the video quality [3]. Therefore, bits can be treated differently, and it is not necessary to deliver all bits reliably. Also, uncompressed video stream contains rich spatial redundancy, which can be used to overcome some pixel errors.

Motivated by these observations, the mmWave system includes the following features: **Pixel Partitioning**: usually the neighboring pixels have very similar or even same values. In the proposed system, spatial redundancy is exploited by partitioning adjacent video pixels into different video packets. Normally, channel errors are uncorrelated, thereby successfully received video packets can help in concealing an erroneous video packet from the same pixel partition. **MAC/PHY efficiency**: pixel data is unequally protected based on the perceptual importance, and separate CRCs are provided for MSB and LSB portions of video pixels. This helps in invoking an error concealment scheme for corrupted pixels only, and hence enhances the MAC/PHY efficiency in terms of effective PSNR. **Error concealment**: RS (Reed-solomon) code based error concealment is adopted, wherein erroneous RS codes are replaced with *good* (i.e., uncorrupted) RS codes having higher spatial correlation with the erroneous codes. The proposed error concealment makes use of pixel partitioning and multiple CRCs.

The rest of the paper is organized as follows. Section II summarizes the current research activities in the 60GHz band. Section III presents the system architecture and the error concealment schemes developed in this work. A performance



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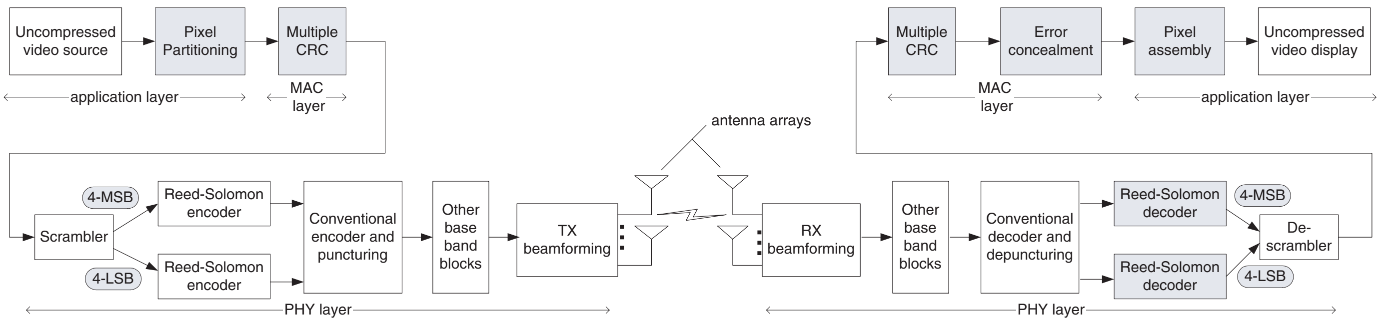



Fig. 1. Block diagram of the transmitter and the receiver of the mmWave system; shaded blocks are the contribution of the paper.

study using real uncompressed HD images is presented in section IV. Finally, Section V concludes the paper.

## II. Related Work

A number of industry/academia research and standardization activities related to the 60GHz band are underway: Wigwam [4], a project funded by the German Ministry of Research and Foundation is aiming to develop a Gigabit system for short range communications using mmWave band. In [5] IBM research presented a system level design supporting uncompressed video up to 2Gbps using SiGe radio chipsets in mmWave band. WirelessHD (WiHD) [6] is an industry-led effort to define a next generation wireless high-definition interface specification for consumer electronics products. Ecma International TC32-TG20 Task Group [7] is also developing a standard for 60GHz technology for very high data-rate short range unlicensed communications to support bulk data transfer such as downloading data from a kiosk and high-definition multi-media streaming. In addition, the IEEE 802.15.3c Task Group [8] is considering a millimeter-wave alternate physical layer for the IEEE 802.15.3-2003 standard for WPANs. The work is expected to complete in 2008.

Our work here has had a step ahead by developing and simulating the major modules of the system to support uncompressed HD video over 60GHz mmWave band without seeking retransmissions.

## III. System Model

The proposed system for supporting uncompressed video streaming over mmWave wireless networks is shown in Figure 1. The application layer at the video source implements pixel partitioning such that pixels with minimal spatial distance (i.e., neighboring pixels) are placed into different video packets. If a video packet is corrupted, then the receiver recovers the error using pixel information in other received packets containing neighboring pixels. As a result, retransmission of corrupt pixels is not required. The MAC layer aggregates multiple video packets into one MAC frame. For each video packet, the MAC layer supports two CRC fields: MSB and LSB CRCs (cyclic redundancy checksum) which are actually filled in at the PHY layer. At the PHY layer, information bits are first scrambled to randomize the input sequence. Then

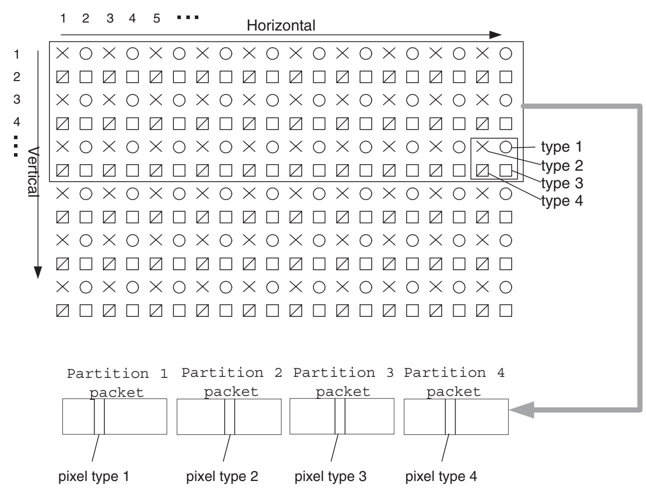



Fig. 2. Example of spatial partitioning of pixels into four partition packets.

the 4 MSB[1] (most significant bits) are parsed into the first data path, and the second 4 LSB (least significant bits) are parsed into the second data path. On each data path, RS (Reed-Solomon) and convolutional codes are concatenated to protect the information bits. We consider RS code (224, 216, t=4) having the hamming distance of $d_{min}$ = $2t+1$ [9]. The two bitstreams are of different importance; the MSB bitstream carries more weightage towards the picture quality. Therefore, in comparison to the LSB data path, the MSB data path is strongly protected which allows better error protection for the MSB portion of video pixels. At the receiver side, RS code based error concealment scheme (RSS) is used to overcome pixel errors. Finally, the PHY layer is equipped with array antennas which can form a directed beam towards a desired angular direction to maximize SINR (signal-to-interference and noise ratio). The following subsections present detailed description of the modules developed in this work:

[1]We assume a color depth (i.e., the number of bits per color component) of 8-bit. However, the proposed system can be easily extended to other video streams using a deep-color (i.e., 12- or 16-bit color) depth.

### A. Pixel Partitioning

In a typical uncompressed video stream, geographically neighboring (spatially correlated) pixels usually have very similar, or even the same values. This kind of spatial redundancy is exploited such that pixels with minimal spatial distance are partitioned into different video packets. Figure 2 shows a diagrammatical example of pixel partitioning and packetizing scheme wherein four neighboring pixels are partitioned into four video packets. If one video packet is corrupted then, one or more other packets which contain pixels that are spatially related to the corrupted pixel(s) can be used to recover (compensate for) the corrupted pixel information.

### B. MAC/PHY layer support

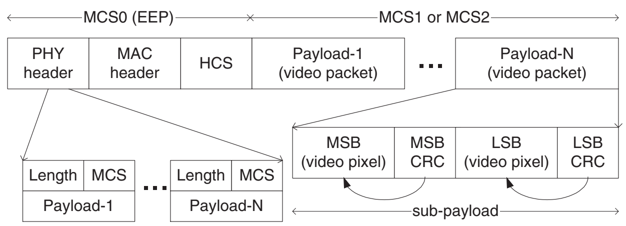



Fig. 3. The frame structure used in the mmWave system.

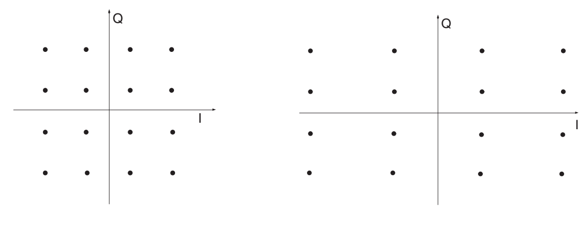
Figure 3 shows the frame structure used in the mmWave system. The packet header includes a PHY header, a MAC header, a CRC (Header checksum - HCS) for the header portion. The payload field contains multiple video packets. Various portions of the packet can be modulated and coded using various modulation and coding schemes (MCS). To facilitate the receiver to accurately parse the received packet, the PHY header contains a field indicating which MCS mode is used for error control coding and modulation of the corresponding sub-payload and the length of the sub-payload portion in the payload. The MCS modes may include EEP (Equal Error Protection) and UEP (Unequal Error Protection). EEP modes use the same coding rate and modulation (e.g., QPSK or 16-QAM) for both most significant bits (MSBs) and least significant bits (LSBs).

UEP provides a way to protect bits differently. UEP can be provided by *coding* or *mapping*. In UEP by coding mode, a lower coding rate is allocated to more important bits (i.e., MSBs) and high coding rate to less important bits (i.e., LSBs). For example, the MSBs (bits 7, 6, 5 and 4) with a lower coding rate than the LSBs (bits 3, 2, 1 and 0). UEP can also be provided by *mapping* wherein some bits are strongly protected in caparison to other bits in the constellation diagram. For the purpose of illustration, Figure 4(a) shows the constellation diagram of EEP mode (16-QAM) by maintaining a perfect square. In the UEP mode, bits mapped onto the I-branch get stronger (unequal) protection than the bits on the Q-branch. Therefore, the constellation diagram looks like a rectangle, Figure 4(b). However, the average energy per symbol remains unaffected.

Table I presents the MCS considered in this system. Figure 5 presents the BER performance of UEP (by mapping) and EEP modes. In the UEP mode, the BER performance of MSBs is boosted at the expense of poor BER for LSBs.

TABLE I
TRANSMISSION MODES.

| **Index** | **Mode** | **Modulation** | **Code rate** | | **Data rate (Gbps)** |
|---|---|---|---|---|---|
| | | | **MSB** (bits [7-4]) | **LSB** (bits [3-0]) | |
| MCS0 | EEP | QPSK | 1/3 | | 0.940 |
| MCS1 | EEP | 16-QAM | 2/3 | | 3.761 |
| MCS2 | UEP by mapping | 16-QAM | 2/3 | | 3.761 |
| MCS3 | UEP by coding | 16-QAM | 4/7 | 4/5 | 3.761 |




(a) 16-QAM EEP. (b) 16-QAM UEP.

Fig. 4. Constellation diagrams of 16-QAM EEP and UEP by mapping modes.

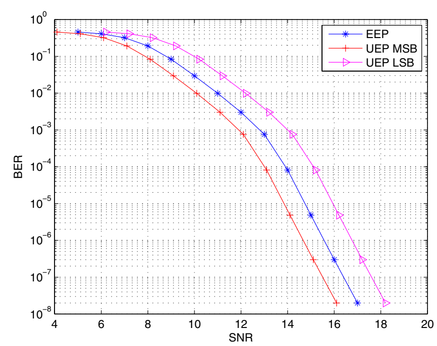



Fig. 5. BER performance of EEP and UEP by mapping modes.

The header is transmitted using the most reliable MCS and also employs EEP (Equal Error Protection) for both the most significant bits (MSBs) and the least significant bits (LSBs). Each video packet is appended with two CRCs: MSB-CRC for the MSBs and LSB-CRC for the LSBs, Figure 3. These CRC fields are actually filled in at the PHY layer. Since the MSB portions are strongly protected in the UEP mode, two separate CRCs for MSB and LSB portions help in identifying which portion is in error, thereby limiting the error concealment to the erroneous portion of the video packet only. Correctly received portion of the video packet is forwarded to the higher layers as it is.

### C. Error concealment

The quality of uncompressed video streams is highly vulnerable to channel disturbances when they are transmitted over an unreliable medium such as a wireless channel. After identifying that a video packet has not successfully reached the destination, there are a number of methods that can be considered to conceal its effects on the quality of the received video signal. The most straightforward option however, would be to retransmit the erroneous video packet. This option introduces additional delay and complex buffer management and requires extra bandwidth to support retransmissions. Therefore, retransmissions may not be acceptable for delay sensitive multi-gigabit uncompressed video delivery.

In the context of compressed video (e.g., MPEG stream), a considerable amount of research work on error concealment schemes has already been done, [10], [11], [12] and others. However, our work significantly differs from all these in that we consider uncompressed video streaming while developing the following error concealment schemes when no retransmissions are permissible:

*1) Display adjacent partition (DAP):* If one video packet is received corrupted (i.e., pixels received with errors) then, video packets carrying the neighboring pixels are used to recover the pixels in the corrupted packet. For instance, in Figure 2 if video packet[2] 1 is received in error and other video packets are successfully received then, packet 1 can be replaced with one of the adjacent video packets. Furthermore, mutiple CRCs help to conceal (or replace) only the erroneous portion(s) with the adjacent packets.

*2) Display random pixels (DRP):* In this error concealment scheme, erroneous video packets are simply replaced with random pixels.

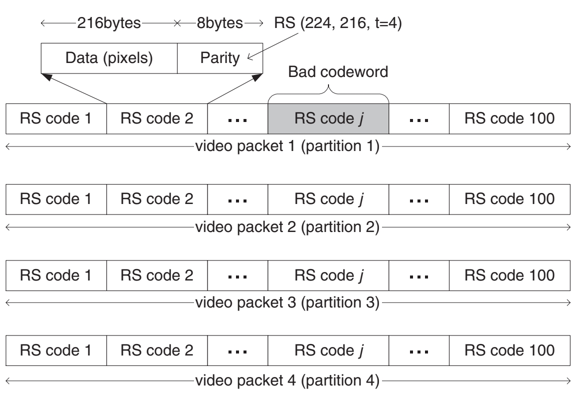



Fig. 6. Illustration of RSS error concealment scheme. A video packet is composed of one hundred RS codewords. RS code $j$ in Packet 1 is in error. Correctly received RS code $j$ in other packets (2–4) from the same partition can be used to conceal the wrong code.

*3) RS code swap (RSS):* We use Reed-Solomon (RS) codes for concealing some pixel errors. We combine *g*ood (i.e., uncorrupted) RS codes from a corrupted video packet and adjacent partitions to reconstruct the original video packet. While developing the RSS error concealment scheme, we consider a *cross-layer feedback* from the PHY layer to the MAC layer.

[2]One partition is mapped onto one video packet.

In the proposed mmWave system, each video packet constitutes of 100 RS codes to achieve a high channel efficiency, and thus to meet the delay constraints of uncompressed videos. Therefore, the length of each video packet is 21600 bytes, and one 1080x1920p (HD) frame is evenly divided into 288 video packets. The RS code (224, 216, t=4) considered in the mmWave system can correct errors up to 4 symbols (bytes). If more than 4 symbols are in error, it flags as an uncorrectable codeword. We use this kind of *feedback* from the PHY layer. For each video packet, the PHY layer (i.e., RS decoder) signals to the MAC layer those RS codewords received correctly and those in error. Afterwards, the MAC layer (or the application layer) conceals the effect of failed RS codes on the video quality. Identified failed RS codes are replaced with *good* RS codes having pixels with minimum spatial variations. For a video packet, if the receiver detects error, it takes the following steps:

- Erroneous RS codewords are identified at the PHY layer and signaled to the MAC layer.
- RS codes at the same position in other video packets from the same partition are used to replace the erroneous RS code. As shown in Figure 6, RS code $j$ in video packet 1 is received in error. One of the RS codes at the same position $j$, which carry neighboring pixels, from video packet 2, 3 or 4 is used to replace the faulty codeword.
- If the previous step could not be successfully completed because none of the three adjacent partitions had the same indexed RS code correctly received then, one of the adjacent *good* RS codes within the corrupted packet is used to replace the erroneous codeword. In the next step, adjacent RS codes from different partitions are used.
- Finally, if some of the codewords could not be concealed then display them as it is.

We implement the above three error concealment schemes and study their impact on the PSNR.

## IV. Performance Study

In this section, we evaluate the performance of the mmWave system. We enhanced the IEEE 802.15.3 MAC in the network simulator (ns2) by implementing the new features described in the previous section. The PHY layer supports both the UEP (by mapping) and EEP modes, Table I. We consider PSNR (peak-signal-to-noise ratio) as the key performance metric. For a received $N_1 \times N_2$[3] 8-bit image, the PSNR is represented as,

$$PSNR = 20\log_{10}\frac{255}{\sqrt{\frac{1}{N_1 * N_2}\sum_{i=0}^{N_1-1}\sum_{j=0}^{N_2-1}[f(i,j)-F(i,j)]^2}} \quad (1)$$

where f(i,j) is the pixel value of the source video frame, and F(i,j) is the pixel of the reconstructed video frame at the display. The measured PSNR indicates the difference between

[3]In our simulation study, $N_1$ and $N_2$ are equal to 1080 and 1920, respectively.

the transmitted and the received video frame. The average PSNR is defined as,

$$AveragePSNR = \frac{1}{F}\sum_{i=1}^{F} PSNR_i \qquad (2)$$

where F is the total number of uncompressed video frames simulated. We simulate one thousand frames from the movie clip *Alexander*; an example frame from the movie is shown in Figure 7. Each frame has 1080×1920 pixels, each pixel has 24bits (i.e., RGB components of 8-bit each), and the frame rate is 60Hz. Thus, the application rate is 3.0Gbps.

Concatenated Reed-Solomon code with convolutional codes are used in the system. Since the errors at the Viterbi decoder are bursty, they tend to present to the RS decoder correlated symbol errors. Using [9], we get the relation of codeword error probability ($P_w$) and bit error probability ($P_b$) as,

$$P_b \approx \frac{d_{min}}{n} P_w \qquad (3)$$

where $d_{min} = 9$, $n = 224$. In the event of error, $d_{min}$ bytes in a codeword are randomly flipped. We compare the performance of the mmWave system wherein video packets are coded as UEP or EEP. We also compare the impact of the error concealment schemes on the PSNR.

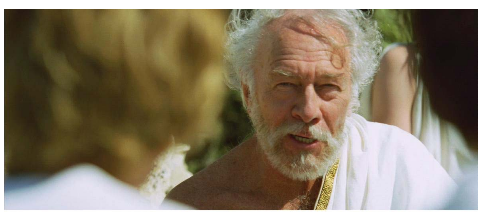


Fig. 7. An example frame simulated from the movie clip *Alexander* [13].

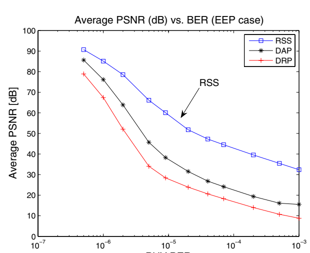



Fig. 8. Average PSNR values for the EEP mode.

## A. The effect of error concealment schemes

Figure 8 presents the average PSNR results as a function of the channel BER for the three error concealment schemes in the EEP mode. Replacing an erroneous video packet with some random pixels (DRP) achieves the worst performance. Even the scheme of displaying adjacent pixel partition (DAP) does not perform as good as the RSS. This is because in DAP, an adjacent partition is used assuming that all pixels belong to a homogeneous region, wherein all pixels have

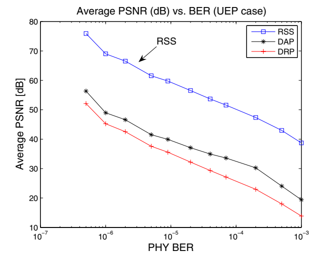



Fig. 9. Average PSNR values for the UEP mode.

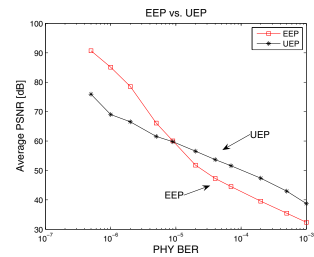



Fig. 10. Average PSNR values for the EEP and UEP modes under RSS error concealment scheme.

almost similar values in comparison to the erroneous video packet. This assumption may not be always true because of the edge effects, wherein pixel values are dramatically changed. Therefore, replacing the whole video packet with the adjacent partition results in significantly changing the pixel values of the erroneous video packet as reflected in the poor PSNR. In the RSS, the erroneous pixels are concealed (or replaced) at the granularity of the RS codeword length, which is much smaller than the whole video packet (comprising of one hundred RS codes) length. Moreover, in the RSS scheme the error concealment is confined to *erroneous* codewords only. The benefit of the RSS scheme is evident from the significantly higher PSNR values, Figure 8. We observe the similar behavior in the case of UEP mode, as shown in Figure 9.

For the rest of the performance study results, we focus on the RSS error concealment only.

## B. The effect of UEP and EEP

The EEP mode treats MSB and LSB portions of a video packet equally. The MSB portions, which contribute more towards the PSNR, are strongly protected in the UEP mode, however, the LSB portions are weakly protected. This is the reason that in the low BER range (BER $<$ 9.0e-06), the average PSNR of the EEP mode outperforms UEP, Figure 10. *However, in the high ber range (BER $>$ 9.0e-06), UEP achieves better average PSNR because MSB portions are strongly protected thereby maintaining a high PSNR (Figure 10)*. For the BER values we simulated in this study, the UEP mode always maintains PSNR values greater than 40dB which is generally accepted as a good picture quality.

## C. The stability of RSS and UEP

Figure 11 presents the PSNR values of one thousand frames simulated for the EEP and UEP modes. The corresponding

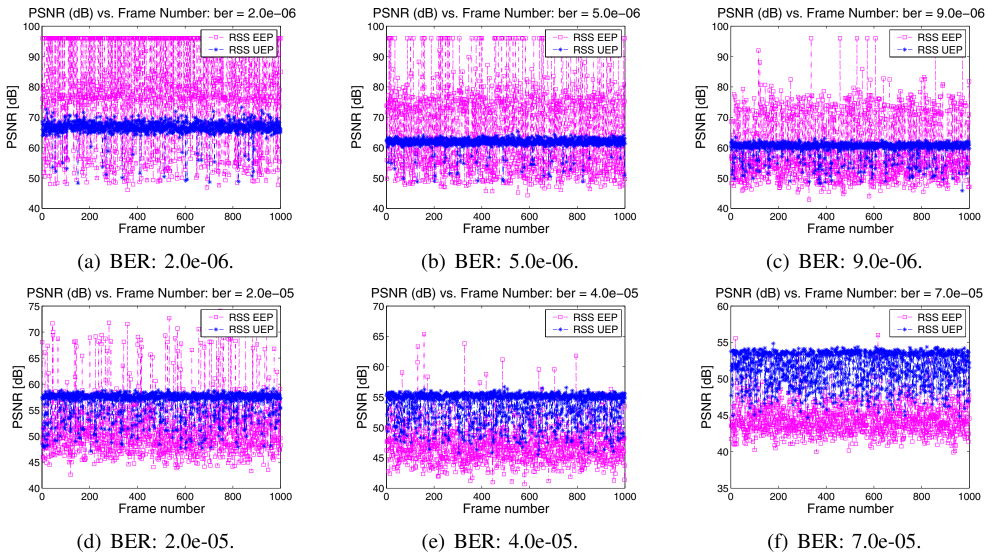



Fig. 11. The PSNR values of one thousand frames simulated under different BER values and for both EEP and UEP modes using the RSS error concealment scheme are shown. The average PSNR value of the presented data is already shown in Figure 10.

average PSNR values are shown in Figures 8 and 9. Since RSS outperforms the other two error concealment schemes, we only show the PSNR results for the RSS in Figure 11. Table II summarizes the mean and variance of PSNR values shown in Figure 11. *Notice that the variances of PSNR for the UEP mode are much smaller than the corresponding result of the EEP mode. This suggests that the UEP results in less fluctuating PSNR values than the EEP. Even though in some cases the EEP mode attains a higher mean PSNR values, the stability effect of the UEP mode provides much better visual quality than the EEP mode because for most human observers, wide fluctuations in the picture quality result in more severe visual degradation.*

TABLE II
MEAN AND VARIANCE OF PSNR RESULTS SHOWN IN FIGURES 11.

| PHY BER | 2.0e-06 | 5.0e-06 | 9.0e-06 | 2.0e-05 | 4.0e-05 | 7.0e-05 |
|---|---|---|---|---|---|---|
| **Mean PSNR (dB)** | | | | | | |
| EEP | 78.55 | 66.12 | 60.05 | 51.79 | 47.28 | 44.52 |
| UEP | 66.53 | 61.56 | 59.77 | 56.54 | 53.67 | 51.95 |
| **Variance ($\sigma^2$)** | | | | | | |
| EEP | 245.51 | 196.32 | 112.78 | 32.95 | 10.89 | 9.58 |
| UEP | 6.95 | 4.19 | 5.93 | 5.75 | 5.90 | 5.21 |

## V. CONCLUSIONS

In this paper, we present a 60GHz mmWave wireless system that supports uncompressed HD video streaming. The system incorporates pixel partitioning, unequal error protection (UEP), multiple CRCs to support uncompressed video streaming without soliciting retransmission of lost video packets. Furthermore, the proposed system mitigates the effect of poor channel condition by using a novel error concealment scheme (RSS) based on a cross-layer-feedback from the RS decoder. Simulations show that the UEP mode together with RSS maintains a good video quality under poor channel conditions. In addition, the video quality is quite stable. This shows the proposed mmWave system would enable transmission of uncompressed HD video wirelessly over the next generation personal area networks.

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