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CONSUMER COMMUNICATIONS AND NETWORKING

A 60 GHz Wireless Network for Enabling Uncompressed Video Communication

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ABSTRACT

Uncompressed high-definition video streaming over wireless personal area networks is a challenging problem because of the high data rate requirement and channel variations. With the advances in RF technology and the huge bandwidth available worldwide in the 57–66 GHz millimeter-wave unlicensed spectrum, mmWave WPANs that can support multigigabit transmission are being developed. However, compared to low-frequency signals (2.4 or 5 GHz), mmWave signals are more fragile; indeed, the propagation losses are significantly higher. In this article we present an mmWave system for supporting uncompressed HD video up to 3 Gb/s. The system includes various efficient error protection and concealment schemes that exploit unequal error resilience properties of uncompressed video. Some of them have been adopted in the emerging 60 GHz WPAN standards such as WirelessHD, ECMA TC48, and IEEE 802.15.3c. Simulations using real uncompressed HD images indicate that the proposed mmWave system can maintain, under poor channel conditions, good average peak-signal-to-noise-ratio and low video quality metric scores.

INTRODUCTION

Wireless has become a prominent technology in consumer communications and networking. For example, WiFi, ultrawideband (UWB), and Bluetooth are eliminating the *wire spaghetti* that has ever plagued multimedia home networks. Wireless connectivity in the home diversifies the configurations of game consoles, PCs, set-top boxes, and digital TVs. Among the many multimedia applications, high-definition (HD) video streaming is of great interest. A wireless video transmission system for supporting HD video having a 1080-pixel video frame (i.e., a frame having 1920 vertical lines and 1080 horizontal lines or 1920 × 1080 pixels on a frame) with each pixel having three color components (8 bits/color), and a frame rate of 60 Hz requires a channel bandwidth of about 3 Gb/s to support video data only. In addition, control signals, audio data, and channel access overhead need additional bandwidth. The high-definition multimedia interface (HDMI) can deliver uncompressed video, but requires interconnection of devices via expensive cables. Current wireless technologies such as MBOA-UWB and IEEE 802.11n can support less than 1 Gb/s data rate. Due to the limitations of the available data rates, HD video streaming using current wireless technologies has always been accompanied by a video compression technique such as MPEG2 or H.264. Therefore, a new system is required to achieve a wireless version of HDMI.

Compression at the transmitter and decompression at the receiver incur problems in wireless multimedia applications. First, the processing time during compression and decompression generates an intrinsic latency, which may not be suitable for some delay-sensitive applications such as interactive gaming. Second, degradation in picture quality at the receiver is inevitable. Third, HD streaming is confined between two devices that employ the same compression technique. A transcodec, which converts a compressed HD video into another compression format, is required if a device is to relay the received HD stream to another device employing a different compression technique. This incurs both cost and complexity at a video display (e.g., HDTV). Hence, the need to support uncompressed HD streaming is great.

The 60 GHz millimeter wave (mmWave) technology opens a new era of multigigabit-per-second transmission for many consumer electronics applications because of the huge bandwidth it can provide in 57–64 GHz unlicensed spectrum available in the United States. The frequency plans and regulations on equivalent isotropically radiated power (EIRP) in major consumer markets worldwide can be found in [1]. Below we enumerate the benefits of the 60 GHz mmWave band for supporting short-range applications such as uncompressed HD video streaming:

- *Coverage*: Due to high attenuation of 60 GHz signals by obstacles, the range for an indoor mmWave network is on the order of 10 m, which makes it suitable for an in-room wireless personal area network (WPAN).
- *Form factor*: Directional antennas are far easier to implement at 60 GHz band than at 2.4 or 5 GHz because of the smaller

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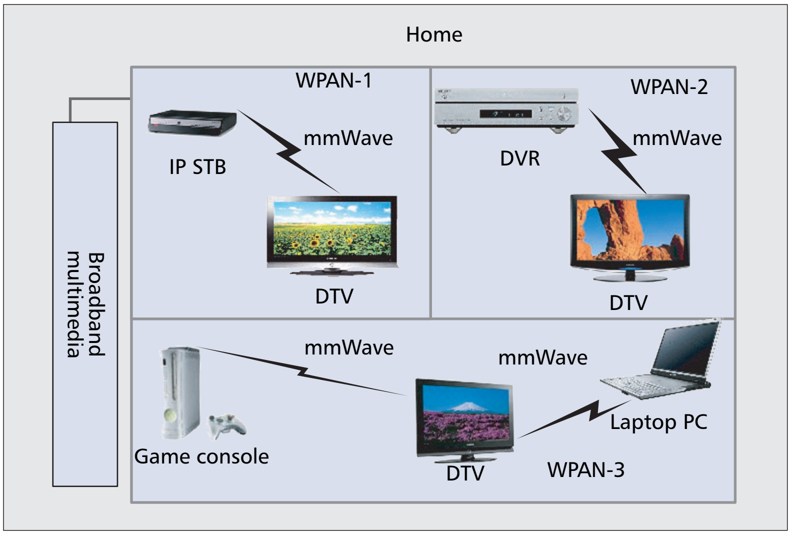


■ **Figure 1.** *Configuration of gigabit WPANs in a typical home environment.*

wavelength, which also reduces the antenna size. Furthermore, directional transmission and reception simplifies the transceiver design by significantly reducing the delay spread and hence the intersymbol interference [2].

- *Channel bandwidth*: 60 GHz band provides 7 GHz contiguous bandwidth, which allows higher data rates with lower spectral efficiency because the data rate is calculated as data rate (bits per second) = spectral efficiency (bits per second per Hertz) × bandwidth (Hertz).

All of the above features make 60 GHz band attractive for supporting uncompressed video within a room. For instance, a user can stream uncompressed HD video from a handheld device or personal video recorder (PVR) to an HDTV, as shown in Fig. 1. The application data rate of a single uncompressed 1080 HD stream with a color depth of 8 bits is 3 Gb/s. In the near future 12- and 16-bit color will become available, thus increasing the data rate even further to 4.5 and 6.0 Gb/s. Clearly, transfer of uncompressed video signals requires more use of frequency bandwidth than that of compressed video signals. As the signal bandwidth becomes wider, the signal processing speed at both the transmitter and receiver becomes higher, requiring about 2.5 Gsamples/s sampling rate with 6–8 quantization bits. It is apparent that the mmWave transceiver with very short sample period is vulnerable to frequency offset, timing drift, and any nonlinearity caused by the instability of 60 GHz RF components such as a low noise amplifier (LNA), voltage controlled oscillator (VCO), and phase locked loop (PLL). The other major challenge that makes the uncompressed HD streaming difficulty in 60 GHz frequency band is the poor link budget. The path losses at 10 m for line-of-sight (LOS) and non-LOS conditions are 88 and 92 dB, respectively, assuming 4 dB shadowing effect [3]. Also, the 60 GHz frequency band has oxygen absorption properties, which means that the transmitted signal is attenuated severely by oxygen molecules encountered in the transmission path. To compensate for the large path loss and obtain a reliable transmission quality, sophisticated antenna array beamforming emerges as a crucial mechanism featuring high antenna gain and adaptive steering. Therefore, maintaining good quality uncompressed HD video streaming in 60 GHz band is a very challenging task, and requires further elaborations in network design.

In this article we present an mmWave system for supporting uncompressed HD video. The system includes the following new features:

- Pixel partitioning that exploits spatial redundancy by partitioning adjacent video pixels into different video packets
- Unequal error protection and related medium access control (MAC)/physical layer (PHY) support
- Error concealment that allows the receiver to recover erroneous pixels by using neighboring *good* pixels having higher spatial correlation

While developing some of these schemes, we resort to cross-layer feedback among different layers in the communication stack.

Standardization Activities in 60 GHz WPAN

Standardization in 60 GHz wireless networks is currently under development by several industry consortia and international standard organizations. WirelessHD [4] is an industry-led effort to define a next-generation wireless HD interface specification for consumer electronics products. The consortium completed the WirelessHD specification version 1.0 in January 2008. European Computer Manufacturer Association (ECMA) International TC48 [5] is also developing a standard for 60 GHz technology for very high data rate short range unlicensed communications to support bulk data transfer such as downloading data from a kiosk and HD multimedia streaming. In addition, IEEE 802.15 Task Group 3c [6] is considering an mmWave alternate physical layer for the IEEE 802.15.3-2003 standard for WPANs. While ECMA TC48 is targeting its specification completion for December 2008, IEEE 802.15.3c standardization is expected to be completed in 2009.

System Model

In data communications all bits are equally important; hence, they must be reliably delivered. In contrast, in uncompressed video streams some bits are more important than others. For instance, compared to the least significant bit (LSB), the most significant bit (MSB) of a color pixel has the maximum impact on the video quality [7]. Therefore, bits can be treated differently, and it is not always necessary to deliver all bits with the same error control scheme. Unequal error protection (UEP) provides a way to protect bits in the order of their importance. In UEP, the bit error rate (BER) for high importance bits is much lower. Numerous studies in the past have shown the benefits of using UEP at the PHY layer in the context of compressed video [8, 9]. In addition, an uncompressed video stream contains rich spatial redundancy, which can be used to overcome some pixel errors.

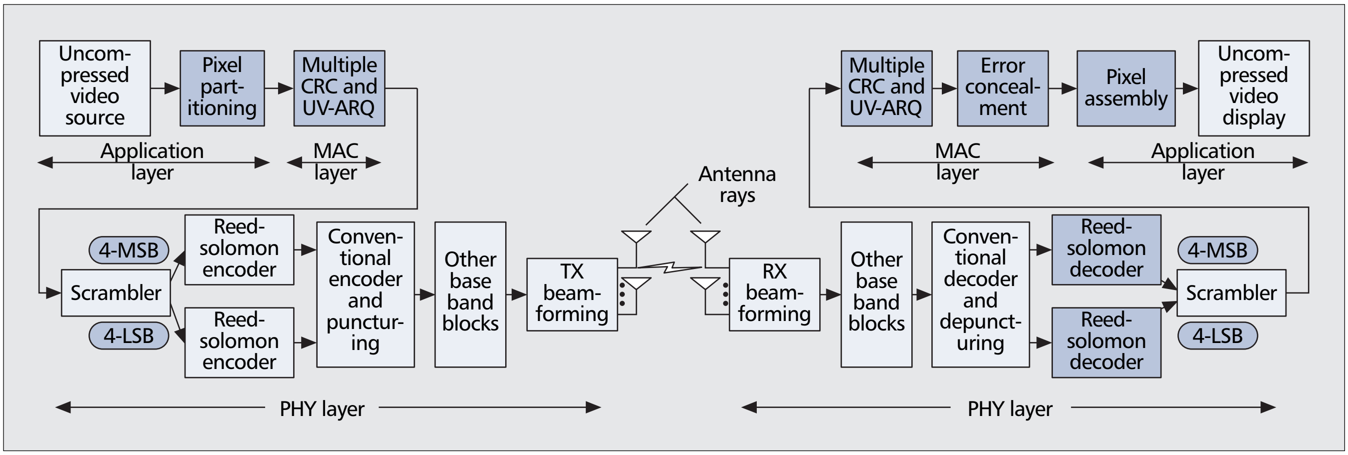


Figure 2. *Block diagram of the transmitter and receiver of the mmWave system; shaded blocks are the focus of the article.*

Motivated by the above observations, we propose the system shown in Fig. 2 for supporting uncompressed video streaming over mmWave wireless networks. 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 transmission is corrupted, the receiver recovers the error using pixel information in other received packets containing neighboring pixels. As a result, further retransmission of corrupted pixels is not required. The MAC layer aggregates multiple video packets into one MAC frame. For each video packet, the MAC layer supports two cyclic redundancy checksum (CRC) fields: MSB and LSB CRC. The aggregation used in this article is a combination of A-MSDU and A-MPDU schemes in IEEE 802.11n. In addition, multiple CRCs are included for each aggregated payload.

At the PHY layer, information bits are first scrambled to randomize the input sequence. Then the four MSBs are parsed into the first data path, and the second four LSBs are parsed into the second data path. On each data path, Reed-Solomon (RS) and convolutional codes are concatenated to protect the information bits. We consider RS code (224, 216, $t = 4$) having a Hamming distance of $d_{\min} = 2t + 1$ [10]. We assume a color depth (i.e., the number of bits per color component) of 8 bits. However, the proposed system can easily be extended to other video streams using a deeper color depth (i.e., 12- or 16-bit color).

The two bitstreams are of different importance; the MSB bitstream carries more weight toward 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, an RS-code-based error concealment scheme (RSS) is used to overcome pixel errors. Finally, the PHY layer is equipped with array antennas, which allows beamforming toward a desired angular direction to maximize signal-to-interference-plus-noise ratio (SINR). The following subsections present detailed descriptions of the modules developed in this work.

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 3a shows an example of a pixel partitioning and packetizing scheme wherein four neighboring pixels are partitioned into four video packets. If one video packet is corrupted, one or more other packets that contain pixels spatially related to the corrupted pixel(s) can be used to recover or compensate for the corrupted pixel information.

MAC/PHY Layer Support

Figure 3b shows the frame structure used in the mmWave system. The packet header includes a PHY header, a MAC header, a video header, and a header checksum (HCS). The payload field contains multiple video packets. Video-specific details are included in the video header. For each payload, a video control field is included in the video header to indicate:

- Partition number, that is, to which partition video pixels belong
- Horizontal and vertical positions of pixels in a video frame prior to partition
- Video frame number

These fields are populated based on cross-layer feedback from the application layer. Various portions of the packet can be modulated and coded using various modulation and coding schemes (MCSs). To facilitate the receiver accurately parsing 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 (Table 1) may include equal error protection (EEP) and unequal error protection (UEP). EEP modes use the same coding rate and modulation (e.g., quadrature phase shift keying [QPSK] or 16-quadrature amplitude modulation [QAM]) for both MSBs and LSBs.

Uncompressed Video ARQ — Wireless systems designed for data communication send a packet with a checksum appended. The receiver

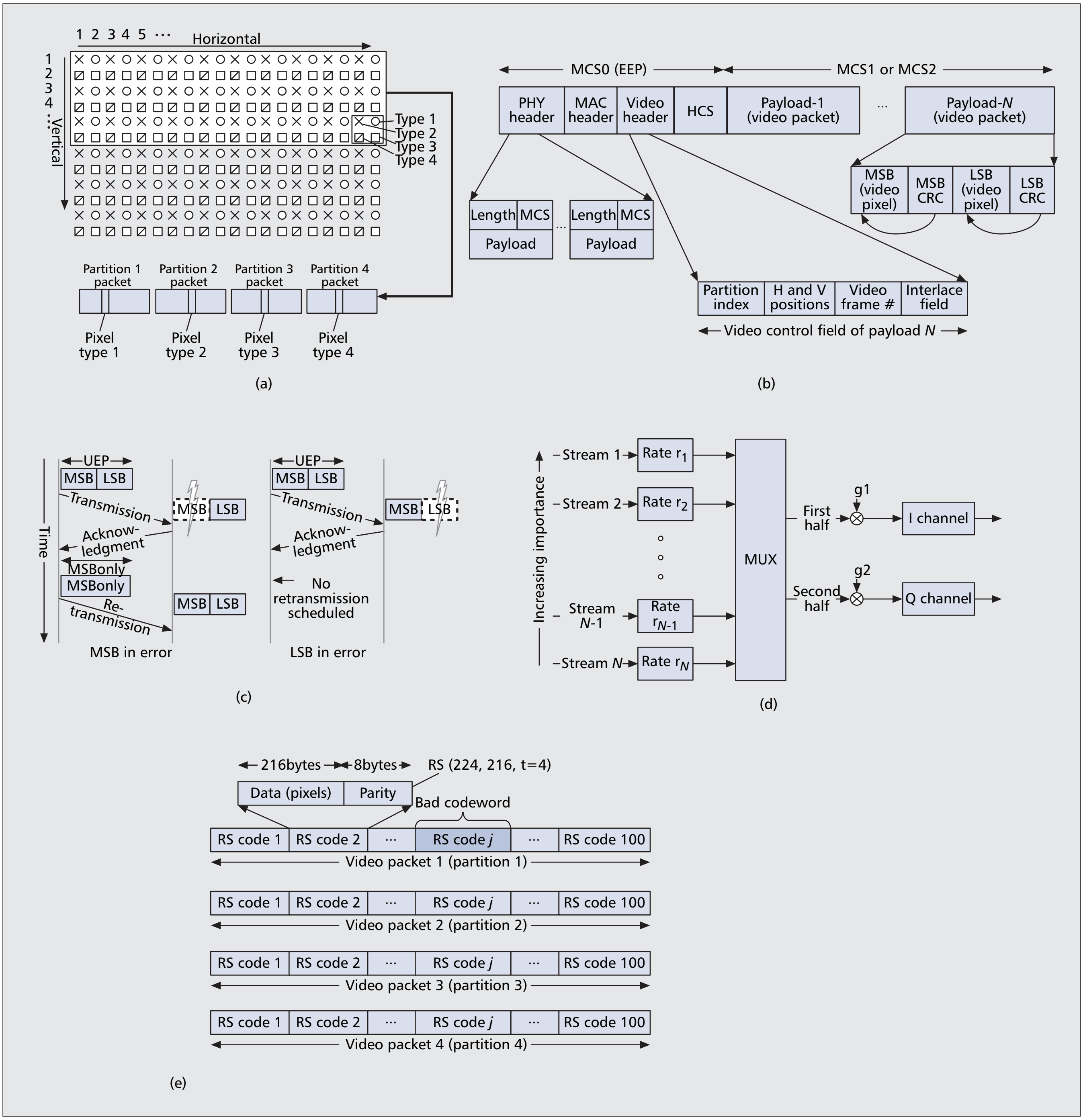


Figure 3. *Illustration of various components of the mmWave System developed in this article: a) pixel partitioning; b) frame format; c) uncompressed video ARQ; d) unequal error protection; e) RSS error concealment.*

recomputes the checksum. If an error is detected by failed checksum, the receiver requests retransmission of the whole packet. It is possible that a chunk of bits have been correctly received; however, the sender retransmits another copy of the whole packet.

The uncompressed video automatic repeat request (UV-ARQ) protocol improves on this by using 2 bits/video packet in the acknowledgment (Ack) to indicate the status of both MSB and LSB portions. If the MSB portion is received correctly, retransmission is not solicited. Otherwise, a robust modulation and coding mode (MSBonly, Table 1) is used to reliably retransmit the MSB portion only. Figure 3c illustrates the functioning of UV-ARQ, which can be summarized as follows:

- The sender appends multiple CRCs per video packet and transmits the packet to the receiver.
- The receiver recomputes the checksums for the MSB and LSB portions. The receiver signals the sender about the status of the MSB and LSB portions.
- If the MSB portion is correctly received, the sender skips retransmission of the LSB por-

tion, as shown in Fig. 3c (LSB error case). Otherwise, the sender retransmits the MSB portion only using the MSBonly MCS (MSB error case).

- Since the same *time* is granted to retransmit the MSB portion as for the original video packet, reduced rate modulation index can strongly protect the retransmitted MSB portion against channel errors by providing a higher signal-to-noise ratio (SNR).

UNEQUAL ERROR PROTECTION

UEP provides an efficient method to protect bits with different weighting. Figure 3d shows a generalized structure of UEP [7]. UEP assumes multiple use of error control coding blocks and applies different coding rates r_i to multiple input bitstreams. In fact, multigigabit-per-second transmission systems inevitably employ parallel signal processing blocks due to the limit of processing speed, and parallel or multiple error control coding blocks are natural in the physical layer design:

- *UEP by coding*: A lower coding rate is allocated to more important bits (i.e., MSBs) and a higher coding rate to less important bits (i.e., LSBs). For example, the MSBs (bits 7, 6, 5, and 4) have a lower coding rate than the LSBs (bits 3, 2, 1, and 0).
- *UEP by mapping*: UEP can also be provided by mapping wherein some bits are more strongly protected than other bits in the constellation diagram. Bits mapped onto the I-branch get stronger (unequal) protection than those on the Q-branch. Therefore, the constellation diagram looks like a rectangle; however, the average energy per symbol remains unaffected.

In both UEP modes the BER performance of MSBs is boosted at the expense of poor BER for LSBs since the MSB portions are strongly protected. The two separate CRCs for MSB and LSB portions help limit error concealment to the erroneous portion of the video packet only. The correctly received portion of the video packet is forwarded to the higher layers as it is.

ERROR CONCEALMENT

Uncompressed video requires huge bandwidth for retransmission, so an unlimited number of retries may not be desirable because of additional latency and buffer requirements at the receiver (i.e., display such as HDTV). We consider one-time retransmission of MSB portions. If the retransmitted packet is also corrupted, the receiver invokes error concealment. In the context of compressed video (e.g., MPEG stream), a considerable amount of research work on error concealment schemes has already been done. However, our work significantly differs from all these in that we consider uncompressed video streaming.

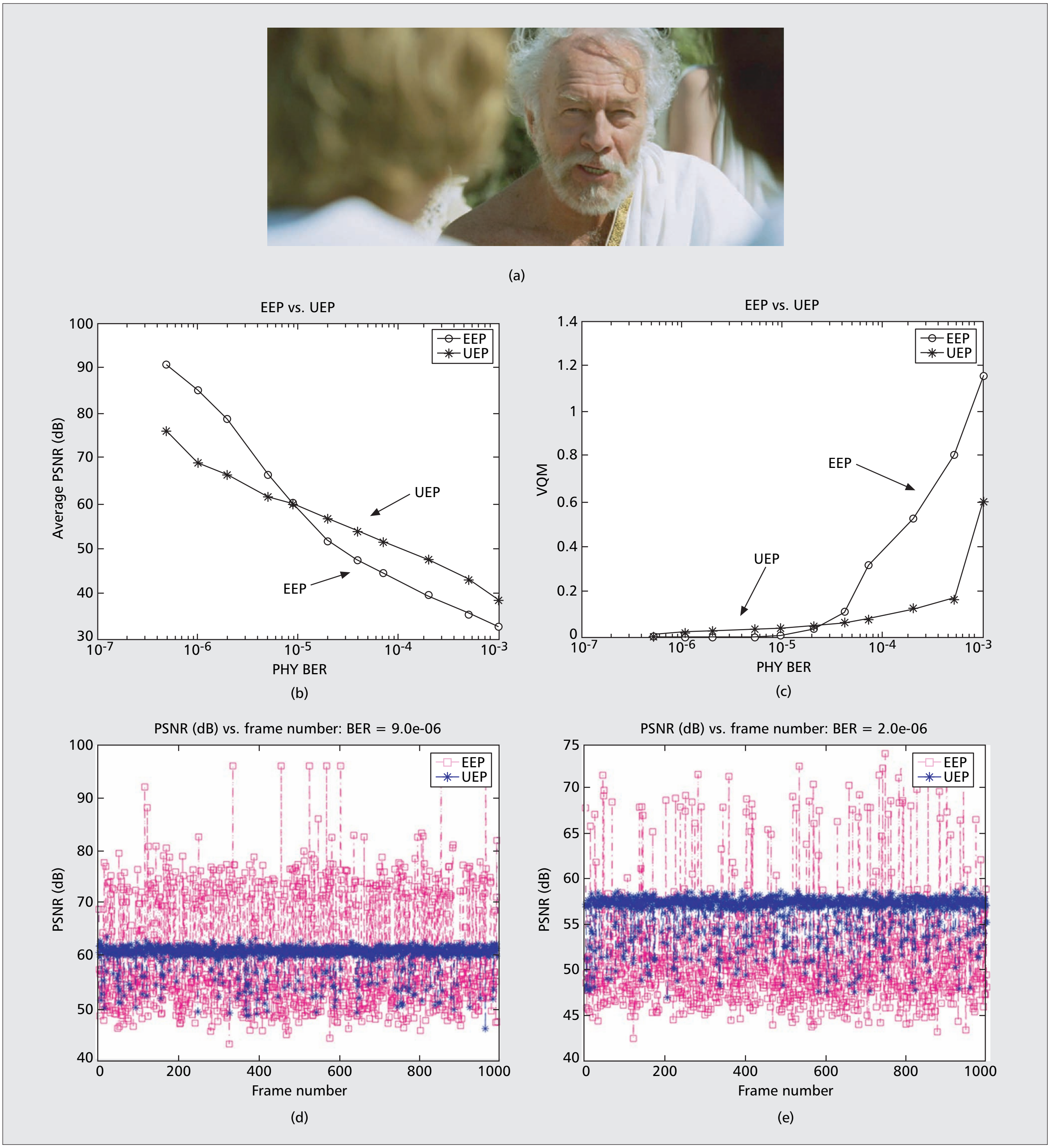
RS Code Swap Error Concealment Scheme — We use Reed-Solomon (RS) codes to conceal some pixel errors. We combine good (i.e., uncorrupted) RS codes from a corrupted video packet and adjacent partitions to reconstruct the original video packet. While developing the RSS error concealment scheme, we considered *cross-layer feedback* from the PHY layer to the MAC layer.

Index	Mode	Modulation	Code rate		Data rate (Gb/s)
			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
MCS4	MSBonly retransmission	QPSK	2/3	N/A	1.881

Table 1. *Transmission modes.*

In the proposed mmWave system, each video packet constitutes of 100 RS codes to achieve high channel efficiency and thus meet the delay constraints of uncompressed videos. Therefore, the length of each video packet is 21,600 bytes, and one 1920 × 1080 pixels (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 an uncorrectable codeword. We use this kind of *feedback* from the PHY layer. We consider cross-layer feedback from the PHY layer to MAC such that 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. Afterward, the MAC layer (or application layer) conceals the effect of failed RS codes on 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 Fig. 3e, RS code j in video packet 1 is received in error. One of the RS codes at the same position j that carries 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, 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 cannot be concealed, display them as is.



■ **Figure 4.** *a) an example frame simulated from the movie clip Alexander [10]; (b) average PSNR values for the EEP and UEP modes; (c) avergae VQM scores for the EEP and UEP modes; d), e) the PSNR values of one thousand frames simulated under different BER values and for both EEP and UEP modes are shown. The average PSNR value of the presented data is already shown in Fig. 4b.*

PERFORMANCE STUDY

In this section, we evaluate the performance of the mmWave system. We enhanced the ns2-based IEEE 802.15.3 MAC simulator by implementing the new features described in the previous section. The PHY layer supports both the UEP (by mapping) and EEP modes (Table 1). We consider PSNR as the key performance metric. For a received $N_1 \times N_2$ 8-bit image, the peak SNR (PSNR) is represented as

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

where $f(i, j)$ is the pixel value of the source video frame, and $F(i, j)$ is the pixel value of the reconstructured video frame at the display. N_1 and N_2 are equal to 1080 and 1920, respectively. The measured PSNR indicates the difference between the transmitted and received video frames. The average PSNR is defined as

$$\overline{PNSR} = \frac{1}{K}\sum_{i=1}^{k} PSNR_i, \quad (2)$$

where K is the total number of uncompressed video frames simulated. We simulate 1000 frames from the movie clip *Alexander*; an example frame from the movie is shown in Fig. 4a. Each frame has 1920 × 1080 pixels, each pixel has 24 bits (i.e., RGB components of 8 bits each), and the frame rate is 60 Hz. Thus, the application rate is 3.0 Gb/s.

Concatenated RS code with convolutional codes is used in the system. Since the errors at the Viterbi decoder are bursty, they tend to present correlated symbol errors to the RS decoder. Using [10], we get the relation of codeword error probability (P_w) and bit error probability (P_b) as

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

where $d_{\min} = 9$, $n = 224$. In the event of error, $d_{\min}$ bytes in a codeword are randomly flipped. We evaluate the performance of the mmWave system, presented in the previous section, under random uniform errors. In the simulation study, video data are coded either UEP or EEP. In both cases we consider no retransmissions and resort to the RSS scheme to conceal pixel errors. We also consider the impact of one-time retransmission of MSB portions using UV-ARQ; however, we omit these results due to limited space. While performing the simulation study, we made realistic assumptions such that given the application rate of 3 Gb/s and transmission rate of 3.761 Gb/s, 20 percent extra bandwidth is available. We assume MAC and other processing overhead of 10 percent; therefore, the remaining extra bandwidth is used to retransmit only 10 percent of the total transmitted packets without exceeding the timing requirements of video signals. One-time limited retransmissions can further improve the quality of video signals at the expense of additional buffer and processing overhead.

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 to the PSNR, are strongly protected in UEP mode; however, the LSB portions are weakly protected. Thus, in the low BER range (BER < 9.0e-06), the average PSNR of the EEP mode outperforms UEP (Fig. 4b). 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 (Fig. 4b). For the BER values we simulated in this study, the UEP mode always maintains PSNR values greater than 40 dB, which is generally accepted as good picture quality. Some of the early results of this simulation study were presented in [12, 13]. An adaptive EEP/UEP scheme, EEP at low BER and UEP at high BER, is also feasible, but UEP alone can maintain good picture quality over the large BER range.

PHY BER	2.0e-06	5.0e-06	9.0e-06	2.0e-05	4.0e-05	7.0e-05
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

Table 2. *Variance (σ^2) of PSNR results shown in Fig. 4b.*

The Stability of UEP

Figures 4d and 4e present the PSNR values of one thousand frames simulated for the EEP and UEP modes. The corresponding average PSNR values are shown in Fig. 4b. Table 2 summarizes the variance of PSNR values shown in Fig. 4b. Notice that the variances of PSNR for the UEP mode are much smaller than the corresponding result of the EEP mode. This suggests that UEP results in less fluctuating PSNR values than EEP. Even though in some cases the EEP mode attains 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 picture quality result in more severe visual degradation.

VQM Scores

The video quality metric [14] is an objective metric that computes the magnitude of the visible difference between the transmitted and received video sequences, and larger visible degradations result in larger VQM values. For instance, zero value represents no impairment between the original and processed video sequence. VQM scores for UEP are lower than EEP in the high BER range as shown in Fig. 4c. In Fig. 4b we observed similar behavior with the PSNR metric; however, the UEP/EEP crossover point for VQM has slightly shifted from 9.0e-06 to 2.0e-05.

Conclusions and Future Work

In this article we present a 60 GHz mmWave wireless system that supports uncompressed HD video streaming reliably. Some of its features have been adopted in several 60 GHz standards. For example, UEP with parallel error control blocks is a major feature of the WirelessHD [4] transmission system, and is also accepted in ECMA and IEEE 802.15.3c standards [5, 6]. In addition, multiple CRCs are defined in the transmission frame specifications of these standards. Currently, next-generation WLAN standards, such as the Very High Throughput (VHT) Study Group of IEEE 802.11, are also considering 60 GHz due to the large unlicensed bandwidth offered. However, limited coverage of 60 GHz signals in indoor environments will necessitate repeaters or multihop link layer solutions for a typical WLAN installation. The coverage can be further enhanced by using advanced coding and steerable antenna technologies. With the current development of 60 GHz mmWave systems for both WPAN and WLAN, wireless uncompressed HD video streaming will become viable in future home networking.

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REFERENCES

[1] S. K. Yong and C. C. Chong, "An Overview of Multi-Gigabit Wireless Through Millimeter Wave Technology: Potentials and Technical Challenges," *EURASIP J. Wireless Commun. Net.*, 2007.

[2] S. Singh *et al.*, "Millimeter Wave WPAN: CrossLayer Modeling and Multihop Architecture," *IEEE INFOCOM Minisymp.*, May 2007.

[3] S. Sarkar and J. Laskar, "A Single-Chip 25pJ/bit Multi-Gigabit 60 GHz Receiver Module," *IEEE/MTT-S IMS*, June 2007, pp. 475–78.

[4] "Wireless High-Definition (WirelessHD)"; http://www.wirelesshd.org/

[5] "ECMA TC32-TG20: High Rate Short Range Wireless Communication"; http://www.ecma-international.org/memento/TC32TG20- M.htm/

[6] "IEEE 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c (TG3c)"; http://www.ieee802.org/15/pub/TG3c.html

[7] S. Kim *et al.*, "UEP for 802.15.3c PHY," IEEE 802.1507/701r4, July 2007.

[8] ETSI, "Digital Video Broadcasting (DVB): Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television," EN 300 744 v 1.5.1.

[9] W. Zheng *et al.*, "A Novel Approach to Unequal Error Protection for Image/Video Delivery with Source Detector," *SPIE :Video Techniques and Software for Full-Service Networks*, Nov. 1996.

[10] S. Benedetto and E. Biglier, *Principles of Digital Transmission with Wireless Applications*, Kluwer Academic/Plenum, 1999.

[11] http://www.microsoft.com/windows/windowsmedia/musicandvideo/hdvideo/contentshowcase.aspx

[12] Harkirat Singh *et al.*, "Support of Uncompressed Video Streaming over 60GHz Wireless Networks," IEEE CCNC, Jan. 2008.

[13] Harkirat Singh *et al.*, "Supporting Uncompressed HD Video Streaming Without Retransmissions over 60 GHz Wireless Networks," IEEE WCNC, Apr. 2008.

[14] M.H. Pinson and S. Wolf, "A New Standardized Method for Objectively Measuring Video Quality," *IEEE Trans. Broadcasting*, vol. 50, Sept. 2004, pp. 312–22.

BIOGRAPHIES

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With the current development of 60 GHz mmWave systems for both WPAN and WLAN, wireless uncompressed HD video streaming will become viable in future home networking.