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Very High Throughput WLAN System for Ultra HD 4K Video Streaming

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***Abstract*—**

We have been developing a very high throughput WLAN system based on IEEE802.11ac's criteria. It combines MIMO and OFDM technology to provide throughput over 1 Gbps for 150 feet propagation distance by using 80MHz of bandiwdth on 5GHz frequency band. 4 by 5 antennas MIMO is set to get 2^{nd}-order diversity gain to maintain high throughput and performance. Greenfield preamble with novel phase rotation is employed to mitigate the overhead problem while reducing the peak to average power ratio of the signals. Run test to broadcast the ultra high definition video which resolution 4096 × 1714 pixels/frame with 30 frame/second under in-door channel model demonstrates an excellent performance of the developed system.

***Keywords*—very high throughput, WLAN IEEE802.11 ac, MIMO, OFDM, Low PAPR, Ultra HD Video Streaming**

I. Introduction

In line with the exponential increment of the demand of high throughput wireless communication, the IEEE802.11 work group have been discussing to increase the system throughput based on user's experience. Although the maximum throughput of WLAN 802.11n is 600Mbps by using modulation coding scheme (MCS) 31 with short guard interval (GI) on 40MHz of bandwidth [1], it still can not accomodate modern multimedia communications which need very high throughput wireless system. The IEEE802.11 very high throughput (VHT) task group (TG) or known as TG-802.11ac (TGac) is formed for this purpose, i.e. to define the standard of new WLAN system that can provide at least 1 Gigabit of throughput. [2]. One of the points to be considered in developing this VHT system is the usage models, i.e. the kind of applications that can be supported by VHT system, such as high definiton (HD) video streaming, high-speed data transfer, etc. [3], [4].

In this paper, we propose a very high throughput (VHT) wireless system based on IEEE802.11TGac's criteria and examine its performance through ultra HD 4K video streaming. It combines MIMO and OFDM technology to provide throughput over 1 Gbps for 150 feet propagation distance by utilizing 80MHz bandwith on 5Ghz frequency band. Greenfield format is employed due to its compact form to endorse the throughput. Novel phase rotation is employed to get low peak to average power ratio (PAPR) of the OFDM signals on each stream. Four transmssion streams which are received by five receive antennas contribute 2^{nd}-order diversity gain. This configuration is set to maintain both high throughput and performance. [5] Run test for streaming ultra HD video which has resolution of 4096×1714 pixels/frame with 30 frame/second demonstrates an excellent performance of the developed system. The test is conducted under in-door channel which is a modification of channel model B of IEEE TGn [6]

This paper is organized as follows. The developed VHT WLAN system with greenfield preamble is briefly explained in section 2. Section 3 deals with the scenario of performance examination by streaming the ultra HD video. In section 4, System performance, link budget, and video quality due to wireless transmission errors are analyzed. Finally, we draw some conclusions and future works in section 5.

II. The VHT Wireless LAN system with Greenfield Preamble

Block diagram of transmitter and receiver of the developed system which based on IEEE802.11TGac's criteria is shown in Fig. 1 and 2. Three options of modulation coding scheme (MCS) which define the parameteres to calculate the data rate of this system is summarized in Table I. The timing related constants used in this system is listed in Table II. 1.2 Gbps throughput is accomplished by using 400ns GI on MCS K-3, where R is the data rate, N_{BPSC} (i_{ss}) is number of bit per sub carrier of i-th spatial stream, N_{SD} is number of data subcarrier, N_{SP} is number of pilot symbol, N_{CBPS} is number of coded bit per OFDM symbol, N_{DBPS} is number of data bit per OFDM symbol, N_{SS} is number of spatial stream, and GI is guard interval length.

Since the aim is boosting the throughput, greenfield (GF) format preamble is the only choice. GF has efficient frame format which consists of a VHT-short training field (VHT-STF), VHT-long training fields (VHT-LTF), and a VHT-Signal (VHT-SIG) field before the data portion (VHT-Data).

Each preamble field has 8μs duration, except the VHT-LTFs that are used for channel estimation purpose has 4μs duration for each. The duration of data fields may vary depend on the intended data rate. The placement of these fields and theirs time boundaries is shown in Figure 3.

A. Signal Description

In the VHT GF format, the transmitted signal on each transmit chain $i_{TX}, i = 1, 2, 3, 4$ is:

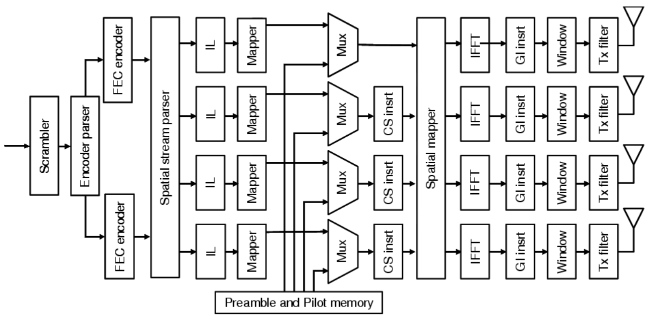

Fig. 1. The developed VHT WLAN transmitter

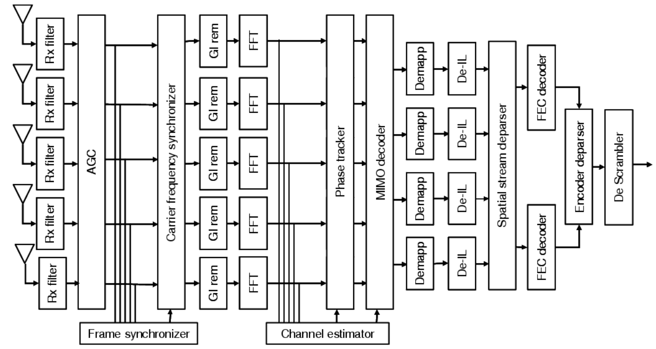

Fig. 2. The developed VHT WLAN receiver

TABLE I. RATE DEPENDENT PARAMETER

MCS	Modulation	R	N_{BPSC} (i_{ss})	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{SS}	Data rate [Mbps]	
									800ns GI	400ns GI
K-1	64-QAM	2/3	6	228	8	5472	3648	4	912	1013
K-2	64-QAM	3/4	6	228	8	5472	4104	4	1026	1140
K-3	64-QAM	5/6	6	228	8	5472	4560	4	1140	1266

TABLE II. TIMING RELATED CONSTANTS OF THE DEVELOPED VHT WLAN SYSTEM

Parameter	Value
N_{SD}	228
N_{SP}	8
N_{ST}	236
Δ_F	312.5kHz (80MHz/256)
T_{DFT}	3.2 μs ($1/\Delta_F$)
T_{GI}	0.8 / 0.4 / 0.2 (μs)
T_{SYM}	4 / 3.6 / 3.4 (μs)
T_{STF}	8 (μs)
T_{LTF1}	8 (μs)
T_{SIG}	8 (μs)
T_{LTFs}	4 (μs)

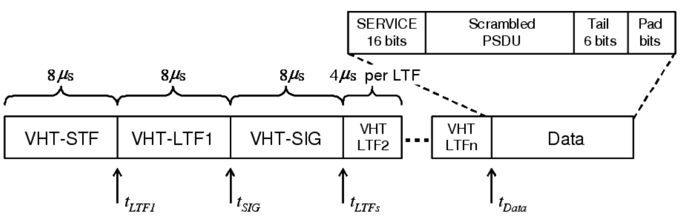

Fig. 3. Greenfield preamble with time boundaries for each transmit chain.

$$
\begin{aligned}
s_{PPDU}^{(i_{TX})}(t) = & s_{STF}^{(i_{TX})}(t) \ + \ s_{LTF1}^{(i_{TX})}(t - t_{LTF1}) \\
& + s_{SIG}^{(i_{TX})}(t - t_{SIG}) \\
& + \sum_{i_{LTF}=2}^{N_{LTF}} s_{LTF}^{(i_{TX}, i_{LTF})}(t - t_{LTFs} - (i_{LTF} - 2)T_{LTFs}) \\
& + s_{Data}^{(i_{TX})}(t - t_{Data})
\end{aligned}
\tag{1}
$$

where by refering to Fig. 3 and Table II
$t_{LTF1} = T_{STF}$
$t_{SIG} = t_{LTF1} + T_{LTF1}$
$t_{LTFs} = t_{SIG} + T_{SIG}$
$t_{Data} = t_{LTFs} + (N_{LTF} - 1)T_{LTFs}$

Each baseband waveform, $s_{field}^{(i_{TX})}(t)$, is defined by the discrete Fourier transform as:

$$
s_{field}^{(i_{TX})}(t) \ = \ \frac{1}{\sqrt{N_{field}^{tone} \cdot N_{TX}}} \ w_{T_{field}}(t) \sum_{k} \Upsilon_k X_k^{(i_{TX})} \ e^{j2\pi k \Delta_F t} \tag{2}
$$

where the $\frac{1}{\sqrt{N_{field}^{tone} \cdot N_{TX}}}$ with $N_{TX} = 4$ scale factor in Eq. 2 ensures that the total power of the time domain signal as summed over all transmit chains is either 1 or lower than 1 when required. Table III lists the various values of N_{field}^{tone} which descibes the number of utilized subcarriers in one OFDM symbol.
$w_{T_{field}}(t)$ is time windowing function which is defined as a rectangular pulse $w_T(t)$ of duration T.

$$
w_T(t) = \begin{cases}
\sin^2(\frac{\pi}{2}(0.5 + \frac{t}{T_{TR}})) & \text{for } (\frac{-T_{TR}}{2} < t < \frac{T_{TR}}{2}) \\
1 & \text{for } (\frac{T_{TR}}{2} \le t < \frac{T_{TR}}{2}) \\
\sin^2(\frac{\pi}{2}(0.5 - \frac{(t-T)}{T_{TR}})) & \text{for } (\frac{T - T_{TR}}{2} \le t < \frac{T + T_{TR}}{2})
\end{cases} \tag{3}
$$

The frequency-domain simbols $X_k^{(i_{TX})}$ represent the output of any spatial processing in subcarrier k for each transmit chain i_{TX} required for the field.
The function Υ_k is used to represent a rotation of the tones in 80MHz channel to reduce PAPR of the signal, effectively. The tones in subcarriers -65 to 0 are phase rotated by $+90$ deg, the tones in subcarriers 1 to 64 are phase rotated by $+75$ deg, the tones in subcarriers upper than 65 are phase rotated by $+165$ deg, as stated in Eq. 4. [7]

$$
\Upsilon_k = \begin{cases}
1 & \text{for} \quad k \le -64 \\
e^{j\frac{\pi}{2}} & \text{for} \quad -64 < k \le 0 \\
e^{j\frac{5\pi}{12}} & \text{for} \quad 0 < k \le 64 \\
e^{j\frac{11\pi}{12}} & \text{for} \quad k > 64
\end{cases} \tag{4}
$$

k is the subcarier index in the spectral line $S_{-128,127}$.

B. The Greenfield Preamble

Throughout the GF format preamble for VHT, cyclic shift (CS) is applied to prevent beamforming when similar signals

TABLE III. VALUE OF TONE SCALING FACTOR N_{field}^{tone}

field	N_{field}^{tone} for **80 MHz**
SIG	228
STF	48
LTF	228
Data	236

TABLE IV. THE CYCLIC SHIFT VALUES ($T_{CS}^{i_{STS}}$)

T_{CS}^{1}	T_{CS}^{2}	T_{CS}^{3}	T_{CS}^{4}
0 ns	- 400 ns	- 200 ns	- 600 ns

are transmitted on different spatial streams. CS is done in frequency domain. The values of the CS are specified in Table IV.

1) VHT Greenfield Short Training Field: is used for synchronization purposes and placed at the beginning of GF preamble. The time domain waveform of the VHT-STF on transmit chain i_{TX} is:

$$s_{STF}^{(i_{TX})}(t) = A\ B \sum_{k=-122}^{122} \sum_{i_{STS}=1}^{4} [\mathbf{Q}_k][\mathbf{P}]\Upsilon_k S_k . e^{j2\pi k \Delta_F (t - T_{CS}^{i_{STS}})} \quad (5)$$

where A and B are the scale factor and time windowing function, respectively. $T_{CS}^{i_{STS}}$ represents the CS for the space time stream i_{STS} and takes values from Table IV.
$\mathbf{Q}_k$ is the spatial mapping matrix which maps STS symbols onto transmit symbol chain $X_k^{(i_{TX})}$. For the case of direct mapping $\mathbf{Q}_k$ is an identity matrix $\mathbf{I}_{N_{TX}}$ which is sufficient for line of sight (LOS) environment. For NLOS environment, expansion mapping is applied.
$\mathbf{P}$ is 4 by 4 orthogonal mapping matrix defined as:

$$\mathbf{P} = \begin{bmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 \end{bmatrix} \quad (6)$$

Υ_k is phase rotation of the tones as defined in Eq. 4. S_k is the frequency-domain short training symbol which consists of 28 symbols of $e^{j\frac{\pi}{4}} = \sqrt{1/2}(1 + j)$ and 20 symbols of $e^{j\frac{5\pi}{4}} = \sqrt{1/2}(-1 - j)$ placed at indices that are a multiple of 4 in spectral lines of $S_{-122,122}$.

The waveform defined by Eq. 5 has a period of 0.8μs, and the VHT-STF field includes ten such periods, with a total duration of $T_{STF} = 8\mu$s.

2) VHT Greenfield Long Training Field: provides a means for the receiver to estimate the MIMO channel characteristics. This field has duration 4μs for each, except the first one (VHT-LTF1) which is twice longer. The VHT-LTF1 consists of two periods of the long training symbol (6.4μs), preceded by a doublelength of GI (1.6μs) to improve channel estimation accuracy. The VHT-LTF1 is assigned for VHT-SIG while the subsequent VHT-LTFs are intended for VHT Data portion. The placement of the first and subsequent VHT-LTFs in an VHT GF format frame is shown in Fig. 3. The time domain waveform of the VHT-LTF1 on transmit chain i_{TX} is:

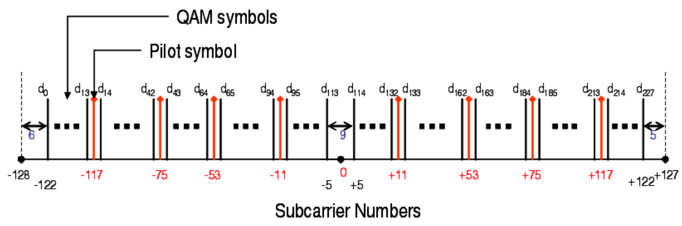

Fig. 4. Subcarriers allocation on OFDM symbol.

$$s_{LTF1}^{(i_{TX})}(t) = A\ B \sum_{k=-122}^{122} \sum_{i_{STS}=1}^{4} [\mathbf{Q}_k][\mathbf{P}]\Upsilon_k L_k . e^{j2\pi k \Delta_F (t - 2T_{GI} - T_{CS}^{i_{STS}})} \quad (7)$$

where L_k is the frequency domain long training symbol which has 228 tones in spectral lines of $L_{-122,122}$.

3) VHT Greenfield SIGNAL Field: contains information about the transmitted packet. It is transmitted with the same number of subcarriers, the same CS, and the same spatial mapping as the preceding portions of the preamble (VHT-LTF1). This is done to accommodate the estimation of channel parameters needed to robustly demodulate and decode the information contained in this field. The time domain waveform of the VHT-SIG on transmit chain i_{TX} is:

$$s_{SIG}^{(i_{TX})}(t) = A\ B \sum_{k=-122}^{122} \sum_{i_{STS}=1}^{4} [\mathbf{Q}_k][\mathbf{P}]\Upsilon_k (jD_{k,n} + p_n P_k) . e^{j2\pi k \Delta_F (t - \tau)} \quad (8)$$

where $\tau = nT_{SYM} + T_{GI} + T_{CS}^{i_{STS}}$. $D_{k,n}$ and P_k are the data and pilot allocation on the subcarrier k of OFDM symbol n as illustrated in Fig. 4 p_n is the sequence generated by scrambler with the "all ones" initial state and by replacing all "1's" with -1 and all "0's" with 1.

C. The Data Field

The Data field consists of the 16-bit SERVICE field, the PSDU, 24 TAIL bits for 4 encoding streams, and PAD bits. All bits in the Data field are scrambled.

The SERVICE field is used for scrambler initialization. It is composed of 16 bits, all set to zero before scrambling. The TAIL bits are 6 bits of zero for each stream which are required to return the convolutional encoder to the"zero state."These TAIL bits are produced by replacing 6 scrambled "zero" bits following the message end with six nonscrambled"zero" bits. The PAD bits is appended so that the number of bits in the DATA field is a multiple of N_{CBPS}.

To reduce the probability of long sequences of zeros or ones, the Data field is scrambled by using frame synchronous scrambler which has generator polynomial $G(x) = 1 + x^4 + x^7$.

The scrambled data is encoded using forward error correction (FEC) encoder to enhance the performance against channel noise. Two options of FEC are provided, binary convolutional code (BCC) and low density parity check (LDPC) code. If BCC encoding is to be used, the scrambled data bits are divided between four BCC encoders by sending alternating bits to the four different encoders. The BCC encoder has generator polynomials $G_0 = 133_8$ and $G_1 = 171_8$ of rate $R = 1/2$. After encoding, the encoded data is punctured to achieve the rate selected by the MCS index. If LDPC encoding is to be used the scrambled data bits are divided between two LDPC encoders by sending alternating bits to the two different encoders. The LDPC encoder is systematic, i.e., it encodes an information block, c = $(i_0, i_1, \ldots, i_{(k-1)})$, of size k, into a codeword, **c**, of size n, $\mathbf{c} = (i_0, i_1, \ldots, i_{(k-1)}, p_0, p_1, \ldots, p_{(n-k-1)})$, by adding $n-k$ parity bits obtained so that $\mathbf{H} \cdot \mathbf{c}^T = 0$, where $\mathbf{H}$ is an $(n-k) \times n$ parity-check matrix.

The bits at the output of the Spatial stream parser are divided into blocks of$N_{CBPSS}(i_{SS})$, $i_{SS} = 1, 2, 3, 4$ bits. If BCC encoding was used, each block is interleaved by a three steps permutation interleaver in frequency domain. If LDPC encoding was used, no frequency interleaving is performed, hence the parsed streams are directly mapped to 64QAM symbols

Two options of Spatial mapper [**Q**] are available, direct and extension mapping, as described in subsection VHT GF STF. The later mapping promises robust communication in NLOS environment.

For VHT 80MHz, eight pilot symbols are inserted in the sub-carriers -117, -75, -53, -11, 11, 53, 75 and 117. Pilots allocation in one OFDM symbol is illustrated in Fig. 4. Each spatial time stream $i_{STS} = 1, 2, 3, 4$ has a different determined pilot patterns.

The 256 IFFT point is used to get the time domain signals. The coefficients 1 to 122 are mapped to the same numbered IFFT inputs, while the coefficients -122 to -1 are copied into IFFT inputs 134 to 255. The rest of the inputs, 123 to 133 and the 0 (dc) input are set to zero. After performing an IFFT, the output is cyclically extended as a GI. Two options of GI are available to get the desired data rate, as listed in Table I. The time domain waveform of the VHT-Data on transmit chain i_{TX} is:

$$s_{Data}^{(i_{TX})}(t) = A \;\; B \sum_{k=-122}^{122} \sum_{i_{STS}=1}^{4} [\mathbf{Q}_k][\mathbf{P}]\Upsilon_k(D_k + p_{n+2}P_k).e^{j2\pi k\Delta_F(t-\tau)} \tag{9}$$

where $\tau = nT_{SYM} + T_{GI} + T_{CS}^{i_{STS}}$.

D. The Receiver Side

This part briefly introduces the receiver side. After all frame are synchronized and the GIs are removed each stream is demodulated using the fast Fourier transform (FFT). Five streams of received training sequences are maximally ratio combined and exploited to estimate the MIMO channel characteristics including phase error. Minimum mean square error (MMSE) based MIMO decoder is used to cancel the interference signals. The ergodic capacity of this MIMO MMSE receiver under frequency selective channel can be verified in [8].

If BCC encoding is used, the de-interleaver is needed to return the data block to original sequence, before errors are corrected by soft decision Viterbi decoder. If LDPC encoding is used no de-interleaver is needed and the data is decoded using the min-sum algorithm based LDPC decoder. Finally, de-scrambler returns the data to its original order.

E. Link budget analysis of the developed VHT WLAN System

The propagation distance of the developed VHT WLAN system can be calculated by:

$$d = \frac{\lambda}{4\pi 10^{\frac{L}{20}}} \tag{10}$$

where λ is transmitted wave length, $L = L_{d\leq 5} = 10\log_{10}(P_x B\alpha) + G_{TX} - G_{RX} - (SNR + 10\log(kTB) + NF + IM)$ is the path loss for $d \leq 5$ m, and $L = L_{d\leq 5} + 35\log_{10}(d/5)$ for $d > 5$ m. Constant 5 is the break-point distance for channel model B TGn [6].

III. Run test of ultra HD Video streaming

The run test configuration of the developed VHT WLAN system by ultra HD Video streaming is shown in Fig. 5. This configuration consists of 3 main parts, (1) Pre and post processing part, (2) JPEG 2000 coding part and (3) Wireless LAN system part.

The Pre Processing part separates the data from a video player such as Blue-ray Disc or a DVD player into video, audio, and control. If the video data is a compressed codestream, the codestream is decoded to generate the uncompressed video data and fed into JPEG-2000 encoder. At the receiver side, after the received data is decoded by JPEG-2000 decoder, the post processor returns the video data to its original ultra HD 4K format. The JPEG-2000 has seven error resilience tools (ERT) which make it has high durability against the error [9]. Normally, data is transmitted using packets, in this case the system uses streams transmssion to increase the throughput

During examination total 90 frames of ultra HD 4K are transmitted within three seconds. Table V lists the simulation parameters.

Three scenarios are conducted to transmit those frames with different coding rate and soft decision Viterbi decoder as the FEC.

1) Transmit the video using MCS K-1: 64QAM with $\frac{2}{3}$ coding rate which throughput 1.013 Gbps.
2) Transmit the video using MCS K-2: 64QAM with $\frac{3}{4}$ coding rate which throughput 1.140 Gbps.
3) Transmit the video using MCS K-3: 64QAM with $\frac{5}{6}$ coding rate which throughput 1.266 Gbps.

Fig. III shows the performance comparison of these three scenarios. As expected, the lower coding rate show better performance with the cost of lower throughput. For BER 10^{-6} the coding gain enhances the performance of MCS K-1 about 8dB better than MCS K-3 while MCS K-2 about 5dB better than MCS K-3.

The link budget analysis result of three scenarios that show the throughput v.s. propagation distance is shown in Fig. III. For the LOS case, as expected K-1 has the longest propagation distance compare to the others. However it can be seen that all scenarios give throughput over 1Gbps for 150 feet distance. For the NLOS case all scenarios give throughput over 1Gbps for about 60 feet propagation distance.

The quality of ultra HD 4K video streaming is evaluated using the peak signal to noise ratio (PSNR) in dB. PSNR is

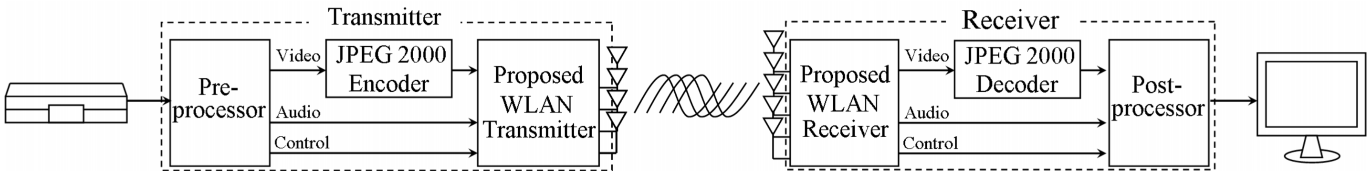

Fig. 5. Configuration of ultra HD 4K video streaming to examine the performance of the developed VHT WLAN

TABLE V. SIMULATION PARAMETER

Parameter	Value
MCS Index	K-1; K-2; K-3
Frequency Carrier (f_c)	5.2 [GHz]
Antenna Configuration	4 by 5
Bandwidth	80 [MHz]
Format Packet	VHT Greenfield Mode
FEC Encoder	BCC with soft Viterbi decoder
Spatial Mapping	Direct
MIMO Decoder	Linear MMSE
Guard Interval Length	400 [ns]
Transmitted Frame Size	4K (4096×1714)
Frame Rate	30 fps
System Throughput	1.013; 1.140; 1.266 [Gbps]
Channel Model	modified B TGn
Antenna Gain (G_{TX}, G_{RX})	0 [dB]
Noise Figure (NF)	7 [dB]
Implementation Margin (IM)	5 [dB]
Transmit Power per BW (P_x)	2.5 [mW/MHz]
Boltzmann Constant (k)	1.381×10^{-23} [J/K]
Temperature (T)	290^o [K]
Light speed (c)	3.01×10^8 [m/s]

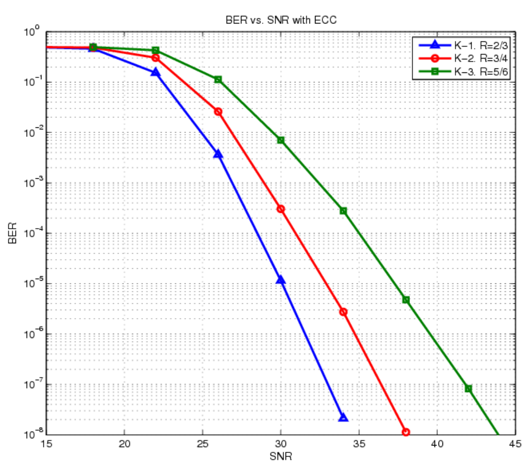

Fig. 6. Performance verification of the developed VHT WLAN with different coding rate

the ratio between the maximum possible power of a signal and the power of corrupting noise which affects the fidelity of its representation. Acceptable values of PSNR for wireless transmission quality loss are considered to be about 20dB to 25dB [10], [11]. However our target PSNR is over 30dB for excellent ultra HD video streaming.

Fig. 9 shows the PSNR results of Ultra HD video streaming by using the developed VHT WLAN system. MCS K-3 uses 40dB of SNR which ahieves the average PSNR of 55.53dB. This makes the received frames are superior for Ultra HD video streaming service. MCS K-2 uses 35dB of SNR, the average PSNR is 56.35dB which provides magnificent Ultra

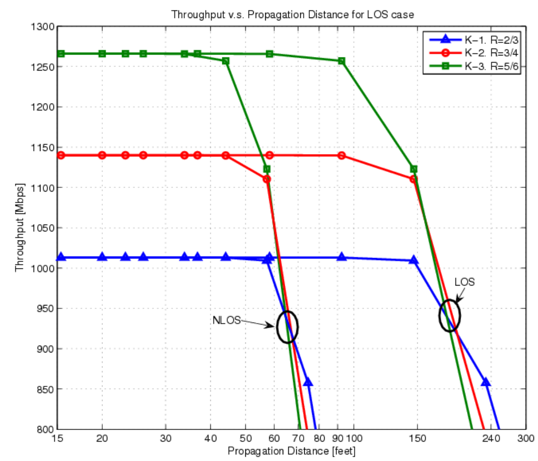

Fig. 7. Propagation distance of the developed VHT WLAN in LOS and NLOS environment.

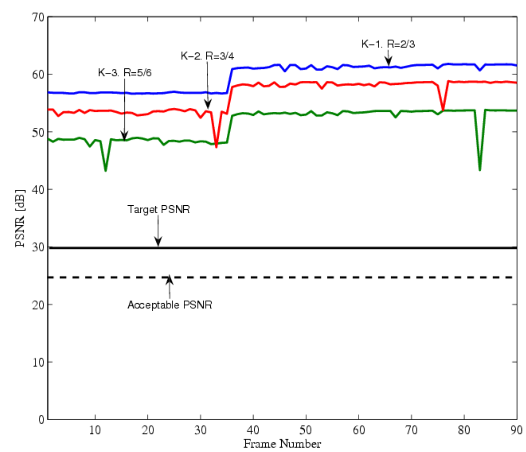

Fig. 8. Ultra HD video streaming quality by using the developed VHT WLAN. The PSNR value exceeds the expectation.

HD video streaming. MCS K-1 uses 32dB of SNR, the average PSNR is 59.56dB which promises an excellent Ultra HD video streaming. Trade off between the throughput and the SNR to enhance the digital cinema quality can be drawn as follow: Lower thoughput system needs lower SNR, propagates longer and gives better transmission quality. These results prove that the developed VHT WLAN system has high performance and can be employed for ultra HD 4K video streaming satisfactorily.

TABLE VI. Trade-off between throughput and SNR of the developed VHT WLAN system regarding the ultra HD video streaming quality

Scenario	Throughput[Gbps]	SNR[dB]	average PSNR[dB]
MCS K-1	1.013	32	59.56
MCS K-2	1.140	35	56.35
MCS K-3	1.266	40	55.53

IV. Conclusion

We have been developing a VHT WLAN system and examined its performance through Ultra HD video streaming. It provides throughput over 1Gbps for 150 feet propagation distance by occupying 80MHz of bandwidth on 5GHz frequency band. Run test to broadcast the ultra HD video using different coding rate demostrates its high performance. The developed VHT WLAN system can be used to serve an excellent ultra HD 4K video streaming. Examining the developed VHT WLAN system in the FPGA board will become the next challenge.

References

[1] "Draft STANDARD for Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements", IEEE P802.11n./D3.00, Sept. 2007

[2] E. Perahia, "IEEE P802.11 Wireless LANs: VHT below 6GHz PAR Plus 5C's", doc.:IEEE 802.11-08/0807r4.

[3] H. Jeon, "IEEE P802.11 Wireless LANs: 802.11 TGac Functional Requirements", doc.:IEEE 802.11-08/1285r0.

[4] Mark G and Rolf de V, "Introduction to VHT Usage Models", doc.:IEEE802.11-08/1323r0.

[5] W. A. Syafei and H. Pratista, "Performance Evaluation of Wireless LAN IEEE802.11n by Antenna Spacing," International Conference on Information Technology and Electrical Engineering (ICITEE) 2011, Gadjah Mada University, Jogjakarta, Indonesia, July 28, 2011.

[6] V. Erceg et al "TGn Channel Models," doc.:IEEE 802.11-03/0940r4

[7] W. A. Syafe, Y. Nagao, M. Kurosaki, B. Sai, and H. Ochi, "PAPR Reduction Technique for Next Generation Gigabit WLAN System," Journal of Signal Processing Vol. 14, No. 5, pp.384-386, September 2010. ISSN: 1342-6230.

[8] Cedric A, Philip L and Belkacem M, "On the Ergodic Capacity of Frequency Selective MIMO Systems equipped with MMSE Receivers: An Asymptotic Approach", IEEE The 51th GLOBECOM 2008, New Orleans, USA, Dec. 2008.

[9] ISO/IEC, "Information technology - JPEG 2000 image coding system - Part 1: Core coding system," ISO/IEC 15444-1, 2000.

[10] Thomos, N., Boulgouris, N. V., and Strintzis, M. G. ,"Optimized Transmission of JPEG2000 Streams Over Wireless Channels". IEEE Transactions on Image Processing, January 2006.

[11] Xiangjun, L., and Jianfei, C.,"Robust Transmission of JPEG2000 Encoded Images Over Packet Loss Channels." IEEE ICME 2007, July 2-5, 2007, Beijing, China.

Fig. 9. Transmitted ultra HD 4096×1714 pixels/frame

Fig. 10. Received ultra HD 4096×1714 pixels/frame using MCS K-3 of the developed VHT WLAN system. Throughput=1.266Gbps, SNR=40dB, propagation distance=100 feet, image quality in average PSNR is 55.53dB