Uncompressed Full HD Video Transmission using Uncoded OFDM over Multipath Fading Channels at 60 GHz

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Abstract*—This paper presents a detailed analysis of the impact of channel impairments on the performance of a mm-Wave wireless uncoded Orthogonal Frequency Division Multiplexing (OFDM) architecture system based on IEEE 802.15.3c standard, for high data-rate applications. The performance of OFDM is known to be severely affected by multipath fading channel when its excess delay exceeds the time guard interval of the OFDM symbol. Hence, this paper analyses the impact of uncompressed Full HD video content transmission over various radio propagation environments suggested by the standard. The impact of the propagation channel impairments is evaluated through appropriate metrics based on Bit Error Rate (BER) and Peak Signal-to-Noise Ratio (PSNR) analysis for residential, office and kiosk scenarios under Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS). The feasibility of real-time high-definition video transmission using 60 GHz radio systems will be demonstrated through a proof-of-concept test, which will allow one to perfectly understand the system limitations, and consequently the range of applications that might be developed.

***Keywords*–OFDM; Multipath Fading channels; RF-impairments; IEEE 802.15.3c; mmWave signals.**

I. Introduction

Communication systems at 60 GHz have recently attracted a great deal of interest allowing multi-gigabit transmission rates. However, radio communications at these frequencies are characterized to yield high free space path losses and thus limited radio coverage. Hence, the target applications or usage models at 60 GHz are mainly short-range indoor applications [1]. In fact, this is an advantage for indoor applications, since the high free space loss in addition to high attenuation by walls, furniture and other objects increases the possible frequency re-use density [2]. Therefore, co-channel interference is reduced and, consequently, it enables a more simplified radio network planning in such environment scenarios.

The IEEE 802.15.3c [3] standard has been created by the IEEE 802.15.3c Task Group 3c (TG3c) [4] as the Wireless Personal Area Network (WPAN) standard for the 60 GHz band, ranging from 57-66 GHz in Europe [5]. As data capacity is ultimately tied to modulation bandwidth, the date rates required for High Definition Multimedia Interface (HDMI) for uncompressed video/audio streaming and for multi-gigabit file transfers are finally met for the first time by standard [5]. Also, the high quantities of information inherent to, e.g., medical image and video, as well as the latency free required transmission, only by means of uncompressed video transmission, demands the utilisation of mmWave in conjunction with protocol independent and processing free information paths. Thus, using 60 GHz millimetre wave band provides the necessary bandwidth and pace for future HD systems.

To this extent, the IEEE 802.15.3c Task Group 3c has proposed a Audio-Visual mode (AV-PHY), where OFDM has been adopted due to its inherent higher bandwidth efficiency [6] and relatively low complexity. An OFDM system is well known to be an effective anti-multipath technique. The latter is primarily due to its reduced channel equalization complexity in the frequency domain due to a single-tap Frequency Domain (FD) equalizer and increased time of transmitted symbol, ain addition to the orthogonality properties between subcarriers [6]. On the other hand, in a single carrier system, the transmitted time symbol is the inverse of the system bandwidth, which means that for multi-gigabit data rates the symbol time becomes very short. This fact leads to a much more complex receiver, i.e., a time-domain equalizer with hundred of taps [7].

In this paper, the reliability of an uncoded OFDM wireless communication system to transmit uncompressed video content at 60 GHz, based on the IEEE 802.15.3c standard [3], under the presence of propagation channel impairments, is assessed. The multipath fading channel models considered are the ones suggested by TG3c [4] for office, residential and kiosk indoor environments, considering both LOS and NLOS scenarios. Moreover, in order to ensure a relatively low system complexity, Zero Forcing (ZF) equalizer is considered and Forward Error Correction Coding (FEC) is not employed. For example in [8], it is shown that using Low Density Parity Check Codes (LDPC) improves the system performance by about 8 to 9 dB at the expense of system complexity and throughput.

The paper is organized as follows. Section II presents the work proposed by the IEEE 802.15.3c Task Group 3c (TG3c) on the 60 GHz channel modeling. Section III introduces

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OFDM and its parameters in the system design. The details about the proposed mm-Wave framework are presented in Section IV. Finally, Section V provides results of the performed analysis.

II. Indoor Channel Modelling at 60 GHz

This section presents the channel modeling [4] proposed by TG3c at 60 GHz for the following indoor environments: office, residential and kiosk. These channel models are based on a frequency sweep technique performed using a Vector Network Analyzer (VNA) to measure the frequency response of the radio channel. The centre frequency and the bandwidth considered in these measurements were 62.5 GHz and 3 GHz, respectively. For each environment, both LOS and NLOS scenarios were considered, except in the kiosk environment, where only LOS has been considered. In such indoor scenarios, multipath components are mainly obtained from reflected or scattered signals from furniture, floor and ceiling.

A. Considered Power Delay Profiles

The IEEE 802.15.3c standard has adopted the generic Complex Impulse Response (CIR) based on the clustering of propagation phenomena in both time and spatial domains, as observed in measurement data [4]. The cluster model is based on the extension of the Saleh-Valenzuela (S-V) model [9] to the angular domain by Spencer [10]. Hence, the IEEE 802.15.3c channel modeling group [11] proposed a statistical channel model dependent on the temporal and spatial domains, where signals arrive at the receiver first in a LOS component, calculated with a two-ray model, and then in clusters (modified S-V model). This 60 GHz channel modeling is utilized in this work, allowing the performance evaluation of OFDM systems over different multipath environments. Additionally, each indoor environment has been mapped onto a channel model and scenario, as presented in Table I.

Table I maps the environment to the channel model and scenario [1].

TABLE I. MAPPING OF ENVIRONMENT TO CHANNEL MODEL AND SCENARIO.

Environment	Channel Model	Scenario
Residential	CM1	LOS
	CM2	NLOS
Office	CM3	LOS
	CM4	NLOS
Kiosk	CM9	LOS

Several channel realizations may be considered to yield different power delay profiles (PDP) for the same multipath environment. This occurs due to the fact that the considered channel modeling tool [11] takes into account the uniform distribution in terms of the scatters movements between transmitter (TX) and receiver (RX) and at different antennas height. Consequently, CIR of each channel model is obtained from 100 quasi-static realizations. Moreover, the PDP has been analyzed in terms of averaged RMS delay spread ($\bar{\tau}_{RMS}$), coherence bandwidth for signal correlation of 0.9 ($\bar{B}_{c_{0.9}}$) and Rician factor ($\bar{K}$). The B_c is a key metric involved in expressing the performance of any digital wireless system over fading channels, where a system bandwidth smaller than the coeherence bandwidth of the channel is required to be considered a flat-fading channel. Otherwise, the fading channel is considered frequency-selective, making the digitally modulated data experiencing Inter-Symbol Interference (ISI) and, thus, higher BER. Coherence bandwidth is normally defined as the maximum frequency difference at which two signals are highly correlated and a correlation of 0.9 ($B_{c_{0.9}}$) is most commonly used. It has been calculated by (1), which is inversely proportional to $\bar{\tau}_{RMS}$ [12].

$$\bar{B}_{c_{0.9}} = \frac{1}{50\bar{\tau}_{RMS}}, \tag{1}$$

Channel quality indicator values of each model are presented in Table II, where HPBW is the Half Power Beamwidth of T_X/R_X antennas.

TABLE II. STATISTICAL PARAMETERS FOR EACH MULTIPATH CHANNEL ENVIRONMENT.

CM #	$\bar{\tau}_{rms}$ (ns)	$\bar{\tau}_{max}$ (ns)	$\bar{B}_{c_{0.9}}$ (MHz)	$\bar{\mathrm{K}}$ (dB)	HPBW° (TX/RX)
1	3.547	67.42	5.64	14.6	(360,15)
2	2.73	68.9	7.33	-	
3	22.75	464	0.88	14.61	(30,30)
4	57.7	651	0.35	-	(30,15)
9	2.7	183	7.41	30.9	(30,30)

III. Orthogonal Frequency Division Multiplexing and Single Carrier Frequency Domain Equalization

OFDM is a well known multi-carrier transmission scheme that is mostly used to provide high-data rate links in frequency-selective channels [6]. At the transmitter, a high-rate data stream is transformed into N_c low-rate parallel streams allocated to different orthogonal carriers that can be easily equalized in the frequency domain due to the orthogonality among all those sub-carriers. OFDM can be seen as a multiplexing technique since the output signal is the linear sum of modulated subcarrier signals.

The discrete expression of (2) is given by [6]:

$$x(mT_s) = \sum_{n=0}^{N_c-1} X_n e^{j2\pi nm/N}, \tag{2}$$

where, X_n, n = 0,1,..., N_c-1, is the N_c data symbols corresponding to a two-dimensional QAM constellation.

From (2), it is verified that the discrete OFDM version is an Inverse Fast Fourier Transform (IFFT) operation, which maps the data symbols into adjacent sub-carriers. In the receiver, the Fast Fourier Transform (FFT) is used to demodulate the data symbols.

Although OFDM allows increased time symbol duration for high data rate transmission in comparison with single carrier transmission schemes, the overlapping of OFDM symbols due to multipath effects still has an important impact on system performance. This fact results in the loss of orthogonality among sub-carriers, which severely increases ISI and BER performance. To overcome this issue, a Cyclic Prefix (CP) is introduced and the symbol is cyclically extended from the original harmonic wave of the Fourier period T_s by a guard interval of length T_{CP}. Additionally, the cyclically extended guard interval transforms the convolution of the signal and the channel from linear to a circular convolution and hence a traditional complex time domain equalizer is replaced by a simple single-tap Frequency Domain (FD) equalizer. Moreover, the CP functionality is only efficient when the CP interval time is larger than the maximum delay spread of the multipath channel.

IV. mmWave System Models based on IEEE 802.15.3c standard

The OFDM is implemented based on IEEE 802.15.3c standard, as illustrated in Fig. 1. At the transmitter, a data source is employed to generate pseudo-random bits, which are then mapped into a Gray-coded constellation of QAM symbols. The modulated symbols are mapped into K-subcarriers through K-points IFFT transform. Next, a cyclic extension is inserted. Finally, the wireless channel effect, based on the IEEE model proposed in [4], is taken into account through the convolution of its CIR, presented in subsection II-A, for each channel realization. At the receiver, CIR is ideally estimated and its FFT performed to equalize the received data. Additionally, bit and tone interleaver are used in the OFDM system to enhance its frequency diversity.

In order to shape the OFDM signal Power Spectral Density (PSD), the sub-carriers are allocated into the IFFT according to Table IV [3].

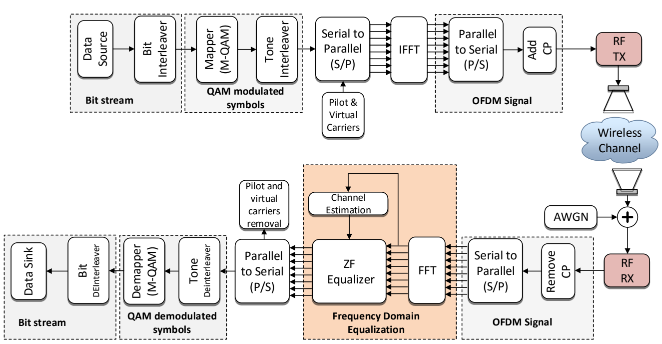

Figure 1. OFDM block diagram.

TABLE III. SUMMARY OF THE MAIN PARAMETERS CONSIDERED IN THE DESIGN OF OFDM SYSTEM BASED ON IEEE 802.15.3C STANDARD.

Parameter	Value
FFT size block (N_{fft})	512
Cyclic prefix (N_{cp})	64 samples
Sampling rate	2640 MHz
Sub-carrier bandwidth	5.15 MHz
Cyclic prefix time (T_{cp})	24.24 ns
Symbol time	218.18 ns
Modulation	16 QAM
Nominal Used Bandwidth	1.815 GHz
Throughput	6.2 Gbps

The data rate requirement to transmit a Full HD video content at a frame rate of 90 Hz and 30 bits per channel per pixel, which are the expected specifications for the next-generation of HDTV [6], is 5.6 Gbps. Therefore, from Table III it is verified that the considered system design provides enough data rate to enable such wireless application.

TABLE IV. SUBCARRIER ALLOCATION IN THE FREQUENCY SPECTRUM DOMAIN.

Subcarrier type	Number of subcarriers	Logical subcarrier indexes
Null	141	[-256:-186]∪[186:255]
DC	3	-1;0;1
Pilot	16	[-166:22:-12]∪[12:22:166]
Guard	16	[-185:-178]∪[178:185]
Data	336	All others

A. Received Signal and Frequency Domain Equalization

The received signal, $y(t)$, after being processed using K-point FFT, is converted into its frequency domain, $Y(k)$. The received OFDM signal, Y_l, considering that $T_{cp} \geq \tau_{max}$ is given by:

$$Y_l(k) = H_l(k).X_l(k) + Z_l(k), \tag{3}$$

where, k^{th} denote the subcarrier frequency component of the l^{th} transmitted OFDM signal, $H_l(k)$ is the Channel Frequency Response (CFR) and $Z_l(k)$ is the AWGN in the frequency domain. The original transmitted information, $X_l(k)$ can be recovered using a Frequency Domain Equalization (FDE) [13], which is performed as a K-branch linear feed-forward equalizer with $C(k)$ being the complex coefficient of the k^{th} subcarrier. In this work, only one FDE approach is considered, namely Zero Forcing (ZF) due to its relatively low implementation complexity, i.e., it does not require signal-to-noise ratio (SNR) estimation. For the ZF criterion, $C(k)$ is defined by (4).

$$C_{ZF}(k) = \frac{\hat{H}(k)^*}{|\hat{H}(k)|^2} \tag{4}$$

where, $\hat{H}(k)$, * and $|.|$ denote the estimated CFR, conjugate transpose and modulus, respectively.

V. Effect of Channel Impairments on the OFDM performance

In this section, the uncoded OFDM system performance over the IEEE standard channel model [4] at 60 GHz is assessed using ZF equalization and employing 16 QAM modulation. The quality of the transmitted uncompressed video content in Full HD, is assessed through BER and PSNR analysis. In addition, it is possible to estimate the minimum value of E_b/N_o to ensure a relatively satisfactory subjective quality of the video frame depicted in Fig. 2 used for this purpose. This is achieved by using the relation between the PSNR (objective quality assessment metric) and the subjective quality assessment based on viewer's impression, presented in Table V [14].

TABLE V. RELATION BETWEEN SUBJECTIVE AND OBJECTIVE QUALITY INDICATORS.

PSNR [dB]	ITU Quality scale
> 37	5 - Excellent
$31 - 37$	4 - Good
$25 - 31$	3 - Satisfactory
$20 - 35$	2 - Poor
< 20	1 - Very poor

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Figure 2. Reference frame from the Full HD Cactus.yuv video sequence for the PSNR calculation.

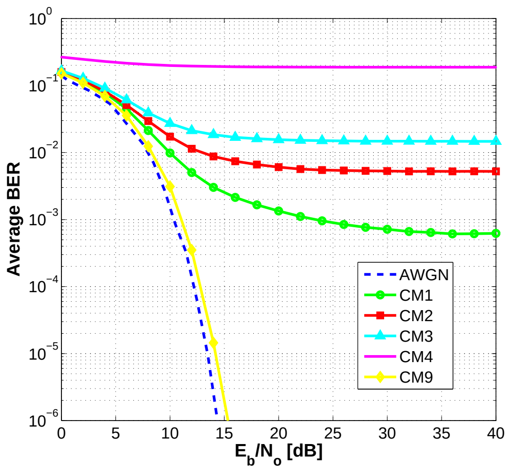
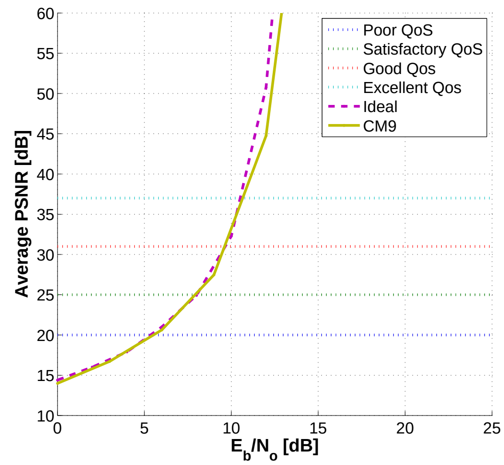


Figure 3. Uncoded OFDM BER performance for various channel models.

The average uncoded OFDM BER results, computed for each channel model, are displayed in Fig. 3. It is evident from these results that the performance of OFDM is severely affected by the propagation channel environment. As depicted only the performance of 16 QAM uncoded OFDM over CM9 meets the recommended BER target for video streaming applications, that is 10^{-6} [4]. This is explained by the fact CM9 is channel model characterized with the highest Rician factor and lowest frequency selectivity. The performance of uncoded OFDM over CM2, CM3 and CM4 environments is relatively poor, since an uncoded OFDM systems are well known to lack of frequency diversity and thus in such radio propagation channels a wireless communication is not reliable. Additionally, CM1 fails to meet the BER target, despite being characterized by a relatively low RMS delay, since CP interval time is shorter than the maximum delay spread of the multipath channel.

In order to evaluate the effectiveness of uncoded OFDM for a relatively good Quality of Service (QoS) at appropriate E_b/N_o values, the degradation of the quality of the video frame for CM9 has been studied. The video frame content (Fig. 2) is divided into several transmitting OFDM symbols and then transmitted over the channel model. PSNR results are depicted in Fig. 4 using 16 QAM, together with those obtained for an ideal radio propagation channel, i.e., no temporal dispersion is presented (dash curve). It be can seen that the effect of CM9 model have not significant impact on the degradation of the quality of reference video frame, with the maximum achievable PSNR of about 60 dB (for a $E_b/N_o = 13$ dB). This characterizes the video frame subjective quality as excellent (Table V).

(a)



(b)

Figure 4. Video quality performance of the received frame transmitted: a) subject video frame quality at PSNR of 14.01 dB b) objective video frame quality vs E_b/N_o.

VI. CONCLUSIONS

In this paper, the study of the impact of channel impairments on a 60 GHz uncoded OFDM system, implemented according to the IEEE 802.15.3c standard, for high data-rate applications, and considering 16 QAM, was presented. The performance assessment of the OFDM system was conducted through BER and PSNR analysis considering the transmission of an uncompressed Full HD video frame over residential, office and kiosk environments, for both NLOS and LOS scenarios.

It has been shown that multipath effect modeled by CM4 induces the largest performance degradation of the system when compared with CM3, CM2 and CM1. It is concluded that the presence of LOS in the multipath scenario is required in a uncoded communication systems, for example it is demonstrated at $E_b/N_o = 40$ dB the maximum BER of OFDM over CM3 is lower than 10^{-3}, whereas at the same E_b/N_o over CM4 the maximum achievable BER is around 0.2. Hence, it is verified that a uncoded 16 QAM OFDM system operating over a relatively low dispersion multipath channel and in a LOS scenario is robust enough to provide a excellent quality of service in streaming uncompressed video for wireless applications. Furthermore, in order to minimize

ISI, for the cases where the BER target is not achieved, FEC coding should be considered at the expense of system complexity and throughput. Apart from CM9 model, no other channel yielded relatively good communication link quality, i.e., the desired BER target was not met for a minimum QoS.

Finally, results presented in this work demonstrate that CM9 is appropriate for low complexity mmWave wireless communication systems envisaged for next generations of HDTV standards, where wireless uncompressed video streaming content is a demand.

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