

## Performance Evaluation of 60 GHz OFDM Communications under Channel Impairments over Multipath Fading Channels at 60 GHz

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**Abstract:** This paper presents a detailed analysis of the impact of multipath propagation phenomena on the performance of mm Wave wireless systems for both uncoded and coded OFDM architectures, based on IEEE 802.15.3c standard for high data rate applications. The performance of OFDM is known to be severely affected by channel impairments when its excess time delay exceeds the time guard interval of the OFDM symbol. Hence, this paper evaluates the impact that such impairments have on both uncoded and coded system performances through appropriate metrics based on BER, operating range and PSNR for residential, office and kiosk scenarios under LOS and NLOS. The feasibility of real-time high-definition video transmission using 60 GHz radio systems will be demonstrated through the transmission of uncompressed Full HD video content over various radio propagation environments, which will allow one to perfectly understand the system limitations, and consequently the range of applications that might be developed. *Copyright © 2016 IFSA Publishing, S. L.*

**Keywords:** OFDM, Multipath Fading channels, RF-impairments, IEEE 802.15.3c, mmWave signals.

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### 1. 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 relatively 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 data 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 huge quantities of information inherent to e.g. medical image and video,

as well as the required latency free transmission, only by means of uncompressed video transmission, demands the utilization of millimeter wave (mmWave) in conjunction with protocol independent and processing free information paths. Thus, using the mmWave spectrum provides the necessary bandwidth and pace for future HD systems.

To this extent, the IEEE 802.15.3c Task Group 3c has proposed an Audio-Visual mode (AV-PHY) and a High-Speed Interface mode (HSI-PHY), where Orthogonal Frequency Division Multiplexing (OFDM) has been adopted due to its inherent higher bandwidth efficiency [6] and relatively low complexity. An OFDM based system is well known to be effective under multipath conditions. 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, in 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 hundreds of taps [7].

The preliminary study done by the authors in [8] demonstrated that uncoded OFDM systems are very sensitive to the multipath radio propagation environment, in which good quality of service was only observed for a kiosk environment in Line-Of-Sight (LOS). The work presented in this paper provides an extension to previous simulation framework, where channel coding is considered in order to overcome the effect of such impairments. That is to say that in the presence of a high frequency selective fading, subcarriers of the multicarrier system will experience relatively high and low attenuations. In fact, modulated information being carried by such attenuated subcarriers are likely to be lost, which yield to a relatively poor system performance. In order to overcome this, the use of Forward Error Correction Codes (FEC) are mandatory.

The study presented in this paper builds upon previous work so that the reliability and performance of mmWave coded OFDM wireless communication system, based on the IEEE 802.15.3c standard [3], is assessed and compared with the uncoded OFDM results. This has been achieved through Bit Error Rate (BER), operating distance and subjective quality analysis of a transmitted Full-HD uncompressed video content, under the presence of propagation channel impairments at 60 GHz. The multipath fading channel models considered are the ones suggested by TG3c [4] for office, residential and kiosk indoor environments, considering both LOS and Non-Line-Of-Sight (NLOS) scenarios. Moreover, as for channel coding, Reed Solomon (RS) and Low-Density Parity-Check (LDPC) codes are considered, and in order to ensure a relatively low system complexity, Zero Forcing (ZF) equalizer is employed.

The paper is organized as follows. Section 2 introduces the IEEE 802.15.3c standard [3] target applications and its PHY layer design modes. Section 3 presents the work proposed by the IEEE 802.15.3c Task Group 3c (TG3c) on the 60 GHz channel modeling. Section 4 introduces OFDM and its parameters in the system design. The details about the proposed mmWave framework are presented in Section 5. Section 6 provides results of the performed analysis for uncoded and coded OFDM. Finally, the main conclusions are drawn in Section 7.

## 2. IEEE 802.15.3c Standard

### 2.1. Target Applications

The target applications or usage models (UMs) foreseen in the 60 GHz band for IEEE 802.15.3c standard are five [1]: **UM1) Uncompressed video streaming:** transmission of HDTV contents, eliminating the need for video cables from the video players to the display devices. The range should be around 10 m; **UM2) Uncompressed multivideo streaming:** similar to UM1), however multiple video signals could be supplied by a single transmitter. **UM3) Office desktop:** This UM aims the communication of a personal computer with external computer peripherals, e.g. printers and hard disks; **UM4) Conference ad hoc:** In this UM, the target scenario is where many computers are communicating each other; and finally **UM5) Kiosk file downloading:** it aims the connection of portable devices with electronic kiosks, enabling data uploads and downloads with their fixed antennas. This model requires at least 1 m of range.

### 2.2. PHY Layer Design Modes

The target applications presented in the previous subsection have different requirements. Therefore, in order to deploy such communication links, the IEEE 802.15.3c Task Group 3c has developed three different PHY modes: Single Carrier mode (SC-PHY), High-Speed Interface mode (HSI-PHY) and Audio-Visual mode (AV-PHY). The SC-PHY is best suitable for UM3 and UM5 environments, since the multipath channels are characterized by low time dispersion, low frequency selectivity and Line-of-Sight (LOS). It is well known that SC yields rather low performance in these scenarios [9]. On the other hand, Modes AV-PHY (UM1 and UM2) and HSI-PHY (UM4) utilizes OFDM as transmission scheme, as they are mainly designed for NLOS scenarios, which means more multipaths components arriving at the receiver. Usually, SC mode allows lower complexity and low power operation, whereas OFDM ensure high spectral efficiency and it is more robust in large delay spread from the multipath environment. A comparison of the different PHY modes is presented in Table 1 [5].

**Table 1.** Comparing the three modes provided by the standard.

Modes	SC PHY	AV PHY	HSI PHY
Main usage model	UM3 and UM5	UM1 and UM2	UM3 and UM4
Transmission scheme	SC-FDE	OFDM	OFDM
Forward error codes	RS/LDPC	RS	LDPC
Block size	512	512	512

In this work, the OFDM is the selected transmission scheme mode, as it is the one targeting uncompressed multivideo streaming. Single Carrier Frequency Domain Equalization (SC-FDE) mode is not considered due to its disadvantage of not allowing flexible management of the bandwidth. Unlike OFDM, it is not possible to allocate sets of subcarriers to a user (OFDMA), making the management of the network less efficient and more complex. As it can be seen from Table 1, two families of linear block codes are proposed in the standard: Reed-Solomon (RS) codes (mandatory) and Low-Density Parity-Check (LDPC) codes (optional). RS codes are known for their good capability of burst error correction at a relatively high Signal-to-Noise Ratio (SNR). LDPC codes, despite having high complexity, with its iterative decoding process, ensures a better error correction performance than RS codes or Turbo codes [10] and its performance is very close to the *Shannon* coding limit [11].

### 3. Indoor Channel Modeling 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/dor scattered signals from furniture, floor and ceiling.

#### 3.1. Considered Power Delay Profiles

The IEEE 802.15.3c standard has adopted the generic Complex Impulse Response (CIR) approach based on the clustering of propagation phenomena in both time and spatial domains, as observed in

measurement data [4]. The cluster model used is based on the extension of the *Saleh-Valenzuela* (S-V) model [12] to the angular domain by *Spencer* [13]. Hence, the IEEE 802.15.3c channel modeling group [14] 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 2 [1].

**Table 2.** 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 in order to obtain different power delay profiles (PDP) for the same multipath environment. This occurs due to the fact that the considered channel modeling tool [14] takes into account the uniform distribution in terms of scatterers' movement between transmitter (TX) and receiver (RX) and at different antennas heights. 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 ( $B_c$ ) for signal correlation of 0.9 ( $\bar{B}_{c0.9}$ ) 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 coherence bandwidth of the channel is required to be considered as a flat-fading channel. Otherwise, the fading channel is considered as 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 is most commonly used. It has been calculated by (1), which is inversely proportional to  $\bar{\tau}_{RMS}$  [15].

$$\bar{B}_{c0.9} = \frac{1}{50\bar{\tau}_{RMS}}, \quad (1)$$

Channel quality indicator values of each model are presented in Table 3, where HPBW is the Half Power Beamwidth of TX/RX antennas.

**Table 3.** Statistical parameters for each multipath channel environment.

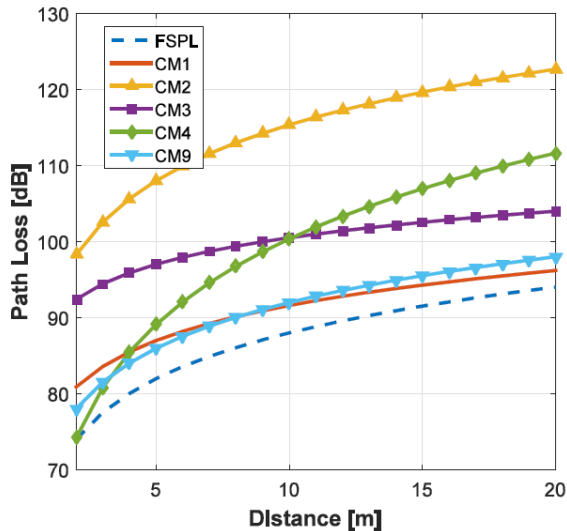
CM #	$\bar{\tau}_{RMS}$	$\bar{\tau}_{MAX}$	$\bar{B}_{c0.9}$	$\bar{K}$	HPBW °
	(ns)	(ns)	(MHz)	(dB)	(TX/RX)
1	3.547	67.42	5.64	14.6	(360,15)
2	2.73	68.9	7.33	-	
3	22.75	464	0.88	14.61	(30,30)
4	57.7	651	0.35	-	(30,15)
9	2.7	183	7.41	30.9	(30,30)

### 3.2. Link Budget for IEEE 802.15.3c Applications

To find the maximum operation range of a wireless communication, the Path Loss (PL) between the transmitter and receiver must be known. The PL describes the attenuation of mean power as function of distance, and according to the TG3c group [4], and it is modeled as:

$$PL(d) = PL_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) [dB] + X_\sigma [dB], \quad (2)$$

where  $PL_0$  is the path loss at  $d_0 = 1m$ ,  $n$  is the path loss exponent,  $d$  is the distance and  $X_\sigma$  a zero mean Gaussian distributed random variable with a standard deviation  $\sigma_s$ , which in this work,  $X_\sigma$  is chosen to be 80% of  $\sigma_s$  [16]. The representation of (2) as function of distance traveled is depicted in Fig. 1 for each CM, taking into account the values of each variable presented in Table 4.

**Fig. 1.** Path loss over distance for each channel model.

As it can be seen from Fig. 1, the path loss varies from each CM model to another, where NLOS scenarios, such as CM2 and CM4, are characterized by much higher losses than the other channel models in LOS scenario.

**Table 4.** Typical values of  $n$ ,  $PL_0$  and  $\sigma_s$  for different environments and scenarios [6].

CM #	$n$	$PL_0$	$\sigma_s$
		(dB)	(dB)
1	1.53	75.1	1.5
2	2.44	86	6.2
3	1.16	84.6	5.4
4	3.74	56.1	8.6
9*	2	68	5

\* the parameters considered for this CM are the ones suggested by [17].

Consequently, the PL value in its maximum range can also be obtained from a link budget equation, represented in (3) [18]:

$$PL = EIRP + G_{RX} - P_N - Eb/N_0 - IL - M [dB], \quad (3)$$

where EIRP is the Equivalent Isotropically Radiated Power,  $P_N$  is the average noise power per bit, where  $P_N = N + N_f$  and  $N = -174 + 10 \log_{10}(\text{Throughput [bps]})$ ,  $N_f$  is the receiver noise figure,  $IL$  is the implementation loss of the transceiver and  $M$  the 60 GHz link margin. Additionally,  $N_f$  and  $IL$  are usually characterized by 8 dB and 2 dB, respectively [17].

Finally, relating both equations (2) and (3), the maximum operation range for a required  $E_b/N_0$  is calculated using the following equation [18]:

$$d = 10^{(PL - PL_0)/10n} [m] \quad (4)$$

Based on the suggested EIRP of 40 dBm [19] and a receiver gain antenna ( $G_{RX}$ ) of 10 dBi (typical value of gain on-chip antennas at 60 GHz) [20], the maximum operating range can be estimated for a specific  $E_b/N_0$  and with either presence or absence of human shadowing.

## 4. 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 (5) is given by [6]:

$$x(mTs) = \sum_{n=0}^{N_c-1} X_n e^{j2\pi nm/M}, \quad (5)$$

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

From (5), 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.

## 5. 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. 2. At the transmitter, a data source is employed to generate pseudo-random bits, which are coded and 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 3.1, 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 5 [3].

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 6 it is verified that the considered system design provides enough data rate to enable such wireless application.

**Table 5.** Subcarrier allocation in the frequency spectrum domain.

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

**Table 6.** 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
Subcarrier 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

### 5.1. 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:

$$Y_l(k) = H_l \cdot X_l + Z_l(k), \quad (6)$$

where  $k^{th}$  denotes 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) [21], 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 (7).

$$C_{ZF}(k) = \frac{\hat{H}(k)^*}{|\hat{H}(k)|^2}, \quad (7)$$

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

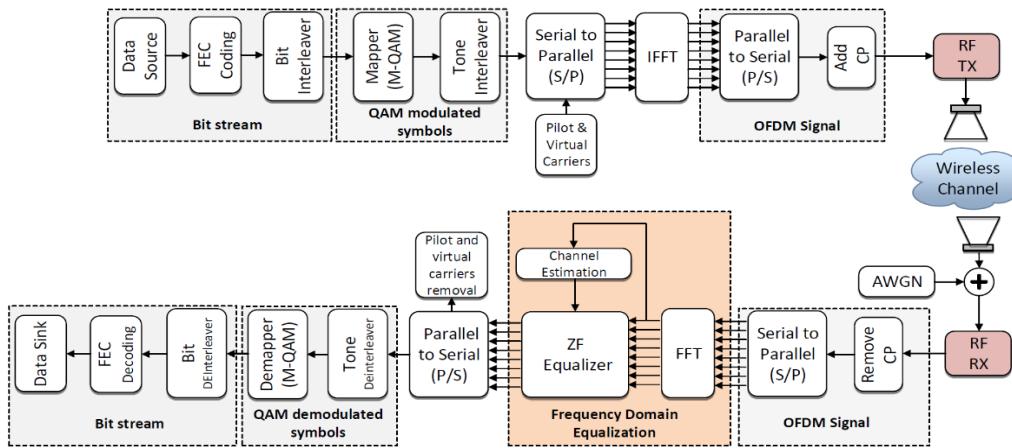


Fig. 2. OFDM block diagram.

## 6. Effect of Channel Impairments on the OFDM Performance

In this section, both uncoded and coded OFDM system performances 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 High Definition (HD), is assessed through BER, operation range and Peak Signal-to-Noise Ratio (PSNR) analysis. In addition, it is possible to estimate the minimum value of  $E_b/N_0$  to ensure a relatively satisfactory subjective quality of the video frame depicted in Fig. 3 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 7 [22].



Fig. 3. Reference frame from the Full HD Cactus.yuv video sequence for the PSNR calculation.

Table 7. Relation between subjective and objective quality indicators.

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

## 6.1. Uncoded OFDM System Performance Assessment

To estimate the minimum distance between the TX and RX in this particularly application, several parameters presented in (3) must be known. For example, when no human blockage is considered, link margin is equal to the shadowing margin, but when it is presented additional losses must be taken into account. According to [16], the losses caused by a person moving and crossing the propagation path varies from 18 to 36 dB, in indoor environments at 60 GHz. Additionally, typical values of EIRP and  $G_{RX}$  for such mmWave communication systems are 40 dBm [19] and 10 dBi (typical value of gain on-chip antennas at 60 GHz) [20], respectively. Assuming such values, the maximum operating range vs.  $E_b/N_0$  for uncoded OFDM over the considered multipath fading channels when either absence or presence of human shadowing is presented, is given in Fig. 4.

The average uncoded OFDM BER results, computed for each channel model, are displayed in Fig. 5. 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], and according to Fig. 4, it is ensured a maximum operable range of 28.5 m and 5.4 m in absence and presence of human blockage, respectively. 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.

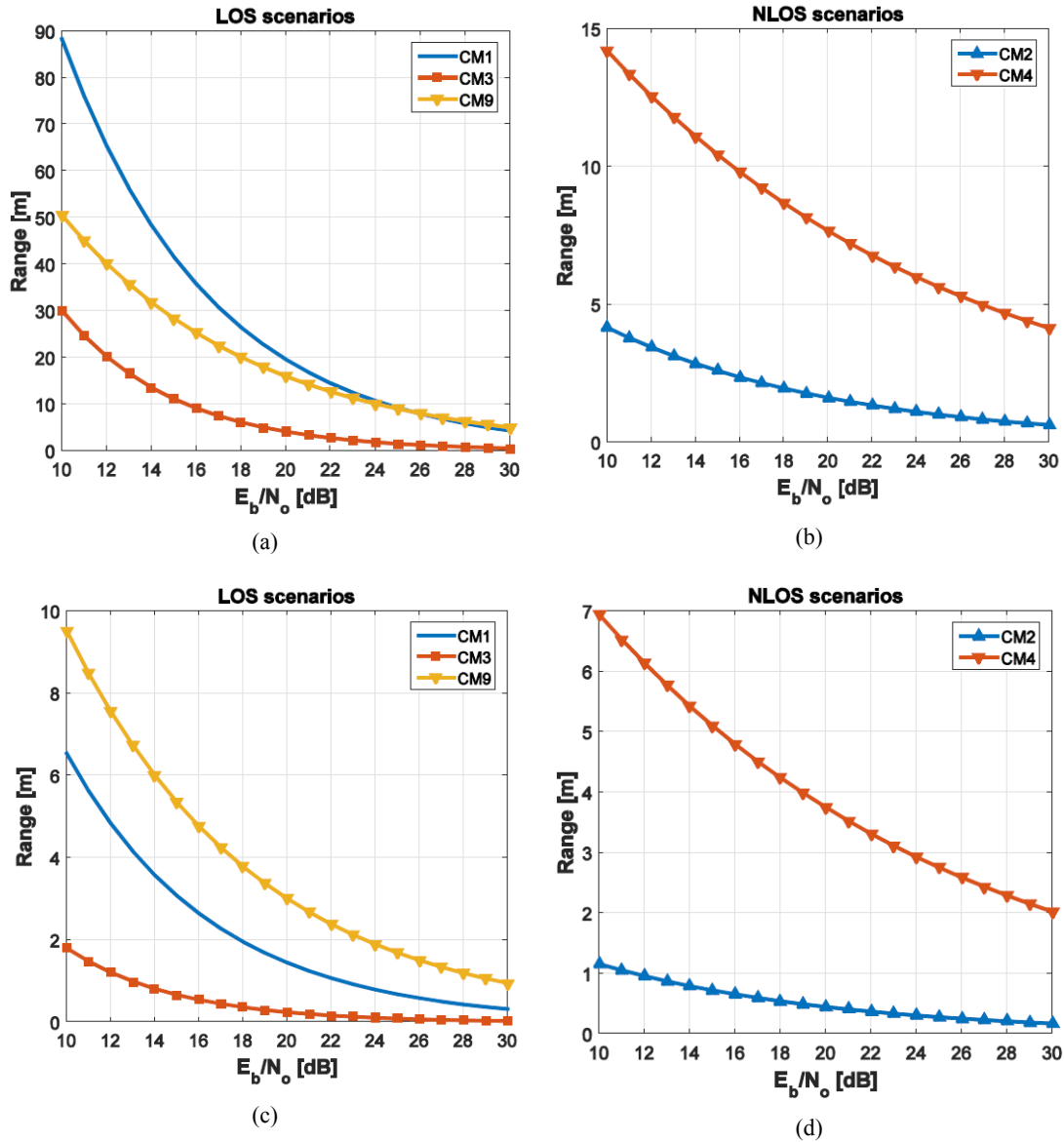


Fig. 4. Estimated maximum operating range for uncoded OFDM vs.  $E_b/N_0$  for each channel model: (a) and (b) without human shadowing; (c) and (d) without human blockage.

In order to evaluate the effectiveness of uncoded OFDM for a relatively good Quality of Service (QoS) at appropriate  $E_b/N_0$  values, the degradation of the quality of the video frame for CM9 has been studied. The video frame content (Fig. 3) is divided into several transmitting OFDM symbols and then transmitted over the channel model. PSNR results are depicted in Fig. 6 using 16-QAM, together with those obtained for an ideal radio propagation channel, i.e., no temporal dispersion is presented (dash curve). It can be 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  $E_b/N_0 = 13$  dB). This characterizes the video frame subjective quality as excellent (Table 7), with a maximum distance between both TX and RX antennas of 34 m and 7 m, for absence and presence of human obstacles in the link.

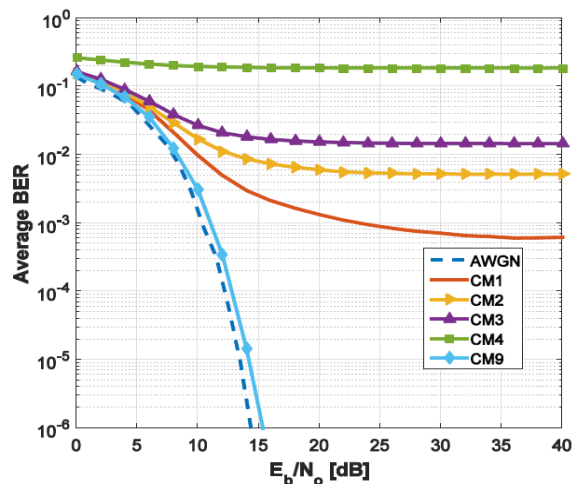
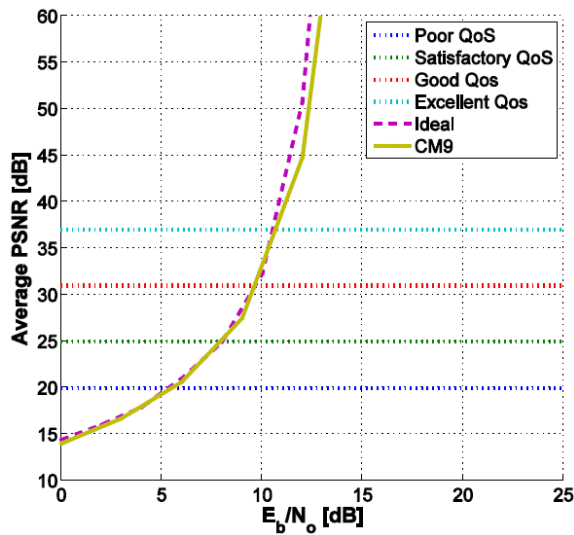


Fig. 5. Uncoded OFDM BER performance for various channel models.



(a)



(b)

**Fig. 6.** 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.  $E_b/N_0$ .

## 6.2. Coded OFDM System Performance Assessment

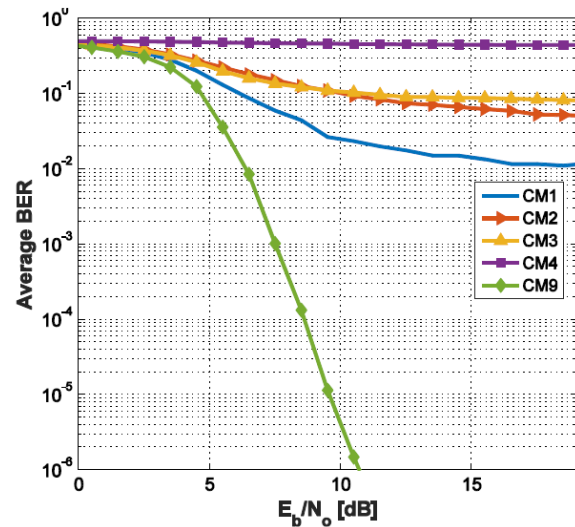
In this subsection, similar analysis to the one presented in Section 6.1, is conducted. The maximum operating range vs.  $E_b/N_0$  for coded OFDM over the considered multipath fading channels is calculated considering the same parameters, except the system throughput, which varies according to Table 8. In addition, the type and coding rate of each FEC codes employed, is also presented in Table 8.

**Table 8.** Summary of the OFDM FEC schemes.

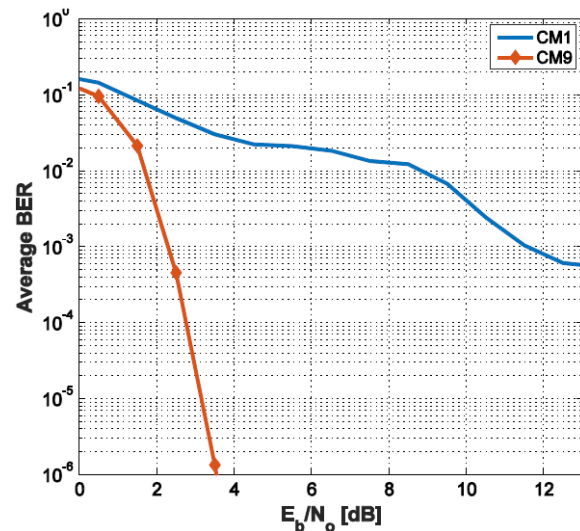
FEC	Overall code rate	Throughput (Gbps)
RS (224,216)	9/14	3.96
LDPC (672,336)	1/2	3.08

The average coded OFDM BER results, computed for each channel model, are depicted in Fig. 8 a) and b) for RS and LDPC codes, respectively. It is evident

from these results that the performance of coded OFDM is also significantly affected by the propagation channel environment. In fact, the target BER is only achieved for the kiosk channel model, and thus results for LDPC coding are just computed for CM1 and CM9. This can be explained by the fact the IEEE 802.15.3c OFDM design parameters are not well suitable for very dispersive multipath channels. Comparing the cyclic prefix time of 24.4 ns with the average excess delay, the latter is always greater than 65 ns for all channels. Hence, due to the fact that  $\bar{\tau}_{MAX}$  is more than twice the  $T_{CP}$ , strong ISI is presented. Therefore, the use of channel coding fails to improve the OFDM performance.



(a)



(b)

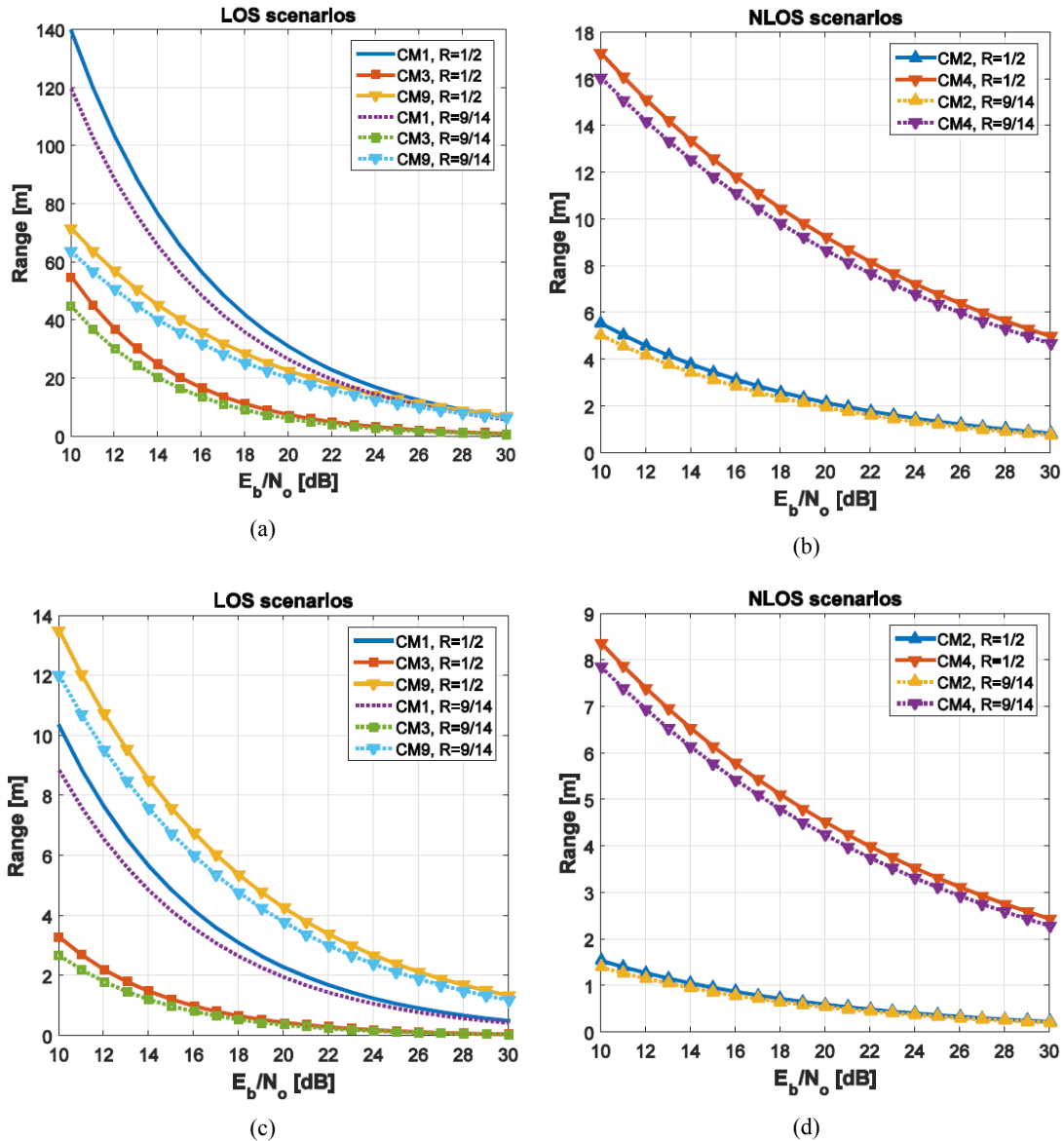
**Fig. 8.** Coded OFDM BER performance for various channel model: (a) RS (224,216) (b) LDPC (672,336).

However, it is also important to refer that when such ISI is reduced, the use of FEC codes enables the communication at very low Signal-to-Noise Ratios

(SNRs). BER target is achieved for  $E_b/N_0$  values of 10 dB and 3.6 dB for RS and LDPC coding.

This allows the TX and RX to be antennas to be apart of 150 m and 28.2 m (this one in the presence of human shadowing) considering a coding rate of  $\frac{1}{2}$ , as can be seen in Fig.9. Similarly, when a coding rate of  $\frac{9}{14}$  is used, both distances are 133.2 m and 25 m,

which means that channel coding make the system more robust against noise and thus its operating range is significantly increased. For example, when LDPC coding is employed this distance increases 121.5 m and 22.8 m, for absence and presence of disturbances in the transmission medium, relatively to the uncoded OFDM system.



**Fig. 9.** Estimated maximum operating range for coded OFDM vs.  $E_b/N_0$  for each channel model: (a) and (b) without human shadowing; (c) and (d) without human blockage.

## 7. 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 an uncoded communication systems. For example, it is demonstrated at  $E_b/N_0 = 40$  dB the maximum BER of OFDM over CM3 is lower than  $10^{-3}$ , whereas at the

same  $E_b/N_0$  over CM4 the maximum achievable BER is around 0.2. Hence, it is verified that an uncoded 16-QAM OFDM system operating over a relatively low dispersion multipath channel and in a LOS scenario is robust enough to provide an excellent quality of service in streaming uncompressed video for wireless applications, considering a range shorter than 34 and 7 m in the absence and presence of human blockage, respectively. 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. Moreover, it can be concluded that despite channel coding reduces the system throughput (depending on the coding rate), it can significantly increase the OFDM system operating range. Thus, the relatively high path losses presented in typical indoor environments are mitigated. In fact, a more efficient coverage area for mmWave target applications is provided.

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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