Performance Evaluation of a Dual-Mode OFDM and SC-FDE System at mmWave enabling Joint Radar and 5G Multi-Gigabit/s Wireless Communications

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***Abstract*—In this paper we introduce a dual-mode OFDM/SC-FDE 60 GHz millimeter wave (mmWave) Physical (PHY) layer to provide both radar and transmission data rates over 10 Gbps, as known as radar type sensors and wireless communications (RadCom). Such feature goes towards one of the vertical requirements for future wireless communications, such as 5G. The system is evaluated and assessed through metrics of BER and required E_b/N_0 for a target BER of 10^{-5}, under both residential LOS and NLOS scenarios. In the simulation results, it is demonstrated that SC-FDE is more robust against RF impairments, and does not requires channel coding contrary to OFDM. In addition to this, the fact that it has lower peak-to-average power ratio (PAPR), makes such transmission scheme a very promising alternative to OFDM. For example, employing 256 QAM modulation, it has 6 dB of E_b/N_0 gain in comparison with OFDM, under the same conditions.**

I. INTRODUCTION

Nowadays, advancements in wireless communication systems are currently being subject to a great deal of interest. For example to accommodate an expected strong growth of mobile data traffic and devices, where the exchange of data between devices must be performed at very low latency and at very high data-rates, the scientific wireless community is working on evolving the existing mobile networks towards the fifth generation (5G). A overloading of the frequency spectrum at lower frequencies, particularly below 6 GHz, will come aside as consequence. Therefore, millimeter wave (mmWave) band, especially the unlicensed 60 GHz and 80 GHz bands, is seen as promising approach providing continuous GHz of available spectrum, supporting Gbps of data rates without interfering in other mature networks technologies, such as 4G-LTE cellular networks.

Transmissions schemes as Orthogonal Frequency Division Multiplexing (OFDM) and Single-Carrier Frequency Domain Equalization (SC-FDE), also known as Single-Carrier Block Transmission (SCBT), are seen as preferred choices for high-throughput systems due to its inherent higher bandwidth efficiency [1]. The main difference between both is, while OFDM transmits multiple subcarriers in parallel, where which of each occupies a narrow band, SC-FDE uses a single modulating carrier to transmit the same data, but at a higher symbol rate. In addition, the former one has an inherent advantage of having lower peak to average power ratio (PAPR) against OFDM [2]. In this scope, authors introduce and examine a dual-mode OFDM and SC-FDE wireless system based on the Physical Layer (PHY) specifications presented in the 60 GHz IEEE 802.15.3c standard [3] (ranging from 57-66 GHz of spectrum). In particular, some waveform refinements design have been to enable transmission throughput rates higher 10 Gbps, which is the established for 5G communications, according to [4]. Moreover, realistic channel models for residential wireless applications (usage model) in both LOS and NLOS are considered [5], as multipath environment scenarios.

For a fair comparison between different transmission schemes, both OFDM and SC-FDE are compared considering the same symbol rate, sampling rate, modulation, guard time interval, and common receiver algorithm structure, i.e., channel and Signal-to-Noise Ratio (SNR) estimations and equalization. To enable this, channel equalization is performed in the frequency domain, employing a Minimum Mean Square Error (MMSE) equalizer, which ensures better performance than Zero Forcing (ZF) one at lower SNR. Additionally, both channel and SNR estimations required in the MMSE technique are yield from the auto-correlation properties of a transmitted Channel Estimation Sequence (CES) preamble defined in the IEEE 802.15.3c. It becomes obvious that information from CES can also be used for radar applications, also known as RadCom [6]. Finally, Low-Density Parity-Check (LDPC) Forward Error Correction (FEC) codes are considered in order to increase robustness to both transmission schemes over frequency selective multipath channels. As system assessment metrics, Bit Error-Rate (BER) and required E_b/N_0 for a target BER of 10^{-5} are considered.

Despite the existence of a large number of articles addressing channel impairments at 60 GHz, published in the literature, to the authors' knowledge, none of them present a comprehensive critical comparison analysis on the performance of OFDM and SC-FDE over 60 GHz fading channels. For example, in [7], only LOS scenario considering ZF method for equalization is considered. In [8], channel and SNR estimation are ideally considered. Finally in [9], both schemes are only compared in terms of BER analysis for NLOS scenarios and in uncoded conditions, where only IEEE standard design specifications are considered.

The paper is organized as follows, section II presents the fol-

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lowed 60 GHz channel modeling considered in this work. Section III introduces OFDM and SC-FDE transmission scheme concepts. The Channel Frequency Response (CFR) and SNR estimation techniques are presented in section IV, utilizing a pair of Golay complementary sequences as CES. The details about the block diagram of the considered framework, system simulation parameters for the dual-mode mmWave network is presented in V. Finally, simulation BER results are shown in section VI.

II. INDOOR CHANNEL MODELLING AT 60 GHZ

A. Considered Power Delay Profiles

In this work a 60 GHz indoor residential channel model modeled by the IEEE 802.15.3c channel modeling group [10], is considered. For such environment, the Complex Impulse Response (CIR) is obtained based on the clustering of phenomenon in both time and spatial domains, where the cluster model is based on the extension of the Saleh-Valenzuela (S-V) model [11] to the angular domain by Spencer [12].

Power Delay Profiles (PDPs) based on the CIR model of both LOS (CM1) and NLOS (CM2) residential environment scenarios are calculated considering an Equivalent Isotropically Radiated Power (EIRP) of 40 dB, and a receiver antenna gain (G_{RX}) of 10 dBi. Furthermore, the dynamic range of each PDP is obtained considering 10 dB above the thermal noise of the system as threshold, which is defined by:

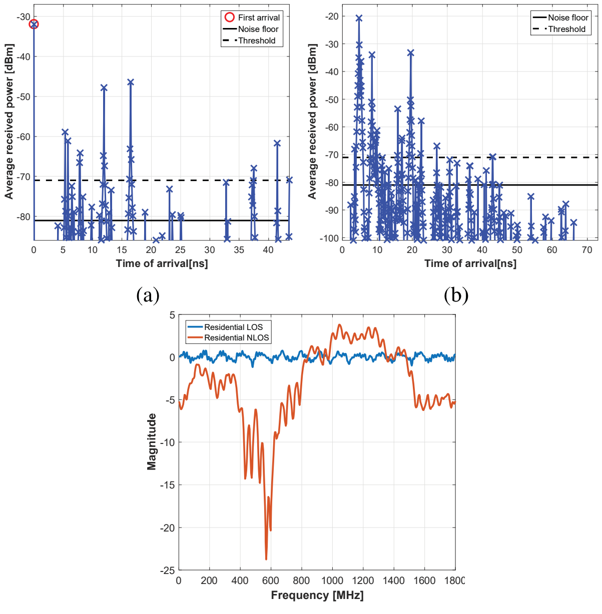
$$N = k.T.B_W \ [W], \tag{1}$$

where N, k, T and B_W are the noise power, Boltzmann constant, temperature in Kelvin and the signal bandwidth of both transmitted signals, respectively. The system noise floor -81 dBm, considering $T = 290$ K and $B_W =$ 1.8 GHz. Additionally, threshold of 10 dB above the noise floor considered. Fig. 1 illustrates the used method to obtain the average PDP for CM1 and CM2, respectively.

The RMS delay spread (τ_{RMS}), coherence bandwidth (B_c), and excess delay spread (τ_m) are Channel Quality Indicator (CQI) parameters that can be determined from a PDP. The B_c is a key metric involved in expressing the performance of any digital wireless system over a fading channel. For example, if the system bandwidth is larger than B_c, amplitude and phase distortion of the signal will occur, characterizing the channel as frequency-selective. Coherence bandwidth is 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, and is the one considered in this work. Table I presents the CQI for the considered channel models, where it can be seen that CM2 is the most frequency selective channel, i.e., $B_{c_{0.9}}|CM2 << B_{c_{0.9}}|CM1$.

III. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING AND SINGLE CARRIER FREQUENCY DOMAIN EQUALIZATION

OFDM is a well known multi-carrier transmission scheme that is especially used to provide robust high-data rate links in frequency selective channels [1], as the one depicted in Fig. 1c, is converted into several flat parallel narrow sub-channel (subcarriers spacing) that can be easily equalized in the frequency domain.



(a)

(b)

(c)

Fig. 1: PDP calculation method for the channel models: a) CM1 b) CM2.

TABLE I: CQI parameters for the considered multipath fading channels.

CM #	τ_{RMS} (ns)	$B_{c_{0.9}}$ **(MHz)**	τ_m (ns)
1	3.92	36	43.6
2	3.1	18	43

The discrete expression of (2) is given by [1]:

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

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 data symbols into adjacent sub-carriers. In the receiver, the Fast Fourier Transform (FFT) is used to demodulate the data symbols.

Although OFDM increases the 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 have an important impact on system performance. This fact results in the loss of orthogonality

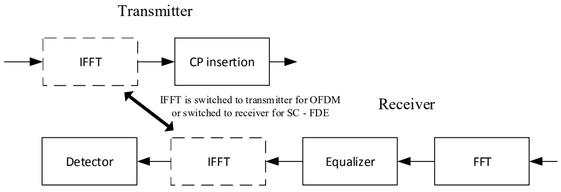


Fig. 2: Conversion between OFDM and SC-FDE.

among sub-carriers and a guard time interval is inserted, which is only efficient when it is larger than the maximum delay spread of the multipath channel.

SC-FDE can be seen as a traditional digital transmission scheme in which data symbol is transmitted at a fixed symbol rate. However, equalization is performed by a linear frequency domain equalizer on a block of data to minimize the ISI from the multipath [13], which makes this concept very similar to OFDM, as it can be verified in Fig. 2. Evidently, the difference between both systems mainly in the employment of IFFT block placement, enabling both systems to operate on a dual-mode wireless system. This brings many advantages such as:

- Lower sensitivity to carrier frequency offset [14];
- When OFDM is employed in the downlink, means that most of the signal processing complexity is concentrated at the base station, when compared to SC-FDE;
- When SC-FDE is used in the uplink, power efficiency on the user equipment is higher in terms of power consumption, reducing the cost of the power amplifier and enhancing the battery life.

In addition, OFDM is characterized by higher values of Peak-to-Average Power Ratio (PAPR) in comparison with SC-FDE [15], causing critical non-linear distortions at RF Power Amplifier Power Amplifier [2], at mmWave bands.

IV. CHANNEL FREQUENCY RESPONSE AND SNR ESTIMATION BASED ON GOLAY SEQUENCES

Golay complementary sequences are suggested by the IEEE 802.15.3c standard to be used in the PHY preamble for synchronization and channel estimation purposes. According to [3], the recommended CES is given by (3), and should be transmitted prior to the data for channel estimation purposes at the receiver. In this work, authors have obtained each Golay sequence pair through the recursive complementary sequence generator algorithm presented in [16], considering all the coefficients $W_n = 1$, where n is the number of delay line blocks.

$$CES = [\mathbf{a}_{256}\mathbf{b}_{256}\mathbf{a}_{256}\mathbf{b}_{256}\mathbf{b}_{128}], \tag{3}$$

where, the first transmitted bit is the leftmost bit of $\mathbf{a}_{256}$. Hence, the CES sequence consists of the Golay pair $(\mathbf{a}_{256}, \mathbf{b}_{256})$ repeated twice and preceded by the cyclic prefix $\mathbf{b}_{128}$. Such pair of Golay sequences have an attractive property that the sum of their auto-correlations has maximum peak with zero side-lobes [17]. Let $\mathbf{a}_N$ and $\mathbf{b}_N$ be the pairs of Golay sequences of length equals to $N = 2^M$ (M natural number) and $[\mathbf{R}_a, \mathbf{R}_b]$ the auto-correlation of each pair respectively, where the sum both auto-correlations is defined:

$$\mathbf{R}_{ab}(i) = \mathbf{R}_a(i) + \mathbf{R}_b(i) = 2N\delta(i - N), \tag{4}$$

where, $i \in [0, ..., N-1]$ and $\delta_{(i)}$ is the Kronecker delta function. At the receiver, authors have considered the counter part of the Golay sequence generator, which is known as Efficient Golay Correlator (EGC) algorithm [16]. Such digital signal algorithm performs outputs a CIR from each sum of the auto-correlation of each transmitted pair. Thus two estimated CIRs, $\hat{h}_1(t)$ and $\hat{h}_2(t)$ are obtained. After an FFT operation on both CIRs, the average CFR is estimated according to:

$$\hat{H}(k) = \frac{1}{M}\sum_{m=1}^{M}\hat{H}(m,k), \tag{5}$$

where, $\hat{H}(k)$ is the CFR estimated average magnitude the k^{th} sub-carrier, M is the number of Golay pair repetitions in the transmitted CES sequence, which is specifically for this case equals to 2, and finally, m is the index of each pair.

Moreover, to estimate SNR (η) at the receiver, both signal power, P_s, and noise power, P_n, must be estimated. According to [18], such values are obtained from the estimated CFR and given by:

$$P_s = \frac{1}{MK}\sum_{m=1}^{M}|\hat{H}(k)|^2, \tag{6}$$

$$P_n = \frac{1}{MK}\sum_{m=1}^{M}\sum_{k=1}^{K}|\hat{W}(m,k)|^2, \tag{7}$$

where, $\hat{W}(m,k) = \hat{H}(k) - \hat{H}(m,k)$, $m \in [2:M]$ and K is the FFT length.

Furthermore, an enhancement on the CIR estimation against noise is also considered. This is, by comparing the average power estimated on each individual CIR path, $|\hat{h}(k)|^2$, with a certain threshold, λ, only the significant CIR paths are selected as inputs to the K - point FFT. The value of λ is determined by the average noise power at receiver (7). Therefore, whose average power estimation are below the threshold are assumed that they contain only noise samples, and thus set to null. As result the accuracy of the average estimated CFR is significantly increased. The mathematical representation is presented in (8).

$$\hat{H}(k) = \begin{cases} \hat{H}(k), & |\hat{H}(k)|^2 > \lambda \\ 0, & otherwise \end{cases} \tag{8}$$

V. MMWAVE SYSTEM MODELS BASED ON IEEE 802.15.3C STANDARD

The SC-FDE system mode suggested in this work is developed based on the OFDM PHY parameters described in the IEEE 802.15.3c standard [3], with the necessary adjustments to the transmitter and receiver block chains that ensures a fair comparison performance between them. Therefore, both modes share the same PHY operating parameters, as depicted in Table II. Particularly for the SC-FDE mode, stuff symbols are inserted to match the same data length of an OFDM symbol. The considered dual-mode OFDM/SC-FDE system has been developed in *Matlab* and its block diagram can be found in Fig. 3. In this figure, white blocks indicate those that are common to both transmission schemes, the grey ones are those specific to SC-FDE, while green ones are OFDM specific blocks. At the transmitter, data source are coded with a FEC block and then mapped into QAM symbols. Following this, and only for OFDM, QAM symbols are mapped into K-subcarriers through 512-points IFFT transform. Next, a cyclic extension is inserted, namely CP in OFDM and Pilot Word (PW) in SC-FDE, between data. Finally, a Golay CES is prefixed to the payload sequence, and a Root Raised Cosine (RCC) is considered to limit the bandwidth and output band emissions of the transmitted signal. In particular for OFDM waveforms, such results in smoothing the discontinuities between adjacent OFDM symbols in frequency domain.

TABLE II: Summary of the main parameters considered in the design of OFDM/SC-FDE dual mode system based on IEEE 802.15.3c standard.

Parameter	**Value**
FFT size block (N_{fft})	512
Data block size	336
Symbol rate	2640 MHz
Sub-carrier bandwidth	5.15 MHz
Modulation	16/64/256 QAM
Stuff symbols (SC-FDE only)	112
Guard time interval*	114/116 samples
FEC code	LDPC(504,672)
Maximum throughput	11.3 Gbps
FIR filter	RCC with interpolation factor 4X
Roll-off factor	0.25
Sampling rate	10560 MHz

(*) number of samples required to meet the maximum excess delay spread of CM2 and CM1, respectively.

At the receiver, a match filter similar to the one used at the transmitter is considered. The CIR is estimated according to those algorithms described in section IV, and data is equalized. In the SC-FDE system unlike OFDM, after equalization data is transformed to time domain for data decision by applying the IFFT prior to QAM demodulation.

A. Received Signal and Frequency Domain Equalization

According to [1], SC-FDE system is equivalent to an OFDM system with a linear FFT pre-coding, where original transmitted information can be recovered with a Frequency Domain Equalization (FDE) for both systems. From [18], FDE is performed as a K-branch linear feed-forward equalizer with $C(k)$ as the complex coefficient at the k^{th} subcarrier. In this work, the FDE approach is the MMSE equalizer. For such criterion, $C(k)$ is defined by (9).

$$C(k) = \frac{\hat{H}(k)^*}{|\hat{H}(k)|^2 + \frac{1}{\eta}} \tag{9}$$

where, $\hat{h}(k)$, η, * and $|.|$ denote the estimated CFR, SNR, conjugate transpose and module, respectively.

VI. Effect of the Channel Impairments on the performance of OFDM and SC-FDE

In this section, both uncoded and coded OFDM and SC-FDE transmission schemes are assessed over the channel models presented in subsection II-A. However before that, Golay sequences accuracy, in estimating CIR and SNR, are evaluated in terms of overall demodulation performance, i.e., through BER analysis. For this, a comparison between BER results from an ideal versus channel and SNR estimations for uncoded SC employing 256 QAM modulation over CM1 is considered. From Fig. 4a, it can be seen that such results and are in good agreement, which validates Golay complementary pair sequences as a good choice for channel and SNR estimations.

Also, noise mitigation on estimated CIR samples, method suggested in (8), is assessed. For that, λ is obtained through the following parametric study. Firstly, a reference threshold is considered as P_n, and then such is decreased dB in dB, until an optimized value of BER is achieved. From Fig. 4b, it can be verified that such happens for λ equals to 10 dB below P_n.

A. Uncoded Systems

BER comparison performance of uncoded SC-FDE and OFDM modes over CM1 and CM2, employing 16, 64 and 256 QAM, are depicted in Fig. 5a and Fig. 5b, respectively. As it can be verified from these results, OFDM is significantly more effected by CM2 than SC-FDE, due to the lack of frequency diversity. Such feature is an intrinsic characteristic of SC systems, since one single symbol shares all channel bandwidth, whereas, in OFDM systems every sub-carrier experience difference attenuation values caused by the CFR. Thus, when several sets of sub-carriers are experiencing a frequency null presented in the CFR, all the information contained in them are lost except if, at receiver, SNR values are higher than those attenuation values. For example, considering the CFR of CM2, see Fig. 1c, SNR values higher than 10 dB at the receiver must ensured, otherwise all the information around 425 and 620 MHz will be lost. This explains the fact that over CM2 channel model, SC-FDE clearly outperforms OFDM BER results. On the other hand, for a relatively flat CFR as the CM1 one, see 1a, both systems performance are very similar.

B. Coded Systems

In order to enhance the lack of frequency diversity of OFDM demonstrated in previous results, LDPC(504,672) FEC codes are employed. BER results of coded SC-FDE and OFDM are shown in Fig. 6. From these, it can be seen that the performance of OFDM is now closer to the SC-FDE

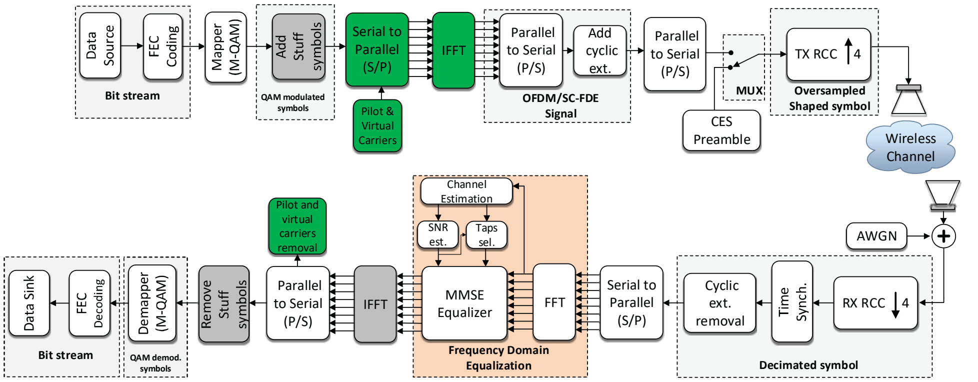
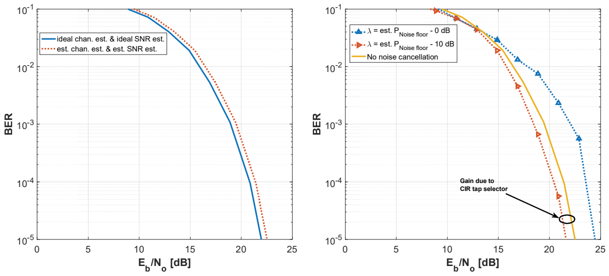


Fig. 3: Dual mode system block diagram.



(a) (b)

Fig. 4: Golay pair sequences performance on estimating both CIR and SNR using 256 QAM for SC-FDE (a), and its enhanced performance using a noise cancellation method (b).

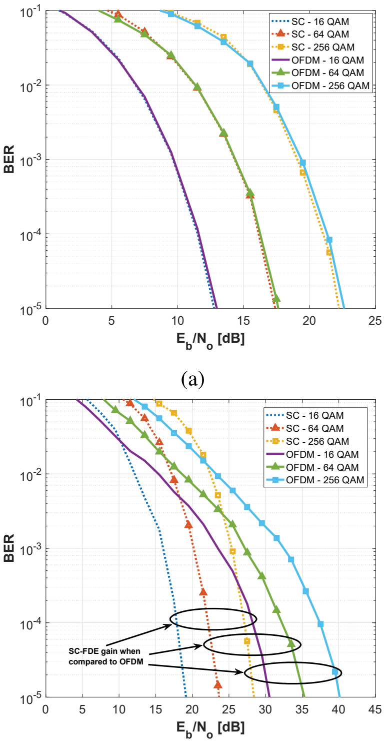
when channel coding is employed. However, SC-FDE still outperforms OFDM over both CM1 and CM2 channel models, as it is summarized in Table III. For example, considering 256 QAM modulation, it has 6 dB of E_b/N_0 gain in comparison with OFDM, under the same conditions.

VII. CONCLUSIONS

A detailed study on the system performance comparison of OFDM and SC-FDE systems at a 60 GHz, considering Golay sequences for channel and SNR estimations under mmWave environments, has been presented.

In this work it has been proven that Golay sequences presented as PHY preamble are a relatively a good choice for channel and SNR estimations for mmWave signals operating at multi-gigabit/s of data rates. Such high resolution CIR (better than 0.35 ns or 11 cm) yielded by these sequences may ultimately provide valuable information on the bistatic radar signature of surrounding objects, targeting RadCom applications. Moreover, it has also been demonstrated, through BER analysis, that removing the effect of noise on estimated CIR samples, the FDE overall performance significantly increases.

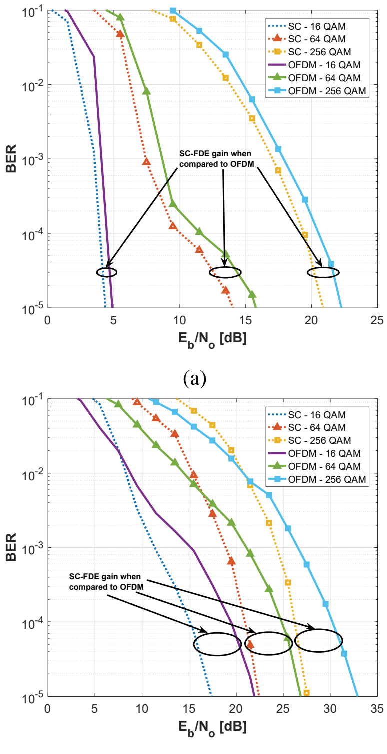
Finally, SC-FDE and OFDM modes have similar BER performance over non frequency selective channels, while SC-FDE mode proves to be more robust against frequency selective multipath fading channels. OFDM not even with frequency diversity introduced by channel coding achieves similar performance in comparison with SC-FDE mode, the same conditions. Therefore, SC-FDE should be seen as a serious alternative to OFDM, specially, in deployment scenarios where high PA efficiency is required, since it does not suffers from high PAPR values. Furthermore, 11 Gbps data transmission throughput over mmWave channels using



(a)

(b)

Fig. 5: BER comparison performance uncoded OFDM and SC-FDE employing uncoded 16/64/256 QAM modulations over: a) CM1 b) CM2.



(a)

(b)

Fig. 6: BER comparison performance coded OFDM and SC-FDE employing uncoded 16/64/256 QAM modulations over: a) CM1 b) CM2.

both OFDM and SC-FDE are possible. This is achieved with slightly design refinements, from the original IEEE 802.15.3c proposal, which proves wireless communications systems providing multi-Gigabit/s of data rates, transmitted at such higher frequencies, will work on 5G networks.

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TABLE III: Summary of the required E_b/N_0 dB for CM1 and CM2 channel models, employing both OFDM and SC-FDE modes.

Channel model [#]	**Modulation order**	**Required SC-FDE E_b/N_0 [dB]†**	**SC-FDE Gain [dB]***
1	16	5	0.5
	64	15.5	1.5
	256	21.5	1.5
2	16	17.5	4
	64	21.5	5.5
	256	27.5	6

(*) difference between the required SC-FDE E_b/N_0 with OFDM one, under the same conditions.

(†) considering a BER target of 10^{-5}.

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