

Performance and PAPR Analysis of Single-Carrier Massive MIMO Systems with Channel Imperfections

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Abstract—The performance of a single carrier system employing a large number of antennas is explored in this paper, considering the realizability in the millimeter-Wave (mmWave) range in 5G standardization. A significant disadvantage of Orthogonal Frequency division Multiplexing (OFDM) systems, which are currently being used in 4G LTE downlink, is its large peak-to-average power ratio (PAPR). In addition, considering massive multiple-input-multiple-output (MIMO) scenario, implementing Inverse fast Fourier transform (IFFT)/fast Fourier transform (FFT) blocks per antenna branch makes the transceivers susceptible to higher complexity in implementation. A single carrier system has therefore the advantage of being relatively simple at the receiver side. However, due to the precoding needed in the downlink, the PAPR value increases with the number of channel taps. Performance of the system is investigated through simulations for single and multiuser cases with different large antenna configurations. Various channel configurations were considered including channel correlation, a measured channel model, and errors in the channel estimate. It can be seen from the results that single carrier scheme with sufficiently higher number of antennas at the base station side provides good bit error rate (BER) performance.

Index Terms - Single Carrier; Massive MIMO; OFDM; PAPR; Frequency selective channels

I. INTRODUCTION

5G mobile communications standard, which is expected to be in use by the year 2020, needs to cater a wide range of usabilities. The enhanced mobile broadband scenario of 5G requires network capacity of thousand times the capacity of the current network, 10 Gbps peak data rate with 100 Mbps at cell edge, and less than a millisecond of network latency. In order to cater these requirements, 5G needs technologies to enhance spectral efficiency, energy efficiency, bandwidth, and coverage, compared to existing standard. Adoption of massive MIMO and the millimeter-wave (mmWave) spectrum are two of the key technologies considered for 5G in order to achieve expected parameters. The regular, highly applied multi-carrier system is essentially OFDM based in current 3GPP standards, covering LTE and its evolution. This will be the likely scenario even in 5G subject to some filtered transmissions for the lower frequency region below 6 GHz in the development of new radio (NR) air interface [1]. It is well known that the PAPR performance of OFDM systems is quite poor, resulting in distortions and spectral leakage. Given the way 3GPP standardization is evolving, massive MIMO is going to be a reality sooner rather than later [2], [3]. This also takes into account the fact that there will be new frequency ranges being explored in the mmWave range

[4], where work is going on to develop new radio access technologies (RAT). One disadvantage of a large number of antennas in a multi-carrier system will be the large number of IFFT/FFT blocks that will be needed. Given both these issues, it will be good to have a system which can take advantage of the higher number of antennas being deployed in base stations. One direct implication from Marzetta's work [5] is that there is the possibility of a reduced complexity receiver, utilizing the large dimension and hence, realizable orthogonality. It is also important to see the performance of such massive-MIMO systems with closer to reality channel models which are not available in existing work. In this paper, some of the performance results are obtained using measured channels obtained by the colleagues in our laboratory [6], [7]. In addition, correlated channels such as uniform linear array, and exponential correlation are also considered.

The main reason why multi-carrier OFDM based system is universally adopted is due to the simplicity of the receiver implementation, which circumvents the need for sophisticated and complex equalization. With a single carrier system, the issue of equalizer can be managed, provided one of the sides has a large number of antennas. Another practical thing to be dealt with, given the large number of channels to be measured is the accuracy of estimate. Attention must be paid therefore to have a realistic performance analysis.

A survey of single-carrier systems has been presented by Yang et al. [8]. With the incorporation of MIMO methods in practical wireless systems, e.g., LTE, 4G, it has been possible to improve the link reliability and provide a higher capacity, with better spectral efficiency. Moving further along this path, there has been a tremendous amount of research in massive MIMO techniques. Marzetta [5] showed that it is possible to mitigate the effects of fast fading and uncorrelated receiver noise through orthogonality, arising out of large dimensions of matrices due to the large number of antennas. Pitarokoilis et al. [9] considered the application of single-carrier transmission in large scale antenna system in the downlink, where they showed that the receiver side can essentially work without an equalizer. This effect is due to the properties as shown by [5]. Here, the base station transmitter uses a precoding scheme matched to the frequency selective channel. Though single-carrier method here eliminates the use of an equalizer, it is worthwhile to analyze the effect on the PAPR. Sheng et al. [10] investigated a single-carrier modulation uplink scheme for a Rician channel with maximum likelihood (ML) equalization expanding on [9]. A more detailed study is given in [11]. In the case of

a Rayleigh fading channel, the receiver will become simpler with a one tap equalizer similar to that used in an OFDM system. There has also been a lot of work for single-carrier schemes which employ a cyclic prefix and frequency domain equalization [12]. Together with [8], therefore, the literature on single-carrier systems has been gaining significant momentum.

As mentioned previously, there are several issues specific to each downlink and uplink single carrier systems. In the case of downlink with multiple radio frequency (RF) chains for a large antenna system, a signal with least distortion is desirable for transmission, since this has direct consequences to the spectral mask which is tightly regulated. As the number of carriers increase, this poses a considerable challenge in OFDM systems. If, however, this can be resolved with a single carrier scheme which does not have the same PAPR properties, it will be quite useful. Naturally, the fundamental reason why in the first place OFDM was preferred has to be looked in this light, i. e., the need for simpler receiver structure with one tap equalizer. While it can be shown that with a higher number of antennas, the receiver of a single carrier system can still be less complex, as opposed to a full-fledged time domain equalizer needed in a frequency selective channel with multiple taps, and a system employing high level modulation for increased bit rates. The performance of such a system, under less ideal conditions needs to be further investigated in order to benchmark against the traditional OFDM system.

Several aspects of a single-carrier system are investigated, considering a single cell. On the downlink, the issue of beamforming is crucial to deliver a user specific signal without being fully interfered by other user signals. PAPR of the downlink single carrier system needs to be analyzed with beamforming / precoding taken into account since the main advantage of single carrier systems is its low PAPR. At the receiver side for both downlink and uplink cases, the reliability of the channel estimate plays an important role in the performance. These aspects are investigated comprehensively, for different channel profiles, user numbers, and antennas at the base station. Some cases of measured channels will be used as well, in order to get a more realistic understanding of the system being considered.

The rest of this paper is organized as follows. In Section II the system model for uplink is explained, followed by the system model for downlink in Section III, along with corresponding bit error rate (BER) performance and PAPR analysis. Section IV gives a brief explanation on measured channel models. Conclusions are presented in Section V.

II. SYSTEM MODEL: UPLINK

A system with K user terminals (UTs) are considered, each equipped with a single antenna. The base station has M receive antennas. The frequency selective channel has $L + 1$ equi-spaced taps which are Rayleigh distributed. Let $h_k[l, m]$ be the l^{th} tap in the discrete channel from k^{th} UT to m^{th} receive antenna at the Base Station (BS). The notation in [10] is followed.

Let $\mathbf{x}[n] = (x_1[n], x_2[n], \dots, x_K[n])^T$ be the transmitted signal vector and $\mathbf{w}[n] = (w[n, 1], w[n, 2], \dots, w[n, M])^T$ be the additive noise vector. The received signal $\mathbf{y}[n] =$

$(y[n, 1], y[n, 2], \dots, y[n, M])^T$ will be,

$$\mathbf{y}[n] = \sum_{l=0}^L \mathbf{H}[l] \mathbf{x}[n-l] + \mathbf{w}[n], \quad (1)$$

where, $\mathbf{H}[l] =$

$$\begin{bmatrix} h_1[l, 1] & h_2[l, 1] & \dots & h_K[l, 1] \\ h_1[l, 2] & h_2[l, 2] & \dots & h_K[l, 2] \\ \vdots & \vdots & \ddots & \vdots \\ h_1[l, M] & h_2[l, M] & \dots & h_K[l, M] \end{bmatrix}.$$

Considering that channels have $L + 1$ paths, the transmitted symbol vector at time n is estimated by received vectors up to time slot $n + L$. Therefore assembling the transmit, receive and noise vectors as follows;

$$\mathcal{Y} = (\mathbf{y}[n+L], \mathbf{y}[n+L-1], \dots, \mathbf{y}[n])^T, \quad (2)$$

$$\mathcal{X} = (\mathbf{x}[n+L], \mathbf{x}[n+L-1], \dots, \mathbf{x}[n-L])^T, \quad (3)$$

$$\mathcal{W} = (\mathbf{w}[n+L], \mathbf{w}[n+L-1], \dots, \mathbf{w}[n])^T. \quad (4)$$

Then, defining channel matrix as

$$\mathcal{H} = \begin{bmatrix} \mathbf{H}[0] & \mathbf{H}[1] & \dots & \mathbf{H}[L] & \dots & \dots \\ & \mathbf{H}[0] & \mathbf{H}[1] & \dots & \mathbf{H}[L] & \dots \\ & & \ddots & \ddots & \ddots & \ddots \\ & & & \mathbf{H}[0] & \mathbf{H}[1] & \dots & \mathbf{H}[L] \end{bmatrix}. \quad (5)$$

Thus,

$$\mathcal{Y} = \mathcal{H} \mathcal{X} + \mathcal{W}. \quad (6)$$

The maximum likelihood (ML) receiver is,

$$\mathbb{H}^H \mathcal{Y} = \mathbb{H}^H \mathcal{H} \mathcal{X}. \quad (7)$$

Where, $\mathbb{H} = (\mathbf{H}^T[L], \mathbf{H}^T[L-1], \dots, \mathbf{H}^T[0])^T$. Given that the number of base station antennas; M is large enough, a simplified receiver is therefore [5], [10],

$$\tilde{\mathbf{x}}[n] = \frac{1}{M} \mathbb{H}^H \mathcal{Y}. \quad (8)$$

Up to now we have assumed that ideal channel state information (CSI) are available at the receiver side. Let us consider the scenario where there is uncertainty in the CSI used. This can be modeled as follows,

$$\tilde{h}[n, m] = h[n, m] + \epsilon[n, m], \quad (9)$$

where the estimation error or the uncertainty, $\epsilon[n, m]$ is modeled as a circularly symmetric complex Gaussian random variable and is independent for each tap.

A. Simulations

Table I lists the parameters used in the simulations for both uplink and downlink. In this section, the behavior of the performance of the system is investigated with different parameters in terms of the number of users, antennas, channel taps. 16QAM is used as the modulation scheme. The Fig. 1 shows the performance with different number of users with ideal CSI, whereas Fig. 2 shows the performance with different number of antennas for 4 users. From Fig. 1 it can be seen that an error floor is present when the number of users are

TABLE I: Simulation parameters.

System model	Uplink, Downlink
Number of antennas	100-500
Channel	Independent, Correlated, Practical channel
Number of users	1-9
Number of channel taps	2-20
Modulation scheme	QPSK, 8-PSK, 8-QAM, 16-QAM

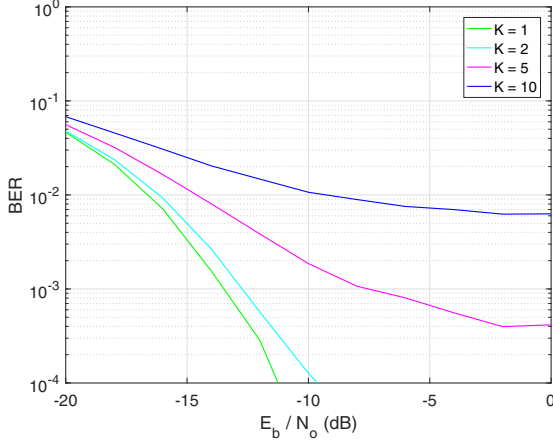


Fig. 1: Uplink performance of a system with 300 receive antennas and 20 channel taps for variable users.

higher (i.e. 5 and 10 users) due to the additional interference. But as seen from Fig. 2, this can be avoided by increasing the number of receive antennas (as 500 and 1000 antennas). Also the results indicate that the reduced complexity receiver performs well in the given antenna regime. This is an important observation since the receiver is not the optimal. In Fig. 3 single and multiple user performance is considered for higher number of taps with ideal CSI and with errors in CSI (0 dB error in variance). The degradation in performance compared to ideal CSI is seen to increase with the number of users. Having a larger number of antennas can address both these issues to a certain extent as seen in the results. Even in the case of OFDM this is the scenario as well, that the performance is compromised with multiple users operating within the same set of subcarriers.

III. SYSTEM MODEL: DOWNLINK

In the case of downlink, a similar scenario with the base station and the users is assumed. The main difference in this case is that the transmit signal will be precoded based on the channel response or CSI at the transmitter (CSIT). Thus, following [9], if $\mathbf{s}[i] = (s_1[i], s_2[i], \dots, s_K[i])^T$, where $s_k[i]$ is the information symbol to be communicated to the k^{th} user at time i , and \mathbf{H}_l is an $M \times K$ matrix whose $(m, k)^{\text{th}}$ element is $h_l[m, k]$, which is the conjugate of the l^{th} tap of the channel between m^{th} transmit antenna to k^{th} user, the transmit vector

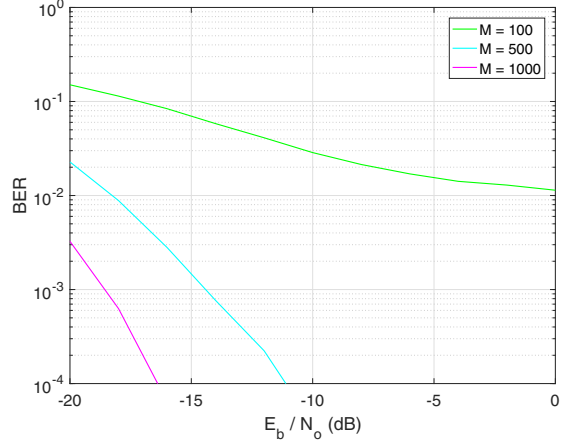


Fig. 2: Uplink performance of a system with 4 users, 20 channel taps for variable number of receive antennas.

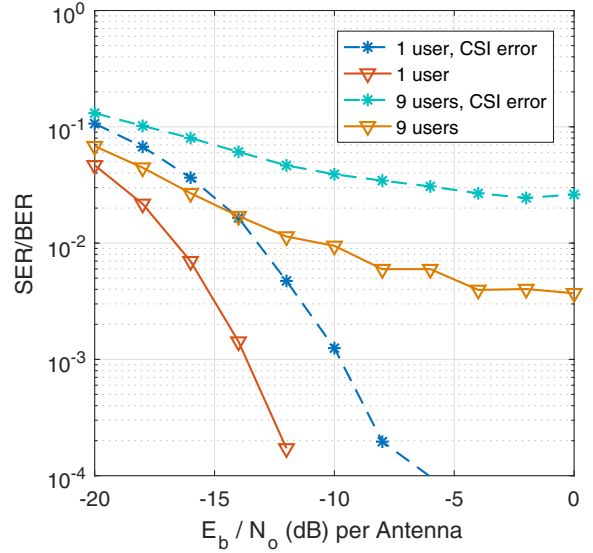


Fig. 3: Uplink symbol error rate (SER)/ BER performance of a system with 300 receive antennas, 9 users and 0 dB Error in CSI.

is given by

$$\mathbf{x}[i] = \sqrt{\frac{\rho_f}{MK}} \sum_{l=0}^{L-1} \mathbf{H}_l \mathbf{D}_l^{1/2} \mathbf{s}[i+l], \quad (10)$$

where, ρ_f is the long term average total power at the BS antennas. If $\mathbf{n}[i] = (n_1[i], n_2[i], \dots, n_K[i])^T$, where $n_k[i]$ is the $\mathcal{CN}(0, 1)$ distributed AWGN at the k^{th} receiver at time i , the received signal vector at time i is therefore [9],

$$\mathbf{y}[i] = \sum_{l=0}^{L-1} \mathbf{D}_l^{1/2} \mathbf{H}_l^H \mathbf{x}[i-l] + \mathbf{n}[i]. \quad (11)$$

Here $\mathbf{D}_l = (d_l[1], d_l[2], \dots, d_l[K])$, where $d_l[K] \geq 0, l = 0, 1, \dots, L-1$ gives the power delay profile (PDP) of each user

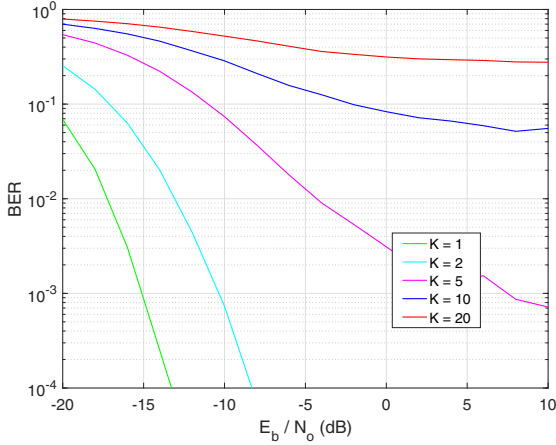


Fig. 4: Downlink performance of a system with 500 transmit antennas and 5 channel taps for variable users.

K . Further PDP for each user is normalized such that,

$$\sum_{l=0}^{L-1} d_l[k] = 1, \quad k = 1, \dots, K. \quad (12)$$

Due to the orthogonality in the channel matrices [5], as in the case of uplink large number of antennas are at the base station side, the information symbol vector can be estimated with asymptotic optimality. We also investigate the issue of CSIT error which is normally unavoidable in this scenario in any practical set up.

A. Simulations

Here, the performance of the system is investigated with different parameters in terms of the number of users, antennas, and channel taps. The degradation in performance when number of taps is large, compared to the single tap channel is not very significant, implying that the reduced complexity receiver is performing quite well. The Fig. 4 shows the performance with a different number of antennas under ideal CSI. The performance in the presence of channel uncertainty is investigated in Fig. 5. The degradation in the presence of CSIT error (0 dB) seems quite significant.

The downlink performance curves show a similar performance to uplink curves, agreeing with the fact that a larger number of antennas are needed to compensate for interference and non-idealities. As a general conclusion, one can say that the single carrier system performs satisfactorily in the massive MIMO paradigm expected to be strengthened by the application in the mmWave frequencies.

B. PAPR Analysis

As mentioned previously, to fairly compare an OFDM system with a downlink single-carrier system, the issue of PAPR [13] needs to be considered. This is due to the fact that the channel is frequency selective and pre-coding is carried out to match the transmit symbols to the channel. This is in contrast to the case of flat fading channel where it is more

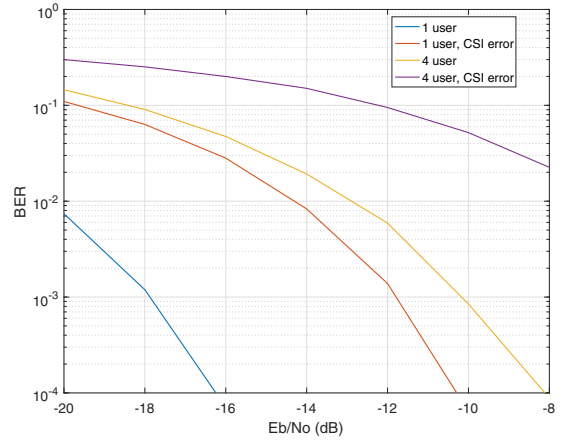


Fig. 5: Downlink performance of a system with 300 transmit antennas and 0 dB Error in CSI

involved due to multiple taps. To better approximate the PAPR of continuous time OFDM signals, OFDM samples are taken by several times oversampling [14], [15], where a survey of methods dealing with this issue is presented. Following the same arguments and assuming a certain carrier frequency f_c , we can calculate PAPR for single-carrier systems.

Using (10) as the transmit signal the PAPR is given by,

$$PAPR\{x[n]\} = \frac{\max_{0 \leq n \leq N} [|x[n]|^2]}{E[|x[n]|^2]}. \quad (13)$$

The complementary cumulative distribution function (CCDF) for PAPR is the probability of OFDM symbols with PAPR exceeding some threshold λ . In the case of OFDM, a typical plot is shown in Fig. 6. The Fig. 7 shows the CCDF plot of single-carrier PAPR. It can be seen that PAPR increases as the number of channel taps increases. As Fig. 7 shows the PAPR value can change significantly when we consider a precoded downlink signal. The values are seen to vary from 6–10 dB without any other modifications such as windowing etc.

In the case of OFDM systems, PAPR can be as high as 12 dB as seen in Fig. 6 [14] and normally some methods are employed for the reduction of these values. Similar approaches can also be considered for the OFDM systems which can lower the values to 4–8 dB range [16]. One can therefore say there is still a significant PAPR advantage in using single-carrier systems in the downlink coupled with the reduced complexity receiver.

C. Correlated Channels

In the previous cases, we did not consider another effect which is normally present in multiple antenna systems. This is the correlation among antennas which also is a significant factor as the number of antennas increases. Therefore, in the following we consider several cases with two of the possibilities; exponential (Exp) and uniform linear array (ULA) correlation.

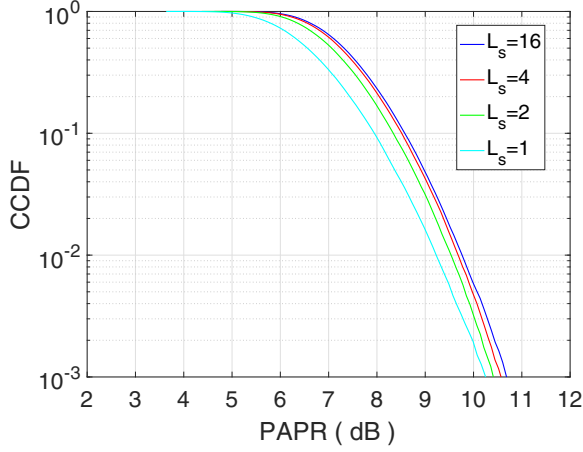


Fig. 6: PAPR performance of OFDM for variable oversample factor L_s .

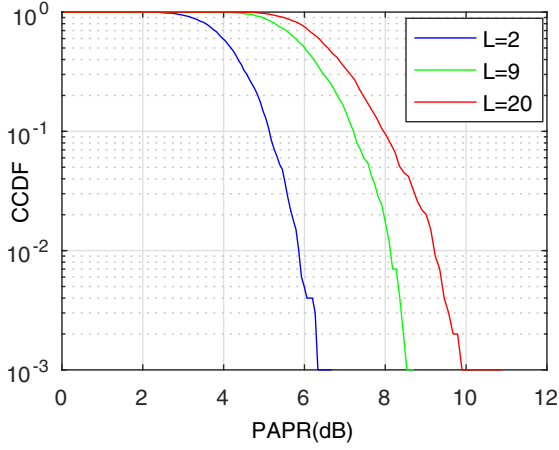


Fig. 7: PAPR performance of a downlink system for variable channel taps.

1) *Exponential correlation*: Let a be the exponential correlation coefficient. Then exponential correlation matrix of a channel with M BS antennas will be

$$\mathbf{t} = \begin{bmatrix} 1 & a & \dots & a^{M-1} \\ a & 1 & \dots & a^{M-2} \\ & & \ddots & \vdots \\ a^{M-1} & \dots & & 1 \end{bmatrix}. \quad (14)$$

2) *Uniform linear array*: In a typical ULA, where antennas are placed along a line with length D , the distance between m^{th} and m_0^{th} antennas will be [11],

$$d = \frac{(m - m_0)D}{M - 1}. \quad (15)$$

Then, spatial correlation between any two antennas with distance d will be

$$\rho\left(\frac{d}{\lambda}\right) = \frac{J_0(2\pi d)}{\lambda}, \quad (16)$$

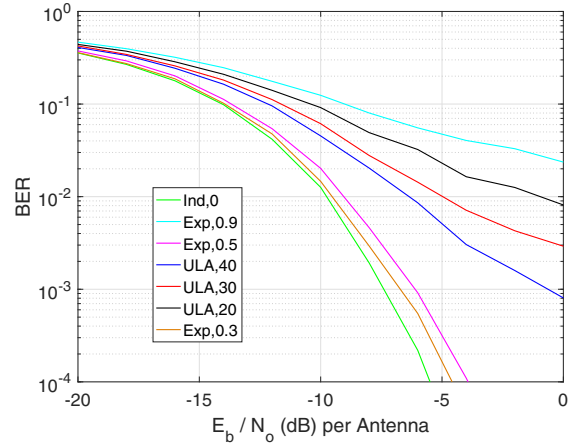


Fig. 8: Downlink QPSK performance of a system with 200 transmit antennas, 5 channel taps, and 4 users for correlated channels.

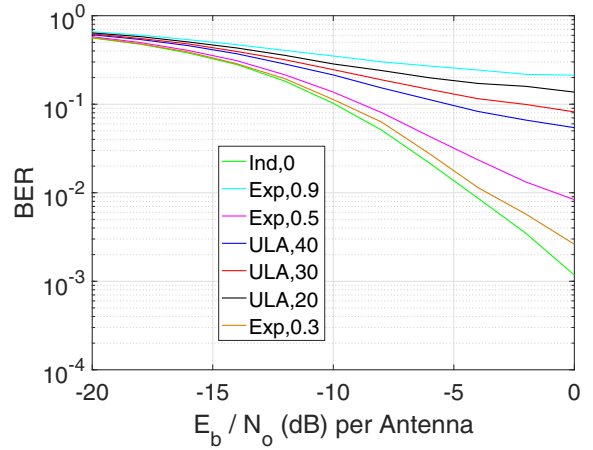


Fig. 9: Downlink 8PSK performance of a system with 200 transmit antennas, 5 channel taps, and 4 users for correlated channels.

where $J_0(\cdot)$ is the zeroth order Bessel function of the first kind.

3) *Simulations*: The Figs. 8 and 9 show the BER curves for different correlated channels with *QPSK* and *8PSK* respectively with clear degradation for higher correlation. The correlation is unavoidable given the cases where the close spacing of antennas is likely or needed even in the mmwave region. Application of suitable channel codes may be one way to address this [17], [18].

IV. PRACTICAL CHANNEL MODELS

It is also important to evaluate the performance of a single carrier system with a measured channel model; in the case of 5G, at 10GHz, in order to get a more realistic idea about the performance. Here, a Quadriga based model modified as given in [6], [7] is employed. The coefficients of the channel matrix are in the order of $10^{-5} - 10^{-9}$, which is very low. Thus,

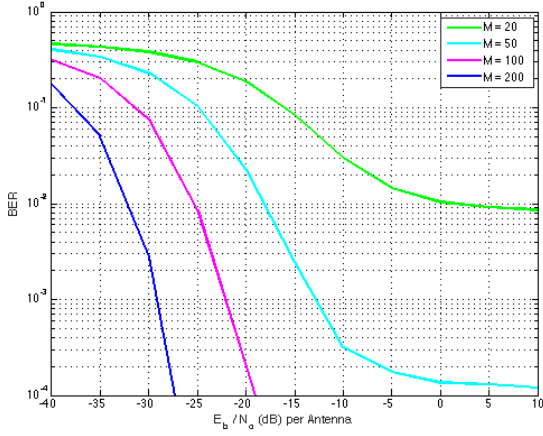


Fig. 10: Uplink QPSK performance of a system with 2 users, 9 channel taps and variable number of antennas in a practical channel model.

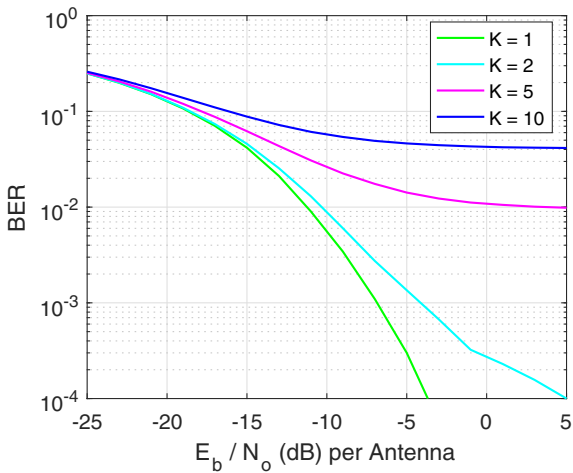


Fig. 11: Uplink 8PSK performance of a system with 200 antennas, 9 channel taps and variable number of users in a practical channel model.

in our case the channel matrix is normalized across M BS antennas to produce coefficients in the order of 10^{-1} .

A. Simulations: Uplink

The Figs. 10 and 11 show the BER with $QPSK$ and $8PSK$ modulated signals. $QPSK$ modulated signals have acceptable performance with 50 BS antennas for four user case. In the case of 8 PSK with 100 BS antennas a higher number of users will degrade the performance.

V. CONCLUSION

In this paper, the performance of a single carrier massive MIMO system is presented for both uplink and downlink with single user and multiple user cases. A variety of channel configurations were investigated from errors in channel estimate, correlated channels, to measured channels. As opposed

to traditional single carrier systems, we did not consider any cyclic prefix or frequency domain equalization. A simplified receiver structure is used which is shown to be effective as the number of antennas increases. The degradation in performance is evident with the number of users. However, this will be the same for any other multi-user system as well. The PAPR performance shows that higher values are obtained with a higher number of taps in the case of the downlink, due to beamforming needed. On the other hand, in the case of uplink, the main processing will be done in the base station. Therefore, the proposed single carrier system will be a good match there. In general as an access method for mmWave region of the new air-interface of 5G New Radio, this is seen to be a viable alternative to multicarrier techniques currently being standardized for the lower frequency range.

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