INTERNATIONAL JOURNAL OF TECHNO-ENGINEERING
IJTE

ISSN: 2057-5688

Analysis of 5G Wireless Systems in FR1 and FR2 Frequency Bands

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***Abstract*—** According to 3GPP, the frequency bands of 5G technologies are occupied at various parts of the frequency spectrum. E.g. mmWave frequencies are used for short-range communications in 5G mobile communications which can provide much higher bandwidth, supports greater data rates and also overcome the effect of path loss using carrier aggregation feature. However, the frequency bands for 5G wireless technology are classified into FR1 and FR2 frequency ranges. FR1 (4.1 GHz to 7.125 GHz) band of frequencies are used for carrying most of the traditional cellular mobile communications traffic, while the FR2 (24.25 GHz to 52.6 GHz) band of frequencies are focused on shortrange, high data rate capabilities. A frequency selective wireless channel is converted into a parallel collection of frequency flat sub-channels using "Orthogonal Frequency Division Multiplexing (OFDM)" techniques that improve multipath fading issues and bandwidth efficiency, also reduces the inter-sub carrier interference. The recent wireless communication standards like 802.11x families combine the techniques of multiple-inputmultiple-output (MIMO) and OFDM to provide improved data rates. As MIMO uses an array of antennas, and it is possible to achieve a higher signal-to-noise ratio (SNR) using "beamforming" which in turn reduces the bit error rate (BER). This research paper is focused on the performance of hybrid beamforming for single user and multi-user "massive MIMO-OFDM systems" and facilitate to explore various system-level configurations for different channel modellings in FR1 and FR2 bands.

***Keywords*—**5G, mmWave communication, massive MIMO, hybrid beamforming, OFDM.

I. INTRODUCTION

Modern wireless communication systems are using "Spatial multiplexing" to enhance the throughput of transmitting data within the wireless system in severe scattered channel conditions. To transmit multiple data streams through the wireless channel, a channel matrix is used to derive a set of precoding and combining weights both magnitude and phase terms. At the receiver (Rx), each data stream is recovered independently. 5G wireless systems have an advantage of higher bandwidth at "millimeter wave" (mmWave) frequency. Also, 5G wireless systems minimize severe propagation loss in the mmWave band by deploying large scale of antenna arrays at the cost of unique technical challenges. 5G NR defines the cyclic prefix lengths for all subcarrier spacings in such a way that OFDM symbols align regularly, irrespective of the subcarrier spacing. A carrier and bandwidth part in 5G is characterized by a subcarrier spacing, several resource blocks, and a starting resource. For the given bandwidth, the number of resource blocks is less at higher subcarrier spacings and vice versa. A bandwidth part is associated with the carrier that has the same subcarrier spacing, but there are several bandwidth parts with the same carrier spacing. Bandwidth parts can be seen as a way to address the available spectrum to a UE. Bandwidth parts address the issues like when UEs may not be able to receive the full bandwidth, even when UE is capable of receiving a large bandwidth, it will save power if it can be addressed with smaller bandwidth. Situations when UEs doesn't want high data rates then. One UE can be associated with up to four bandwidth parts, however, one UE can only have a single bandwidth part active at a time. These bandwidth parts are preconfigured, and the UE can be instructed to switch between these different parts over time. The resource element in 5G NR is the smallest time by frequency unit, which is one subcarrier by one OFDM symbol. A resource block is defined as a group of 12 subcarriers with no associated time duration. Beamforming is a method of concentrating radio frequency (RF) energy in a particular direction and this technology allows Access Point (AP) to see where the signal is getting dropped and adjust accordingly. MIMO wireless systems are increasingly being used in recent communication systems for higher gains in capacity by realizing them using multiple antennas that use spatial dimension apart from time and frequency dimensions, without varying bandwidth of the wireless system. Table I shows the various possible operating

ISSN: 2057-5688

frequencies in FR1 of 5G NR [11] [12]. As the carrier frequencies in 5G can be as high as 60 or 70 GHz, (whereas in LTE carrier frequencies are < 6GHz) there has been significant consequences on the design of the physical layer, as beamforming becomes required to support those higher frequencies. At those higher frequencies, more spectrum is available, and 5G NR is set to take advantage of this spectrum with up to 400 MHz of bandwidth. At higher carrier frequencies, signals need to be beamformed to overcome propagation losses. As a result, it is both difficult and not useful to provide cell-wide reference signals. The signal strength would be too low and each channel is beamformed which means that the UE would need to be informed of the precoding matrix separately. Instead, UEs in 5G rely on reference signals that undergo the same beamforming as the associated channel. The 5G standard distinguishes between two ranges for carrier frequencies called FR1 (< 6GHz with TDD & FDD), FR2 (23-53 GHz with TDD). These two ranges correspond to very different propagation conditions and some physical layer settings only apply to one of those modes [8] [13] [14].

TABLE I. 5G NR OPERATING FREQUENCIES IN FR1

Band	Range of frequencies in FR1			
	Uplink [GHz]	Downlink [GHz]	Bandwidth [MHz]	Duplex Mode
n1	1.92- 1.989	2.11-2.17	60	FDD
n2	1.85-1.91	1.93-1.99	60	FDD
n3	1.171-1.785	1.805-1.88	75	FDD
n5	0.824-0.849	0.869-0.894	25	FDD
n7	2.5-2.67	2.62-2.69	70	FDD
n8	0.88-0.915	0.925-0.96	35	FDD
n20	0.832-0.862	0.791-0.821	30	FDD
n28	0.703-0.748	0.758-0.803	45	FDD
n66	1.71-1.78	2.11-2.2	90	FDD
n70	1.695-1.71	1.995-2.02	15/25	FDD
n71	0.663-0.698	0.617-0.652	35	FDD
n74	1.427-1.47	1.475-1.518	43	FDD
n38	2.57-2.62	2.57-2.62	50	TDD
n41	2.469-2.69	2.469-2.69	194	TDD
n50	1.431-1.517	1.431-1.517	85	TDD
n51	1.427-1.432	1.427-1.432	5	TDD
n77	3.3-4.2	3.3-4.2	900	TDD
n78	3.3-3.8	3.3-3.8	500	TDD
n79	4.4-5	4.4-5	600	TDD

5G NR defines the waveform to be OFDM [7] with a cyclic prefix. It decreases the guard band for the waveform (5G waveforms are not limited to 90% of the bandwidth unlike in LTE). The subcarrier spacing in 5G is variable and it is powers of two multiples of 15 kHz up to 240 kHz. As a result, the OFDM symbol duration is reciprocal of the subcarrier spacing, and it shrinks by a factor 2, 4, 8, 0r 16 for the highest subcarrier spacing. The maximum supported bandwidth is 50MHz at 15 kHz subcarrier spacing and it doubles each time to reach 100, 200, 400MHz at 120 kHz spacing. For the highest subcarrier spacing of 240 kHz, the number of supported subcarriers is halved, which means that the bandwidth is still 400MHz. As subcarrier

ISSN: 2057-5688

spacing increases, supported bandwidth increases and duration of OFDM symbol and latencies at physical layer decreases. 5G NR retains the concept of 10msec frame divided into 10 subframes of 1msec duration each however, the slot definition is different from LTE. One slot is defined as 14 OFDM symbols, which corresponds to one subframe in LTE. In 5G, the number of slots per subframe changes due to variable subcarrier spacing. As the subcarrier spacing doubles, the slot length is halved, because the OFDM symbol length is halved. For this reason, the number of slots per subframe doubles. The subcarrier spacing of 15, 30, 60 kHz is available in FR1. For FR2, which corresponds to mmWave frequencies, data transmission can only use subcarrier spacing 60 kHz or 120 kHz. But, 240 kHz subcarrier spacing is reserved for non-data channels (synchronization signal block).

TABLE. II 5G NR SUPPLEMENTARY FREQUENCY BANDS IN FR1

Band	Range of frequencies in FR1		
	Uplink [GHz]	Downlink [GHz]	Bandwidth [MHz]
n75	---	1.432-1.517	85[a]
n76	---	1.427-1.432	5 [a]
n80	1.171-1.785	---	75 [b]
n81	0.88-0.915	---	35 [b]
n82	0.832-0.862	---	30 [b]
n83	0.703-0.748	---	45 [b]
n84	1.92-1.98	---	60 [b]

[a.] Supplementary Downlink band(SDL)

[b.] Supplementary Uplink band (SUL)

TABLE. III 5G NR OPERATING FREQUENCIES IN FR2 BANDS

Band	Range of frequencies in FR2			
	Uplink [GHz]	Downlink [GHz]	Bandwidth [MHz]	Duplex Mode
n257	26.5- 29.5	26.5- 29.5	50-400	TDD
n258	24.25- 27.5	24.25- 27.5	50-400	TDD
n259	39.5- 43.5	39.5- 43.5	50-400	TDD
n260	37.0- 40.0	37.0- 40.0	50-400	TDD
n261	27.5-28.35	27.5-28.35	50-400	TDD

II. LITERATURE SURVEY

There are 3 types of beamforming (BF), static BF is performed by using many directional antennas grouped aiming away from a center point to provide a fixed radiation pattern. Dynamic BF can dynamically adjust the radiation pattern to provide the best signal for each device connecting. The adaptive antenna array is used in this type to manoeuvres the beam in the direction of a targeted Rx and this technology is called “smart antenna technology” or “beam steering”. It can focus a beam in the direction of an individual user. Lastly, transmit beamforming (TxBF) performed by transmitting multiple phase-shifted signals and all these signals hopefully will arrive in-phase at the receiver. [1] classifies the hybrid beamforming techniques based on (i) amount of required CSI for the analog beamformer portion (ii) complexity (reduced/full complexity and switched), and (iii) range of carrier frequencies (cm-wave versus mm-wave, as the channel characteristics and RF impairments, are different for these range of frequencies). [1] Shows that instantaneous CSI provides improved Signal-to-Noise ratio (SNR) and Signal-to-interference ratio (SIR) and the average CSI provides minimum overhead for CSI acquisition. [2] explored the hybrid beamforming designs for Massive MIMO FDD downlinks and functionalities various RF chains at the UE. [2] Proves that the optimal design decoupling of analog precoder & combiner using strongest eigenbeams of the receive covariance matrix with Kronecker model of the channel and digital precoder to improve the conditional average signal-to-leakage and noise ratio. [2] Also proposes a weighted average mean square error minimization (WAMMSE) algorithm for improving a lower bound of the conditional average net sum rate. The simulated outputs show that the proposed algorithm gives better performance to support Massive MIMO FDD downlink under various scenarios also tells the essentiality of using conditional 2nd order channel statistics in designing a digital precoder to combat the inter-group interference [2]. [3] Chooses a single user transmit precoding & Rx combining in mmWave communication systems where traditional MIMO has been made high dependence on RF precoding. By taking the advantage of mmWave channel structures, [3] proposed a low cost and low complex hardware precoding algorithms and formulated mmWave precoder design as a sparsity-constrained signal recovery and proposed an algorithm that accurately approximates the optimal performance using orthogonal matching. The framework proposed in [3] also applied in designing MMSE combiners for mmWave communication systems. The precoding algorithm is well-applicable to limited feedback systems and quantized efficiently, also the output results in [3] match the theoretical values of spectral efficiency. [3] Showed the directions of research towards mmWave precoding techniques by relaxing the assumptions made like perfect CSI at Rx, information about antenna array structure and lastly the limited to narrowband channels. [4] Gives the guidelines for optimized pre-beamforming, for spectral efficiency under max-min fairness and proportional fairness criteria which gives good results. Proposed [5] two suboptimal techniques in the multiuser channel for optimum information transfer. First, block diagonalization algorithm asymptotically approaches capacity at high

INTERNATIONAL JOURNAL OF TECHNO-ENGINEERING
IJTE
ISSN: 2057-5688

SNR, second is successive optimization algorithm is well suited to minimizing the output power for fixed transmission rates. For lower SNR channels, it can outperform the first technique. However, both the techniques are straightforward, computationally efficient and allow a good tradeoff between computational complexity and performance. For channels where both the techniques are not applicable directly, the third technique called joint transmitter and Receiver (Tx-Rx) processing can be used to minimize the problem dimensionality. Both the algorithms proposed in [5] needs partial or complete Channel information at the Tx. Such information is very less at higher SNR for the single-user channel. The performance gap between theoretical and practical increases for higher and higher values of SNR or as many Tx antennas increases in the case of multiuser. This may lead to a higher cost of having CSI at the Tx more justifiable [6]. The authors [9] defined a transmission scheme "a joint spatial and power-domain multiuser (JSPM)" and it gives higher Power-domain multiplexing gain when it was compared with traditional spatial multiplexing schemes. The results were validated with 16 users/cell at system-level simulation and it was shown that JSPM gives 15% higher spectrum efficiency gain and it increases with the number of active users per cell. Another observation from the simulation results is that antenna array with a larger number of horizontal column antennas gives better performance, as the user distribution in the horizontal plane is more intensive compared to the vertical plane in practical networks.

TABLE IV. 5G NR PHYSICAL LAYER SPECIFICATIONS IN FR1 AND FR2 BANDS

Specification	FR1	FR2
Bandwidth/Carrier	5,10,15,20,25,30,40, 50,60,70,80,90,100 MHz	50, 100, 200, 400 MHz
Subcarrier Spacing	15, 30, 60 kHz	60, 120,240 kHz
Max. no. of subcarriers	3300 (FFT 4096)	---
Carrier aggregation	Up to 16 number of carriers	---
Modulation	QPSK, 16 QAM, 64 QAM, 256 QAM	---
Length of Radio frame	10msec	---
Length of Radio subframe	1msec	----
Duplex Mode	FDD, TDD	TDD
Multiple Access Scheme	Downlink: CP-OFDM Uplink: CP-OFDM, DFT-s-OFDM	---
MIMO Scheme [14]	Max. of 2 codewords mapped to Max. of 8 layers in downlink and 4 layers in the uplink	---

III.PROPOSED SYSTEM

This paper tells us the techniques of introducing "hybrid beamforming" at the Tx end of a "massive MIMO" wireless communications system for both single-user and multi-user wireless systems. To find the "channel state information (CSI)" at the Tx, full channel sounding technique is used. It divides the required precoding into analog RF components and digital baseband for single-user and multi-user wireless systems using various techniques. Simplified all-digital Rxs recover the multiple transmitted data streams to highlight the “error vector magnitude (EVM)” and BER which are common figures of merit for a wireless communications system and a static-flat MIMO channel is used for validating simulation

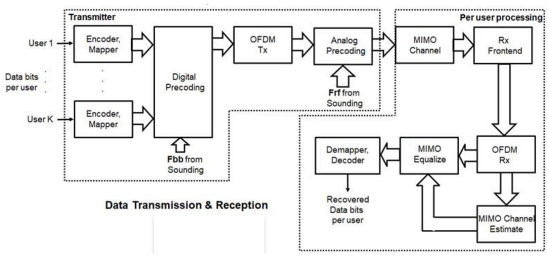

Fig. 1. Model for Data Transmission and Reception in MIMO-OFDM Systems

This paper uses two-channel types for validation purposes, namely, static-flat MIMO channel and spatial MIMO channel. While simulating the wireless system, single-bounce ray tracing approximation scattering model was used with a 100 parameterized number of scatterers. During the simulation, the scatters are modelled and randomly placed around the Rx within a spherical shape using “Scattering” option same as the one-ring model shown in [6]. The path-loss modeling can be performed for “line-of-sight (LOS)” as well as non-LOS propagation conditions while modeling the wireless channel. In our simulations, linear and rectangular array antennas are considered with isotropic radiation pattern for non-LOS path scenarios. Channel sounding and Data transmission were performed with the same channel conditions. Data transmission usually depends on the number of data symbols that can be more duration. The preamble is appended to the data symbols and it is used to evaluate the channel transmission stage and channel sounding stage. For data transmission stage validation, preamble improves the success of channel to a valid state and it is refused from the output of the channel. Multiple independent channels/user can be modeled for a multi-user system, and the Rx is modeled for each user that amplifies the signal for path loss compensation and thermal noise is added. Rx of a MIMO-OFDM system contains stages that include channel decoding, QAM demapping, MIMO equalization and OFDM demodulation. The received constellation of the equalized symbols provides a quality of MIMO system model. The actual BER can provide the quantitative analysis by comparing the received decoded bits/user with the transmitted bits. At the Tx, system parameters are configured which includes channel coding, mapping of bits to complex symbols, converting the individual data streams into more number of transmitted data streams, baseband precoding of the transmitting streams, pilot mapping of OFDM modulation and analog beamforming of RF sections for all the Tx antennas.

IV. RESULT

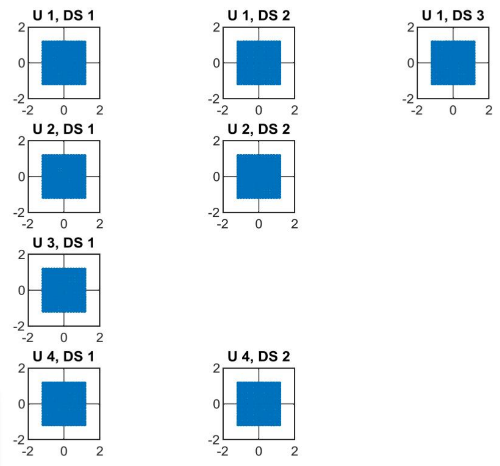

Fig. 2. Equalized Symbol Constellation per Stream for MIMO Channel

The simulation was performed by considering 4 users with multiple data symbols and the channel type was MIMO, the modulation schemes were chosen was QPSK, 16-QAM, 64- QAM and 256-QAM. The analysis was performed at a carrier frequency of 28 GHz in FR2 band and 6 GHz, 4 GHz in FR1 band with a channel sampling rate of 100 Mbps and the precoding weights of baseband and RF analog are determined for single-user, multi-user systems using Orthogonal Matching Pursuit algorithm and Joint Spatial Multiplexing algorithms respectively. The analysis is performed by calculating the Error vector magnitude for different modulation schemes at frequencies belongs to FR1 and FR2 bands with single and multiple users as shown in Table V.

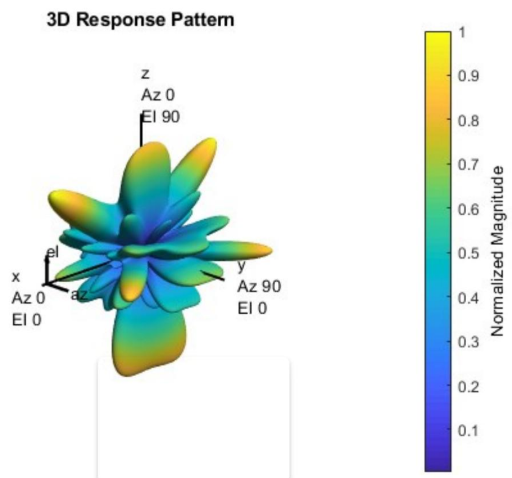

Fig. 3. Radiation Pattern for 256-QAM Modulation Scheme for MIMO Channel at a Carrier Frequency of 28 GHz

ISSN: 2057-5688

TABLE V PERFORMANCE OF MASSIVE MIMO BEAMFORMING OVER FR2 BANDS

Modulation Type	Number of Users	Output Parameters		
		RMS EVM (%) @ 28 GHz	RMS EVM (%) @6	RMS EVM (%) @4 GHz
QPSK	1	0.0003772	0.48885	0.58714
	2	0.0002321	1.3148	1.3114
	3	9.6198e-05	1.3807	1.5296
	4	0.0002179	0.55241	1.1716
16 QAM	1	0.00038581	0.49017	0.59282
	2	0.00023183	1.5244	1.2927
	3	9.4397e-05	1.3876	1.5435
	4	0.00021584	0.56225	1.1707
64 QAM	1	0.00037348	0.49095	0.59808
	2	0.000233	1.1141	1.456
	3	9.5877e-05	1.4276	1.544
	4	0.00022087	0.55508	1.1663
256 QAM	1	0.00039011	0.49437	0.592
	2	0.00022946	1.5608	1.372
	3	9.8535e-05	1.3833	1.5652
	4	0.00022505	0.55373	1.1552

From the results shown in Table V, it is clear that the error vector magnitude is higher at lower frequencies and it decreases with increasing frequencies. The figures from Fig. 2 to Fig. 7(except Fig. 3) represents the radiation patterns and equalized symbol constellation diagrams of various modulation schemes like QPSK, 16-QAM, 256-QAM and the corresponding radiation patterns at different carrier frequencies like 4 GHz, 6 GHz and 28 GHz. We have also compared the performance characteristics of MIMO Channel with Scattering channel and the corresponding radiation pattern was shown in Fig. 3. From the results, it is clear that the MIMO channel outperforms the Scattering channel in terms of signal transmission and the errors.

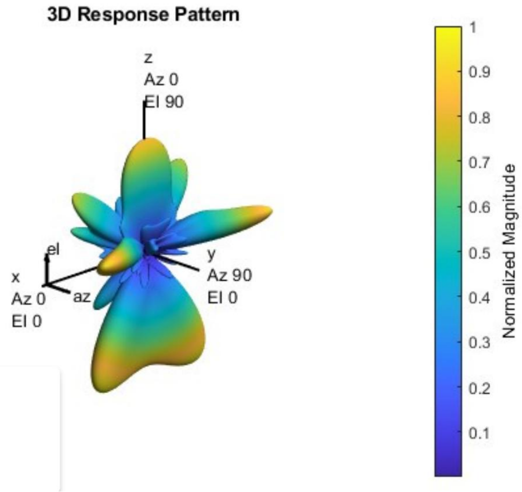

Fig. 4. Radiation Pattern for 256-QAM Modulation Scheme for Scattering Channel at Carrier Frequency of 6 GHz

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