Nonlinear Distortion Analysis in Wireless Cellular 5G IoT Systems

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***Abstract*—The performance analysis of the post-OFDM waveforms such as FBMC and UFMC as a potential 5G Redcap IoT modulation waveforms at n78 (3.3–3.8 GHz) 5G below 6 GHz frequency band and 64QAM, FBMC and UFMC waveforms at n258 (24.5 -27.5 GHz) is presented. The power spectral density and linearity improvement of FBMC which has the lowest OOB (out-of-band) emission over UFMC is about 8 dB and 5 dB for channel bandwidths of 3 MHz and 10 MHz respectively. Both 5G IoT FR 1 modulated waveforms are evaluated by simulation at saturation power levels for nonlinear distortions of the power amplifier (Mini-Circuits ZHL 4240W) using Matlab and Keysight's ADS software tools. The nonlinear distortion of the power amplifier (Analog Devices HMC930A) using the 5G IoT FR 2 64QAM, FBMC and UFMC waveforms for channel bandwidth of 100 MHz are evaluated using Keysight's System Vue. Power spectral density and linearity for 100 MHz FBMC waveform over UFMC waveform is about 20 dB achieved.**

Keywords—64QAM, FBMC; UFMC; 5G IoT Redcap; PSD; Spectral efficiency; OOB; and ACPR.

I. INTRODUCTION

Due to the growing popularity of 5G and IoT wireless cellular devices which has grown faster than LTE/4G [1]-[3]. According to 5G Americans, this technology has already exceeded 1.4 billion and it is anticipated to reach the 2 billion marks by the end of 2024 and is on track to reach 8 billion connections by 2028. IoT smart devices mean that there is going to be a massive connection of these devices to the network which must deliver higher throughput, and higher date rates. Almost 60 percent of cellular IoT connections are forecast to be broadband IoT, with 4G connecting the majority by the end 2028. With the emergence of 5G NR-Light (New Radio-Ligiht) known as RedCap (Reduced Capability) officially adopted into 3GPP Release 17 specifications in June of 2022, designed to address several specific use cases for 5G NR Release 15 (Rel-15), aimed at bringing mid-tier 5G capability, along with better power efficiency, and lower costs. 5G NR Rel-15 (Release 15) was primarily designed to address use case areas requiring lower latency, higher peak data rates, and ultra-reliability beyond legacy 4G wireless networks. A RedCap (Rel-17 NR) device is required to support up to 20 MHz in frequency range 1 (FR 1) and 100 MHz in frequency range 2 (FR 2), respectively for reception and transmission with maximum transmit power of 23 dBm in FR 1 and FR 2, respectively. For a baseline NR, (smartphone) these requirements are increased to 100 MHz in frequency range 1 (FR 1) and 200 MHz in FR 2, respectively with maximum transmit power of 26 dBm or 24 dBm in FR 1 and 23 dBm in FR 2. Some of the following Release 13, 14 and 17 and 18 IoT technology capabilities are:

Spectrum bandwidth:
NB-IoT (Rel-13/14): Licensed 700 – 900 MHz
Channel bandwidth: 200 kHz in LTE channel, and in LTE guard bands
LTE-M (Rel-13/14): Licensed 700 – 900 MHz
Channel bandwidth: 1.4/3/5 MHz in LTE channel
RedCap (Rel 17): Channel bandwidth: FR1: 5/10/15/20 MHz and FR2: 100 MHz in NR channel
RedCap (Rel 18): Channel bandwidth: FR1: 5 MHz in NR channel

Maximum data rate:
NB-IoT (Rel-13/14): < 100 kbps
LTE-M (Rel-13/14): up to 4 Mbps
RedCap: DL: 2 Mbps up to 150 Mbps
UL: 2 Mbps up to 50 Mbps, depends on use case

Modulation:
NB-IoT (Rel-13/14): BPSK, QPSK
LTE-M (Rel-13/14): 16QAM
RedCap: up to 64QAM

Antennas:
NB-IoT (Rel-13/14): 1
LTE-M (Rel-13/14): 1
RedCap: 1 (or 2 RX MIMO)

Latency:
NB-IoT (Rel-13/14): 1.6 s to 10 s
LTE-M (Rel-13/14): 10 ms to 15 ms
RedCap: Can be as low as 5 ms, depends on use case

Battery:
NB-IoT (Rel-13/14): up to 10 years
LTE-M (Rel-13/14): up to 10 years
RedCap: Up to 2 years, depends on use case

An evaluation and performance analysis of the nonlinear distortion behavior of two RF power amplifiers in cellular IoT systems using 64 QAM, FBMC and UFMC modulated waveforms are presented in this paper. All waveforms were evaluated and compared for 3 MHz, 10 MHz (FR 1 – R17 NR RedCap) and 100 MHz (FR 2 – R17 NR RedCap) channel bandwidths at the PA's nonlinear region. The paper is organised as follows. Section II considers the potential cellular 5G IoT waveforms and characteristics that form the basis of this paper. In section III, simulation results for 64 QAM, UFMC and FBMC waveforms are evaluated and presented. The conclusion is described in section IV.

II. Cellular Potential 5G IoT Waveforms and Characteristics

Here we will briefly describe Universal filtered multicarrier (UFMC) and Filter-bank multicarrier (FBMC) as potential post-OFDM 5G IoT waveforms [4]. In contrast to Cyclic Prefix (CP) OFDM which greatly reduces the bandwidth efficiency, FBMC is a type of modulation scheme, which is derived from OFDM which overcomes the drawbacks of OFDM. Unlike OFDM, there is no CP or guard time requirement in FBMC. Therefore, FBMC provides the high spectral efficiency at the output of the wireless transmitters compared to OFDM with designing a proper prototype filter and minimizes the interference between the adjacent subcarriers. The detail theoretical analysis of FBMC is described in [5]. UFMC is a filter technique between OFDM and FBMC. It uses a filter with sub-bands to achieve more spectral efficiency and robustness [6]-[7]. The detail theoretical analysis of UFMC is described in [8]. The illustration of the differences between baseline NR device (smartphone) and RedCap IoT device capabilities is shown Figure 1.

FR 1: 5/10/15/20 MHz (R17 NR RedCap)
FR 2: 100 MHz (R17 NR RedCap)

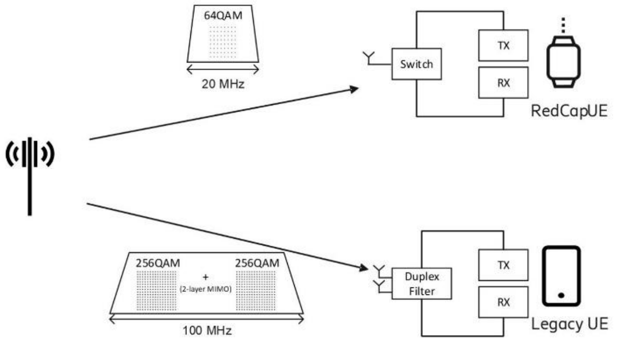

Figure 1. Illustration of the differences between R17 NR RedCap device and baseline NR device (smartphone) capabilities.

The comparison between the main cellular IoT device capabilities is shown in Table I. The main use cases of the 5G IoT RedCap specifications defined in 3GPP Release 17 are: industrial wireless sensors (motion, temperature, pressure and humidity sensors, and many existing and new applications), wearables (health monitors, smart watches, VR headsets), and surveillance video (agriculture, smart cities, factories). They have differing requirements in terms of data rate, availability, size, latency, and battery life already mentioned in Section I.

TABLE I. COMPARISON OF 4G AND 5G IoT DEVICE CAPABILITIES

	R17 NR RedCap	R18 NR e-RedCap	LTE-M (eMTC)	NB-IoT
Bandwidth	5/10/15& 20 MHz (FR 1) 100 MHz (FR2)	5 MHz (FR 1 only)	Cat1: 1.4MHz Cat2: 1.4/3/5 MHz	180 kHz
Duplex mode	FD/HD-FDD & TDD	FD/HD-FDD & TDD	FD/HD-FDD & TDD	HD-FDD & TDD
Antennas MIMO	1Tx1Rx 1Tx2Rx	1Tx1Rx 1Tx2Rx	1Tx1Rx	1Tx1Rx
Modulation	64QAM 256QAM (optional)	64QAM 256QAM (optional)	16QAM	QPSK
Max data rate (DL/UL)	2-150 Mbps 2-50 Mbps	10Mbps 10Mbps	CatM1: 600 – 1119 kbps CatM2: 4 – 7 Mbps	CatNB1 20-66kbps CatNB2 120-166 kbps

III. Results

This section evaluates, filter bank multicarrier (FBMC), and universal filtered multicarrier (UFMC) modulated waveforms at the compression point of the RF power amplifiers at 3.5 GHz. The frequency bands n78 (3.3–3.8 GHz) and n258 (24.5 – 27.5 GHz) respectively, were chosen as it is two of the main 5G IoT FR 1 (R17 NR RedCap) and FR 2 (R17 NR RedCap) frequency bands. Both modulated waveforms with channel bandwidths of 3 MHz, and 10 MHz, respectively were fed into RF power amplifier (Mini-Circuits ZHL-4240W) model at 3.5 GHz shown in Figure 1. with the following features:

Frequency range: 10 to 4200 MHz
Connectors: SMA
Gain: 40 +/- 1.5 dB
Max. output power P_{1dB}: 28 dBm
IP_{3dBm}: 38 dBm

Simulated output power spectra of the RF power amplifier fed by FBMC and UFMC waveforms are shown in Figure 2, and Figure 3, respectively. The simulations were performed using Keysight's ADS software tools and Matlab. The simulation setup is shown in Figure 4. The ACPR (Adjacent Channel Power Ratio) of the power amplifier for FBMC waveform is about 8 dB better in comparison with UFMC for 3 MHz channel bandwidth as shown in Figure 2.

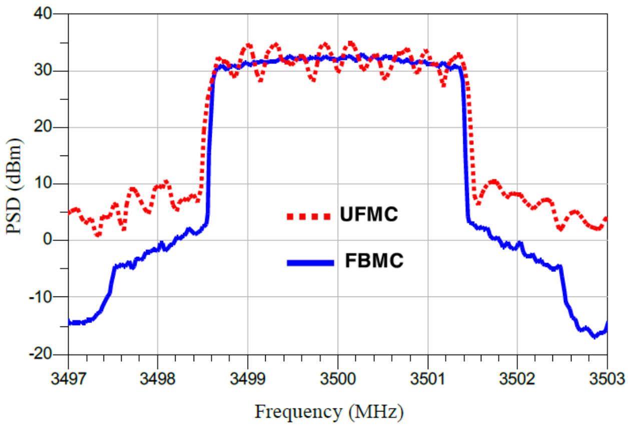

Figure 2. Output power spectra simulation of the power amplifier for 3 MHz channel bandwidth.

FBMC waveform seems to be a better choice here in terms of spectral efficiency for the 3 MHz bandwidth. Figure 3 also shows better spectral efficiency and linearity for FBMC. FBMC has gained about 5 dB improvement over UFMC. Therefor, for wider bandwidth such as 10 MHz, the spectral efficiency of FBMC shows a few dB improvement over UFMC.

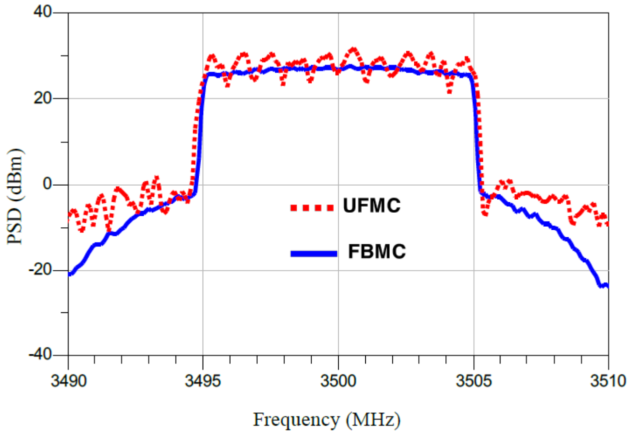

Figure 3. Output power spectra simulation of the PA for 10 MHz channel bandwidth.

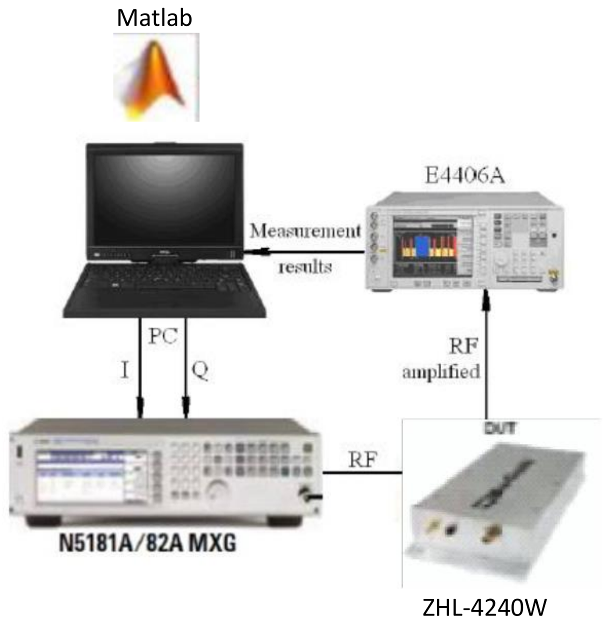

Figure 4. Simulation setup

The power amplifier (Analog Devices HMC930A) distortion performance for FR 2 64QAM, FBMC and UFMC waveforms with 100 MHz bandwidth at 26 GHz is shown in Figure 5.

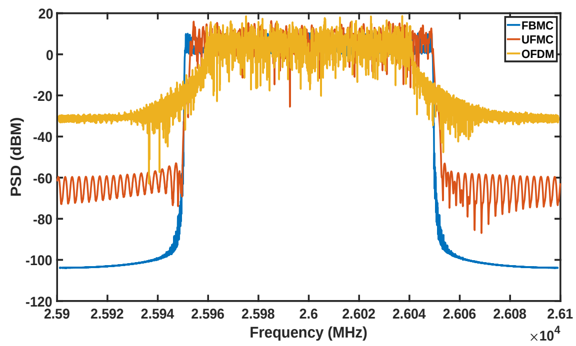

Figure 5. Output power spectra simulation of the power amplifier for 100 MHz channel bandwidth.

IV. Conclusion

This paper evaluates the performance of the two potentially post-OFDM leading 5G IoT waveform candidates such as FBMC and UFMC at m78 (3.3–3.8 GHz) 5G FR 1 frequency band. The channel bandwidths of interest were 3 MHz, and 10 MHz, respectively. Simulated results show that the spectral efficiency improvement of FBMC over UFMC has been about 8 dB and 5 dB for channel bandwidth of 3 MHz and 10 MHz respectively. These two 5G IoT FR 1 modulated waveforms have been evaluated by simulation at saturation power levels for nonlinear distortions of the power amplifier (Mini-Circuits ZHL 4240W) using Keysight's ADS software tools and Matlab. The 5G IoT FR 2 64QAM, FBMC and UFMC waveforms for channel bandwidth of 100 MHz have been evaluated for nonlinear distortion of the power amplifier (Analog Devices HMC930A) using Keysight's System Vue.

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