5G Candidate Waveforms Comparison Regarding Time-Frequency Resources in the Nonlinear HPA

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***Abstract* - New waveforms for the 5th generation cellular system have been studied in many ways. The sharper out-of-band (OOB) spectrum characteristics are greatly desired for improving the spectrum efficiency. Generally, universal filtered multi-carrier (UFMC), filter bank multi-carrier (FBMC) and weighted overlap and add orthogonal frequency division multiplexing (WOLA-OFDM) waveforms are regarded as strong waveform candidates for the 5th generation mobile system. Similar to the conventional orthogonal frequency division multiplexing (OFDM) system, these modulation methods use multi-carrier. So, these systems have high peak to average power ratio (PAPR), which can cause nonlinear distortion and the out-of-band (OOB) power will increase because of the nonlinear high power amplifier (HPA). In this paper, we evaluate the spectrum characteristic and bit error rate (BER) performance of the waveforms under the effect of nonlinear HPA. Also, we show the comparison of the time-frequency resources of each system because it is very important to estimate the spectral efficiency and communication throughput. As simulation results, it is confirmed that the OOB power of each system increases, and the OOB power increase of the FBMC system is the largest. We provide the comparison table for the time-frequency resources requirement for the each multi-carrier system.**

Keywords—OFDM; FBMC; UFMC; WOLA-OFDM; HPA nonlinearity

I. INTRODUCTION

Recently, mobile traffic has increased dramatically because the number of various mobile devices and multimedia services has increased [1]. Also, the growth of mobile traffic has accelerated. It is difficult for the present mobile communication system to support the mobile traffic required in the future [2]. In order to solve the problem, studies for next generation 5G mobile communication are being actively carried out [3] [4].

Conventional orthogonal frequency division multiplexing (OFDM) based on multi-carrier has high-power out-of-band (OOB) [5]. This characteristic causes adjacent channel interference (ACI). OFDM uses a wide guard band in order to avoid ACI. It decreases spectral efficiency when a number of mobile devices simultaneously access a base station. Next generation mobile communication system requires high-level key performance indicators (KPIs). It is difficult for OFDM to satisfy the KPIs. Universal filtered multi-carrier (UFMC) and filter bank based multi-carrier (FBMC) are known as the waveform candidates for 5G mobile communication [6] [7]. When the f-OFDM, suggested by Huawei, appeared in the first place, the filtered-OFDM system adopted one-filter system for the sharper OOB spectrum characteristics. However, they changed into the multiple filter system, which became very similar to the UFMC system. These systems use filtering techniques based on the multi-carrier. These techniques have the characteristic of low OOB power spectrum in comparison with the conventional OFDM. Therefore, these systems have high spectrum efficiency. FBMC uses the filtering technique in each sub-carrier. UFMC uses a filtering technique in each sub-band [8] [9].

However, these systems based on the multi-carrier are vulnerable to non-linearity of high-power amplifier (HPA), like OFDM. OFDM has high peak-to-average power ratio (PAPR) because multi-carrier signals are overlapped. High PAPR causes nonlinear distortion in HPA because it saturates HPA. Similarly, UFMC and FBMC have high PAPR because these systems are based on multi-carrier [10] [11]. In UFMC and FBMC systems, if nonlinear distortion is caused by high PAPR, the OOB power of these systems is increased. That is, the advantage of these systems vanishes. Therefore, this drawback should be overcome in the candidate techniques for 5G mobile communication.

In this paper, in order to overcome the drawback, we focus on the spectrum characteristic analysis and the performance evaluation of FBMC and UFMC systems under the effect of nonlinear HPA. Firstly, we describe and explain OFDM, UFMC, FBMC, weighted overlap and add orthogonal frequency division multiplexing (WOLA-OFDM) system. Then, we design the systems in the linear environment and we analyze the spectrum characteristic of each system and evaluate the bit error rate (BER) performance of each system in this linear condition. Next, we consider the nonlinear condition. So, we analyze the spectrum characteristic and evaluate the bit error rate (BER) performance of each one of the modulation systems under the effect of nonlinear HPA.

Also, we show the comparison of the time-frequency resources of each system because it is very important to estimate the spectral efficiency and communication throughput. We provide the comparison table for the time-frequency resources requirement for the each one of modulation systems.

In Section 2, each candidate multi-carrier system is described and the Saleh model is included for the nonlinear modelling. Simulation parameters are set for the OOB power evaluation and time resource requirement in Section 3. Finally, we conclude this paper in Section 4.

II. SYSTEM MODEL

A. OFDM

In the transmitter of OFDM system, the data symbols are converted into a parallel stream from a series stream by the serial to parallel (S/P) block. The changed symbols are mapped onto each subcarrier by the inverse fast Fourier transform (IFFT) operation. IFFT operation transforms the frequency-domain signal into time-domain signal. After the IFFT operation, the time-domain signals are converted into the stream by parallel to serial (P/S) block. Then, cyclic prefix (CP) is added in order to reduce the effect of inter-symbol interference (ISI). Next, the base-band signals are applied to the radio frequency (RF) chain. Finally, the RF signal is amplified by high-power amplifier (HPA). The receiver of OFDM system consists of the reverse structure in comparison with the OFDM transmitter. In the OFDM receiver, an equalizer is used to compensate the multi-path effect. Simple one-tap equalizer can be used because of the CP. This is an advantage for the OFDM system. However, each subcarrier of OFDM system has high side-lobe power. Therefore, OOB power spectrum increases, which makes the guard band wider between the information channels. As a result, channel capacity is decreased in the OFDM system [12]. These drawbacks should be overcome for 5G mobile communication.

B. UFMC

The UFMC system also uses orthogonal multi-carrier, like the OFDM system. UFMC filters each sub-band that consists of orthogonal multi-carrier in order to reduce the OOB power [6]. Each sub-band signal is converted into a series stream by the P/S. Secondly, in the UFMC receiver, the received signal is applied to the RF chain. The received signal is transformed into a baseband signal by the RF chain. The baseband signal is converted into digital signal by ADC. Then, time-domain pre-processing is done. After this process, the series data stream is converted into a parallel data stream by S/P. The time-domain parallel data stream is converted to frequency-domain stream by the 2N-FFT operation [6]. After the 2N-FFT operation, odd numbered data symbols are selected and equalized. The spectrum of the UFMC system has lower OOB power in comparison with the spectrum of the OFDM system. This is an advantage. However, because the UFMC system uses multi-carriers and multi-carriers are overlapped, the UFMC system has high PAPR. The high PAPR characteristic can distort the signal of the UFMC system [6].

C. FBMC

The FBMC system uses multi-carrier, too. The FBMC system filters each sub-carrier in order to reduce the OOB power spectrum [7]. In the transmitter of the FBMC system, data symbols are converted into a parallel stream from a series stream by the S/P. The parallel symbols are modulated to offset the quadrature amplitude modulation (OQAM) signal [7]. The modulated OQAM signal is converted into a signal filtered by each sub-carrier by using a synthesis filter bank which consists of IFFT and poly phase network (PPN) [7]. Finally, the amplified FBMC signal is transmitted by the antenna. The receiver of the FBMC system consists of a reversed structure in comparison with the FBMC transmitter. The FBMC system has lower OOB power in comparison with the UFMC system and the OFDM system. This is an advantage. However, the FBMC system has high system complexity. Additionally, because the FBMC system uses multi-carriers, it has high PAPR.

D. WOLA-OFDM

The WOLA-OFDM is an improved version of the OFDM system. Fig.1 shows the WOLA-OFDM system. The WOLA-OFDM system does not use the filter, but it uses the extension and windowing method on each OFDM symbol in order to reduce the OOB power spectrum.

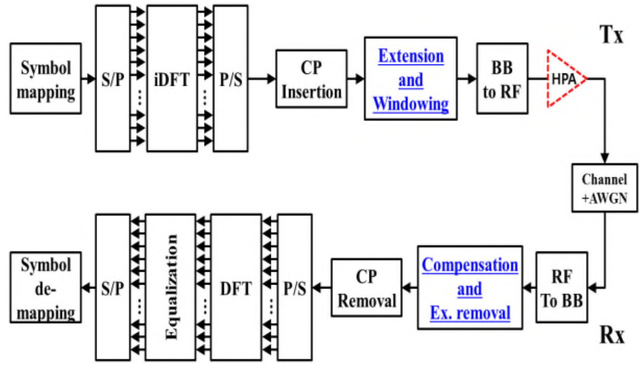

Fig. 1. Block diagram of WOLA-OFDM system.

In this paper, the research purposes are spectrum characteristic analysis and performance evaluation of OFDM, UFMC, FBMC and WOLA-OFDM systems under the effect of nonlinear HPA. Therefore, we have investigated each system including the nonlinear HPA system. The famous Saleh model is used for the nonlinear HPA. The characteristics of AM-AM and AM-PM in the Saleh model are as follows [13].

$$G[A(t)] = \frac{\alpha_A A(t)}{1+\beta_A A(t)^2} \quad (1)$$

$$\Phi[A(t)] = \frac{\alpha_\Phi A(t)^2}{1+\beta_\Phi A(t)^2} \quad (2)$$

Equation (1) shows the AM-AM characteristic of the Saleh model for the nonlinear HPA. A is the amplitude of input signal. α_A and β_A are coefficients for adjusting amplitude of the output signal. Equation (2) shows the AM-PM characteristic of the Saleh model. α_Φ and β_Φ are coefficients for adjusting phase of the output signal.

III. SIMULATION RESULTS AND ANALYSIS

Table 1 shows the parameters setting for getting the communication performance of each multi-carrier system.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Modulation	QPSK
# of total subcarrier	64
# of used subcarrier	32
# of null subcarrier	32
Filter for FBMC	Phydyas prototype : H0 = 1 , H1 = 0.97196 H2 = 0.7071 H3 = 0.235147
Filter for UFMC	Chebyshev : Attenuation = 60dB, Length = 10
# of sub-band in UFMC	64/8
# of used sub-band in UFMC	4

Table 2 shows the parameters setting of the HPA nonlinear conditions. Condition 0 is the linear case. Conditions 1 to 5 are

ISBN: 978-1-61208-544-9

the nonlinear conditions. Condition 1 is the weakest nonlinear. Condition 5 is the strongest nonlinear.

TABLE II. NONLINEAR HPA PARAMETER SETTING OF SALEH MODEL.

Condition	AM-AM	AM-PM
0 (Linear)	$\alpha_A = 1$	$\alpha_\Phi = 0$
	$\beta_A = 0$	$\beta_\Phi = 0$
Nonlinear 1	$\alpha_A = 1$	$\alpha_\Phi = 0.26$
	$\beta_A = 0.04$	$\beta_\Phi = 15.9$
Nonlinear 2	$\alpha_A = 1$	$\alpha_\Phi = 0.26$
	$\beta_A = 0.2$	$\beta_\Phi = 2.38$
Nonlinear 3	$\alpha_A = 1$	$\alpha_\Phi = 0.26$
	$\beta_A = 0.4$	$\beta_\Phi = 0.69$
Nonlinear 4	$\alpha_A = 1$	$\alpha_\Phi = 0.26$
	$\beta_A = 0.6$	$\beta_\Phi = 0.127$
Nonlinear 5	$\alpha_A = 1$	$\alpha_\Phi = 0.26$
	$\beta_A = 0.8$	$\beta_\Phi = -0.155$

TABLE III. COMPARISON OF OOB POWER CHARACTERISTICS

Condition	OFDM	UFMC	FBMC	WOLA-OFDM
Linear	-26 dB	-83 dB	-120 dB	-90 dB
condition 1	-26 dB	-82 dB	-85 dB	-85 dB
condition 2	-26 dB	-74 dB	-75 dB	-75 dB
condition 3	-26 dB	-66 dB	-67 dB	-69 dB
condition 4	-26 dB	-61 dB	-62 dB	-63 dB

After the simulation using the parameters from Tables 1 and 2, we can get the OOB (out-of-band) power spectrum at the output of the HPA of each system. Table 3 shows the OOB power spectrum comparison for each system. The lower the OOB power, the more desirable it is to set the smaller guard band and finally to increase the spectrum efficiency. From Table 3, it can be confirmed that under the HPA nonlinearity environment, the FBMC system shows the biggest change of OOB power, and the OFDM system shows the smallest change.

Figures 2 to 5 show BER performances of each multi-carrier system. Compared with the linear condition, BER performance of every system is degraded in the nonlinear HPA environment. Importantly, the FBMC system shows the smallest degradation of BER performance. However, even though the FBMC system is the strongest against HPA nonlinearity, every multi-carrier system needs the PAPR reduction method for the nonlinear distortion compensation and power saving.

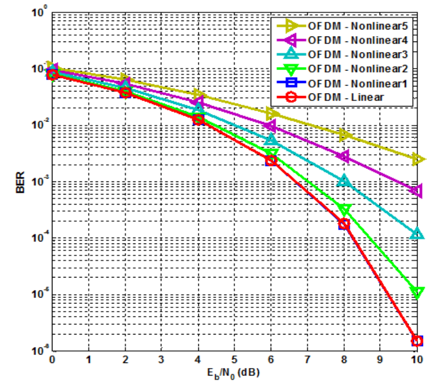

Fig. 2. BER of OFDM system.

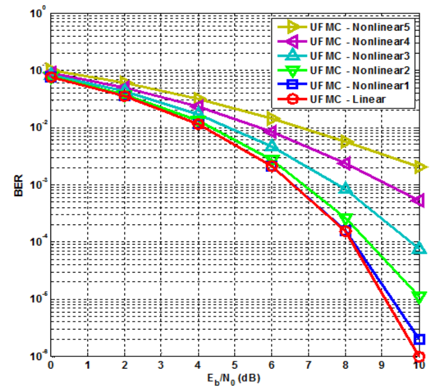

Fig. 3. BER of UFMC system.

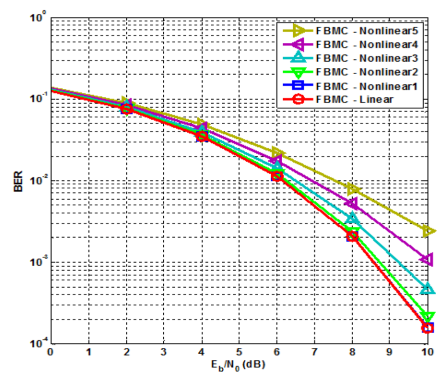

Fig.4. BER of FBMC system.

 ISBN: 978-1-61208-544-9

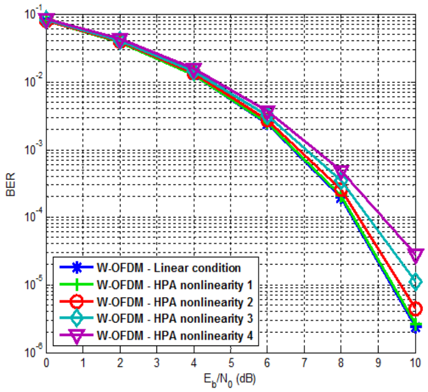

Fig.5. BER of WOLA-OFDM.

Next, in order to compare the time-frequency resources of each multi-carrier system, we have set some necessary parameters conditions for the simulation, as in the below.

Allocated bandwidth : 20MHz

# of used sub-carriers : 16

# of transmission bits : 128

4QAM modulation (2bit) * 16 sub-carrier * 4 synthesis symbols : 128 bits

IFFT size : 64, and CP length : 9

FBMC, Overlapping Factor (K) : 4

WOLA-OFDM, Extension length : 6

OOB emission suppression (Frequency, 7.5MHz Offset) / TTI length (Time)

TABLE IV. COMPARISON OF THE TIME-FREQUENCY RESOURCES

	OFDM	UFMC	FBMC	WOLA-OFDM
Linear	-26 dBc / 292	-83 dBc / 292	-130 dBc / 480	-66 dBc / 304
HPA condition 1	-26 dBc / 292	-82 dBc / 292	-85 dBc / 480	-66dBc / 304
HPA condition 2	-26 dBc / 292	-74 dBc / 292	-75 dBc / 480	-66dBc / 304
HPA condition 3	-26 dBc / 292	-66 dBc / 292	-67 dBc / 480	-65dBc / 304
HPA condition 4	-26 dBc / 292	-63 dBc / 292	-65 dBc / 480	-63dBc / 304

After the investigation of OOB spectrum power at 7.5MHz offset frequency from the information signal band and time resource requirement for the above 4-QAM transmission, we can get Table 4 showing the OOB (out-of-band) power and required time resource for each multi-carrier system under several nonlinear HPA conditions. As seen in Table 4, OFDM and WOLA-OFDM have almost no change from the linear case to the nonlinear condition 4. However, UFMC and FBMC have some quite big change from the linear case to the nonlinear condition 4. As in Table 4, OFDM and UFMC systems have the time resource length of 292. WOLA-OFDM system has time resource length of 302. However, FBMC system has the longest time length of 480. So, FBMC requires longer time resource even though it has very sharp OOB power spectrum in the linear condition.

Even though 4-QAM is used for the simulation and time frequency requirement, the trend would be almost the same when extended into higher modulation levels.

IV. CONCLUSIONS

The FBMC and UFMC systems are strong modulation candidates for 5G mobile communication systems. Since these systems are basically multi-carrier systems, it is important to study the non-linearity sensitivity. In this paper, we have focused on spectrum characteristic analysis and BER performance evaluation of OFDM, FBMC, and UFMC, WOLA-OFDM systems under the effect of nonlinear HPA. As simulation results, we have confirmed that, if the HPA non-linearity rises in each multi-carrier system, the OOB power of each multi-carrier system increases. The OOB power increase of the FBMC system is the biggest. Additionally, we have confirmed that the performance of every multi-carrier system is degraded by the strength of the HPA non-linearity, and every system needs the PAPR reduction method for the non-linear distortion compensation and power saving, even though it would be more complicated. Also, we show the comparison of the time frequency resources of each multi-carrier system because it would be very important to estimate the spectral efficiency and communication throughput. We provide the comparison table for the time-frequency resources requirement for each multi-carrier system.

The next step will be on the system design and evaluation of the PAPR reduction scheme and complexity comparison for the system implementation.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No.2013R1A2A2A01005849)

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