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LETTER

Generation of OFDM waveform with 4.8 GHz bandwidth passing through terahertz and millimeter-wave bands in Beyond 5G system

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Abstract The "virtualized terminal" system which uses an OFDM waveform spanning 4.8 GHz bandwidth passing through terahertz and millimeter-wave bands has been studied towards the Beyond 5G. This paper studied the effect of the "2-stage nonlinearity" caused by two amplifiers at both of those bands. This study also evaluated two baseband circuits for the OFDM signal generation: one that generates a 4.8 GHz OFDM signal in a single batch, and another one that divides the 4.8 GHz into 400 MHz sub-bands and generates OFDM signal for each sub-band. The results of the evaluation that assumed the phase noise, fading, and 2-stage nonlinearity showed there was little degradation by the 2-stage nonlinearity or sub-band division.

Keywords: Beyond 5G, virtualized terminal, terahertz, millimeter-wave, wideband OFDM, nonlinearity
Classification: Wireless communication technologies

1. Introduction

Beyond 5G/6G, the next-generation mobile communication systems, are expected to be launched in the 2030s. Towards the Beyond 5G ultra-high-speed wireless communication, the "virtualized terminal" system is studied [1]. In the virtualized terminal system, as illustrated in Fig. 1, a user terminal transmits/receives the OFDM signal with a 4.8 GHz bandwidth (BW) to/from a peripheral device over terahertz (THz) radio wave (300 GHz). The peripheral device performs up/down-conversion without baseband processing and connects with an access point over millimeter radio wave (mmW). Both large traffic capability and wide coverage are achieved by the wide BW and mmW connection.

Our previous study [2] evaluated the link-level performance of the virtualized terminal with considering the effect of the phase noise at THz and fading at mmW channel. But the effect of the nonlinearity of amplifiers or generation of a GHz-class BW was not considered.

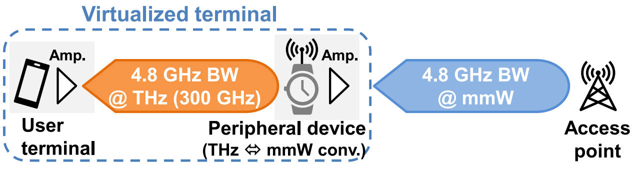

Fig. 1 Virtualized terminal system

This study considered the effect of 2-stage nonlinearity of the amplifiers at THz (user terminal) and mmW (peripheral device), and the generation methods of OFDM signal with a 4.8 GHz BW for the virtualized terminal. In Chapter 2, the effects of the nonlinearity on the link-level performance and interference to adjacent channels are evaluated. In Chapter 3, two types of the baseband circuits for the OFDM signal generation at the user terminal are evaluated: one circuit that generates a 4.8 GHz OFDM signal in a single batch, and another circuit that divides the 4.8 GHz into the 400 MHz sub-bands and generates OFDM signal for each sub-band. In Chapter 4, the conclusion is stated.

2. Effect of 2-stage nonlinearity of amplifiers

Figure 2 shows the system model for the evaluation of uplink. As degradation factors, the 2-stage nonlinearity by amplifiers on the user terminal and the peripheral device, phase noise at mmW and THz on the user terminal, and fading at mmW channel are considered. This chapter evaluates the link-level performance and interference to adjacent channels.

2.1 Model of nonlinearity

This study employs the RAPP model [3]. The AM-AM modulation of the model is shown by the Equation (1) where G, V_{SAT}, and p are the gain, saturation amplitude, and smoothness factor of an amplifier, respectively:

$$F_{AM-AM}(x) = \frac{Gx}{\left(1 + \left|\frac{Gx}{V_{SAT}}\right|^{2p}\right)^{\frac{1}{2p}}} \tag{1}$$

Figure 3 shows the input-output power characteristic of the model. The smoothness factor p mainly represents the char-

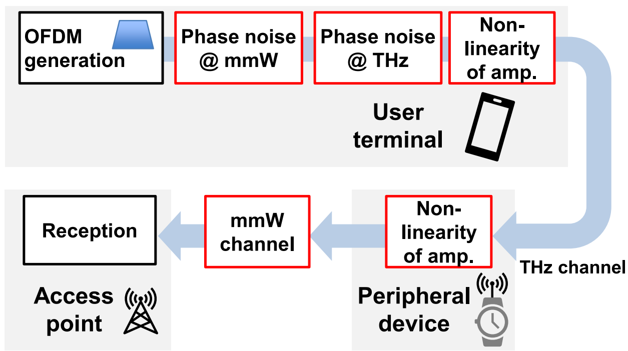

Fig. 2 System model for the evaluation for uplink

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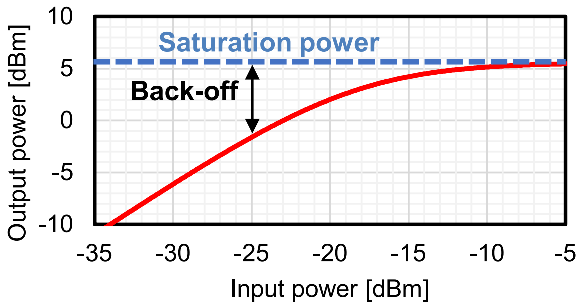

Fig. 3 Input-output power characteristic of the RAPP model with $p = 1.1$

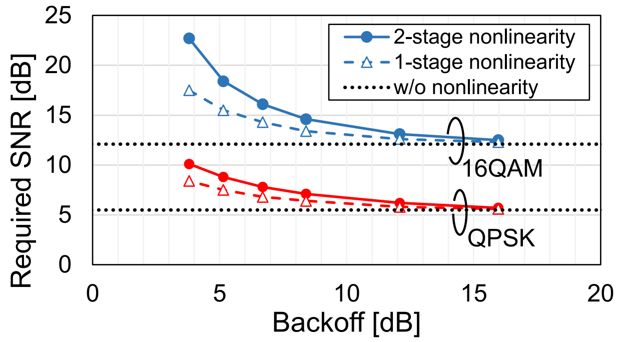

Fig. 4 Evaluation results of link-level performance with the nonlinearity

Table I Assumptions for the link-level evaluation

Waveform	OFDM
Carrier frequency	300 GHz
Subcarrier spacing	120 kHz
Number of resource blocks (RB)	273
Modulation	QPSK, 16QAM
Channel coding, Code rate	LDPC, 0.6
Transmission scheme	Single layer
UE speed	3 km / h
Channel model	3GPP TDL-D [5]
Delay spread	100 ns
Phase noise level at mmW	−113 dBc/Hz @ 1 MHz offset
Phase noise level at THz	−102 dBc/Hz @ 1 MHz offset
Nonlinearity model	RAPP with $p = 1.1$
Channel estimation	Realistic

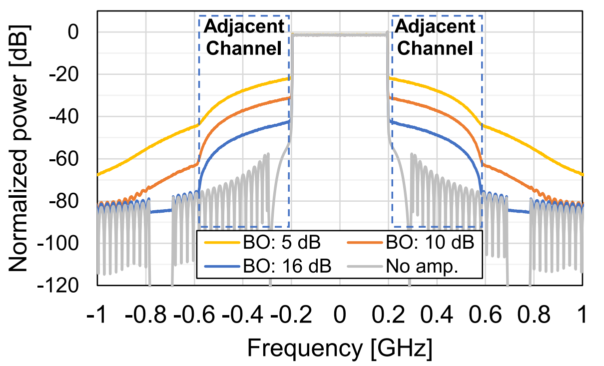

Fig. 5 Simulation results of OOBE spectrum

acteristic of an amplifier. Considering the characteristic of an amplifier at THz, $p = 1.1$ is adopted. Note that the power back-off [dB] is defined as {saturation power [dBm] – output power [dBm]} in this paper.

2.2 Link-level performance evaluation of 2-stage nonlinearity

In this section, the effect of the 2-stage nonlinearity by two amplifiers on the user terminal and the peripheral device on the uplink performance is evaluated. The performance measure is the signal-to-noise ratio (SNR) required to achieve Block Error Rate (BLER) 10% (target value having been used since the LTE [4]).

Table I shows the evaluation assumptions. The waveform of OFDM with subcarrier spacing 120 kHz is adopted which is robust against the phase noise at THz and fading at mmW as studied in [2]. The level of the phase noise at mmW is based on the mmW phase noise model with compound semiconductor with carrier frequency 30 GHz specified by the 3rd Generation Partnership Project (3GPP) [3]. OFDM signal with 390 MHz bandwidth which corresponds to 273 resource blocks (RB) is used as a scale model of 4.8 GHz BW in the simulation since the number of subcarriers does not affect the intensity of the intermodulation caused by the nonlinearity. The coding/modulation scheme and data/reference signal mapping refer to the 5G NR. The channel estimation and phase noise compensation are performed using the reference signal. QPSK and 16QAM are assumed as modulation orders since the target SNR is around 10 dB considering the large propagation loss in terahertz [1].

Figure 4 shows the evaluation results of the required SNR to achieve the 10 % BLER vs. the back-off at the amplifiers. The cases of 2-stage nonlinearity (the same RAPP model and back-off value are applied on the amplifiers), 1-stage nonlinearity, and without nonlinearity are compared.

Based on the results, the required SNR is high (i.e., the performance is degraded) when the back-off is low because the constellation point is distorted by the nonlinearity.

On the other hand, the performance degradation of the 2-stage nonlinearity case compared with the 1-stage nonlinearity case is less than 1 dB when the back-off is larger than 7 dB for QPSK. Considering that such back-off range will mainly be used in the actual operation, the effect of the 2-stage nonlinearity is not crucial for the system.

2.3 Interference to adjacent channels

Out-Of-Band Emission (OOBE) occurs when OFDM passes through the amplifier and interferes with adjacent channels.

Figure 5 shows the simulation results of the OOBE spectrum for OFDM with a 390 MHz BW (instead of 4.8 GHz as explained in Section 2.2). The lower the back-off the amplifier is, the higher the effect of the distortion is. Thus, the OOBE level becomes higher.

The Adjacent Channel Leakage Ratio (ACLR) is used as a measure of the interference by the OOBE, which is shown as in the Equation (2) below:

$$ACLR\,[\mathrm{dB}] = \frac{\text{Power at the allocated channel [dBm]}}{\text{Power leaked to an adjacent channel [dBm]}} \tag{2}$$

Figure 6 shows the calculation results of the ACLR of the OFDM with a 390 MHz BW. When back-off is larger than 7 dB, the ACLR becomes larger than 28 dB. Therefore, the effect on the virtualized terminal system whose target SNR is 10 dB is small even if any other THz signal is mapped on

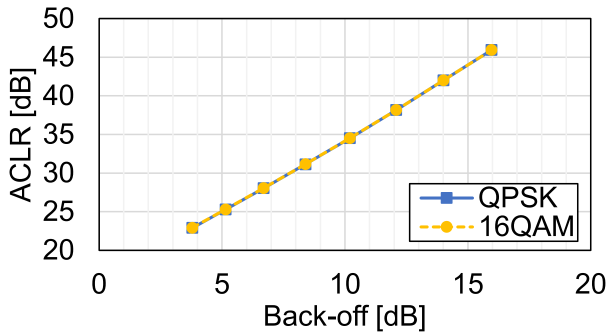

Fig. 6 Calculation results of ACLR

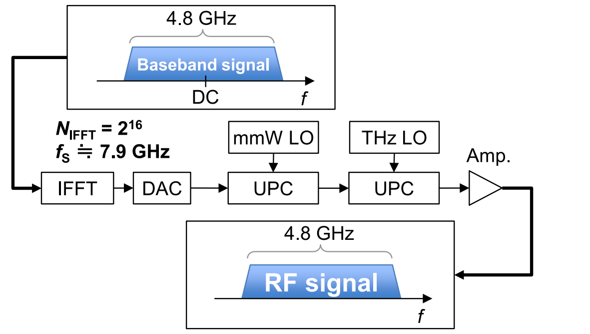

Fig. 7 Example of Circuit A: processing 4.8 GHz BW in a single batch

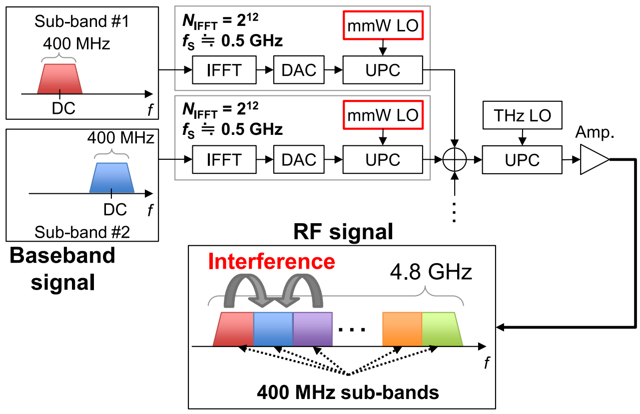

Fig. 8 Example of Circuit B: dividing 4.8 GHz into 400 MHz sub-bands

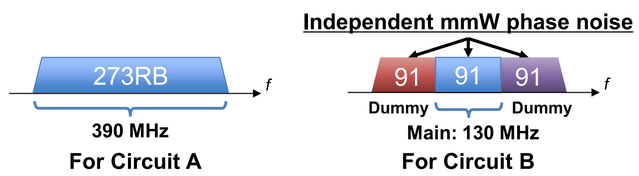

Fig. 9 Simulated signal for the link-level performance evaluation

the adjacent channels.

2.4 Summary

Based on the evaluations, the effect of the nonlinearity of the amplifiers is not significant as summarized as follows.

When the back-off is larger than 7 dB:

- The link-level performance degradation of the 2-stage nonlinearity compared with 1-stage nonlinearity is less than 1 dB.
- The ACLR is larger than 28 dB.

3. Generation of OFDM with a 4.8 GHz BW

This chapter studies the generation methods of OFDM signal with a 4.8 GHz BW for the virtualized terminal. The performance of the candidate baseband circuits at the user terminal is also evaluated.

3.1 Candidate baseband circuits at the user terminal

As in Chapter 2, the waveform of OFDM with subcarrier spacing 120 kHz is adopted. In this case, a 4.8 GHz BW comprises more than 40 thousand subcarriers.

To generate the signal, two candidate baseband circuits at the user terminal are considered: One circuit that generates a 4.8 GHz OFDM signal in a single batch (Circuit A), and another circuit that divides the 4.8 GHz into the 400 MHz sub-bands and generates OFDM signal for each sub-band (Circuit B).

Figure 7 shows an example of the Circuit A. This circuit requires the high performance per component such as 2^{16} points for Inversed Fast Fourier Transform (IFFT) and sampling rate of around 7.9 GHz to process a BW with 4.8 GHz in a single batch. But the number of components can be fewer.

Figure 8 shows an example of the Circuit B. This circuits divides 4.8 GHz into 12 sub-bands with a 400 MHz BW. In this circuit, the required performance per component is relatively low such as 2^{12} points for IFFT and sampling rate of around 0.5 GHz. But the number of components becomes larger in proportion to the number of sub-bands. Also, there is a concern of the potential phase noise interference across sub-bands since the mmW local oscillators (LO) emit independent phase noise for each sub-band.

3.2 Link-level performance evaluation

Figure 9 shows the simulated OFDM signals for Circuit A and B. In this evaluation as well, a 4.8 GHz BW is scaled down to a 390 MHz BW equivalent to 273 RBs for 120 kHz subcarrier spacing because sufficient number of subcarriers are contained in 390 MHz BW to simulate the interference across the sub-bands due to the phase noise.

For Circuit A, the signal comprises the 273 RBs and the BLER of the whole 273 RBs is measured.

For Circuit B, the 273 RBs are divided into the 3 sub-bands each of which comprises 91 RBs. The BLER of the signal on the main sub-band allocated in the center is measured. The signals on dummy sub-bands are allocated adjacent to each side of the main sub-band. As stated later, the independent mmW phase noise is applied for each sub-band.

Figure 10 shows the system model for the evaluation where the peripheral device and access point are omitted. For Circuit A, the system model is the equivalent to Fig. 1. For Circuit B, the components to generate the OFDM signal and phase noise at mmW for the dummy sub-bands are added at the user terminal.

The other evaluation assumptions are the same as Table I except that the number of the RBs for Circuit B is 91 RBs. As in Chapter 2, the coding/modulation scheme and data/reference signal mapping refer to the 5G NR. The

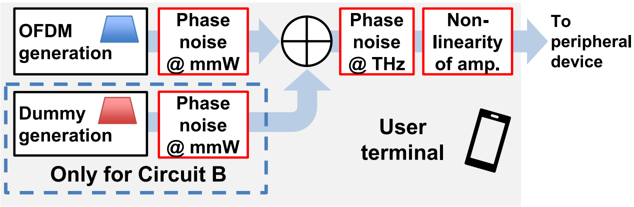

Fig. 10 System model for the link-level performance evaluation

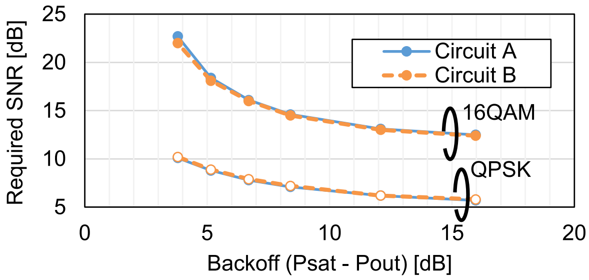

Fig. 11 Results for the link-level performance evaluation

same RAPP model and back-off value are applied on both amplifiers at mmW and THz.

Figure 11 shows the evaluation results of the required SNR to achieve 10 % BLER vs. the back-off of the amplifiers for Circuit A and Circuit B. According to the results, the required SNR is almost identical between Circuit A and B. Therefore, it can be said that the effect of the interference across sub-bands in the Circuit B on the performance is limited. That is, the degradation by sub-band division is not significant.

4. Conclusion and future plan

This paper has studied the effect of the 2-stage nonlinearity by the two amplifiers at the THz and mmW bands on the virtualized terminal system. Compared with 1-stage nonlinearity, the 2-stage nonlinearity had little degradation on link-level performance. Also, the ACLR by the nonlinearity was not problematic.

This paper has also evaluated two baseband circuits for the OFDM signal generation: one circuit that generated a 4.8 GHz OFDM in a single batch, and another circuit that divided the 4.8 GHz into the 400 MHz sub-bands and generated OFDM for each sub-band. The results of the evaluation that assumed the phase noise, fading, and 2-stage nonlinearity showed that there was little degradation on the link-level performance by the sub-band division.

Figure 12 illustrates an extended virtualized terminal system with multiple peripheral devices and access points. Multiple-Input and Multiple-Output (MIMO) can be applied between peripheral devices and access points to further extend the traffic capability. The performance and issue with MIMO will be studied in the future.

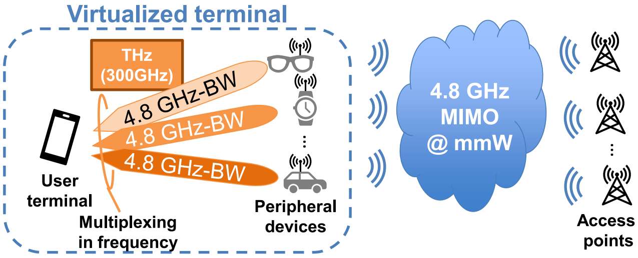

Fig. 12 Virtualized terminal system with MIMO

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