Effect of terahertz-wave phase noise and millimeter-wave multipath fading on Beyond 5G wireless system

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Abstract: Towards the Beyond 5G ultra-high-speed wireless system, the “virtualized terminal” system is studied. By connecting a user terminal to multiple peripheral devices over terahertz radio wave (300 GHz) which are utilized as virtual antennas communicating with access points using millimeter radio wave, the spatial multiplexing capability is enhanced. In this system, the waveform is required to be robust against both phase noise from a terahertz-wave oscillator and multipath fading over the millimeter-wave since the baseband waveform is common to those frequencies. This work evaluates the effect of those factors and reveals that the effect of phase noise and multipath fading is dominant for OFDM and DFT-s-OFDM, respectively.

Keywords: Beyond 5G, terahertz-wave, millimeter-wave, phase noise, multipath fading

Classification: Wireless communication technologies

References

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 this system, a user terminal is connected to multiple peripheral devices over terahertz radio wave (300 GHz) and the peripheral devices are further connected to access points over millimeter wave radio wave. The terminal utilizes the peripheral devices as virtual millimeter-wave antennae, and then the spatial multiplexing capability is enhanced without increasing the size or power consumption of the terminal itself.

Several papers have reported an evaluation [2] and demonstrations [3,4] of a communication using the orthogonal frequency division multiplexing (OFDM) around 300 GHz band, but none of them considered the conversion to the millimeter radio wave or the effect of the multipath fading over the channel.

In the system with the virtualized terminal, the peripheral devices perform only up/down-conversion and amplification without baseband processing. Since the baseband waveform is common to the terahertz-wave and millimeter-wave transmissions, the baseband waveform is required to be robust against both phase noise from a terahertz-wave oscillator and multipath fading over the millimeter-wave channel. To realize this system, it is necessary to evaluate the performance of the transmitted signal passing through both radio frequencies’ propagation channels.

In this paper, the effect of the phase noise and delay spread on the performance of the waveform used in the system with the virtualized terminal is evaluated. In Chapter 2, the system model is explained. In Chapter 3, the evaluation conditions including the phase noise level, delay spread, and waveform type are presented. In Chapter 4, the results of the evaluation are reported. In Chapter 5, the conclusion is stated.

2 System model

Fig. 1 shows the system model with the virtualized terminal. The system comprises three kinds of communication nodes, user terminal, peripheral device, and access point. The user terminal and the peripheral devices work as a virtual terminal. The user terminal has a terahertz-wave transceiver and a directional antenna to communicate with peripheral devices around the user. The peripheral device is
composed of sets of transceivers including up/down-converter, amplifiers, and antennae for terahertz-wave and millimeter-wave to communicate with the user terminal and the access points, respectively. With such a simple function, the peripheral devices are potentially mounted on wearable devices (e.g., smart glasses or smart watches), PCs, tablets, or vehicles.

3 Evaluation conditions

The goal of this study is to evaluate the effect of terahertz-wave phase noise and delay spread in millimeter wave propagation as deterioration factors experienced by the virtualized terminal system. To this end, a link-level simulation of a SISO (single-input and single-output) communication between a transmitter and a receiver is conducted, where the 300 GHz phase noise and millimeter-wave delay spread caused by the multipath fading are both simulated. OFDM and DFT-spread-OFDM (DFT-s-OFDM) based on the 5G New Radio (NR) are used as waveform.

3.1 Phase noise level

The phase noise level used in the evaluation is based on the millimeter-wave phase noise model specified by the 3rd Generation Partnership Project (3GPP) in 2017 [5]. One model corresponds to a device with compound semiconductor. This model brings phase noise power spectrum density (PSD) which can be scaled with carrier frequency. In this evaluation, the following two levels are assumed considering the device evolution:

- Level-A: millimeter-wave model with compound semiconductor [5] with carrier frequency 300 GHz, $-92 \text{ dBc/Hz @ 1 MHz offset}$
- Level-B: 10 dB lower level than Level-A, $-102 \text{ dBc/Hz @ 1 MHz offset}$

It should be noted that this evaluation considers only 300 GHz phase noise as a dominant deterioration factor because phase noise level is larger for higher frequency, and millimeter-wave phase noise whose level is lower by around 14-20 dB is not considered.

3.2 Channel model and delay spread

This evaluation uses 3GPP TDL-D [6] as the channel model, which assumes line-
of-sight with K-factor of 13 dB, to simulate the millimeter-wave multipath fading. Delay spread of 20 ns and 100 ns are adopted which are typical in the millimeter-wave channel [6]. The multipath of terahertz-wave is not considered because of the light-like property of terahertz wave.

3.3 Waveform

The 5G NR, standardized by 3GPP, supports OFDM and DFT-s-OFDM as the baseband waveforms operating up to 71 GHz. To mitigate the effect of the phase noise, the phase-tracking reference signal (PT-RS) and wider subcarrier spacing (SCS) than LTE (Long Term Evolution) are introduced. The NR PT-RS is mapped on a subcarrier per 2 or 4 resource blocks (RB, 12 subcarriers per each) to compensate the common phase error (CPE) caused by phase noise. SCS 60, 120 kHz for 6-52 GHz and 120, 480, 960 kHz for 52-71 GHz are supported to mitigate the effect of inter-carrier interference (ICI).

In this evaluation, NR-based OFDM and DFT-s-OFDM are considered. The (de-)coding, (de-)modulation, and mapping of data and reference signal comply with NR. A low overhead PT-RS that occupies one subcarrier per 2 RBs is assumed for CPE compensation although a denser reference signal may allow for ICI compensation [7]. As SCS, this evaluation adopts 120, 480, 960 kHz as in NR and 1920 kHz being more robust against ICI.

3.4 Other conditions

Table I summarizes the evaluation conditions. The length of cyclic prefix (CP) added to an OFDM symbol is around 7% of the symbol as in NR. The number of RBs corresponds to the transmission bandwidth 368.64 MHz regardless of the SCS. The target block error rate (BLER) is 10% the same as the target used since LTE [8].

Considering the link budget of the system possible signal-to-noise ratio (SNR) is around 10 dB due to the large propagation loss in terahertz [1]. Therefore, QPSK and 16QAM are used as modulation orders. Perfect channel estimation is assumed in this evaluation to focus on the effect of the phase noise and multipath fading.

Table I. Evaluation assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency [GHz]</td>
<td>300</td>
</tr>
<tr>
<td>Channel model</td>
<td>3GPP TDL-D [6]</td>
</tr>
<tr>
<td>Delay spread (DS) [ns]</td>
<td>20, 100</td>
</tr>
<tr>
<td>Phase noise level</td>
<td>Level-A, Level-B stated in the Section 2.1</td>
</tr>
<tr>
<td>Waveform</td>
<td>OFDM, DFT-s-OFDM</td>
</tr>
<tr>
<td>User speed [km/h]</td>
<td>3</td>
</tr>
<tr>
<td>Transmission scheme</td>
<td>Single layer</td>
</tr>
<tr>
<td>Number of OFDM symbols</td>
<td>12 per slot</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 16QAM</td>
</tr>
<tr>
<td>Channel coding, Code rate</td>
<td>LDPC, 0.6</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Perfect</td>
</tr>
<tr>
<td>CPE compensation</td>
<td>Compensated using PT-RS (one subcarrier per 2 RB)</td>
</tr>
<tr>
<td>Subcarrier spacing [kHz]</td>
<td>120, 480, 960, 1920</td>
</tr>
<tr>
<td>OFDM symbol length [us]</td>
<td>2.08, 1.04, 0.52</td>
</tr>
<tr>
<td>CP length [ns]</td>
<td>587, 146, 73, 36</td>
</tr>
<tr>
<td>Number of resource blocks</td>
<td>256, 64, 32, 16</td>
</tr>
</tbody>
</table>
4 Evaluation results

Fig. 2 shows the required SNR to achieve the 10% BLER vs. the SCs. Figs. 2(a) and (b) corresponds to OFDM and DFT-s-OFDM, respectively.

4.1 Effect of phase noise

For 16QAM, the required SNR with phase noise Level-A is higher than that with Level-B especially for SCS 120 kHz because of the ICI caused by the phase noise. The difference is up to 5 dB and 1 dB for OFDM and DFT-s-OFDM, respectively. Since different data bits are carried in different subcarriers, the OFDM is less robust against the ICI compared with DFT-s-OFDM. For the other SCS where influence of the ICI is less, the performance difference for 16QAM is within 1 dB. For QPSK, the performance difference by phase noise level or SCS is not significant.

4.2 Effect of delay spread

For 16QAM, the greater the SCS is, the higher the required SNR is in general except SCS 120 kHz where the influence of the ICI is dominant. In OFDM and DFT-s-OFDM, the CP length is shorter when the SCS is wider. Therefore, wider SCS is more likely to suffer from the delayed multipaths. Besides, when comparing Figs. 2(a) and (b), the required SNR in SCS 1920 kHz is higher in DFT-s-OFDM than OFDM by around 2 dB. It is thought to be because
of the difference of the gain from the channel coding in frequency selective fading. In DFT-s-OFDM, the data in each symbol is mapped in serial in time domain, and then the part of signal is significantly degraded by the delayed multipaths beyond the CP length. On the other hand, in OFDM, the data is mapped in parallel in frequency domain, and then the degradation is distributed to whole the OFDM symbol. Therefore, the data is more likely to be recovered by the channel coding and BLER is improved in OFDM.

For QPSK, the performance difference by different delay spread levels is not significant.

### 4.3 Summary

Based on the comparison of the evaluation results with the different levels of phase noise and delay spread, the observation is summarized as follows.

- For OFDM, the effect of the phase noise on the performance is dominant compared with that of the multipath fading. The degradation is especially significant for narrower SCS (e.g., 120 kHz) due to the ICI caused by the phase noise.
- For DFT-s-OFDM, the effect of the multipath delay is dominant compared with that of the phase noise. The degradation is significant especially for wider SCS (e.g., 480-1920 kHz) due to shorter length of the CP.
- The tendency described above is true especially for the higher modulation order (e.g., 16QAM). The degradation by phase noise or multipath delay is not significant for the lower modulation order (e.g., QPSK).

### 5 Conclusion

In this paper, the performance of the 5G-based baseband waveform, OFDM and DFT-s-OFDM, applied for the system with the virtualized terminal has been evaluated. Since the transmitted signal passes through terahertz-wave and millimeter-wave propagation channels in this system, this work has focused on the effect of the terahertz-wave phase noise and delay spread of multipath fading of millimeter-wave. The evaluation results have revealed that the effect of phase noise and multipath fading is dominant for OFDM and DFT-s-OFDM, respectively, especially for 16QAM or higher modulation order. The greatness of the effect depends on SCS as well.

In the future, the performance with realistic channel estimation would be evaluated. The degradation due to interpolation of the channel estimation is foreseen especially in case of a large SCS depending on frequency domain density of the reference signal. Besides, the evaluation would be expanded into the case of multi-input and multi-output (MIMO) towards the enhancement of the spatial multiplexing capability of this system.

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