Phase Noise Compensation for Beyond 5G Virtualized Terminal with MIMO

Yasuaki YUDA[†a], *Member*, **Shotaro MAKI**[†], *Nonmember*, **Tomohiro KIMURA**[†], *Nonmember* *and* **Akihiko NISHIO**[†], *Member*

SUMMARY Towards the Beyond 5G/6G, the "virtualized terminal" system is studied. In the virtualized terminal system, a user terminal is connected to multiple surrounding relay devices using SISO transmission with frequency division multiplexing over terahertz radio wave and the relay devices are further connected to a base station using MIMO transmission over millimeter radio wave. In such a high frequency as the millimeter or terahertz radio wave, a phase noise causes a degradation of the link performance. In the virtualized terminal system, the phase noise in the relay devices dominantly impacts on the entire link performance due to the terahertz radio wave. In addition, the phase noise in each relay device is generated independently by each local oscillator. For MIMO transmission, an appropriate phase noise compensation differs depending on whether the dominant phase noise is generated at the transmission side or reception side. In this paper, we investigate the effect of phase noise in the virtualized terminal system with MIMO, and propose a compensation method of common phase error (CPE) caused by the phase noise. In addition, consideration on the CPE compensation when MIMO precoding is employed is given. According to the simulation results, proposed compensation method improves the BLER performance for both uplink and downlink.

keywords: *Beyond 5G/6G, Virtualized Terminal, MIMO, Phase Noise*

1. Introduction

For beyond 5G/6G (B5G/6G) system, wireless transmission using high-frequency bands such as millimeter waves and terahertz waves, which are capable of broadband transmissions, is studied in order to realize higher data rate communication than 5G. The virtualized terminal system, where the user terminal and its surrounding relay devices are connected using the terahertz band (e.g. 300 GHz) and the relay device and the base station are connected using millimeter-wave band, is studied [1]. The relay device performs frequency conversion between the millimeter wave band and the terahertz band. SISO transmission using frequency division multiplexing is employed between the user terminal and the relay devices while MIMO transmission is employed between the relay devices and the base station. In high frequency bands such as the millimeter-wave band and the terahertz wave band, there is a concern about the influence of the phase noise. In a virtual terminal system, the phase noise generated in the terahertz band between the user terminal and the relay devices gives a dominant impact on the system performance. The authors have so far studied the effects of phase noise and multipath propagation [2] [3] and the nonlinear characteristics of transmission amplifiers [4] on wireless transmission waveforms in the virtual terminal systems.

The phase noise and its compensation methods for SISO systems were discussed in [5]. This paper focuses on studying the effects of the phase noise for MIMO transmission in the virtualized terminal systems. Since the phase noise in the terahertz link, i.e. between the user terminal and relay devices, is dominant rather than that in the millimeter-wave link, i.e. between the relay devices and the base station, there is a difference between uplink and downlink in whether the dominant phase noise is added to the transmission side or to the reception side of the MIMO transmission. In addition, since the relay devices are physically separated, the oscillators are independent and the generated phase noise is also independent. Considering the above-mentioned features, we investigate the method of phase error compensation suitable for each uplink and downlink in MIMO transmission of the virtualized terminal system, and evaluate the performance by simulation.

The rest of this paper is organized as follows. Section 2 explains the virtualized terminal and effect of phase noise. Section 3 describes proposed phase error compensation method for MIMO transmission, and Section 4 provides the simulation results. Conclusions are provided in Section 5.

2. Virtualized terminal system and effect of phase noise

Figure 1 shows the concept of the virtual terminal system. In a virtual terminal system, multiple devices in the vicinity of a user terminal are used as relay devices to connect to a base station. The link between a user terminal and relay devices uses SISO transmission with frequency division multiplexing in the terahertz band. On the other hand, the link between relay devices and a base station uses MIMO transmission with the same frequency in the millimeter wave band. In the relay device, frequency conversion is performed between terahertz band and millimeter-wave band.

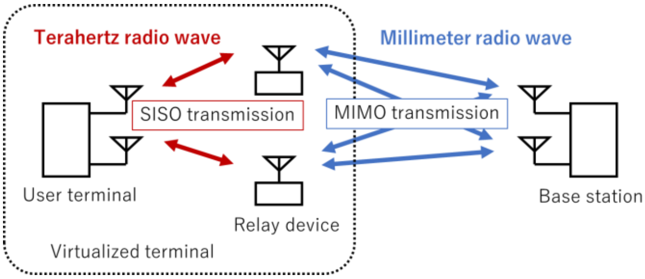

Fig. 1 Virtualized terminal system

[†] The authors are with Panasonic Holdings Corporation, Yokohama-shi, Kanagawa-ken 224-8539, Japan.

[a] E-mail: yuda.yasuaki@jp.panasonic.com

Phase noise is generated in the local oscillators in communication equipment in the systems. However, since the magnitude of the phase noise depends on the oscillation frequency, the phase noise generated in the terahertz band (i.e. the link between the user terminal and the relay devices), has much larger effect than the phase noise generated in the millimeter-wave band (i.e. the link between the relay devices and the base station). In addition, each relay device generates independent phase noise.

For uplink, i.e. link from the user terminal to the base station via the relay device, independent and dominant phase noise is added to each antenna branch on the transmission side of the MIMO transmission. On the other hand, for downlink, i.e. link from the base station to the user terminal via the relay device, independent and dominant phase noise is added to each antenna branch on the reception side of the MIMO transmission.

Phase noise is generated as a slight fluctuation of the signal generated by the local oscillator in communication equipment due to the characteristics of the oscillator and PLL (Phase Lock Loop). This fluctuation can be seen as an irregular fluctuation of the phase component of the time signal. In the reception side, it is possible to correct the common phase error (CPE) due to the phase noise by estimating the average CPE for each symbol.

The CPE can be estimated by reference signals called DMRS (DeModulation Reference Signal) and PT-RS (Phase Tracking-Reference Signal) in the reception side, as specified in 3GPP NR. For example, DMRS is mapped on a specific OFDM symbol and PT-RS is mapped on specific subcarriers (e.g. in every 24 subcarriers) in each OFDM symbol as illustrated in Fig.2. Because CPE due to the phase noise is also added on the DMRS symbol, phase rotation of each OFDM symbol relative to DMRS symbol can be estimated by the DMRS and PT-RS. CPE compensation is performed using the estimated relative phase rotation.

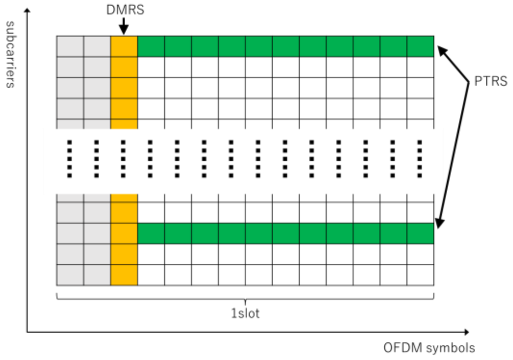

Fig. 2 DMRS and PT-RS

3. CPE compensation methods for virtualized terminal system

In this section, proposed CPE compensation methods for the virtualized terminal system are explained. In the virtualized terminal system using MIMO transmission, the influence of CPE are different depending on whether the dominant phase noise is generated on the transmission side or on the reception side. Fig. 3 shows a conceptual diagram of phase noise and MIMO reception processing. In the case the dominant phase noise is generated at transmission side, the transmitted signal propagates through the MIMO channel after the phase noise is added to the transmission signal. In this case, the appropriate reception processing is to first remove the effects of MIMO channels by performing MIMO reception processing to separate the data streams, and then apply CPE compensation to remove the effects of phase noise for each data stream.

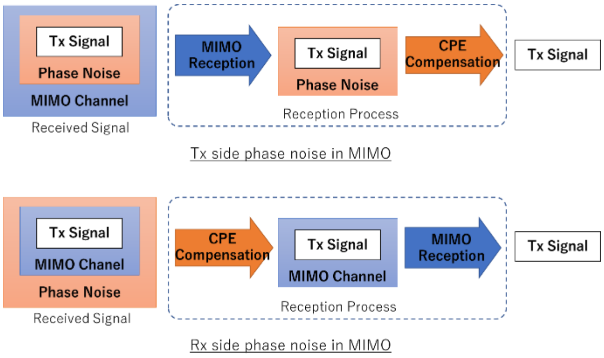

Fig. 3 Phase noise and MIMO reception processing

On the other hand, in the case the dominant phase noise is generated on the reception side, the phase noise is added after the transmitted signal propagates through the MIMO channel. In this case, the appropriate reception processing is to first apply CPE compensation to remove the effect of phase noise for each reception antenna and then perform the MIMO reception processing to separate the data streams.

3.1 CPE compensation for virtualized terminal system

Details on the CPE compensation methods for virtualized terminal system are explained. OFDM transmission with 2-stream MIMO using two relay devices is assumed.

First, CPE compensation method for uplink, where the dominant phase noise is on the transmission side, is explained below. Let $x_{T1,k,l}$ and $x_{T2,k,l}$ be the transmitted signals of the 1st and 2nd streams at the k-th symbol and the l-th subcarrier, respectively. Received signal of the 1st and 2nd antennas, $r_{R1,k,l}$ and $r_{R2,k,l}$, can be expressed as follows.

$$\begin{bmatrix} r_{R1,k,l} \\ r_{R2,k,l} \end{bmatrix} = \begin{bmatrix} h_{11,k,l} & h_{21,k,l} \\ h_{12,k,l} & h_{22,k,l} \end{bmatrix} \begin{bmatrix} e^{j\phi_{T1,k}} & 0 \\ 0 & e^{j\phi_{T2,k}} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix} \quad (1)$$

where $h_{11,k,l} \sim h_{22,k,l}$ are the channel responses between the transmission and reception antennas, $e^{j\phi_{T1,k}}$ and $e^{j\phi_{T2,k}}$ are CPE due to the phase noise at the 1st and 2nd transmission antennas, $N_{R1,k,l}$ and $N_{R2,k,l}$ are the noises at the 1st and 2nd reception antennas, respectively.

Here, the phase rotation in the DMRS symbol ($e^{j\phi_{T1,d}}$ and $e^{j\phi_{T2,d}}$) and the relative phase rotation to the DMRS symbol in each symbol ($e^{j\Delta_{T1,k}}$ and $e^{j\Delta_{T2,k}}$) can be expressed separately. Equation (1) can be written as follows.

$$\begin{bmatrix} r_{R1,k,l} \\ r_{R2,k,l} \end{bmatrix} = \begin{bmatrix} h_{11,k,l} & h_{21,k,l} \\ h_{12,k,l} & h_{22,k,l} \end{bmatrix} \begin{bmatrix} e^{j(\phi_{T1,d}+\Delta_{T1,k})} & 0 \\ 0 & e^{j(\phi_{T2,d}+\Delta_{T2,k})} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix}$$

$$= \begin{bmatrix} h_{11,k,l} \cdot e^{j\phi_{T1,d}} & h_{21,k,l} \cdot e^{j\phi_{T2,d}} \\ h_{12,k,l} \cdot e^{j\phi_{T1,d}} & h_{22,k,l} \cdot e^{j\phi_{T2,d}} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \cdot e^{j\Delta_{T1,k}} \\ x_{T2,k,l} \cdot e^{j\Delta_{T2,k}} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix} \quad (2)$$

In equation (2), MIMO channel matrix includes the phase rotation on the DMRS symbol and transmitted signal vector includes the relative phase rotation of each OFDM symbol. Therefore, MIMO reception processing is performed first using the MIMO channel matrix estimated by DMRS, and then, the CPE (relative phase rotation to the DMRS symbol) in each symbol is compensated using the relative phase error estimated by PT-RS.

Next, CPE compensation method for downlink, where the dominant phase noise is on the reception side, is explained. Similar to the uplink case, the received signal is shown as follows. Here, the phase rotation due to the phase noise is added after the transmitted signal propagates through the MIMO channel.

$$\begin{bmatrix} r_{R1,k,l} \\ r_{R2,k,l} \end{bmatrix} = \begin{bmatrix} e^{j\phi_{R1,k}} & 0 \\ 0 & e^{j\phi_{R2,k}} \end{bmatrix} \begin{bmatrix} h_{11,k,l} & h_{21,k,l} \\ h_{12,k,l} & h_{22,k,l} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix} \quad (3)$$

$e^{j\phi_{R1,k}}$ and $e^{j\phi_{R2,k}}$ denote the phase error (CPE) due to the phase noise at the 1st and 2nd reception antennas. The phase rotation in the DMRS symbol ($e^{j\phi_{R1,d}}$ and $e^{j\phi_{R2,d}}$) and the relative phase rotation to the DMRS symbol ($e^{j\Delta_{R1,d}}$ and $e^{j\Delta_{R2,d}}$) can be expressed separately. Equation (3) is expressed as follows.

$$\begin{bmatrix} r_{R1,k,l} \\ r_{R2,k,l} \end{bmatrix} = \begin{bmatrix} e^{j(\phi_{R1,d}+\Delta_{R1,k})} & 0 \\ 0 & e^{j(\phi_{R2,d}+\Delta_{R1,k})} \end{bmatrix} \begin{bmatrix} h_{11,k,l} & h_{21,k,l} \\ h_{12,k,l} & h_{22,k,l} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix}$$

$$= \begin{bmatrix} e^{j\Delta_{R1,k}} & 0 \\ 0 & e^{j\Delta_{R2,k}} \end{bmatrix} \begin{bmatrix} h_{11,k,l} \cdot e^{j\phi_{R1,d}} & h_{21,k,l} \cdot e^{j\phi_{R1,d}} \\ h_{12,k,l} \cdot e^{j\phi_{R2,d}} & h_{22,k,l} \cdot e^{j\phi_{R2,d}} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix} \quad (4)$$

To derive the transmitted signal $x_{T1,k,l}$ and $x_{T2,k,l}$ in equation (4), the CPE in each symbol is first compensated using the relative phase error to the DMRS symbol estimated by PT-RS on each receiver antenna, and then, MIMO reception processing is performed using the MIMO channel matrix estimated by DMRS.

3.2 Consideration on CPE compensation with MIMO precoding

If precoding is performed in the virtualized terminal system, equation (2) for uplink transmission and equation (4) for downlink transmission can be expressed as follows.

< Uplink >

$$\begin{bmatrix} r_{R1,k,l} \\ r_{R2,k,l} \end{bmatrix} = \begin{bmatrix} h_{11,k,l} \cdot e^{j\phi_{T1,d}} & h_{21,k,l} \cdot e^{j\phi_{T2,d}} \\ h_{12,k,l} \cdot e^{j\phi_{T1,d}} & h_{22,k,l} \cdot e^{j\phi_{T2,d}} \end{bmatrix} \begin{bmatrix} e^{j\Delta_{T1,k}} & 0 \\ 0 & e^{j\Delta_{T2,k}} \end{bmatrix} \begin{bmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix} \quad (5)$$

< Downlink >

$$\begin{bmatrix} r_{R1,k,l} \\ r_{R2,k,l} \end{bmatrix} = \begin{bmatrix} e^{j\Delta_{R1,k}} & 0 \\ 0 & e^{j\Delta_{R2,k}} \end{bmatrix} \begin{bmatrix} h_{11,k,l} \cdot e^{j\phi_{R1,d}} & h_{21,k,l} \cdot e^{j\phi_{R1,d}} \\ h_{12,k,l} \cdot e^{j\phi_{R2,d}} & h_{22,k,l} \cdot e^{j\phi_{R2,d}} \end{bmatrix} \begin{bmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{bmatrix} \begin{bmatrix} x_{T1,k,l} \\ x_{T2,k,l} \end{bmatrix} + \begin{bmatrix} N_{R1,k,l} \\ N_{R2,k,l} \end{bmatrix} \quad (6)$$

w_{ms} denotes the precoding weight for stream *s* and transmission antenna *m*. The precoding weight is multiplied with DMRS and PT-RS as well as data. For uplink, CPE is added to the weighted transmission signal, and therefore, CPE component appears in between the channel matrix and the weight matrix in equation (5). Because estimated channel matrix using DMRS includes the effect of precoding weight but does not include the CPE component on each OFDM symbol, MIMO reception processing using the estimated channel matrix to separate the streams is not accurate. On the other hand, for downlink, CPE is added after the transmitted signal that is multiplied with the precoding weight goes through the channel. Therefore, MIMO reception processing using the channel matrix estimated by DMRS works well after CPE compensation on each receiver antenna using PT-RS. Because it is expected that uplink performance is degraded due to the precoding as explained above, MIMO without precoding is assumed in the performance evaluation in the next section.

4. Simulation

The CPE compensation methods for uplink and downlink explained in Section 3 are evaluated by simulation. Table 1 shows the simulation assumptions. The signal format in 3GPP NR is used. The transmission waveform is OFDM with subcarrier spacing of 120kHz, which is resistant to phase noise assuming a high frequency band. The 2-port PT-RS is used for CPE estimation for the 2-layer MIMO transmission. The phase noise was set to -102dBc/Hz@1MHz offset [4] as the noise level when using a compound semiconductor in the 300GHz band using the phase noise model in 3GPP [6].

Table 1 Simulation assumptions

Parameter	Value
Waveform	OFDM
Subcarrier spacing	120kHz
Number of resource blocks	256
Modulation	QPSK,16QAM
Channel coding	LDPC R=0.6
Channel model	3GPP TDL-A[7]
Delay spread	20 [ns]
Doppler frequency	83.3 [Hz]
Antenna configuration	MIMO：2x2
MIMO processing	MMSE
DM-RS	Front loaded (i.e. mapped on the first OFDM symbol in each slot)
PT-RS	2 ports Time domain: every OFDM symbol Frequency domain: 1 subcarrier in every 2RBs per port
Phase noise model	3GPP model in [6]
Phase noise level	-102dBc/Hz@1MHz offset
Channel estimation	Practical

Figures 6 shows the BLER performance when the phase noise is added to the transmission side in the MIMO transmission, i.e. uplink in the virtualized terminal system. Figure 7 shows the BLER performance when the phase noise is added to the reception side in the MIMO transmission, i.e. downlink in the virtualized terminal system. As the effective CPE compensation methods, CPE compensation before MIMO reception processing (captioned as CPE compensation A) and CPE compensation after MIMO reception processing (captioned as CPE compensation B) are evaluated for the reception side phase noise and the transmission side phase noise, respectively.
From Figs. 6 and 7, in the case of QPSK, even if CPE compensation is not applied, the deterioration of the BLER performance is slight. On the other hand, in the case of 16QAM, it can be seen that the BLER performance is improved by applying CPE compensation. Comparing the BLER performance in both figures, the BLER performance of reception side phase noise (Fig.7) is slightly degraded than that of transmission side phase noise (Fig.6). This would be because the residual phase noise of the CPE compensation impacts on the subsequent MIMO reception processing for the stream separation. For reception side phase noise, CPE compensation is first applied and then the MIMO reception processing is performed. The PT-RS used for CPE estimation is mapped on every symbol in the time domain, but mapped on only 1 subcarrier in every 2 RBs (i.e. 24 subcarriers) in the frequency domain. Since the number of PT-RSs per OFDM symbol is limited and subject to frequency-selective fading, the estimated CPE is less accurate than the channel estimation using DMRS which is mapped on every 2 subcarriers. Therefore, it can be considered that the residual phase noise influenced the subsequent MIMO reception processing.

4. Conclusion

Influence of phase noise in MIMO transmission and CPE compensation method in virtualized terminal system were investigated. Since in the virtual terminal system, frequency conversion between the millimeter wave band and the terahertz band is performed in the relay devices, the phase noise in the terahertz band has dominant impact on the entire link. Furthermore, each relay device generates independent phase noise. For MIMO transmission in the virtualized terminal systems, we proposed the compensation method of CPE due to the phase noise. The CPE compensation methods differ depending on whether the dominant phase noise is the transmission side (i.e. uplink in the virtualized terminal system) or the reception side (i.e. downlink in the virtualized terminal system) in the MIMO transmission. For the former case, CPE compensation is performed after MIMO reception processing to separate the streams. For the latter case, CPE compensation is performed before the MIMO reception processing. We evaluated BLER performance of these CPE compensation methods by link level simulation and showed the BLER is improved due to the CPE compensation for both uplink and downlink.

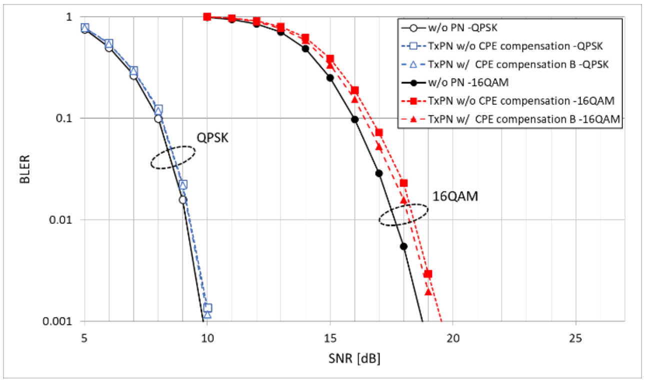

Fig. 6 BLER performance for MIMO with Tx-side phase noise

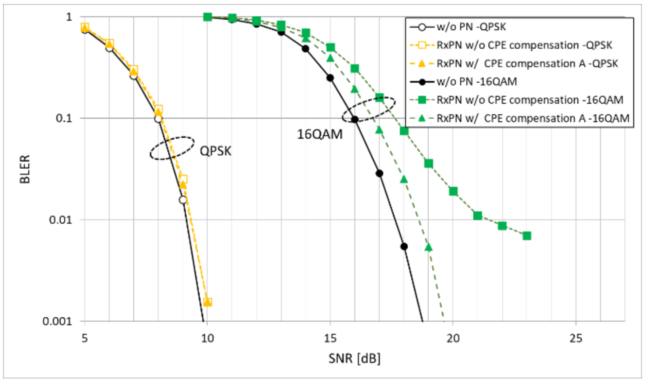

Fig. 7 BLER performance for MIMO with Rx-side phase noise

Acknowledgments

The results of this research were obtained from research commissioned by the National Institute of Information and Communications Technology (acceptance number 00401).

References

[1] K. Yamazaki, T. Ohseki, Y. Amano, T. Murakami, H. Shinbo, and Y. Kishi, "PROPOSAL FOR A USER-CENTRIC RAN ARCHITECTURE TOWARDS BEYOND 5G," IEICE Technical Report, SAT2021-43, Oct. 2021.
[2] S. Maki, Y. Yuda, and A. Nishio, "Study on the effect from the terahertz phase noise for the Beyond 5G wireless system," IEICE General Conference 2022, B-5-35, March 2022.
[3] S. Maki, Y. Yuda, and A. Nishio, "Effect of terahertz-wave phase noise and millimeter-wave multipath fading on Beyond 5G wireless system," IEICE ComEx, Volume 11, Issue 12, Dec. 2022.
[4] S. Maki, Y. Yuda, and A. Nishio, "Effect of non-linearity from Beyond 5G virtualized terminal on performance and adjacent channel," IEICE Society Conference 2022, B-5-51, Sept.2022.
[5] K. Matsumoto, Y. Chang, G. K. Tran, and K. Araki, "Frequency Domain Phase Noise Compensation Employing Adaptive Algorithms for Millmeter-Wave OFDM Systems," IEICE APMC 2014, Nov. 2014.
[6] 3GPP TR38.803 V14.4.0, Sept. 2017
[7] 3GPP TR38.901 V14.3.0, Dec. 2017