IEICE Communications Express, Vol.12, No.12, 591–594

ComEX

Special Cluster in Conjunction with IEICE General Conference 2023

LETTER

Evaluation of TDD timing detection error using UL and DL received signals in the relay device

Yoshio Kunisawa[1, a)] **and Takahiro Hayashi**[1]

Abstract A slot timing detection method as realized by a detector and a comparator in a TDD-operated RF relay device causes timing detection errors due to received signal power fluctuations caused by fading. Here, we clarify the timing detection errors by simulating such a timing detection method using the DL received signal and the UL received signal in a relay device for various fading characteristics. When the CDL-A model is used and the moving speed is 5 km/h, the timing detection error using the DL received signal exceeds 16.7 μsec, which is the OFDM symbol length, and the BER of the UE degrades significantly, while the error is within 1 μsec using the UL signal.

Keywords: virtualized terminal, terahertz, relay device, timing detection
Classification: Wireless communication technologies

1. Introduction

Virtualized terminals using frequency-converting radio frequency (RF) relay devices have been proposed as a new terminal configuration to achieve over 100 Gbps uplink (UL) speeds required for Beyond 5G (B5G) mobile communication [1]. The virtualized terminal consists of user equipment (UE) and relay devices for external mounting antennas (Fig. 1). Relay devices are attached to or built into a wristwatch, eyeglasses, or other devices on the user's person. Since the distance between the UE and the relay device is short, terahertz (THz) band radio waves are used. After frequency conversion between the THz band and millimeter wave (mmWave) band and signal amplification at the relay device, the downlink (DL) signal is sent to the UE and the UL signal to the base station (BS) (Fig. 2). In B5G, when time division duplex (TDD) is considered as a duplexing method, the RF relay device should be able to detect UL and DL timing and switch the relay circuit according to the power fluctuations of the received signal to achieve compact size and low power consumption. We present a timing detection circuit configuration consisting of detectors and comparators and a new timing detection method for RF relay devices that uses both the received DL signal and the received UL signal. Through simulation, we show the lower bounds of the received C/N and received power for timing detection in a static environment [2]. We also showed the timing detection errors in fading channels when using the DL received signal [3]. When the DL signal was used for slot timing detection, we found that the timing error exceeded the OFDM symbol period in the CDL-A environment. Thus, we clarified timing detection errors when UL signals were used for slot timing detection.

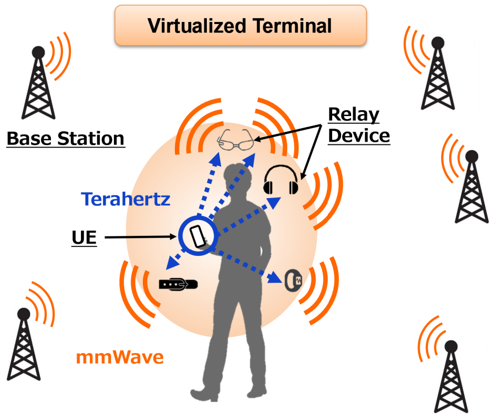

Fig. 1 Wireless system configuration using the virtualized terminal.

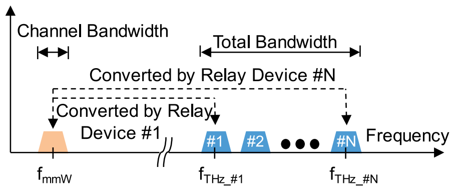

Fig. 2 Frequency conversion by relay devices.

2. RF frontend configuration and TDD timing detection circuit of the relay device

Figure 3 depicts the block diagram of the RF front-end part and the TDD controller of the relay devices. One of the radio waves transmitted in the THz band from the UE is received by the multibeam antenna of a relay device and sent to the UL relay circuit from the THz band TDD switch (SW). We assume that the beams of the transmitting and receiving antennas are exactly opposite each other due to the beam control function, such as in [4]. The UL THz band signal is frequency-converted to the mmWave band and amplified by the UL relay circuit. The mmWave band signal is sent to the mmWave band antenna through the mmWave band TDD SW. Conversely, radio waves transmitted in the mmWave band from the BS are converted to the THz band through two TDD SWs and a DL relay circuit and are transmitted

[1] Radio and Spectrum Laboratory, KDDI Research, Inc., Fujimino-shi, Saitama 356-8502, Japan
a) yo-kunisawa@kddi.com

DOI: 10.23919/comex.2023COL0005
Received June 27, 2023
Accepted August 1, 2023
Publicized November 21, 2023
Copyedited December 1, 2023

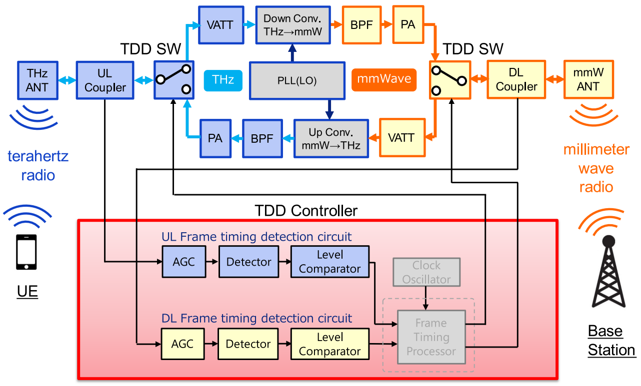

Fig. 3 Block diagram of RF front-end and frame timing detection circuit of relay device.

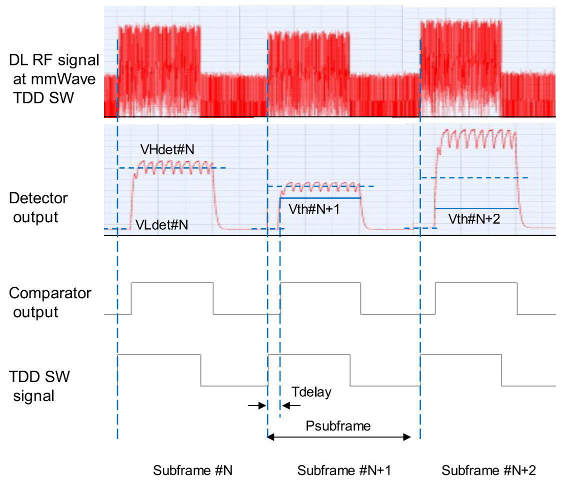

Fig. 4 Timing relationship of RF signal, detector output, comparator output and TDD SW switching signal.

to the UE in the THz band. These two TDD SWs must switch the UL and DL relay circuits precisely when the UL and DL signals change in the TDD frame structure used between the BS and the UE. The signals to switch the TDD SWs are generated in the TDD controller by detecting fluctuations in the received signal power. The frame timing detection circuits for UL and DL in the TDD controller amplify and detect the RF signals split by the coupler in the relay circuits and then use comparators to determine whether or not a signal is present and detect UL slots and DL slots. Figure 4 depicts the timing relationship of the detector output, comparator output, and TDD SW switching signal to the received RF signal. Let $VHdet_{\#N}$ and $VLdet_{\#N}$ be the average values of the detector output voltage during the signaled and unsignaled periods in the #Nth subframe, respectively. Then, the comparator threshold $Vth_{\#N+1}$ in the #N+1st subframe is determined by

$$Vth_{\#N+1} = \frac{VHdet_{\#N} + VLdet_{\#N}}{2} \text{ [V]}. \quad (1)$$

Since the detector is composed of a circuit including a diode and a capacitor, delays occur between the input and output and the comparator output rises with a delay equal to the delay in the detector (where this delay is compared to the timing when the RF signal is input to the TDD SWs) [5]. Therefore, the TDD SWs must be switched earlier according to a time delay $Tdelay$ considering the timing after the subframe period from the rising edge of the comparator output. Here, $Tdelay$ is the time delay that occurs in a static environment. Let $Tcomp_{\#N}$ be the rising timing of the comparator output signal in subframe #N and $Psubframe$ be the subframe period; then, the timing $TswLH_{\#N+1}$ for switching the TDD SWs in subframe #$N+1$ is determined by

$$TswLH_{\#N+1} = Tcomp_{\#N} + Psubfame - Tdelay. \quad (2)$$

As mentioned, the detector is composed of a diode and a capacitor, so the higher the received power, the faster the capacitor is charged and the faster the detector output voltage rises. Therefore, the detection timing of the rising edge of the signal by the comparator varies depending on the received power, and fluctuations in the received signal power cause variations in the detection timing or timing detection errors. When a timing detection error occurs, an error also occurs in the switching timing of the TDD SWs, as determined by Eq. (2). As a result, the TDD SW switching timing deviates from the switching timing of the UL and DL signals, leading to the absence of the relay signal. The following section clarifies the timing detection errors and the impact on the bit error rate (BER) in some environments with power fluctuations.

3. Evaluation of timing detection error with fading channels

3.1 System model and TDD configuration

The as-simulated system model is shown in Fig. 5, with the parameters and assumptions of the transceivers for the UE, relay device, and BS listed in Table I. The THz and mmWave frequencies were set to 275 GHz and 39 GHz, respectively. The 5G NR-compliant OFDM signal with subcarrier spacing (SCS) of 60 kHz was used for the DL transmitting the signal from the BS. Nonline-of-sight (NLOS) and line-of-sight (LOS) were assumed for the millimeter band propagation path characteristics, and the CDL-A and CDL-D channel models specified in [6] were used in the evaluation. In the simulated terminal, since the transmission between the UE and the relay device is over a short distance, the THz band channel characteristics were set statically, assuming an LOS environment. Figure 6 shows the TDD configuration used in this simulation. The frame format with a slot time of 0.25 msec and consists of 3 DL slots, 1 special slot, and 1 UL slot was used. All symbols in the special slot were set to guard symbols [7]. The TDD configuration in Fig. 6 is the same as in Japan, except that the SCS is 60 kHz [8].

3.2 Timing detection error using DL received signal and impact on UE BER

Figure 7 shows the timing detection error for the method using the DL received signal at moving speeds of 0 km/h, 3 km/h, and 5 km/h with respect to the horizontal axis of the DL received power of the relay device. The timing detection error value is expressed as the root mean square error (RMSE) of the time difference between the correct timing and the timing detected by the DL timing detection circuit. The correct timing here is the 1.25 msec cycle timing de-

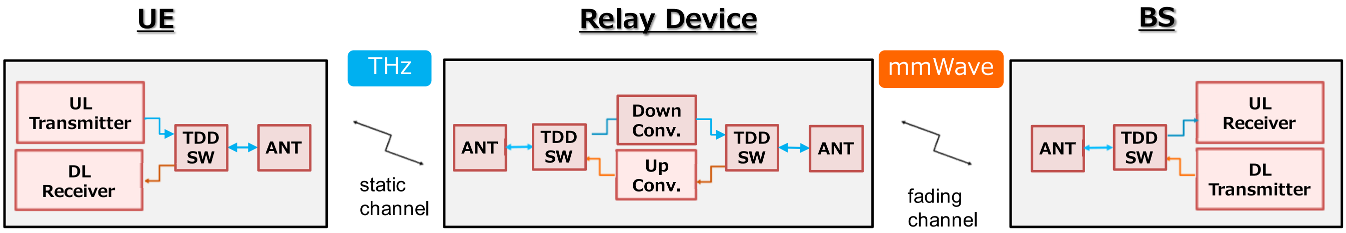

Fig. 5 System model.

Table I Parameters and assumptions of transceivers

Equipment	Parameter	Value
UE	C/N of the UE output (*C/N_UE*)	30.0 dB
	THz antenna power (*Pt_UE*)	-9.0 dBm
	Antenna gain (*Gt_UE*)	27.0 dBi
	Noise figure (*NF_UE*)	9.0 dB
Relay device	THz antenna gain (*Gr_REP*)	12.0 dBi
	mmWave antenna power (*Ptm_REP*)	23.0 dBm
	Maximum UL device gain (*Gmu_REP*)	53.0 dB
	UL noise figure (*NFu_REP*)	13.0 dB
	mmWave antenna gain (*Gt_REP*)	11.0 dBi
	THz antenna power (*Ptt_REP*)	-9.0 dBm
	Maximum DL device gain (*Gmd_REP*)	45.0 dB
	DL noise figure (*NFd_REP*)	13.0 dB
BS	C/N of the BS output (*C/N_BS*)	30.0 dB
	mmWave antenna power (*Pt_BS*)	43.0 dBm
	Antenna gain (*Gr_BS*)	28.0 dBi
	Noise figure (*NF_BS*)	8.0 dB

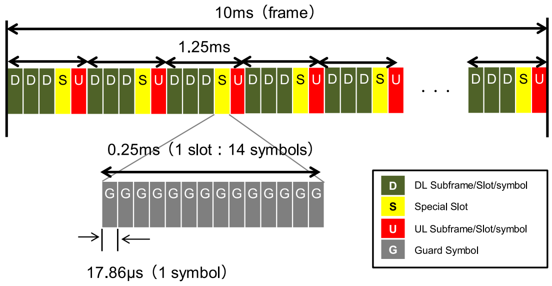

Fig. 6 TDD configuration.

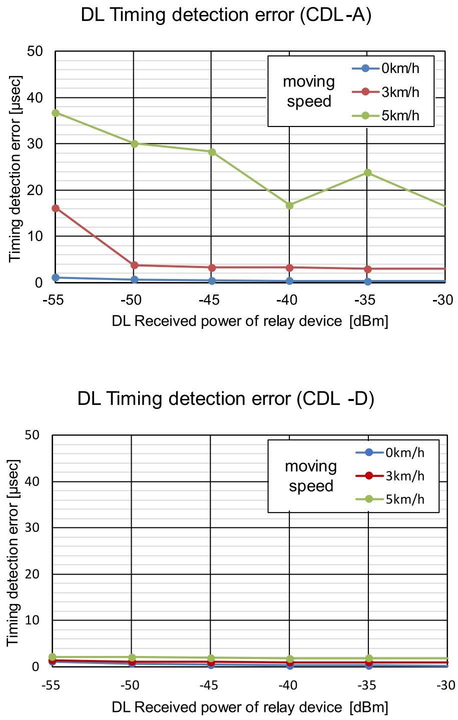

Fig. 7 Timing detection error with DL received signal.

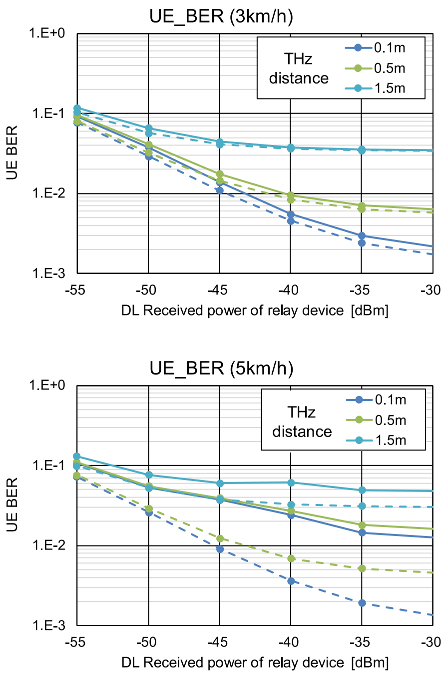

Fig. 8 UE BER when CDL-A model is used for mmWave propagation path.

tected by the timing detection circuit for a static channel with no received power fluctuation. In the NLOS environment, the CDL-A model produced large timing detection errors exceeding the OFDM symbol length of 16.7 μsec at SCS=60 kHz when the moving speed was 5 km/h. On the other hand, the timing detection error in the LOS environment, using the CDL-D model, was less than 1.2 μsec, which is the cyclic prefix (CP) length of an OFDM symbol.

When using a TDD configuration without a guard period included in the switching time between the UL and DL slots, as shown in Fig. 6, timing detection error causes a part of the relay signal to be missing at the end of the UL slot or the beginning of the DL slot, resulting in a reception error at the receiving UE or BS. Therefore, we evaluated the BER of the UE when using the CDL-A model, which showed a large timing detection error (Fig. 8). The solid lines in Fig. 8 depict the BER of the UE at three different THz propagation distances. The dashed line in Fig. 8 represents the BER when the relay device continuously relays DL signals, and all DL signals are relayed without missing. In the case of the

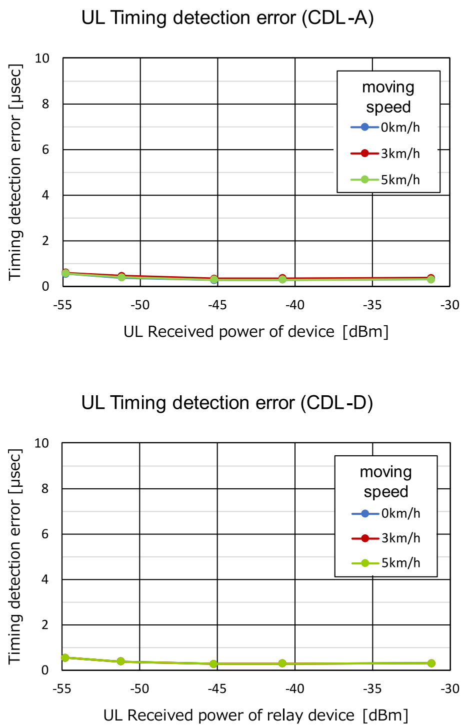

Fig. 9 Timing detection error with UL received signal.

5 km/h moving speed, where a particularly large timing detection error occurred at the relay device, the BER degraded significantly compared to the case where signals are relayed continuously, indicating that the BER is affected by missing DL signals.

3.3 Timing detection error using the UL received signal and consideration

Figure 9 depicts the timing detection error when the relay device detects timing from the UL signal sent from the UE. Under this condition, the TDD SWs of the relay device switch based on the timing detected using the DL signal, and the UE transmits the UL signal at the UL slot timing in the TDD configuration detected by demodulating the relayed DL signal. The timing detection error is expressed as the RMSE of the time difference between the correct timing and that detected by the UL timing detection circuit. Here, the exact detection timing corresponds to the 1.25 msec cycle when the UL slot starts in the TDD configuration (Fig. 6). As shown in Fig. 9, the timing detection error due to the UL signal is small, i.e., less than 1 μsec in both the CDL-A and CDL-D cases. This result indicates that the slot timing detected by the UE demodulating the signal transmitted from the BS and relayed through the relay device is more accurate than the timing detected at the relay device by the DL signal using analog circuits such as detectors and comparators. Fading between the BS and the relay device causes large DL timing detection errors at the relay device because of the fluctuations in the received signal power. Moreover, the timing detection error by the demodulation function of the UE is limited to the time delay range caused by multipath, which is considered smaller than the detection error by the timing detection circuit of the analog configuration. Since the UE demodulates the relayed signal and transmits the UL signal with low timing error, if the relay device can use the received UL signal to perform timing detection and switch the TDD SWs, then it is expected that the device can switch the relay circuit more accurately than when timing detection is performed using only the DL signal.

4. Conclusion

Here, we described a timing detection method at a relay device in a virtualized terminal, which is a new terminal configuration to realize high-speed uplink communication of over 100 Gbps required for B5G mobile communication as proposed in [1]. Timing detection errors were evaluated by simulating an environment with received power fluctuations. The results showed that large timing detection errors occur in fading environments such as CDL-A, where large received power fluctuations occur. BER characteristics at the UE degrade due to missing relay signals. We found that the timing detection error was smaller when using the UL received signal than when using the DL received signal. A specific TDD SW switching algorithm using the detected timings from both DL and UL signals is a subject for our future study.

Acknowledgments

These research results were obtained from the commissioned research (No. 00401) by National Institute of Information and Communications Technology (NICT), Japan.

References

[1] K. Yamazaki, T. Ohseki, Y. Amano, H. Shinbo, T. Murakami, and Y. Kishi, "Proposal for a user-centric RAN architecture towards beyond 5G," Proc. 13th ITU Academic Conference, Online, Session 1.1, pp. 1–7, https://www.itu.int/dms_pub/itu-t/opb/proc/T-PROC-KALEI-2021-PDF-E.pdf, accessed June 20, 2023.
[2] Y. Kunisawa, Y. Amano, and T. Hayashi, "Virtualized terminal utilizing terahertz band radio waves for Beyond 5G: Timing synchronization scheme of relay device," IEEE VTC2022-Fall, Sept. 26–29, 2022. DOI: 10.1109/VTC2022-Fall57202.2022.10012820
[3] Y. Kunisawa, and T. Hayashi, "TDD timing detection using DL received signal in relay device and evaluation on UE BER," IEICE General Conference 2023, B-5-79, March 7–10, 2023.
[4] H. Matsuno, T. Nagao, and Y. Amano, "Angle estimation of wireless devices using power weighted average angle for virtualized terminal using THz band," IEEE AP-S/URSI 2022, July 10–15, 2022. DOI: 10.1109/ap-s/usnc-ursi47032.2022.9886835
[5] D.L. Schilling, and C. Belove, *Electronic Circuits Discrete and Integrated*, 2nd ed., pp. 9–13, McGraw-Hill. ISBN 0-07-055294-0.
[6] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz (Rel. 16)," 3GPP TR 38.901, V16.1.0, Dec. 2019.
[7] 3GPP, "NR Physical layer procedures for control (Rel. 17)," 3GPP TS 38.213, V17.1.0, March. 2022.
[8] Y. Sagae, S. Sawamukai, Y. Ohwatari, K. Kiyoshima, K. Kanbara, and J. Takahashi, "5G Network," NTT Technical Review, vol. 18, no. 12, pp. 87–88, Dec. 2020. DOI: 10.53829/ntr202012fa13