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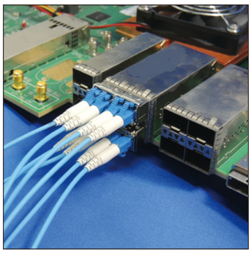

Wavelength-Division-Multiplexing Optical-Transmission Device Using Signal-Compensation Technique and Low-Bandwidth Optical Receivers

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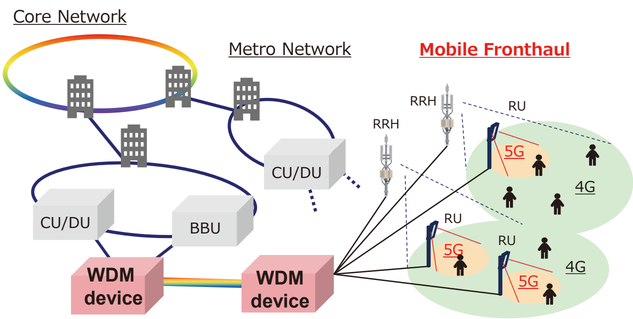
In the 5th generation mobile fronthaul (5G-MFH), a wavelength-division-multiplexing (WDM) optical-transmission device is used to efficiently connect many remote units with fewer optical fibers. WDM optical-transmission device for 5G-MFH is required to meet technical requirements such as long-distance transmission and multi-rate operation at low cost. This paper demonstrates a proof-of-concept of WDM optical-transmission device supporting 10/25 Gbps multi-rate operation using signal-compensated optical transceivers equipped with a 10-Gbps-class-bandwidth optical receiver.

Keywords: mobile fronthaul, optical transmission device, wavelength division multiplexing, signal compensation

1. Introduction

As 5G has begun to use microcells, a large number of remote radio heads (RRHs) and radio units (RUs) need to be rolled out extensively to set up a 5G mobile fronthaul (5G-MFH).*1 The wavelength-division-multiplexing (WDM)*2 optical-transmission device is a promising solution for the efficient deployment of RRHs/RUs. Figure 1 shows a network configuration incorporating WDM optical-transmission devices. The use of WDM optical-transmission devices enables many RRHs/RUs to be rolled out using few optical fibers, proving highly advantageous in terms of cost. The WDM optical-transmission device designed for 5G-MFH is required to support long-distance transmission (≥ 20 km), and multi-rate operation*3 (10/25 Gbps) for simultaneous accommodation of 4G. Conventional WDM optical-transmission devices have met technical requirements by incorporating WDM optical transceivers that meet target specifications. However, as the generation of mobile communications evolves, the transmission rate and cost of optical transceivers are on an increasing trend. Because the cost of a WDM optical-transmission device depends considerably on the cost of optical transceivers, there is concern that it will be difficult to meet the demand for higher speed through development without compromising on cost advantages. We have therefore proposed a novel WDM optical-transmission device(1), employing relatively low-bandwidth optical components for the required transmission speed and using a technology compensating for the performance inadequacy with a signal-compensator(2). Equipped with the capability to use low-cost optical transceivers—even though they do not meet the performance requirements—the proposed device is expected to lead to satisfactory development in terms of both cost and performance.

This paper reports on an evaluation of the characteristics of a prototype optical transceiver equipped with a 10-Gbps-class optical receiver at a transmission rate of 25 Gbps and on a proof-of-concept for 10/25 Gbps multi-rate WDM transmission based on a configuration incorporating proposed WDM optical-transmission devices.



※ CU/DU: Central Unit/Distributed Unit, BBU: Base Band Unit, RRH: Remote Radio Head, RU: Radio Unit

Fig. 1. Schematic diagram of network configuration using WDM optical-transmission devices

2. WDM Optical-Transmission Device

2-1 Configuration incorporating proposed WDM optical-transmission devices

Table 1 lists the target specifications for the WDM optical-transmission device intended for 5G-MFH. The transmission distance, transmission rate, and loss budget*4 comply with the 25G Ethernet Standard (25GBASE-ER*5) applied to the 5G-MFH interface specifications (eCPRI*6)(3). Figure 2 illustrates a structural schematic diagram of the proposed WDM optical-transmission device. The signal-compensator comprised CDR*7 circuits in the transmitter/receiver block and DFE*8 circuits preceding the

Table 1. Target Specifications for WDM Optical-Transmission Devices

Transmission distance	Transmission rate	Loss budget
≥ 30 km	10.31/25.78 Gbps	≥ 20.7 dB

receiver-side CDR circuits. Figure 3 provides a DFE circuit diagram and a schematic diagram of the operating principle. The use of DFE mitigates jitter*9 on the receiver signal and improves the waveform quality. The WDM optical transceiver mounted in the proposed WDM optical-transmission device consists of a 25-Gbps-class DML*10 (25G-DML) transmitter and a 10-Gbps-class APD*11 (10G-APD) receiver.

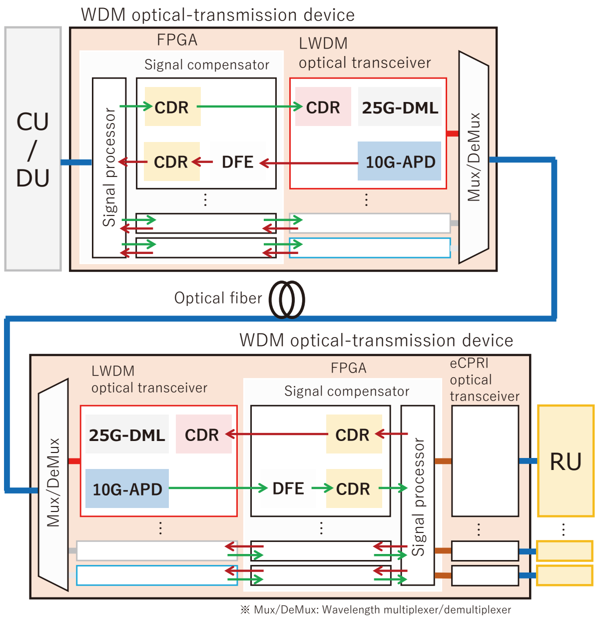


Fig. 2. Schematic diagram of the proposed WDM optical-transmission device

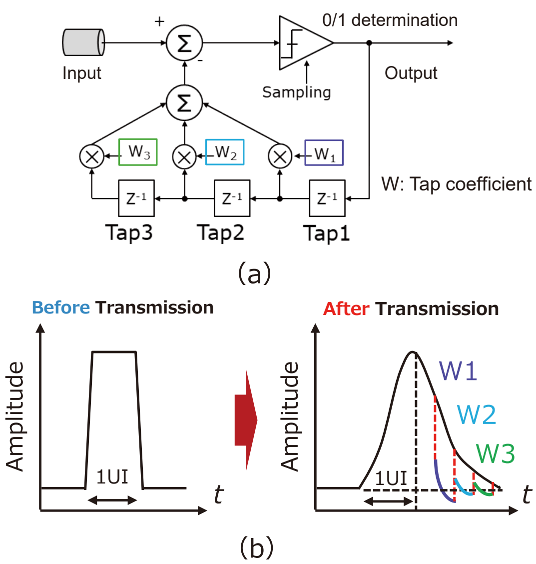


Fig. 3. (a) DFE circuit diagram and (b) schematic diagram of operating principle(4)

2-2 WDM transmission-characteristics-evaluation system

To demonstrate a proof-of-concept for the proposed WDM optical-transmission device, a WDM transmission-characteristics-evaluation system was constructed by combining a prototype WDM transmission-characteristics-evaluation board and WDM optical transceivers. Figure 4 presents a schematic diagram of the WDM transmission-characteristics-evaluation system. The WDM transmission-characteristics-evaluation board was created using a commercially available FPGA*12 evaluation board by incorporating 15-tap DFE-equipped serial transceivers, a PRBS signal*13 generator of NRZ*14 coding, and a bit error ratio (BER) tester. Regarding the maximum number of aggregated fibers, four channels were used due to the number of optical-transceiver cages mounted on the FPGA evaluation board. The transmission rate could be varied, the switching on and off of the DFEs controlled, and the BER test results obtained by an external PC. The prototype optical transceiver compliant with SFP28*15 comprised a 25G-DML and a 10G-APD, as illustrated in Fig. 2. High-optical-output DMLs and high-receiving-sensitivity APDs were used to achieve a high loss budget. The 10G-APD used linear reception*16 without a CDR in the following stage in order to maximize the compensation effect when using DFEs. Table 2 lists the specifications for the prototype optical transceiver. The transmission rates and operating wavelengths comply with multi-rate operation at 10.31/25.78 Gbps and the O-band LAN-wavelength-division-multiplexing (LWDM) wavelengths, respectively. Figure 5 shows the distributions of LWDM and dense wavelength-division-multiplexing (DWDM) wavelengths. LWDM wavelengths are distributed across a wider operating wavelength range than DWDM wavelengths frequently used for WDM transmission. Therefore, LWDM wavelengths are subject to considerable variation—among operating wavelengths—in terms of the effects of chromatic dispersion, making them less suitable for long-distance transmission than DWDM wavelengths. Meanwhile, LWDM wavelengths can use relatively low-cost optical transmitters; the use of LWDM wavelengths leads to reduced cost of WDM optical transceivers. The DFE circuits incorporated in the proposed WDM optical-transmission device can compensate to some degree for communication quality degradation attributed to chromatic dispersion. Therefore, considering the cost-versus-performance tradeoff, we selected LWDM wavelengths as the operating wavelengths.

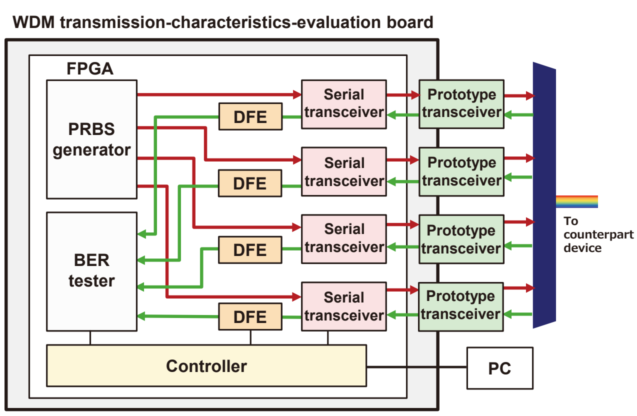


Fig. 4. Schematic diagram of WDM transmission-characteristics-evaluation system

Table 2. Transmission Specifications for Prototype WDM Optical Transceiver

Parameter	Value
Transmission rate	10.31/25.78 Gbps
Operating wavelength	1269 ~ 1318 nm (LWDM)
Mean optical power	2 ~ 8.16 dBm

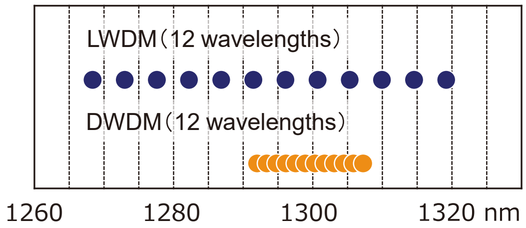


Fig. 5. LWDM/DWDM wavelength distributions

3. Evaluation

3-1 Performance of prototype WDM optical transceivers

Figure 6 presents the optical-transmission waveforms and electrical-reception waveforms of the prototype WDM optical transceivers (operating wavelength: 1,304.58 nm) at a transmission rate of 25.78 Gbps. For this measurement, no DFE was used with the prototype WDM transceivers. The optical-transmission waveforms exhibited favorable characteristics securing a margin of 21% or more in a mask test*[17] specified by the 25GBASE-ER standard. In contrast, the electrical-reception waveforms barely showed an eye pattern. This is attributed to the failure of the optical receiver to follow optical waveform changes because the bandwidth of the optical receiver incorporated in the prototype WDM optical transceiver was relatively low for the transmission rate. Consequently, it is inferred that the operation of the prototype WDM optical transceiver at a transmission rate of 25.78 Gbps is difficult without using a DFE.

Figure 7 shows the receiver sensitivity of prototype WDM optical transceivers (operating wavelength: 1,269.23~1,318.35 nm) operating for 25.78 Gbps transmission with a DFE. The receiver sensitivity was measured by having a prototype WDM optical transceiver receive an optical signal output from a prototype WDM optical transceiver through a 0 or 30 km single-mode optical fiber and a variable attenuator. The receiver sensitivity was defined as the intensity of received optical power when BER = 5.0E-5. In the case of 0 km fiber-optic transmission, the receiver sensitivity of the prototype WDM optical transceiver was favorable at less than –19 dBm with all wavelength samples, showing minimal differences in receiver sensitivity between operating wavelengths. In the case of 30 km fiber-optic transmission, in contrast to 0 km transmission, the receiver sensitivity improved by 1 dB or more for samples at the shorter wavelength end (operating wavelength: 1,300.05 nm or less). This is attributed to optical waveforms being distorted toward improved receiver sensitivity during fiber-optic transmission due to negative chromatic dispersion in the optical fiber.

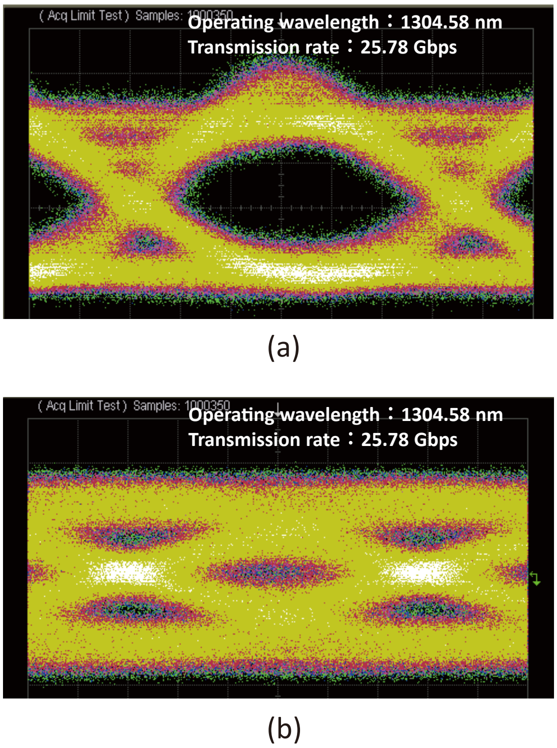


Fig. 6. (a) Optical-transmission waveforms and (b) received electrical waveforms of prototype WDM optical transceivers

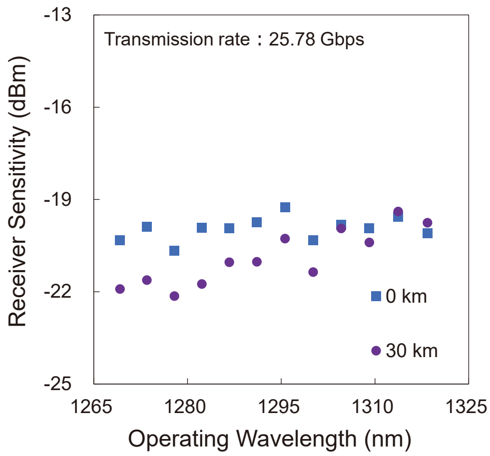


Fig. 7. Receiver sensitivity of prototype WDM optical transceivers

3-2 WDM transmission characteristics of the proposed WDM optical-transmission device

Figure 8 illustrates the WDM-transmission-characteristics-evaluation system for the configuration of the proposed WDM optical-transmission devices. Optical signals output from four prototype WDM optical transceivers were transmitted by WDM through a 30 km optical fiber at transmission rates of 10.31 and 25.78 Gbps; then, the BER characteristic of the test signal (operating wavelength: 1,304.58 nm) was evaluated with and without DFEs. To receive the test signals, commercially available 25 Gbps WDM optical transceivers were also used in addition to prototype WDM optical transceivers. The commer-

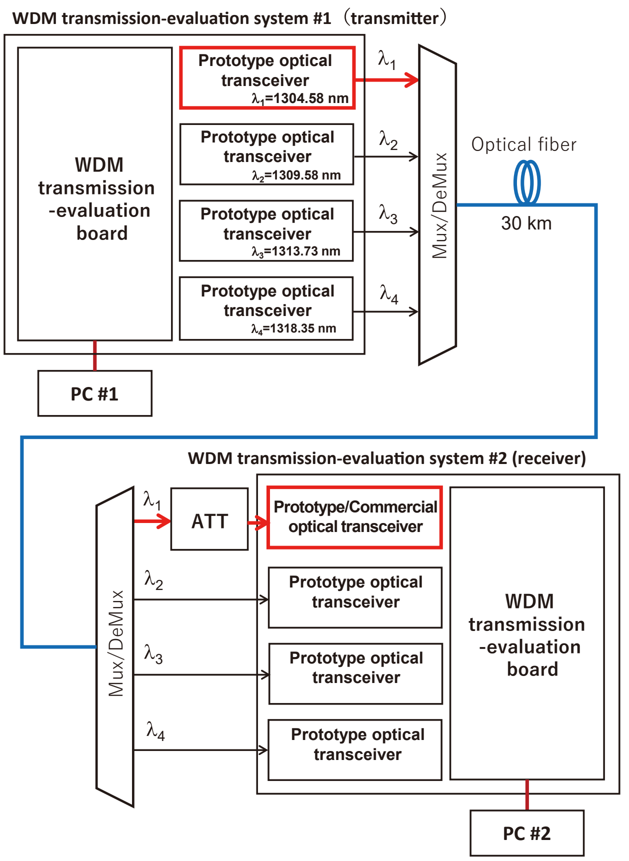


Fig. 8. Schematic diagram of WDM transmission-characteristics-evaluation system

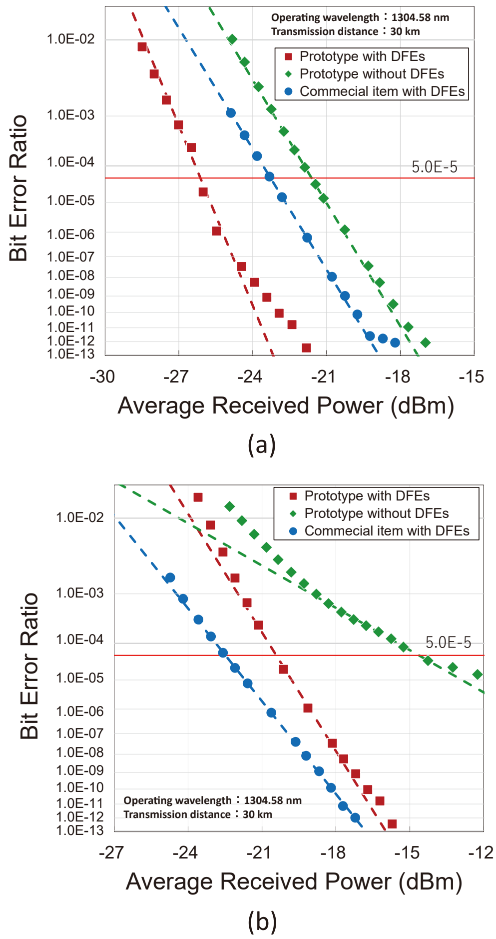


Fig. 9. WDM transmission characteristics at transmission rates of (a) 10.31 Gbps and (b) 25.78 Gbps

cially available WDM optical transceiver was a limiting reception*[18] type incorporating a 25G-APD as a receiver. While its discrete unit can meet the target specifications listed in Table 1, the commercially available WDM optical transceiver is relatively expensive. For the present evaluation, one goal was to deliver comparable transmission characteristics as commercially available WDM optical transceivers while using low-cost prototype WDM optical transceivers.

Figure 9 shows the BER obtained from WDM transmission. When the prototype WDM optical transceivers were used for 10.31 Gbps transmission with and without DFEs, the receiver sensitivity was –26.1 and –21.6 dBm, respectively; thus the use of DFEs improved the receiver sensitivity by 4.5 dB. When commercially available WDM optical transceivers were used, the receiver sensitivity was –23.3 dBm. Consequently, the combination of DFEs and prototype WDM optical transceivers improved on this figure by 2.8 dB. These results are attributed to the linear reception of the prototype WDM optical transceiver, owing to which the DFEs exerted a greater compensation effect, thereby further boosting the originally favorable receiver sensitivity. At a transmission rate of 25.78 Gbps, the receiver sensitivities from the use of the prototype WDM optical transceivers when used with and without DFEs were –20.4 and –14.6 dBm, respectively; the use of DFEs thus improved the receiver sensitivity by 5.8 dB. Table 3 shows the loss budgets calculated from the receiver sensitivity. The intensity of optical power from the prototype or a commercially available WDM optical transceiver was assumed in both cases to be the minimum guaranteed value of 2.0 dBm. At a transmission rate of 10.31 Gbps, the loss budget from the use of prototype WDM optical transceivers was 28.1 dB, surpassing the target loss budget of 20.7 dB by 7.4 dB. At a transmission rate of 25.78 Gbps, the loss budget from the use of prototype WDM optical transceivers was 22.4 dB, which was inferior to the loss budget from the use of commercially available WDM optical transceivers (24.4 dB) by 2.0 dB; nonetheless, it was a favorable result surpassing the target loss budget (20.7 dB) by 1.7 dB.

Table 3. Loss Budgets during WDM Transmission

Transmission rate	Prototype		Commercial item
	w/o DFEs	w/ DFEs	w/ DFEs
10.31 Gbps	23.6 dB	28.1 dB	25.3 dB
25.78 Gbps	16.6 dB	22.4 dB	24.4 dB

4. Conclusion

This paper evaluated the characteristics of a prototype WDM optical transceiver incorporating a 10-Gbps-class optical receiver, operating at a transmission rate of 25 Gbps, and demonstrated a proof-of-concept for 10/25 Gbps multi-rate WDM transmission in a configuration of proposed WDM optical-transmission devices. Combined with DFEs, the prototype WDM optical transceivers achieved a receiver sensitivity of –19 dBm for all wavelength samples. Furthermore, in an evaluation of WDM transmission characteristics in a configuration of proposed WDM optical-transmission devices, loss budgets of 28.1 and 22.4 dB were achieved at transmission rates of 10.31 and 25.78 Gbps, respectively. These results are favorable, surpassing the target loss budget (20.7 dB) at least by 1.7 dB. Thus we have proven that the configuration of the proposed WDM optical-transmission devices can be used to achieve 10/25 Gbps multi-rate WDM transmission. These achievements are expected to enable low-bandwidth and low-cost optical components to be used in WDM optical-transmission devices for certain intended transmission rates and to enable the development of devices that are satisfactory in terms of both cost and performance.

Technical Terms

∗1 5G mobile fronthaul: A network based on optical fibers between CUs/DUs and RUs in a 5G network. The 5G mobile fronthaul is required to efficiently connect a huge number of remote units.

∗2 WDM: A technique used to aggregate and transmit optical signals consisting of multiple wavelengths through one optical fiber.

∗3 Multi-rate operation: The capability of a WDM optical-transmission device to operate at multiple transmission rates for ensuring backward compatibility and building a flexible network.

∗4 Loss budget: The difference between the intensity of optical power from a transmitter and the receiver sensitivity

∗5 25GBASE-ER: The Ethernet communication standard for the 25 Gbps transmission rate.

∗6 eCPRI: Evolved Common Public Radio Interface. An Ethernet-based communication standard that applies to communication between radio base stations and antenna units.

∗7 CDR: Clock data recovery. Recovery of a synchronous clock signal by comparing the internal reference clock and the received signal.

∗8 DFE: Decision feedback equalizer. A device that compensates for waveform distortions by applying a multi-stage delay to the feedback signal, multiplying the output from each stage by a coefficient, and adding up the products.

∗9 Jitter: Time-axis fluctuations in the timing of signal waveforms. Jitter is caused by factors such as thermal noise and waveform distortions occurring during transmission.

∗10 DML: Directly modulated laser. A direct modulation type of optical transmitter.

∗11 APD: Avalanche photo diode. An optical receiver that uses avalanche breakdown.

∗12 FPGA: Field programmable gate array. An IC that allows for circuit reconfiguration after manufacturing according to the operating environment.

∗13 PRBS signal: Pseudo-random binary sequence signal. A binary sequence that exhibits statistical behavior similar to a truly random sequence.

∗14 NRZ: Non-Return to Zero. A modulation scheme in which the voltage between bits does not return to zero.

∗15 SFP28: An optical transceiver form factor.

∗16 Linear reception: A reception technique that converts the received optical signal into an electrical signal through linear amplification. By linear reception, optical signal waveforms are retained through conversion into electrical signals, and the use of DFEs brings about a considerable compensation effect.

∗17 Mask test: A test designed to determine whether or not a signal waveform meets given specifications. A mask pattern is superposed on a signal waveform; the device under test passes the test if the mask pattern does not contain the signal waveform.

∗18 Limiting reception: A technique for converting the received signal into an electrical signal through saturation (limiting) amplification.

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