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研究課題名（和文） Novel fronthaul technology for massive and ultra-dense radio access networks

研究課題名（英文） Novel fronthaul technology for massive and ultra-dense radio access networks

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研究成果の概要（和文）：我々は以下３点の新規技術により、高周波帯における大規模 MIMO (multiple-input multiple-output)無線信号のためのモバイルフロントホールシステムの開発を行った: (i) 高周波数利用効率な光無線 (radio-over-fiber)システム技術、 (ii)高精度キャリア信号発生技術、(iii)高出力集積フォトディテクター技術。

研究成果の学術的意義や社会的意義
The developed system is the first kind of seamless system in high frequency bands that can support large-scale MIMO signal transmission. It can reduce the system cost, complexity, and power consumption, and is promising for facilitating the deployment of new radio access networks in 5G and beyond.

研究成果の概要（英文）：We developed a new mobile fronthaul system for transmission of large-scale multiple-input multiple-output radio signals in high frequency bands, using: (i) high spectral efficiency radio-over-fiber system; (ii) high-precision carrier signal generation, and (iii) high-output integrated photodetector.

研究分野： 工学

キーワード： radio over fiber　mobile fronthaul　mobile network　optical communications

１．研究開始当初の背景

In the fifth-generation and beyond networks, new radio access networks in high frequency, such as those in sub-terahertz bands, and large-scale multiple-input multiple-output (m-MIMO) technology emerge as the most potential and important solutions to provide extremely high throughput to end users. Such new technologies, however, pose new challenges to the transport networks, especially the connections between clouds in central stations and remote small cells, so-called mobile fronthaul systems. Currently, there are two major methods for mobile signal transmission, namely, digitized data transmission using interface protocols, such as common public radio interface, and analog-waveform transmission of mobile signals. Nevertheless, the former method significantly increases the required optical bandwidth. For instance, a fronthaul data rate of beyond terabit/second/sector will be required for transmission of 1-GHz bandwidth and 256-element-MIMO-array signals. The use of analog transmission helps reduce the required optical bandwidth; however, massive parallel systems with high-speed and costly optical components will be needed. The high vulnerability of the transported signals in this method is another big challenging, especially for radio signals in sub-THz bands. To facilitate the deployment of ultra-dense small cells in new radio access networks, a novel fronthaul system is highly demanded for a cost-effective and energy-efficient transmission of m-MIMO signals in high frequency bands. In such a system, the required data rate and the number of parallel optical channels should be significantly reduced while antenna sites should be greatly simplified.

２．研究の目的

In this research, we proposed and developed a new mobile fronthaul system capable of transmitting m-MIMO radio signals in high frequency bands to ultra-dense small cells. The proposed system requires only low-data-rate optical channels for massive radio signal transmission. Specifically, three key technologies were developed in the project, including: (i) a high-performance and high-spectral-efficiency radio-over-fiber (RoF) system for massive data and control signal transmission; (ii) high-precision carrier signal generation and transmission in high frequency bands, and (iii) an integrated photodetector-array receiver for detection of optical signals and power generation. Proof-of-concept demonstrations on the transmission of MIMO radio signals in high frequency band over the developed system was implemented.

３．研究の方法

This research proposed a new fronthaul transmission method by exploiting the advantages of analog waveform transmission and integrated device technologies. Different from other methods, we proposed to extract and transmit data/control and carrier signals separately over parallel optical channels. To reduce the number of optical channels, multiple data/control signals can be mapped and transmitted to antenna sites over the same optical channel using a newly developed RoF system. For the realization of a cost-effective and energy-efficient system, a remote generation and transmission of high-quality carrier signals and power supply were implemented using advanced photonics technologies. In addition, a new integrated photodiode receiver, which has never been developed previously, was developed for detection of the transmitted data/control signals, carriers, and power supply.

４．研究成果

A. 90-GHz high-output integrated photoreceiver development

The optical-to-radio (O/R) converter is a key component and its performance plays a vital role in fiber–wireless systems. The output power of the O/R converter directly affects the signal-to-noise ratio of the entire system. Moreover, the nonlinearity of the output power contributes to the generation of spurious noise from the high-order harmonics. In the project, we designed and fabricated a high-output O/R converter which integrated a 110-GHz uni-travelling carrier photodetector (UTC-PD) chip and a 100-GHz band RF amplifier chip, as shown in Fig. 1(a). Initially, to realize a high-performance integrated O/R module, a high-output UTC-PD device was developed. The essential point of the UTC-PD device design is optimizing epitaxial layer conditions (doping level, thickness) in both the p-InGaAs absorption layer and InP carrier collector layer. With a low pn junction capacitance of approximately 20 fF in 5 mm diameter photodetective area, a very flat frequency response within ±1 dB fluctuation could be achieved up to 110 GHz. Although the UTC-PD was designed for operation under zero-bias condition, it could work well in the high-power region by applying a bias voltage. We characterized the output power linearity at 90 GHz when a bias voltage of up to -3 V was applied to the UTC-PD. We observed that the saturation output power level of -1 dBm at 0 V in the previous work could be improved when applying a bias voltage of - 3 V. A good linearity without any saturation beyond +5 dBm could be confirmed, as shown by the blue dot curve in Fig. 1(b). Subsequently, a high-gain and linear amplifier chip with a minimum gain of 14 dB and a saturation level of +16 dBm in the 85-100 GHz range was integrated with the UTC-PD chip in a metal butterfly package, which was designed with a 1 mm coaxial connector and an optical window. The two chips were hybrid-integrated to minimize insertion loss and to maintain the good frequency response. By using short bonding wire technique, the parasitic inductance between the two chips was minimized. By using a YAG welding process, a pigtail fiber was attached to the package. The output power of the fabricated O/R converter module for different input photocurrent at 90 GHz was measured and compared with that of

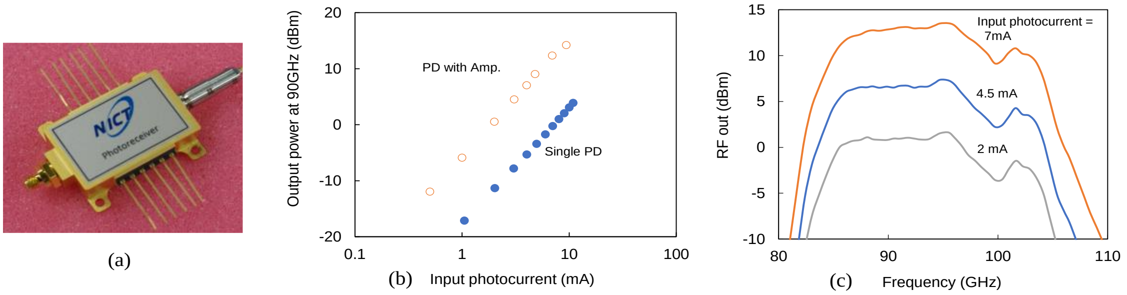

Fig. 1. (a) Fabricated O/R converter; (b) output vs input photocurrent; (c) Frequency response of O/R converter.

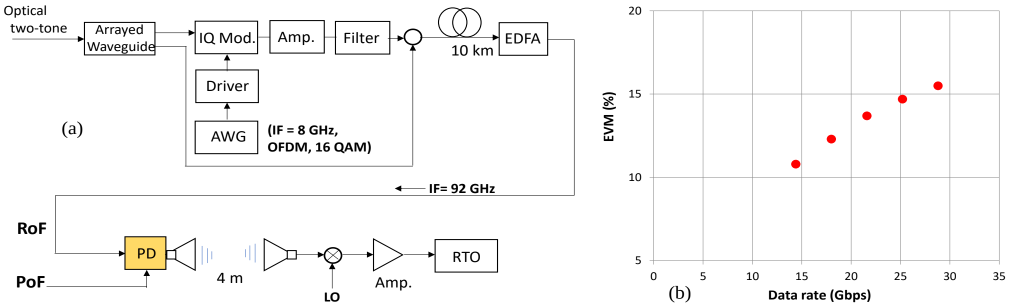

Fig. 2. (a) Experimental setup for 90-GHz RoF and PoF transmission, (b) EVM values for different data rates.

the single UTC-PD, and the results are shown by the red circle curve in Fig. 1(b). An excellent high-power performance and good linearity could be successfully achieved up to +13 dBm. The 1-dB power compression level was estimated as high as +14 dBm, which was dominated by the performance of the amplifier chip. Fig. 1 (c) shows the frequency response of the fabricated O/R converter for three different input photocurrent conditions (2-mA, 4.5- mA, and 7-mA). A flat frequency response within 1 dB fluctuation could be obtained in the 85–97 GHz range, which is sufficient for radio bandpass signal transmission over the system. In addition, the shape of the frequency response curves was similar for the three different input photocurrent conditions. The high output and high linearity performance of the O/R converter will be very useful to enhance the signal performance and increase the wireless transmission range in fiber–wireless systems.

B. Radio-over-fiber and power-over-fiber transmission using 90-GHz integrated photoreceiver

In this subsection, we present a combined RoF and PoF transmission using the developed O/R converter for high-speed wireless communication as well as for simplifying the antenna site. Power-over-fiber (PoF) supplies power through fiber transmission using high-power lasers and photonic power converters (PPC) and demonstrates a good affinity with RoF. Additionally, it is found to be suitable for mitigating power supply issues in populous regions. In this subsection, we present a combined RoF and PoF transmission using the developed O/R converter for high-speed wireless communication as well as for simplifying the antenna site. First, we estimated the power-conversion efficiency through the PoF transmission. Here, the power (0.4 W) in the photoreceiver was consumed predominantly to drive the drain bias in the RF amplifier, rather than the gate bias and UTC-PD bias. This is because the gate bias has a very low power consumption owing to the high-impedance structure, and approximately zero bias was applied for UTC-PD. Therefore, we assumed that the main power consumption in the integrated photoreceiver was attributed to driving the drain of the amplifier. Assuming an RoF-PoF combination transmission, the power-conversion efficiency from the optical input power in the PoF (for drain bias) to the RF output power in the photoreceiver was estimated. The RF output of +13 dBm at 90 GHz was obtained at 1.8 W CW laser in the PoF (at wavelength 830 nm). The RF output level increased from +9.5 to +13 dBm with an increase in the generated drain bias power (0.15─0.4 W) by the PPC. The conversion efficiency between the PPC output and 90-GHz output was as high as 5%. Notably, the conversion efficiency of the PPC was as high as 22%. In addition, the conversion efficiency between the continuous wave laser power on the PoF transmission side and the RF output on the receiver side was estimated as low as 1.1%. For the high data-rate wireless-transmission demonstration of 90-GHz RoF using PoF, the experimental setup was as shown in Fig. 2(a). To create a data-rate signal of tens of Gbps with a 90 GHz range carrier frequency, one of the separated 90-GHz spaced two-tone optical signals was modulated by OFDM signal (16 QAM, bandwidth of 4 to 8 GHz) at an optical IQ modulator and combined with another separated two-tone optical signal (non-modulated) by an optical coupler. After a 10-km RoF transmission, the signal was fed to the integrated photoreceiver, which was supported by 1.8 - 2 W PoF transmission. The signal was fed to a 23-dBi horn antenna and transmitted over a 4-m wireless link. Fig. 2(b) shows a plot of the error vector magnitude (EVM) for different data rates ranging from 14 to 28.8 Gbps. We successfully achieved an EVM of less than 14.9% up to 25.2 Gbps, and an EVM = 15.5% at 28.8 Gbps. These results suggest an error-free condition when applying 7% FEC.

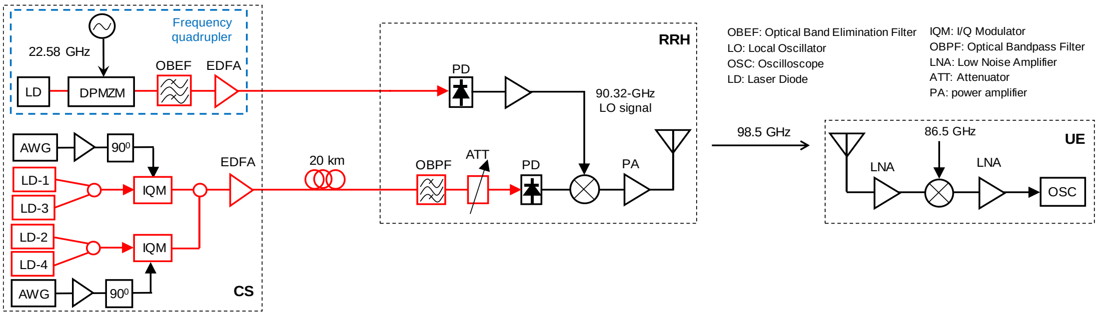

Fig. 3. Experimental setup for OFDM signal transmission over fiber–wireless system in W-band using WDM IFoF transmission.

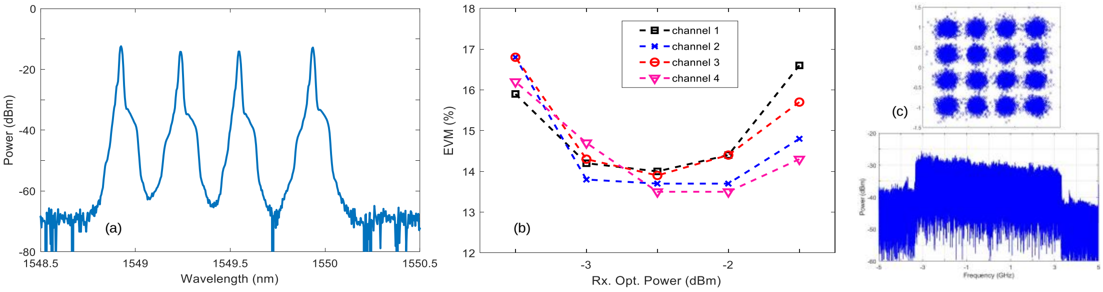

Fig. 4. (a) Optical spectral of WDM IFoF signal; (b) performance of OFDM signals; (c) 16-QAM OFDM signal.

C. Parallel signal transmission using wavelength-division multiplexing technology

Subsequently, we demonstrated a high-speed integrated fiber–wireless system in the W-band for transmission of high-frequency radio signals to ultra-dense small cells and moving cells. The system utilizes a wavelength-division multiplexing intermediate frequency-over-fiber (WDM-IFoF) system and a remote generation and transmission of local oscillator signals. Satisfactory performance was experimentally confirmed for transmission of 4 × 25 Gb/s OFDM signals over the system. A remote generation of a local oscillator (LO) signal and sharing to many antenna sites and/or to many MIMO signal generation can also be considered. This system is suitable for ultra-dense small-cell networks and for the transport of the large traffic volume for massive MIMO and carrier aggregation signals in future mobile networks. The experimental setup for the transmission of high-speed radio signals at 98.5 GHz over a WDM IFoF system is shown in Fig. 3. Optical signals from four different laser diode (LD) are combined by power combiners. The combined optical signals were modulated by OFDM IF signals. Two IQ optical modulators were used to generate optical single-sideband signals to reduce the fiber dispersion effects. In this experiment, 7-GHz bandwidth OFDM IF signals at 8 GHz are generated in Matlab and download to two Arbitrary Waveform Generators. In addition, an optical LO signal with a frequency separation of 90.32 GHz was generated by a frequency quadrupler using a dual-parallel Mach–Zehnder interferometer modulator. The modulated and optical LO signals were amplified by optical amplifiers and transmitted to an antenna site via a 20-km single-mode fiber. At the antenna site, the detected IF OFDM signal was upconverted to a radio signal at 98.5 GHz by being mixed with the generated LO signal. A 90.32-GHz LO signal is generated by feeding the received optical LO signal to a high-speed photodetector. To increase the power level of the LO signal to a sufficient level, a power amplifier was inserted at the output of the photodiode. The up-converted signal was amplified by another power amplifier before being emitted into free space by a 23-dBi horn antenna. After being transmitted over approximately 1 m in free space, the signal was received by another horn antenna, amplified, and downconverted to the IF band by a coherent detection. The down-converted signal was filtered by a high-bandpass filter to remove the DC component. It was amplified and sent to a real-time oscilloscope. Finally, the signal was demodulated in Matlab.

In the experiment, optical signals from different lasers are modulated by a 25-Gb/s OFDM signal at the optical IQ modulators. Fig. 4(a) shows the spectra of the modulated optical signals, which were measured at the input of the photodiode at the optical receiver. The performance of the 25-Gb/s radio signals at 98.5 GHz for different received optical power at the antenna site after being transmitted over the fiber–mmWave link is shown in Fig. 4(b). We should note that, in the experiment we used a single mmWave link for the signal performance evaluation. A tunable optical filter was inserted before the photodiode to select the optical channel in turn for measurement. The performance of the OFDM signals for different optical channels was evaluated in turn by tuning the wavelength the optical filter. Satisfactory performance for 16-QAM OFDM signals was experimentally confirmed. The spectrum of the baseband signal received at the receiver and an example of the received 16-QAM OFDM signal are shown in Fig. 4(c). The system can be useful for transmission of MIMO radio signals to small cells. It can also be suitable for connection between a virtual macro cell and distributed antenna sites to support a cooperative transmission in future mobile networks, especially for radio signals in high frequency bands.

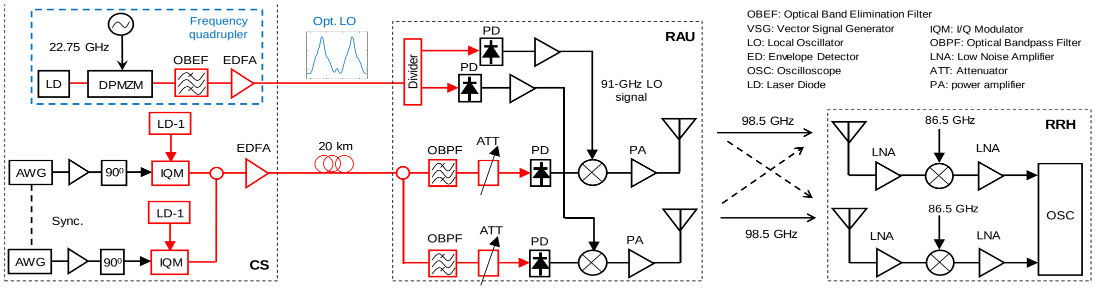

Fig. 5. Experimental setup for the 2 × 2 MIMO fiber–wireless system in the W band using an WDM IFoF transmission.

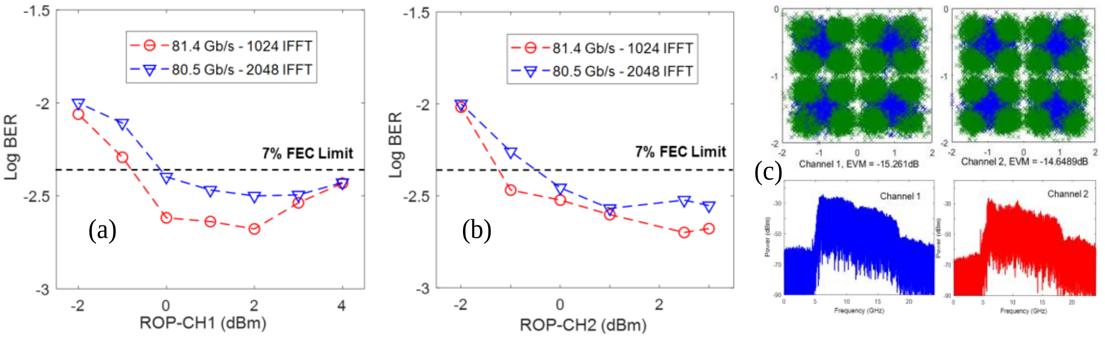

Fig. 6. Performance of the 2 × 2 MIMO fiber–wireless system.

D. MIMO signal transmission using WDM IFoF system

Consequently, we demonstrated a high-speed integrated fiber–wireless system in the W-band for transmission of MIMO signals. The proposed system utilizes a wavelength-division multiplexing intermediate frequency-over-fiber system and a remote generation and transmission of local oscillator signals. Satisfactory performance was experimentally confirmed for 2 × 2 MIMO offset quadrature amplitude modulation-based filter bank multicarrier (OQAM/FBMC) signal transmission with a total capacity of 80 Gb/s. The experimental setup is shown in Fig. 5. Two optical signals with a frequency difference of 50 GHz from two LDs are modulated by 2 × 2 MIMO OQAM/FBMC signals. The modulated optical signals were combined by a 3-dB optical coupler. The received optical signals were separated using another 3-dB OC and filtered using optical bandpass filters to recover the transmitted IFoF signals. After being converted to electrical signals using photodetectors, the signals were upconverted to 98.5 GHz using electronic mixers. The LO signals for the signal up-conversion were generated and delivered remotely from the center. In the experiment, an optical LO signal with a frequency separation of 91 GHz was generated using a two-tone optical signal generator. The generated optical LO signal was transmitted over an SMF. The up-converted signals were filtered using bandpass filters to suppress the carrier and lower sideband signals, amplified using power amplifiers before being emitted into free space by 23-dBi horn antennas. After being transmitted over approximately 1 m in free space, the signals were received, amplified by low-noise amplifiers, and down-converted to 12 GHz using electrical mixers. The signals were amplified, connected to a real-time oscilloscope, and finally demodulated offline. We applied an adaptive modulation to better utilize the signal-to-noise ratios of subcarriers on each channel.

We first transmitted a training signal for estimation of signal-to-noise ratios and respective QAM levels for subcarriers on each channel. During the training phase, only a preamble composing of pilot symbols was transmitted. Using the training signal, the signal-to-noise ratios were estimated at the receiver. The signal-to-noise ratios do not depend on the modulation parameters, but on the channel parameters, noise variance, and symbol variance. We should note that while we changed the modulation level for subcarriers on each channel, the symbol variance remained the same. In other words, no power loading was applied. After the bit loading, the modulation levels are different on different subcarriers and channels. However, the rest of the OQAM/FBMC transceiver chain is the same as in the case of using fixed modulation, including preamble design, synchronization, equalization, channel estimation, and phase tracking. We thereafter applied the estimated modulation levels to the subcarriers on each channel and transmitted the signals over the system. The total capacity is calculated by summing the number of bits applied to all subcarriers. The performance of the signals after being transmitted over the seamless fiber–wireless system is shown in Figs. 6(a) and (b) for different received optical powers in channel 1 and channel 2, respectively. More than 80-Gb/s signal was successfully transmitted over the system with a bit error rate below the soft-decision 7% FEC overhead of 3.8×10^{-3}. In the figures, we compared the performance for two cases: using 1024 subcarriers with a total capacity of 81.4 Gb/s and 2048 subcarriers with a total capacity of 80.5 Gb/s. The performance for the case of using 1024 subcarriers was better. This could be because the use of 1024 subcarrier better balances the trade-off between phase noise and channel frequency response of each subcarrier. Figure 6(c) shows examples of constellations and spectrums of the received signals for the case of using 1024 subcarriers. The frequency responses are different on each channel because the devices used in different channels have different performance characteristics.

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〔産業財産権〕

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７．科研費を使用して開催した国際研究集会

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８．本研究に関連して実施した国際共同研究の実施状況

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