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研究課題名（和文） Development of a high-performance seamless fiber-millimeter-wave system for high-precision analog waveform transmission

研究課題名（英文） Development of a high-performance seamless fiber-millimeter-wave system for high-precision analog waveform transmission

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研究成果の概要（和文）：本研究では、モバイル信号の高精度アナログ波形伝送のための高性能シームレス光・電波融合スシステムを開発するために、いくつかの方法が開発されました。開発された方法には: (1) 高精度な光変調技術を用いた高品質なミリ波信号の生成; (2) 安定および低位相雑音の自己ホモダイン検出技術; (3) 高いスペクトル効率および低いファイバ分散光・無線伝送方法；(4) 低い歪み及び干渉及び高いスペクトル効率のマルチバンド伝送。開発された方法を用いて、システム上の広帯域無線信号の高精度アナログ波形伝送が実験的に確認された。

研究成果の概要（英文）：In this project, to develop a high performance seamless fiber-wireless system for precision analog waveform transmission of mobile signals, several methods were developed, including: (1) a high-quality millimeter-wave signal generation using a high-precision optical modulation technology; (2) a stable and low phase noise self-homodyne detection; (3) a high spectral efficiency and low fiber dispersion fiber-wireless transmission; and (4) a low distortion and interference and high spectral efficient multi-band transmission. Using the developed methods, a high-precision analog waveform transmission of wideband wireless signals over the system was experimentally confirmed. The test signals included wideband (several GHz bandwidth) and high-order modulation format (64-QAM, 256-QAM) signals.

研究分野： 工学

キーワード： Radio over fiber　Seamless Fiber wireless　Optical access network

１．研究開始当初の背景

Small-cell and heterogeneous networks based on cloud-radio-access networks is one the key technologies for future mobile and wireless networks. One of the key enablers to realize such a system would be an efficient and high-performance fronthaul system. The most obvious solution to realize such a system would involve the use of optical fiber cables. However, the associated cost and challenge of installing fiber cables to many small cell sites are prohibitive, especially in urban areas. The use of fiber cable is also unsuitable in many applications because of its lack of flexibility. Millimeter-wave (MMW) communication with a large available bandwidth would be an attractive choice. However, the communication range is limited because of large free-space loss and atmospheric attenuation. A convergence of fiber and MMW system therefore can provide a better solution with high capacity, flexibility, and energy efficiency. A seamless converged system canbe realized using radio-over-fiber (RoF) technology. Nevertheless, the wireless signal quality can be significantly affected by such impairments as phase noise, nonlinear distortion, and fiber dispersion. A stable system with a significantly enhanced dynamic range for high-precision analog waveform transmission of wireless signals is therefore highly demanded.

Study on improvement of the dynamic range of analog RoF systems has been actively conducting. Many methods have been proposed to linearize the systems using pre-distortion and feed-forward methods and so on. However, it is difficult to apply those methods to improve significantly the dynamic range and at the same time to stabilize the performance of the seamless fiber–MMW systems. In the seamless systems, beside nonlinear distortion of the optical modulator as in the RoF systems, the dynamic range and stability are greatly affected by many other factors, including: (i) phase noise during up- and down-conversion of signal to/from MMW region in the fiber-optic and electrical links; (ii) accumulated nonlinear distortion cause by optical modulation, power amplification, photo-mixing, and MMW signal detection; (iii) severe dispersion and nonlinear distortion of optical fiber to MMW signals. New methods thus should be developed to stabilize the performance and enhance the dynamic range of the seamless systems to provide a high-precision analog waveform transmission.

２．研究の目的

The ultimate goal of this research is to develop a stable seamless fiber–MMW system with a high-dynamic range to provide a high-precision analog waveform transmission of wireless signals. Novel methods to minimize and eliminate the impairments associated with the system will be proposed and developed. The proposed solutions include:

(1) high-quality optical MMW signal generation techniques at the transmitter with a low-optical phase noise and phase error;

(2) high-efficient detection scheme at the receiver with low-phase noise and noise floor;

(3) efficient signal processing algorithms to compensate for the accumulated nonlinear distortion and fiber dispersion effects.

At the final state, a stable seamless fiber–MMW system with a high-dynamic range is developed. Proof-of-concept demonstrations on high-precision analog waveform transmission of wideband wireless signals over the system is conducted to confirm the effectiveness and potential of the proposed system. The test signals would include wideband (several GHz bandwidth) and high-order modulation format (64-QAM, 256-QAM) signals.

3. 研究の方法

This research develops and experimentally demonstrates a high-performance seamless fiber–MMW system for precise transmission of analog waveform by combining different methods for increasing the dynamic range and stability, including:

(1) Methods to reduce optical and electrical phase noise;
(2) Methods to reduce electrical noise level;
(3) Method to reduce optical and electrical accumulated nonlinear distortion and fiber dispersion.

The proposed methods based on both hardware and software solutions were proposed and experimentally evaluated. For the optical MMW signal generation, we adopt a high-precision optical modulation technology to generate coherent and high signal-to-noise ratio signals. Compared to the other methods such as using photonic frequency combs, mode-locked lasers, and free-running lasers, this method can generate a high-quality signal suitable for analog waveform transmission. For the signal detection method, a novel scheme based on self-homodyne technique was developed. Compared to the currently available direct detection schemes, it can provide a much higher receiving sensitivity, thus can help to improve the system dynamic range. Compared to the coherent detection method with a phase locked local oscillator, the proposed detection method can help to reduce significantly the electrical phase noise. For the compensation of nonlinear distortion and interference, multi-band signal transmission using a new data mapping algorithm was developed using filtered-OFDM. To overcome fiber dispersion effects, an intermediate frequency over fiber system with a remote delivery of a carrier signal was proposed and successfully demonstrated.

4. 研究成果

The achieved results of this project are summarized as follows,

(1) High-quality MMW signal generation

To generate a phase- and frequency-stabilized MMW signal, we adopted a high-extinction ratio optical modulation technology. In this scheme, a continuous-wave signal from a laser diode is fed into a high-extinction ratio dual-parallel Mach-Zehnder interferometer modulator. An electrical signal is inputted into an electrode of the main MZM to generate even-order sideband components. The generated optical signal is then passed through an optical band-elimination filter to suppress the carrier component. We obtained a coherent two-tone signal with a frequency separation that is four times the value of the fed signal. By using this technique, we can form a completely phase- and frequency-stabilized two-tone optical signal to generate a stable MMW signal. Fig. 1(a) shows an example of the generated two-tone optical signal. By sending this signal to a high-speed photodetector, we can generate an MMW signal. The frequency fluctuation of the generated MMW signal obtained is very small, i.e., less than 100 kHz, as shown in Fig. 1(b).

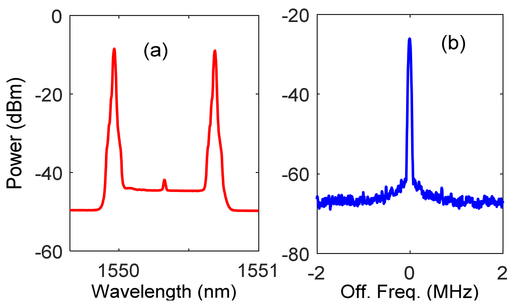

Fig. 1. (a) The generated optical MMW signal, (b) frequency fluctuation of the MMW signal.

(2) Stable and low phase noise self-homodyne detection

The detection of a received MMW signal at the receiver is another key technology that affects the signal performance. To provide a simple solution with high sensitivity and wide bandwidth for mobile-signal transmission, we proposed a self-homodyne detection (SHD) receiver. It uses a diode-type mixer as in the coherent detection; however, no independent local signal source is needed. The received MMW signal is divided into two parts. The signal in one branch is used as the received signal. The other part is used as the local oscillator signal source. To increase the power of this signal to a sufficiently high level, we used a power amplifier. In the branch of the received signal, we used a variable-phase shifter to adjust the phase differences between the two signals. We also inserted isolators to prevent any signal reflection. To evaluate the performance of the proposed detection receiver, we measured the phase noise and dynamic range of the received carrier signal after being transmitted over the seamless system. The measured phase noise characteristics of the received signal using different detection schemes are presented in Fig. 2(a). We observed that using a heterodyne detection with a free-running local oscillator signal source, the phase noise is very unstable. A phase-lock can help stabilize the phase noise, however, the system becomes more complex. The SHD receiver presents a much better performance. Fig. 2(b) presents the spurious-free dynamic range of the systems using an envelop detection and the SHD for the signal detection. Because of limitations in the receiver sensitivity and linearity, the direct detection system presents a low dynamic range of approximately 58 dB·Hz$^{2/3}$. The proposed SHD system improves the dynamic range by about 12 dB to a value of approximately 70 dB·Hz$^{2/3}$.

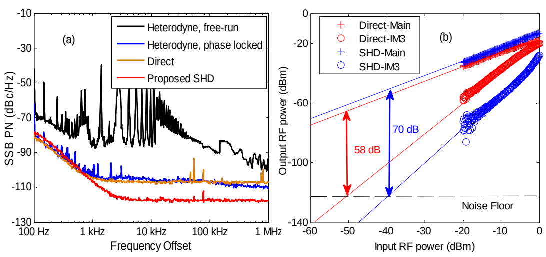

Fig. 2 (a) Single sideband phase noise and (b) spurious free dynamic range characteristics of the proposed SHD.

(3) High spectral efficiency and low fiber dispersion intermediate frequency over fiber system

In RoF systems, radio waveforms in the MMW band are transmitted over fiber links, and radio waves for wireless transmission are generated directly by high-speed photodetectors. On the contrary, waveforms of microwave intermediate frequency signals are transmitted over fiber in intermediate frequency over fiber (IFoF) systems, while radio waves for wireless transmission are generated by a frequency up-convertor at antenna sites. The optical spectral efficiency in RoF system is low because each RAU occupies an optical bandwidth corresponding to the frequency of the MMW signal. Using IFoF systems with the remote delivery of carrier signals, the optical spectral efficiency can be dramatically improved because IF signals are transmitted over fiber links. In addition, optical components in low-frequency regions can be used, helping to reduce the system cost. Furthermore, the same optical local oscillator (LO) signal can be distributed to many antennas for signal up-conversion. Nevertheless, the generation of a high-quality optical MMW signal is of paramount importance to maintain satisfactory performance. In our system, we use our proposed high-quality MMW signal generation technology as described in (2) for a high-quality LO signal. In IFoF systems, because the LO signals can be shared by many antennas, the number of MMW signals that needs to be generated and transmitted over fiber links can be reduced. Furthermore, because the frequency of the generated LO signal can be electrically up-converted to a desired value, a low-frequency LO signal can be generated and transmitted over fiber links. This helps to further improve the optical spectral efficiency and system cost because low-speed optical components can be used. In addition to the high spectral efficiency, the use of IFoF system can help to reduce the fiber dispersion effects, as an example shown in Fig. 3 for 40 GHz signal transmission over fiber.

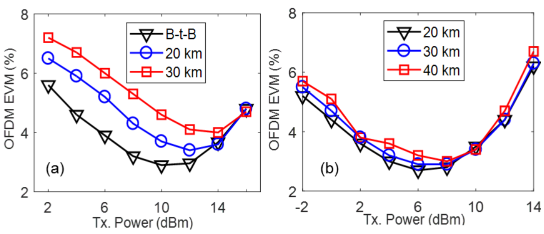

Fig. 3. Performance of 40-GHz OFDM signal over (a) RoF and (b) IFoF system.

(4) Low distortion and interference and high spectral efficient multi-band transmission

For wideband fiber–wireless systems, the performance is affected by non-flat channel response after a cascaded fiber and wireless channel transmission. To overcome the associated effects, the use of multiple-band signal transmission would be very useful. In this work, we propose a high-speed fiber–MMW system using multiple-band filtered-OFDM signal transmission. Comparing to the single-band OFDM and multiple-band OFDM signal transmission, the proposed system can have better spectral efficiency, higher flexibility, and especially lower out-of-band interference as shown by examples shown in Fig. 4.

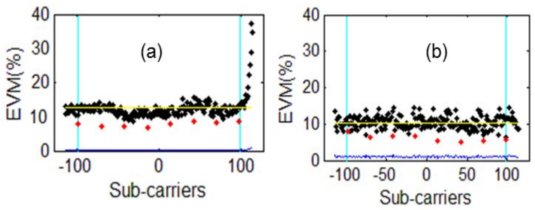

Fig. 4. Effect of out-of-band interference of (a) dual-band OFDM and (b) dual-band filtered OFDM signals.

(5) System demonstration

Using the developed methods, we have demonstrated several signal transmissions over the converged system, including wideband OFDM signals, multiple-band OFDM and filtered-OFDM signals, and higher-order OFDM and LTE-A signals. Simultaneous transmissions of multiple signals over the system was also successfully demonstrated. The results have been published in top-tier international journals, including IEEE/OSA Journal of Lightwave Technology, IEEE Communication Magazine, and presented at international top conferences, including OFC and ECOC.

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