Performance comparison between injection-locked carrier frequency conversion and self-heterodyne detection methods in coherently-linked optical and wireless transmission for 6G

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SUMMARY We compare the performance of an injection-locked carrier frequency conversion and a self-heterodyne methods in our coherently-linked optical and wireless transmission system. By using the carrier frequency conversion method, a 64 Gbit/s 256QAM signal can be transmitted over a 10 km SMF and 10 m wirelessly with a loss budget of 6 dB better than that with a self-heterodyne method.

keywords: Beyond 5G, mobile fronthaul, radio over fiber, coherent optical transmission, injection locking

1. Introduction

Recently, research and development of next-generation large-capacity RAN (Radio Access Network) such as advanced 5G [1] and 6G [2] have been intensively promoted. To increase the mobile data traffic in 6G, consideration is being given to increasing the wireless carrier frequency to the millimeter wave region, where many cells and a large number of multi-input multi-output (MIMO) systems are adopted. When the cells are small, it is necessary to deploy many antennas in a small area. Therefore, there is an urgent need for an economical mobile fronthaul (MFH) for 6G that enables to deliver of a large-capacity data signal to multiple antennas.

Analogue radio over fiber (A-RoF) system has recently attracted attention as a way of realizing a simple and economical MFH [3]. Several A-RoF transmission experiments have been demonstrated in the 60-400 GHz intermediate frequency (IF) band by employing a self-heterodyne method where an optical pilot tone (PT) used as local oscillator (LO) was transmitted with the data [4-6]. In contrast, we have developed a carrier frequency converter (CFC) with an injection-locked LD. This converter can provide an IF data signal with a high S/N and low phase noise [7], where we demonstrated a coherently-linked single-channel 64 Gbit/s, 256 QAM transmission in the 61 GHz IF band over a 10 km single-mode fiber (SMF) and over 40 m wirelessly [8].

In this paper, we compare the performance of an injection-locked CFC (IL-CFC) and a self-heterodyne methods in our coherently-linked optical and wireless transmission system. By using the IL-CFC, it is possible to realize a high SNR heterodyne detection with a high power, high OSNR LO signal. Thus, the loss budget of the transmission system was successfully increased by 6 dB compared to that with the self-heterodyne method.

2. Coherently-linked optical and wireless transmission system

Figure 1 shows the configuration of our coherently-linked optical and wireless transmission system. At the central office, we used a 1.5 μm, LD as a transmitter laser. Its output was first split into two arms. In one arm, the output was IQ-modulated with 8 Gbaud, m-QAM (m=64, 128, and 256) signals (corresponding to 48, 56, and 64 Gbit/s). We used an arbitrary waveform generator (AWG) to generate a simulated IQ baseband signal instead of an actual IQ wireless baseband signal. In the other arm, a PT signal was generated by using an optical frequency shifter consisting of an LN phase modulator and an optical filter. The optical carrier frequency was down-shifted by 61 GHz and was used as a seed signal for injection locking or an LO signal for self-heterodyne detection at the remote unit (RU). The polarization of both signals was adjusted in the same direction. The QAM signal and the PT signal were transmitted over a 10 km SMF toward the RU as a downlink signal. The launch power of the data signal into the SMF was set at -3 dBm.

At the RU, we converted the optical QAM signal to a 60 GHz IF signal using two methods, (a) IL-CFC and (b) self-heterodyne. In the IL-CFC circuit, the LD as an LO was injection-locked to the extracted PT signal with an injection power of -10 dBm. The output of the injection-locked LD was used as an LO signal for heterodyne detection. We also used an optical filter to eliminate the PT from the QAM signal. After filtering, the QAM signal was heterodyne-detected with the LO by using a PIN photodiode (PD) with a bandwidth of 75 GHz. On the other hand, in the self-heterodyne method, the transmitted QAM signal and the PT signal were input directly to the PD for the heterodyne detection. In both systems, the optical input power to the PD was optimized to 6 dBm.

After the heterodyne detection, the IF data signal was amplified and then emitted from a horn antenna toward the user side with an antenna power of 10 mW. We used a horn antenna with a gain of 42 dBi. The propagation distance

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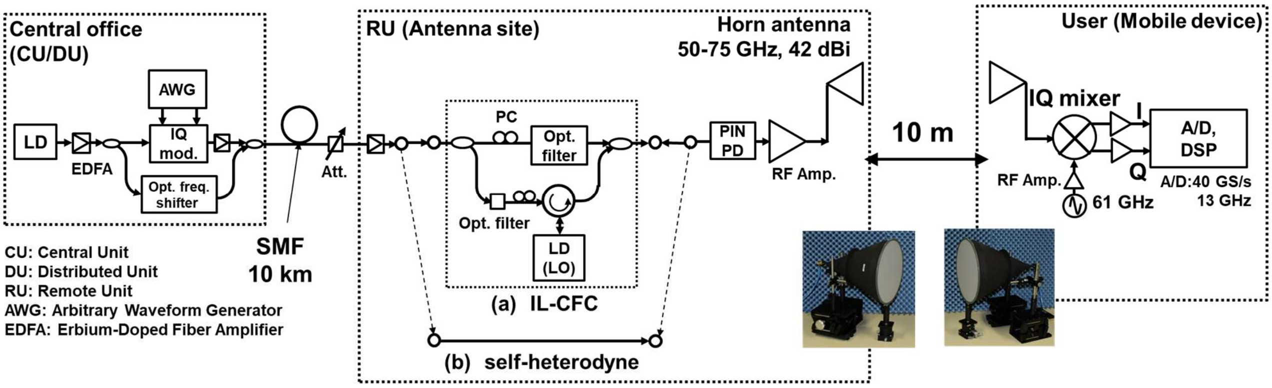

Fig. 1 Experimental setup for coherently-linked optical and wireless transmission.

between the antennas was 10 m and the corresponding free space path loss was 88 dB without taking antenna gain into consideration.

At the user side, the 61 GHz data signal was converted into a baseband IQ signal through an IQ mixer. The baseband signal was then A/D converted and demodulated using an offline digital signal processor (DSP). In the DSP, we compensated for the chromatic dispersion of the 10 km SMF and the waveform distortions induced by optical and electrical hardware imperfections by using a 99-tap finite impulse response filter.

3. Experimental comparison between IL-CFC and self-heterodyne methods

In the transmission system using IL-CFC, the PT to the QAM signal power ratio (P_{PT}/P_{QAM}) was optimized to -13 dB [9] by considering the injection locking performance and the optical SNR (OSNR) of QAM signal. This time, we first optimized P_{PT}/P_{QAM} in the self-heterodyne method under a wireless back-to-back condition without antennas. Figure 2 shows the bit error rate (BER) characteristics of the 64, 128, and 256 QAM signals as a function of P_{PT}/P_{QAM} after transmission through a 10 km SMF. When $P_{PT}/P_{QAM} > 0$ dB, the BER also degrades due to the decrease of QAM signal.

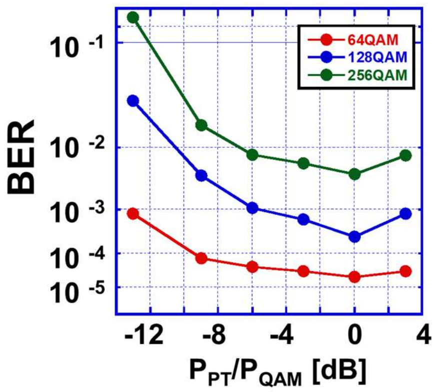

Fig. 2 BER characteristics of each QAM signal as a function of P_{PT}/P_{QAM} under wireless back-to-back condition.

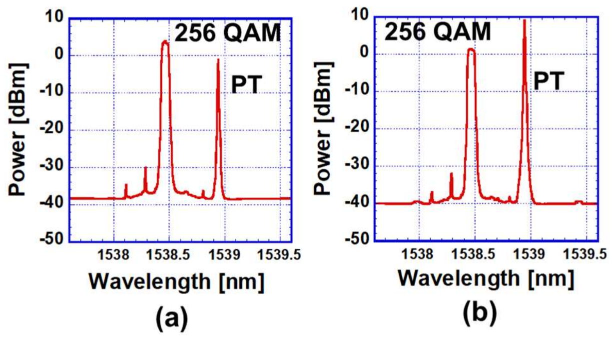

Fig. 3 Optical spectrum of 256 QAM signal and PT in (a) IL-CFC, (b) self-heterodyne method.

From these results, the P_{PT}/P_{QAM} in the self-heterodyne method was optimized to 0 dB.

Figures 3(a) and 3(b) show the optical spectrum of the 256 QAM signal and the PT for the IL-CFC and self-heterodyne method, respectively. The OSNRs of 256 QAM signal with a 0.1 nm resolution bandwidth were 39.5 and 39.0 dB, respectively.

We evaluated the loss budgets of our transmission system with the IL-CFC and the self-heterodyne method under wireless back-to-back condition by intentionally adding an insertion loss with a variable optical attenuator at the transmission fiber link. Figure 4 shows the BER characteristics of each QAM signal when varying the additional insertion loss. When the additional loss is less than 8 dB, the BER characteristics of both transmission systems are almost the same. In the large additional loss region, the BERs of self-heterodyne method are largely degraded. This is because the OSNRs of a QAM signal and a PT used as an LO simultaneously decrease in the self-heterodyne method when increasing an additional insertion loss. With the injection locking method, it is possible to generate an LO signal with high power and high OSNR even with a small power PT. This is the great advantage of injection locking. The loss budget of the IL-CFC method is higher than that with the self-heterodyne method, where the power penalty at a BER of 2×10^{-2} was as high as 6 dB.

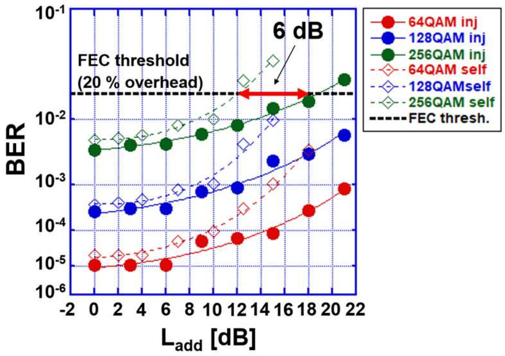

Fig. 4 Evaluation of loss budget for IL-CFC and self-heterodyne transmission methods.

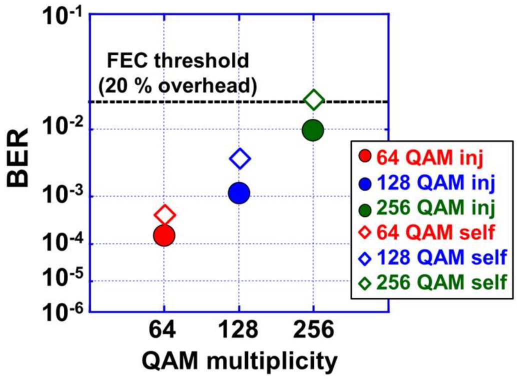

Fig. 5 BER characteristics of 8 Gbaud, 64, 128, and 256 QAM after 10 m propagation wirelessly in the case of a 10 dB additional loss at optical fiber link.

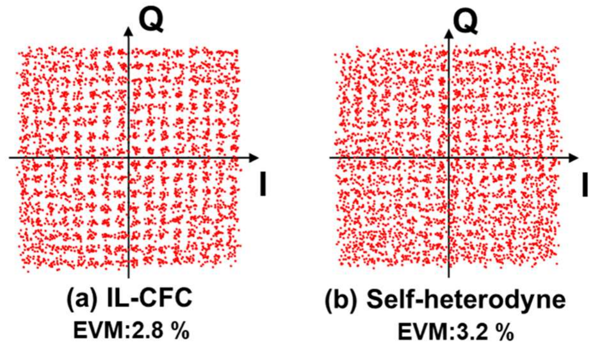

Fig. 6 Constellations of 8 Gbaud, 256 QAM after 10 m propagation with (a) IL-CFC method and (b) self-heterodyne method.

Finally, we evaluated the characteristics of a coherently-linked optical and wireless transmission over a 10 km SMF and over 10 m wirelessly, when the insertion loss was added by 10 dB. Figure 5 shows the BER characteristics of 8 Gbaud, 64, 128, 256 QAM signals by using the IL-CFC and the self-heterodyne methods. Here, the BER of 256 QAM with the IL-CFC was 9.6×10^{-3}, while it degraded to 2.1×10^{-2} and exceeded the FEC threshold (2.0×10^{-2}) with the self-heterodyne method.

Figure 6 also shows the constellations of 256 QAM signal after 10 m wireless propagation with the IL-CFC and the self-heterodyne method. The error vector magnitudes (EVMs) were 2.8 and 3.2 %, respectively, which also indicates that the IL-CFC method is superior to self-heterodyne method.

4. Conclusions

We compared the transmission performance of the IL-CFC and a self-heterodyne methods in our 8 Gbaud coherently-linked optical and wireless QAM transmission in the 61 GHz IF band. The IL-CFC method enabled us to realize heterodyne detection with high SNR, and to increase a loss budget of transmission system by 6 dB compared with that obtained by employing the self-heterodyne method. With IL-CFC, a 64 Gbit/s 256 QAM signal was successfully transmitted over a 10 km SMF and 10 m wirelessly even with an additional insertion loss of 10 dB at an optical fiber link. The coherently-linked optical and wireless transmission scheme using the IL-CFC is expected to be very useful as MFH for a beyond 5G system that delivers large-capacity data signals to multiple antennas.

Acknowledgments

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