# 64 Gbit/s, 256 QAM Coherently-Linked Optical and Wireless Transmission in 61 GHz Band Using Novel Injection-Locked Carrier Frequency Converter

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**Abstract** *We demonstrate 8 Gbaud-256 QAM coherently-linked optical and wireless transmission for next-generation RAN. An injection-locked carrier frequency converter enabled the precise down-conversion of the optical QAM frequency to 61 GHz. Downlink 64 Gbit/s-data were transmitted over 10 km through single-mode-fibre and over 6 m wirelessly.*

## Introduction

Mobile data traffic is increasing at an annual rate of approximately 40 %, and the R&D of next-generation large-capacity radio access networks (RANs), such as advanced 5G[1] and 6G[2], are being intensively promoted. To increase mobile data traffic in such RANs, increasing the wireless carrier frequency up to the millimetre wave region, where many cells and a large number of multi-input multi-output systems are adopted, is being considered. The wireless peak rate is expected to exceed 100 Gbit/s. 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 advanced 5G and 6G that will enable the delivery of a large-capacity data signal to multiple antennas.

In a conventional RAN, digital radio-over-fibre (D-RoF)[3] is adopted as the MFH, where digitised IQ baseband wireless signals are transmitted using a common public radio interface (CPRI) protocol[4] as shown in Fig. 1(a). However, in this system, a CPRI framer/deframer including relatively expensive A/D and D/A converters must be installed in each antenna. Therefore, the conventional D-RoF system may not be suitable as an MFH for next-generation RANs.

On the other hand, analogue RoF (A-RoF) is attractive as a way of realizing a simple and economical MFH[5],[6], where a wireless baseband analogue IQ signal is transmitted on an optical carrier or subcarrier. With heterodyne detection, an intermediate frequency (IF) data signal in the microwave-millimetre wave band is easily obtained in a remote unit (RU) as shown in Fig. 1(b). Several optical wireless linked A-RoF transmission experiments in the 28-400 GHz IF band have already been reported[7]-[9]. In these experiments, a simple self-heterodyne method was used to obtain an IF signal. Here, the reference CW optical tone signal, which was transmitted with the data signal, was used as an LO signal for heterodyne detection in an RU.

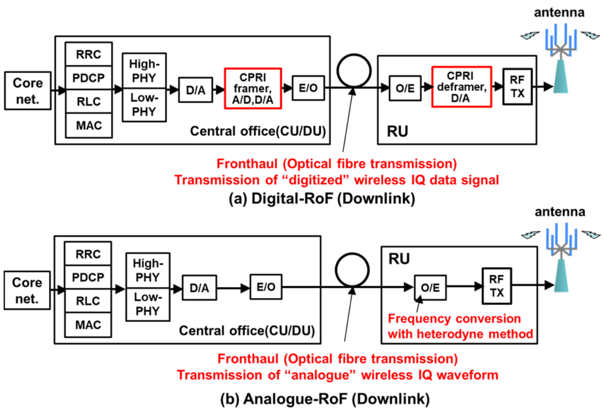


**Fig. 1:** Configuration of (a)digital-RoF and (b)analogue-RoF.

When the data signal is branched into multiple antennas, it seems to be difficult to perform efficient heterodyne detection with a high signal-to-noise ratio (S/N) owing to the increase in insertion loss.

In contrast, we have proposed an injection-locked carrier frequency converter that can provide an IF signal with low phase noise and a high S/N[10]. In this study, we successfully achieved a 64 Gbit/s, 8 Gbaud-256 QAM coherently-linked optical and wireless A-RoF transmission in the 61 GHz band over 10 km through a single-mode fibre (SMF) and over 6 m wirelessly with our carrier frequency converter. We also obtained transmission results with 8 Gbaud 64 and 128 QAM signals.

## Coherently-linked optical and wireless transmission system in the 61 GHz band

Figure 2 shows the configuration of our transmission system. In Japan, the 57-66 GHz band is assigned to low-power data communication systems. We conducted coherently-linked optical and wireless transmission with a single-carrier multi-level QAM signal in the 60 GHz band.

At the central office, we used a 1.5 μm, external cavity LD (ECLD) as a transmitter laser. Its output was IQ-modulated with 8 Gbaud, m-QAM (m=64,

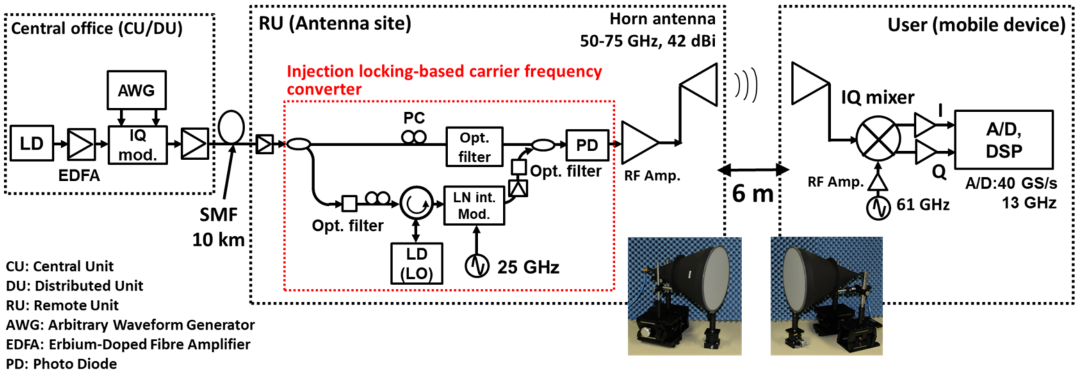


**Fig. 2:** Experimental setup for coherently-linked optical and wireless transmission.

128, and 256) signals (correponding to 48, 56, and 64 Gbit/s) from an arbitrary waveform generator (AWG). We used the AWG to generate a simulated IQ baseband signal instead of an actual IQ wireless baseband signal. A pilot tone (PT) signal, whose frequency was up-shifted by 11 GHz against the transmitter optical frequency, was simultaneously generated. In the AWG, we adopted a Nyquist filter with a roll-off factor of 0.05 to reduce the data signal bandwidth to 4.2 GHz. The m-QAM signal and the PT signal were transmitted over a 10 km SMF toward the RU as a downlink signal, where the launch power of the data signal into the SMF was set to -3 dBm.

At the RU, the LO was injection-locked to the extracted PT signal. The LO was an ECLD whose configuration was the same as that of the LD used in the central office except that an isolator was removed to allow injection locking. The output of the injection-locked ECLD was intensity-modulated with a $LiNbO_3$ (LN) intensity modulator at a modulation frequency of 25 GHz. Then, a second harmonic higher frequency sideband was extracted with a narrowband optical filter, and it was used as an LO signal for heterodyne detection. We also used a narrowband optical filter to eliminate the PT from the QAM signal. After filtering, the downlink m-QAM signal was heterodyne-detected with the LO by using a commercial PIN photodiode (PD) with a bandwidth of 75 GHz. Thus, we obtained a 61 GHz IF m-QAM data signal. A great advantage of our frequency converter is that an IF data signal with low phase noise and a high S/N can be obtained, which is superior to that of a self-heterodyne system without an LO in an RU[7]-[9]. 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 commercial horn antenna with a gain of 42 dBi and a horizontal 3 dB beamwidth of 1.9 degrees. The propagation distance between antennas was 6 m and the corresponding free space propagation loss was 83.5 dB without taking antenna gain into consideration. The 61 GHz

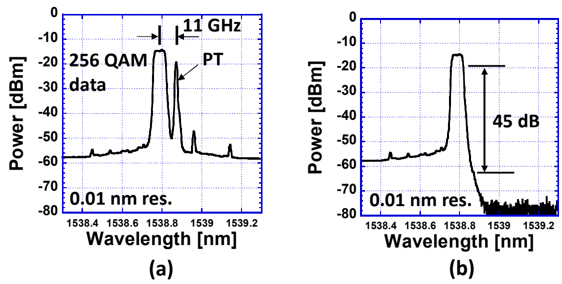


**Fig. 3:** Optical spectra of 8 Gbaud 256 QAM signal after transmission through a 10 km-SMF, (a)without optical filtering, and (b)with optical filtering in RU.

data signal received on the user side was converted into a baseband IQ signal through an IQ mixer. The baseband signal was then A/D converted and demodulated using offline digital signal processor (DSP). Here, we used an A/D converter with a sampling rate of 40 GS/s and an analogue bandwidth of 13 GHz. In the DSP, we compensated for the chromatic dispersion of the 10 km SMF and waveform distortions induced by optical and electrical hardware imperfections by using a 99-tap finite impulse response filter.

## Transmission results

Figure 3(a) shows the optical spectrum after transmission through the 10 km-SMF without optical filtering in the RU. The optical S/N was as high as 41 dB with a 0.1 nm resolution bandwidth. After optical filtering, the PT was eliminated with a suppression ratio of 45 dB as shown in Fig. 3(b)

Figure 4 shows the electrical spectrum of a frequency-converted 8 Gbaud 256 QAM data signal at 61 GHz before propagation. The S/N was approximately 28 dB. The power of the spectrum in the higher-frequency region is slightly reduced. This is due to the frequency characteristics of the RF amplifier with a bandwidth of 50-65 GHz after the PD.

Figure 5 shows the bit error rate (BER) characteristics of the 8 Gbaud 64, 128, and 256 QAM signals. The BERs under a back-to-back condition without antennas, which can be

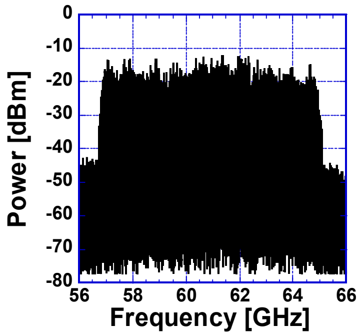


**Fig. 4:** Electrical spectrum of 8 Gbaud 256 QAM data signal at 61 GHz before wireless transmission.

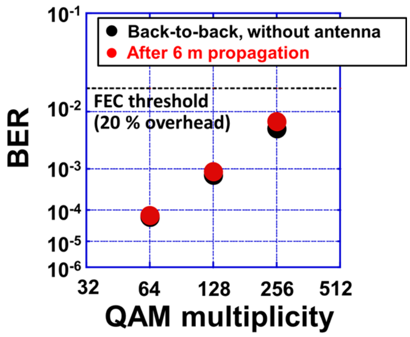


**Fig. 5:** BER characteristics of 8 Gbaud, 64, 128, and 256 QAM.

obtained by directly connecting the RF amplifier and the IQ mixer, are also shown. After a 6 m propagation, the BERs of 64, 128 and 256 QAM were $7.1\times10^{-5}$, $9\times10^{-5}$ and $7.2\times10^{-3}$, respectively. In this transmission experiment, we did not use forward error correction (FEC) encoding/decoding. By adopting a 20 % overhead FEC with a threshold of $2\times10^{-2}$, error-free transmission can be realised with all QAM signals. These BER characteristics were almost the same as those obtained under a back-to-back condition. This is because the data signal was successfully received with a high S/N due to the use of a high gain antenna and our carrier frequency converter, even though the free space propagation loss was large. Figure 6 shows the constellations of each QAM signal after 6 m propagation. The error vector magnitudes (EVMs) were 2.9, 2.6 and 2.7 %, respectively.

## Conclusions

We described a coherently-linked optical and wireless transmission experiment in the 61 GHz band. By using an injection-locked carrier frequency converter, we successfully obtained a QAM data signal with low phase noise and a high S/N at 61 GHz. Thus, 48-64 Gbit/s, 8 Gbaud 64-256 QAM signals were transmitted over a 10 km SMF and 6 m wirelessly. The present transmission scheme is expected to be a large-capacity, high-performance MFH transmission system for advanced 5G and 6G networks.

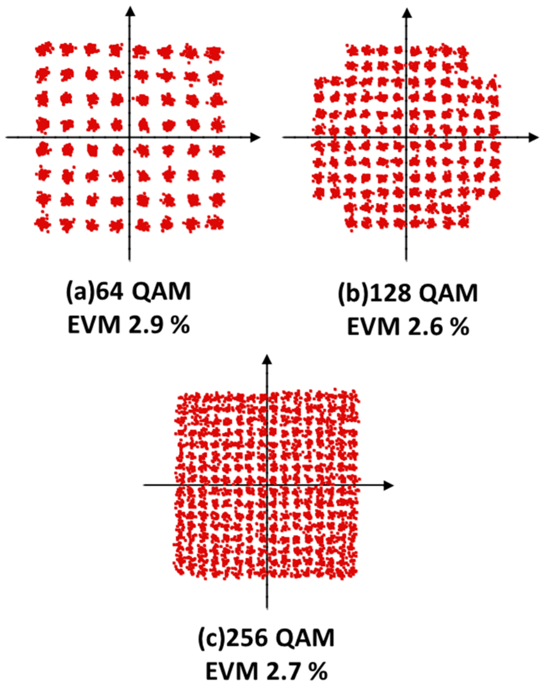


**Fig. 6:** Constellations of 8 Gbaud, 64, 128, and 256 QAM after 6 m propagation.


## Acknowledgements

This research was supported by the National Institute of Information and Communications Technology (NICT), Japan, as a part of the program "Research and development of large capacity mobile access infrastructure for beyond 5G."


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