10 Tbit/s QAM Quantum Noise Stream Cipher Coherent Transmission over 160 km

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Abstract: We present the first 10 Tbit/s secure physical layer transmission over 160 km with a spectral efficiency of 6 bit/s/Hz by using digital coherent QAM quantum noise stream cipher (QNSC) and injection-locked WDM techniques.

1. Introduction

High capacity optical transmission systems have been intensively developed to meet the demands resulting from the rapid growth of data traffic. On the other hand, high capacity networks carry personal and confidential information, and therefore, achieving high security is also a critical issue as regards optical communication. Recently, a physical layer encryption technique using quantum shot noise has attracted a lot of attention with a view to realizing a high-speed and long-distance secure optical transmission system [1]. In this scheme, a stream cipher signal is hidden in quantum noise, and we refer to this as a quantum noise stream cipher (QNSC). By using a multi-level intensity or phase modulation format, a 10 WDM x 10 Gbit/s-120 km transmission [2] and a 1.5 Gbit/s-1000 km transmission [3] have been demonstrated. In these schemes, only one-bit data was encrypted with a basis state. In contrast, we have proposed a multi-bit encoded QNSC scheme that employs the QAM format [4] and demonstrated a 70 Gbit/s-100 km 128 QAM/QNSC transmission [5] and a 40 Gbit/s-480 km 16 QAM/QNSC transmission [6]. However, there has been no report of an ultra-high capacity encrypted transmission beyond Tbit/s.

In this paper, we report a 10 Tbit/s physical layer transmission with a combination of QAM/QNSC and injection-locked WDM techniques. By using an adaptive FPGA-based transmitter and receiver, 165 channel WDM, polarization-multiplexed 5 Gbaud, 4~128 QAM/QNSC (20~70 Gbit/s) on-line transmission over 160 km was demonstrated. In the present transmission, a net capacity of 10.1 Tbit/s was achieved with a spectral efficiency of 6 bit/s/Hz.

2. Operation principle of QAM/QNSC system

In our QAM/QNSC scheme, I (n_I-bit) and Q (n_Q-bit) data are encrypted by m_I and m_Q bit basis states (pseudorandom binary sequence (PRBS)), namely encrypted $2^{n_I+m_I} \times 2^{n_Q+m_Q}$QAM signals are generated [4]. The basis states are generated from a common key prepared in advance between a sender (Alice) and a receiver (Bob). When such an encrypted multi-level data signal is intentionally embedded in quantum noise, an eavesdropper (Eve) has no way of receiving data correctly, whereas Bob can receive the data without error after a mathematical process thanks to the shared key. Extremely high security can be realized by increasing the QAM multiplicity to reduce the phase and amplitude difference between the symbols so that the quantum noise exceeds these differences sufficiently, and the data are completely covered by the noise.

We have demonstrated an FPGA based real-time QAM/QNSC system, where we generated encrypted 5 Gbaud, 2^{10} x 2^{10} QAM data by using a 10 Gsample/s DAC with a 10 bit resolution [5]. The basis states were generated from 2^{63}-1 PRBS generators. In our system, the $n_{I(Q)}$ and $m_{I(Q)}$ bit numbers can be arbitrarily changed, where the relation $n_{I(Q)}+m_{I(Q)}=10$ is maintained. Furthermore, the seed keys of the PRBS generators for the basis states can also be changed with time. These operations enable us to greatly increase the security performance of a QAM/QNSC system. The selection parameters of the QAM data multiplicity M and seed key are prepared in the header of the data frame and sent to the receiver for synchronization.

3. WDM 10 Tbit/s digital coherent QAM/QNSC transmission over 160 km

Figure 1 shows our experimental setup. The transmitter consists of a channel block under measurement and a loading dummy channel block. In the measurement channel block, we used a tunable, 8 kHz linewidth external cavity LD (ECLD) to generate a test channel signal. The output from the ECLD was modulated with a polarization-multiplexed 5 Gbaud, M-QAM/QNSC signal and a pilot tone generated by an FPGA-based transmitter. Here, the bit data stream included a 14 % overhead for a hard decision FEC, whose error correction performance was improved from 4.0x10^{-4} to 3.3x10^{-3} by doubling the overhead rate. The pilot tone frequency was set 3.33 GHz lower than the carrier frequency and was used for injection locking at the receiver [7]. The OSNR of the M-QAM/QNSC signal at the transmitter, $OSNR_t$, was minimized with an attenuator to increase the level of data security against Eve. By setting

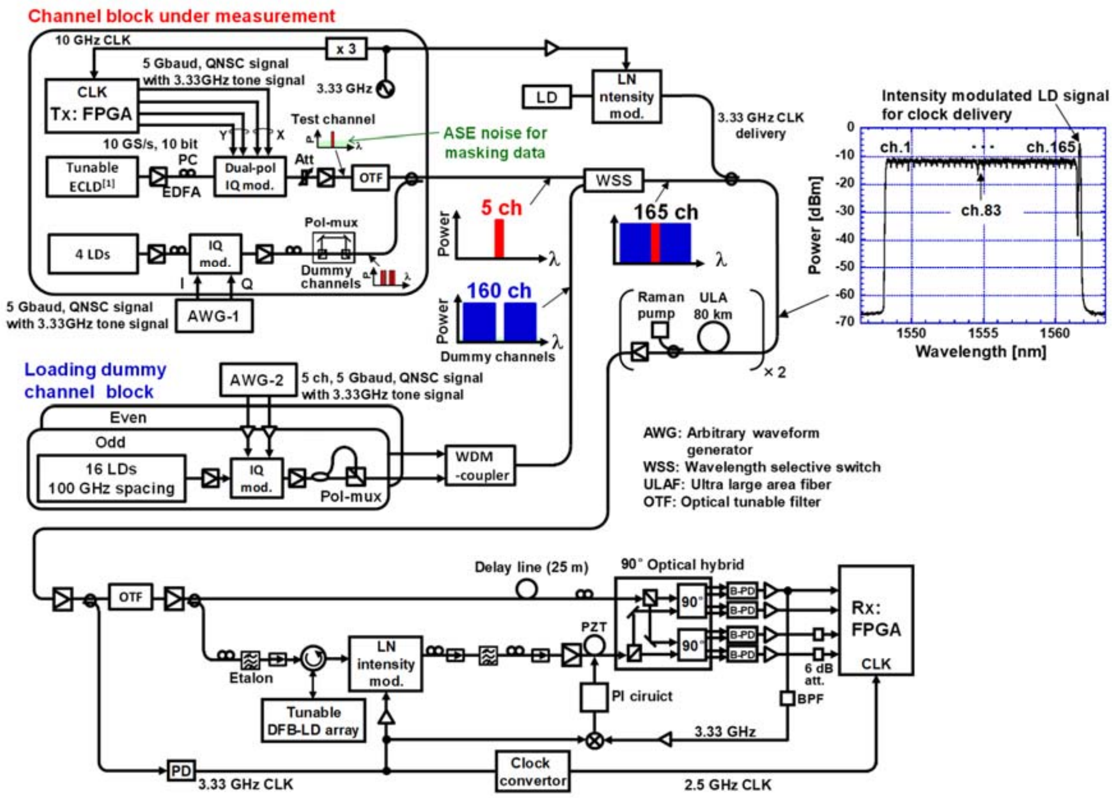

Fig. 1 Experimental setup for 10 Tbit/s WDM digital coherent QAM/QNSC transmission over 160 km.

the signal level sufficiently low, a large shot noise, which originates from the quantum noise caused by amplified spontaneous emission (ASE), can be intentionally added to the received signal. That is, we set $OSNR_t$ at the lowest level at which M-QAM data can be barely transmitted with a BER below the FEC threshold (3.3×10^{-3}) for Bob over 160 km.

In the measurement channel block, four dummy channel signals were also generated by using four LDs with a 100 kHz linewidth and an arbitrary waveform generator (AWG-1). In addition, 160 dummy channel signals were generated by modulating the outputs of 32 LDs with a five-subcarrier modulation scheme using another AWG (AWG-2) at the loading dummy channel block. The test and dummy channels (a total of 165 channels) were combined with a wavelength selective switch (WSS). All the channels were set with a 10 GHz spacing from 1548.2 to 1561.5 nm. Furthermore, an intensity modulated LD signal was used to deliver a 3.33 GHz clock for the synchronous operation between the FPGA based transmitter and receiver. The WDM signal and the intensity modulated LD signal were combined and transmitted over two 80-km spans of ultra-large-area (ULA) fiber. Here, the launch power was optimally set at 11 dBm. The optical spectrum of the output signal from the transmitter is shown in an inset in Fig. 1. The out of signal band was eliminated by the WSS, and the OSNR information could not be obtained from the spectrum, which prevents Eve from estimating the signal multiplicity M from the OSNR.

After transmission, the test channel was wavelength demultiplexed, and then fed into a coherent receiver. At the receiver, a distributed feedback (DFB) LD was injection-locked to the pilot tone and intensity modulated at a modulation frequency of 3.33 GHz. The higher frequency sideband of the intensity modulated signal was used as a local oscillator for homodyne detection. The detected signal was then A/D converted at a sampling rate of 10 GS/s and demodulated with the FPGA receiver [5]. Finally, the BER was measured on-line after FEC decoding. We measured the BER characteristics separately for 33 channels by shifting the wavelength of the test channel.

Figure 2 shows the constellation of a 4~128 QAM/QNSC signal for the center channel (ch.83) after a 160 km transmission without decryption (a) and with decryption (b)-(e). In the encrypted data shown in Fig. 2(a), one of the 4~128 QAM data, corresponding to $n_I + n_Q = 2 \sim 7$, is completely hidden in a constellation of 1024×1024 symbols, which is concealed by the large quantum noise from the laser and ASE noise from the EDFAs. The multiplicity was changed manually from 4~128 QAM. Here, $OSNR_t$ was reduced to 10.6, 17.0, 24.0, and 34.5 dB for 4, 16, 64 and 128 QAM data, respectively. With these $OSNR_t$ values, the pre-FEC BERs were below the FEC threshold (3.3×10^{-3}), and error-free operation was obtained with an improved 14 % overhead FEC.

On the other hand, it is important to count the number of masked signals (NMS) Γ calculated by using the quantum and ASE noise included in the QAM/QNSC signal (see Fig. 2(b)-(e)) for to evaluate the security against Eve [4]. 1/Γ gives us the detection probability, which means that a large Γ results in an extraordinarily low decryption probability. We measured the NMS under a back-to-back condition where Eve can obtain the highest OSNR. The obtained Γ values were 33607, 6506, 1709, and 746 for OSNR$_t$ values of 10.6, 17.0, 24.0, and 34.5 dB, respectively. In comparison with our previous work [5], the NMS value for 4 QAM (QPSK) data was increased from 2.17 x 10^4 to 3.36 x 10^4 due to the improvement in the FEC performance, which enabled us to reduce the OSNR$_t$ value by approximately 1 dB. The obtained Γ value was the highest yet reported for a real-time QNSC system.

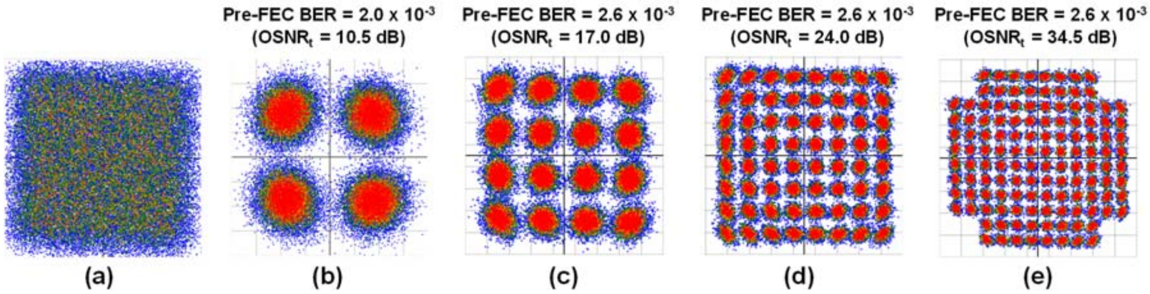

Fig. 2 Constellations of QAM/QNSC signal for ch.83 before (a) and after decryption (b)-(e) after a 160 km transmission.

Figure 3 shows the BER characteristics of the highest 128 QAM/QNSC signal for 66 channels uniformly selected from 165 channels (1548.2 nm ~ 1561.5 nm) after a 160 km transmission. We obtained a pre-FEC BER of around 2 ~ 3 x 10^{-3}, which was below the FEC threshold for all the measured channels. In this transmission, we achieved a net capacity of as high as 10.1 Tbit/s (= 165 ch x 70 Gbit/s / 1.14 (14 % overhead)) with a signal bandwidth of 1.68 THz, which includes 1.65 THz for the WDM signal and 0.03 THz for the intensity modulated LD signal. This indicates that the spectral efficiency reached as high as 6 bit/s/Hz.

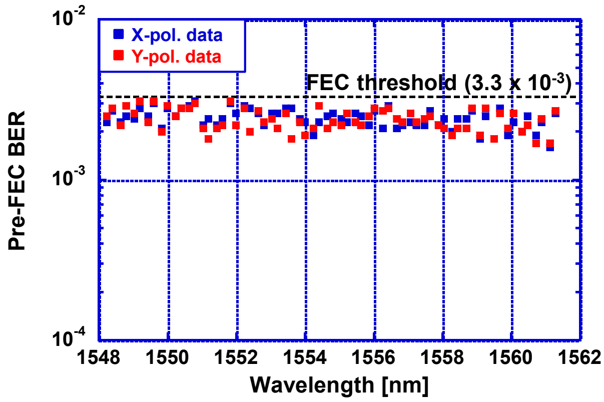

Fig. 3 BER characteristics of 128 QAM/QNSC signal for 66 channels after a 160 km transmission.

4. Conclusion

We demonstrated the first 10 Tbit/s WDM digital coherent QAM/QNSC transmission over 160 km with a spectral efficiency of 6 bit/s/Hz. We also achieved a record NMS value of 3.36 x 10^4 with an improved FEC.

References

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