Recent progress and challenges toward ultrahigh-speed transmission beyond 10 Tbit/s with optical Nyquist pulses

Masataka Nakazawa ①, Masato Yoshida, and Toshihiko Hirooka

Abstract We present recent progress and challenges toward ultrahigh-speed optical time-division multiplexing (OTDM) transmission with a single-channel bit rate beyond 10 Tbit/s using optical Nyquist pulses. First, we review the technological progress made on OTDM/ETDM and digital coherent transmission over the last 20 years and highlight the challenges that must be met to achieve a higher bit rate and a higher spectral efficiency. We then present our proposed scheme that consists of an optical Nyquist pulse and its OTDM transmission and show that coherent Nyquist pulses are very attractive in terms of realizing an extremely high bit rate and high spectral efficiency simultaneously. We describe our recent demonstrations of a single-channel 10.2 Tbit/s (2.56 Tbaud) DQPSK transmission over 300 km using non-coherent Nyquist pulses, and a 15.3 Tbit/s (1.28 Tbaud) 64 QAM transmission over 160 km using coherent Nyquist pulses, in which the highest bit rate we achieved was 15.3 Tbit/s with a spectral efficiency as high as 8.7 bit/s/Hz. We also present a 12.8 Tbit/s (1.28 Tbit/s/ch x 10 ch) transmission of 320 Gbaud DQPSK Nyquist pulses over 1500 km. These results indicate that Nyquist pulses are advantageous not only for achieving an extremely high bit rate but also for realizing a WDM transmission with a 1 Tbit/ch channel capacity over long distances.

Key words: Ultrahigh-speed transmission, optical time division multiplexing (OTDM), optical Nyquist pulse, digital coherent transmission

1. Introduction

Motivated by the rapid increase in global data traffic, ultrahigh-speed transmission with a single-channel bit rate exceeding 1 Tbit/s has become an important research target. In addition, intensive efforts have been made to increase the spectral efficiency to 10 bit/s/Hz and beyond to take full advantage of the available optical bandwidth. To meet these demands, two directions have been explored in optical communications research over the past 20 years, namely the ultrahigh-speed electronic time division multiplexing (ETDM) and optical time division multiplexing (OTDM) transmission toward a faster symbol rate [1, 2] and digital coherent transmission with multi-level quadrature amplitude modulation (QAM) and orthogonal frequency division multiplexing (OFDM) toward a higher spectral efficiency [3]. These trends are described on the left side of Fig. 1. However, there is generally a trade-off between the two directions. For example, faster symbol rates with OTDM require ultrashort optical pulses, but their inherently broad spectral width makes it difficult to improve the spectral efficiency. Faster symbol rates with ETDM require high-speed electronic devices, but as the bandwidth increases in analog and digital devices, the A/D and D/A resolutions (effective number of bits: ENoB) are inherently degraded, which makes it difficult to increase the multiplicity and thus the spectral efficiency.

Recently, we proposed a new optical pulse, which we named a “coherent Nyquist pulse,” which can combine the benefits of both QAM and OTDM transmissions [4], and that is described on the right side of Fig. 1. Coherent Nyquist pulses are very attractive for simultaneously achieving an extremely high bit rate and a high spectral efficiency due to their narrow spectral width and time-domain orthogonality.

In this paper, we first review recent progress made on ultrahigh-speed and digital coherent transmission over the past 20 years and then describe how the single-channel bit rate has evolved up to 10 Tbit/s and beyond with the optical Nyquist pulse. In Sec. 2, we present the progress made on
ETDM and OTDM as well as digital coherent QAM transmissions and highlight challenges that must be met if we are to realize a higher bit rate and higher spectral efficiency simultaneously. In the following sections, we report our recent demonstrations of single-channel 10.2 Tbit/s (2.56 Tbaud) non-coherent Nyquist pulse transmission, 15.3 Tbit/s (1.28 Tbaud) coherent Nyquist pulse transmission, and 12.8 Tbit/s (1.28 Tbit/s/ch x 10 ch) WDM Nyquist pulse transmission.

2. Progress on ultrahigh-speed ETDM/OTDM and digital coherent QAM transmissions

The invention of the erbium-doped fiber amplifier (EDFA) [5, 6] led to the rapid progress made on wavelength-division multiplexing (WDM) capacity in the 1990s [7, 8], where WDM transmission at ~10 Tbit/s was realized by utilizing the C and L bands over an almost 100 nm bandwidth. While the bit rate per single channel remained at ~40 Gbit/s, such a large WDM capacity was easily achieved by the WDM of 100–200 channels. In parallel to the progress on WDM capacity, the single-channel bit rate has also evolved since the 1990s.

The OTDM experiment goes back to 1968 when Kinsel and Denton at Bell Laboratories reported the use of optical multiplexing and demultiplexing to achieve a high-speed optical pulse transmission [9]. They adopted a He-Ne laser as a pulse source and transmitted through air since there was no silica fiber at that time. The realization of ultrafast OTDM transmission was greatly accelerated as the result of a major 10-year project undertaken by the Femtosecond Technology Association (FESTA) between 1995 and 2004 in Japan [10]. Simultaneously, in Europe, projects called Terabit/s Optical Transmission System based on Ultra-high Channel Bitrate (TOPRACE) 2001–2005 [11] and Building the Future Optical Network in Europe (BONE) 2008–2010 [12] were under way. These projects established the fundamental OTDM technology for high-speed pulse generation and detection, high-speed modulators and switches, and high-order dispersion compensation.

Figure 2 shows the evolution of bit rate in ultrahigh-speed OTDM transmission. The red circles represent OTDM, and the blue circles represent OTDM-WDM transmissions. As can be seen, the single-channel bit rate has increased 1000 fold, namely from 10 Gbit/s to 10 Tbit/s, over the past 30 years. Recently there have been many reports on single-channel Tbit/s transmission, but the first Tbit/s OTDM transmission experiment dates back to 2000, when we reported a 1.28 Tbit/s-70 km transmission at 640 Gbaud with polarization-multiplexed on-off keying (OOK) using 400 fs optical pulses [13]. Since then, advanced modulation formats such as differential phase shift keying (DPSK) and differential quadrature phase shift keying (DQPSK) have been employed to realize 2.56 and 5.12 Tbit/s OTDM transmissions [14, 15]. In 2019, the highest bit rate of 15.3 Tbit/s was achieved in a single-channel OTDM transmission [16] as shown in the right top of Fig. 2, and the details will be described in Sec. 5.

In addition to OTDM, ETDM has also made solid progress in recent years. The evolution of ETDM bit rate and symbol rate is shown in Fig. 3(a) and (b), respectively. As shown in Fig. 3(b), the fastest symbol rate has now reached 200 Gbaud by virtue of high-speed electronic devices. An
ETDM coherent transmission at 1 Tbit/s has also been demonstrated with the aid of high multiplicity [17-21]. Currently, backbone networks operating at 100–400 Gbit/s per channel are being deployed with 16–32 QAM at 25–50 Gbaud [22]. Figure 4(a) shows the experimental setup for a 1.52 Tbit/s-80 km ETDM transmission reported in 2020 [21], which corresponds to the circle in the top right of Fig. 3(a). The symbol rate was 128 Gbaud, which was realized with 128 GSa/s digital-to-analog converter (DAC) and 256 GSa/s analog-to-digital converter (ADC). The experimental results are shown in Fig. 4(b). By employing probabilistically-shaped 256 QAM, a net bit rate of 1.52 Tbit/s was achieved after an 80 km transmission.

In parallel to these trends, intensive efforts have been made to achieve a spectral efficiency approaching the Shannon limit in order to maximize the total WDM capacity within a finite optical amplification bandwidth. Figure 5 shows recent multi-level QAM coherent optical transmission experiments with a high spectral efficiency. Higher-order QAM and orthogonal frequency-division multiplexing (OFDM) (e.g. 256–4096 levels) have been adopted to achieve a spectral efficiency exceeding 10 bit/s/Hz, and a total capacity of ~100 Tbit/s has been achieved with digital coherent QAM/WDM transmission [23]. As shown in Fig. 5(b), 256 QAM has been realized as the highest multiplicity in a large-capacity WDM transmission, in which a total capacity of 58.2 Tbit/s was achieved in the C-band alone [24] and 120 Tbit/s in the C- and L-bands [25].

3. Principle of ultrahigh-speed and high spectral efficiency OTDM transmission with coherent Nyquist pulses

High-speed optical and electronic devices have been widely developed to satisfy the growing demand for faster network interfaces in digital coherent transmission. On the other hand, faster symbol rates, for example exceeding 1 Tbaud, can only be realized with an OTDM scheme. However, ultrahigh-speed OTDM has generally not been spectrally efficient and the spectral efficiency has typically remained at < 1 bit/s/Hz, since ultrashort optical pulses require a broad spectral width. A simultaneous increase in bit rate and spectral efficiency has therefore been difficult to achieve with conventional optical pulses such as Gaussian or sech pulses.
To overcome the trade-off between high speed and high spectral efficiency, in 2012 we proposed a new optical pulse, which we named the “coherent Nyquist pulse,” which can combine QAM and OTDM transmissions [4]. The waveform \( a(t) \) and spectrum \( A(\omega) \) of an optical Nyquist pulse are given by

\[
a(t) = \frac{\sin \alpha \omega_N t}{\pi t} \cos \alpha \omega_N t, \quad 1 - \frac{2\alpha}{T} \tag{1}
\]

\[
A(\omega) = \begin{cases} 
\frac{1}{2} \left[ 1 + \sin \frac{T}{2\alpha} (\omega + \omega_N) \right] & \text{for } - (1 + \alpha) \omega_N < \omega < -(1 - \alpha) \omega_N \\
1 & \text{for } |\omega| \leq (1 - \alpha) \omega_N \\
\frac{1}{2} \left[ 1 - \sin \frac{T}{2\alpha} (\omega - \omega_N) \right] & \text{for } - (1 - \alpha) \omega_N < \omega < (1 + \alpha) \omega_N
\end{cases}
\tag{2}
\]

which are shown in Fig. 6. Here, \( T \) is the zero-crossing period, \( \alpha (0 \leq \alpha \leq 1) \) is known as a roll-off factor, and \( \omega_N = \pi/T \). The waveform is defined as the impulse response of a Nyquist filter and is similar to a sinc function. In contrast to ordinary RZ pulses, the tail of a Nyquist pulse does not undergo exponential decay but approaches zero slowly accompanied by a periodic oscillation due to \( \sin \omega t \). The periodic zero crossing makes overlapped pulse interleaving possible without causing intersymbol interference (ISI) as shown in the bottom right hand side of Fig. 1, where when one Nyquist pulse has its peak, all other Nyquist pulses cross zero. This results in a significant increase in the transmission capacity in OTDM transmission as the interleaving occurs every time period \( T \). It should also be noted that the TDM of optical Nyquist pulses has an important property in terms of orthogonality in the time domain [4]. When \( \alpha = 0 \), a time interleaved optical Nyquist pulse centered at \( t = nT \), \( \phi_n(t) = a(t-nT) \), satisfies the following orthogonality condition

\[
\frac{1}{T} \int_{-\infty}^{\infty} \phi_n(t) \phi_m(t) dt = \begin{cases} 
0 & (n \neq m) \\
1 & (n = m)
\end{cases}
\tag{3}
\]

in spite of the overlap with neighboring pulses. Because of these outstanding properties, optical Nyquist pulses have attracted a lot of attention as ideal pulses for achieving ultrahigh-speed and high spectral efficiency simultaneously [26, 27].

Figure 7 compares return-to-zero (RZ) and Nyquist pulses.
At a symbol rate of 2.56 Tbaud, the symbol period becomes as short as 390 fs. Therefore, a conventional Gaussian RZ pulse has to be shortened to about 150 fs to avoid any overlap when interleaved. On the other hand, a Nyquist pulse can realize the same symbol rate as long as its tail crosses zero every 390 fs to avoid intersymbol interference. This allows the pulse width to be extended to between 340 and 350 fs from 150 fs depending on the roll-off factor, \( \alpha \). It should also be noted that at such an ultrafast symbol rate, the RZ pulse spectrum extends outside the C-band as shown by the yellow region, while the Nyquist pulse spectrum is still confined inside the C-band, which is characteristic of the Nyquist pulse shown in Fig. 6. We have demonstrated that, even for such an extremely high-speed transmission beyond 10 Gbit/s, the spectral efficiency can be increased to close to 10 bit/s/Hz by using coherent Nyquist pulses. These demonstrations are described in detail in the following sections.

### 4. Single-channel 10.2 Tbit/s (2.56 Tbaud) DQPSK-300 km non-coherent Nyquist pulse transmission

In this section, we present a single-channel 10.2 Tbit/s non-coherent Nyquist pulse transmission at 2.56 Tbaud, which is the fastest symbol rate yet reported [28]. Figure 8 shows the experimental setup for 10.2 Tbit/s-300 km Nyquist pulse transmission with a polarization-multiplexed DQPSK format. At the transmitter, to generate an ultrashort Nyquist pulse for 2.56 Tbaud, the spectrum of a 1.4 ps Gaussian pulse, which is emitted from a 40 GHz mode-locked fiber laser (MLFL), was broadened over almost the entire the C-band with a highly nonlinear dispersion-flattened fiber (HNLF-DFF). It was then DQPSK modulated at 40 Gbaud with a 2\(^{11}\)–1 PRBS and multiplexed to 2.56 Tbaud with OTDM bit interleavers. The OTDM signal was then shaped into optical Nyquist pulses by using a programmable optical filter as a pulse shaper [29].

After the polarization multiplexing of the 2.56 Tbaud DQPSK signal, the 10.2 Tbit/s data were launched into a 300 km transmission link consisting of 4\(\times\)75 km spans of dispersion-managed fiber using super large area fiber (SLAF) and inverse dispersion fiber (IDF). The residual dispersion was precisely compensated for after a 300 km transmission by using a grating-pair variable dispersion compensator with an accuracy of \(< 0.01\) ps/nm. As regards higher-order dispersion, both the residual third-order and fourth-order dispersions were compensated for with spectral phase manipulation at the pulse shaper before transmission with accuracies of \(0.01\) ps\(^3\) and \(0.001\) ps\(^4\), respectively. The first-order polarization-mode dispersion (PMD) was mitigated by coupling the transmission signal along the principal state of polarization (PSP) of the 300 km transmission link using polarization controllers.

At the receiver, the transmitted signal was first separated into two polarization channels using a polarization-beam splitter (PBS) and then demultiplexed from 2.56 Tbaud to 40 Gbaud using a nonlinear optical loop mirror (NOLM) shown outlined by a blue square in Fig. 8. The NOLM was newly designed for ultrafast optical sampling for a 2.56 Tbaud signal [30]. It was composed of a 20 m dispersion-flattened highly nonlinear fiber (HNLF) with a dispersion

![Fig. 8](image-url)
slope as low as 0.013 ps/nm²/km, which is approximately 6 times lower than that of a standard fiber. This plays an important role in reducing the walk-off between signal and control pulses over a wide bandwidth. To extract the ideal ISI-free points existing only at the symbol period from the interleaved Nyquist pulses, we developed an optical sampling method that is faster than the symbol period (390 fs).

Figure 9(a) shows an autocorrelation trace of the sampling gate profile, measured by launching a continuous-wave (CW) probe light into the NOLM instead of an OTDM signal and by coupling a 40 GHz, 280 fs sech pulse as a control pulse. It can be seen that a gate width as narrow as 230 fs was realized. Figure 9(b) shows the waveform of a 40 Gbaud pulse demultiplexed from a 2.56 Tbaud Nyquist OTDM signal measured with an optical sampling oscilloscope. It can be seen that a tributary is successfully extracted without leakage from other tributaries.

After OTDM demultiplexing, the 40 Gbaud data passed through an RZ-CW conversion circuit for spectral compression [31]. The circuit consisted of a dispersion compensating fiber (DCF) as a dispersive element and a lithium niobate (LN) phase modulator for linear chirping. This technique provided a 5 dB SNR improvement at the spectral peak. The 40 Gbaud DQPSK signal was then demodulated with a one-bit delay interferometer (DI) and detected with a 40 GHz balanced photo diode (PD). Finally, the bit error rate (BER) was measured online with an error detector.

Figure 10 shows an auto-correlation (AC) waveform and the optical spectrum of the generated Nyquist pulse at 40 GHz. The roll-off factor $\alpha$ was set at 0.5, and the zero-crossing period was 390 fs, which corresponds to a symbol rate of 2.56 Tbaud after OTDM. Here, we set $\alpha = 0.5$ taking account of the trade-off between SE and transmission performance. Lower $\alpha$ values are beneficial for higher SE but the ringing of the Nyquist pulse tail increases, which reduces tolerance to transmission impairments. On the other hand, as $\alpha$ becomes closer to 1, the Nyquist pulse approaches a conventional RZ pulse and thus, due to a broader spectral width, the transmission becomes more sensitive to chromatic dispersion and PMD. In Fig. 10(a), it can be seen that AC and actual waveforms have different profiles, and periodic zero crossing cannot be observed in the AC waveform. This is because, when evaluating the overlap integral between two Nyquist pulses, it does not become zero even when they are separated exactly by the...
zero-crossing period because an overlap remains between the two pulses. Instead, the AC waveform exhibits small changes in the curvature of the tail due to the zero-crossing property in the actual waveform. From the AC waveform, the full width at half maximum (FWHM) is estimated to be 340 fs, which agrees well with the ideal FWHM of 330 fs. The spectral profile, whose bandwidth is 30 nm (3.84 THz), also fits the ideal Nyquist pulse spectrum accurately as shown in Fig. 10(b).

Figure 11 shows the bit error rate (BER) characteristics for a 10.2 Tbit/s/ch-300 km transmission. Figure 11(a) shows the relationship between the BER and the received power for one tributary. In a back-to-back configuration, error-free performance was obtained at a received power of ~25 dBm. After a 300 km transmission, the BER curve had an error floor at 2.0x10^-6 in a single-polarization transmission and 1.5x10^-4 in a polarization-multiplexed transmission. The difference in BER is attributed to polarization crosstalk caused by the second-order PMD (depolarization), which inevitably occurs due to the broad spectral width even if the first-order PMD is mitigated [32]. The BERs for all 64 tributaries (2.56 Tbaud / 40 Gbaud = 64) in the polarization-multiplexed transmission are plotted in Fig. 11(b). A BER below the forward-error correction (FEC) threshold of 2x10^-3 (7% overhead) was successfully achieved for all tributaries. As a result, a 10.2 Tbit/s signal was transmitted over 300 km in a 3.84 THz bandwidth, which corresponds to a spectral efficiency of 2.5 bit/s/Hz.

5. Single-channel 15.3 Tbit/s (1.28 Tbaud) 64 QAM-160 km coherent Nyquist pulse transmission

In this section, we describe a single-channel 15.3 Tbit/s coherent Nyquist pulse transmission with a 1.28 Tbaud, 64 QAM format, which is the highest transmission speed yet reported for a single channel [16].

For the coherent detection of the Nyquist pulse, we use the orthogonality of the Nyquist pulses shown in Eq. (3). That is, when the data and the local Nyquist pulse are in the same time slot, demultiplexing and homodyne detection are simultaneously possible, but when they are in a different time slot, the output from the photo-detector goes to zero because of Nyquist pulse orthogonality. Based on time-domain orthogonality, photo-mixing between a Nyquist data pulse and a local oscillator (LO) enables highly efficient demultiplexing [33].

Figure 12 shows an experimental setup for 15.3 Tbit/s, polarization-multiplexed 64 QAM-160 km coherent Nyquist pulse transmission. In a DQPSK transmission, the Nyquist pulse was treated as non-coherent as we did not employ an LO in the system, but in this coherent Nyquist transmission, the Nyquist pulse is treated as a coherent pulse and therefore we use an LO in the system. At the transmitter, we generated an ultrafast coherent Nyquist pulse train for a 1.28 Tbaud transmission, where we employed a 7 m-long HNLF. Here, the HNLF was made as short as possible to maintain coherence during the spectral broadening process [34]. The obtained coherent Nyquist pulse was then 64 QAM-modulated at 10 Gbaud, and multiplexed to 1.28 Tbaud with an OTDM bit interleaver. We also generated a pilot tone for the optical phase-locking of the Nyquist LO pulse, and an intensity-modulated laser diode (LD) signal for 10 GHz clock delivery.

After polarization multiplexing, the 15.3 Tbit/s data were launched into a 160 km transmission fiber. Here we prepared
two types of transmission line, which are shown in Fig. 13(a) and (b). Figure 13(a) shows a dispersion-managed transmission line consisting of large SLAF, \( A_{\text{eff}} = 106 \, \mu \text{m}^2 \) and inverse dispersion fiber (IDF), \( A_{\text{eff}} = 31 \, \mu \text{m}^2 \), and (b) is a combination of ultra large area fiber (ULAF, \( A_{\text{eff}} = 153 \, \mu \text{m}^2 \)) and a 20 m-long chirped fiber Bragg grating (CFBG) [35] as a dispersion compensator. The fiber loss was compensated for by using Raman amplifiers and EDFAs in both cases. In Fig. 13(b), to eliminate the group delay fluctuation of the CFBG, a liquid crystal on silicon (LCoS) filter [29] was inserted after the CFBG. Figure 14(a) and (b) show the group delay characteristics of the ULAF+CFBG transmission line in Fig. 13(b) without and with LCoS, respectively. In Fig. 14(a), there is a group delay fluctuation of 30.5 ps over a 10 nm bandwidth, which is due to a period irregularity in the CFBG. By compensating for the group delay fluctuation with LCoS, it was reduced to less than 1.42 ps as shown in Fig. 14(b), resulting in excellent performance as shown in Fig. 15.

Figure 15(a) shows the BER characteristics for one tributary of a 15.3 Tbit/s signal after transmission as a function of launch power. Here, circles and squares correspond to measurement results obtained with a conventional 150 km transmission line (SLAF + IDF) and a low-nonlinearity, dispersion-compensated 160 km transmission line (ULAF + CFBG), respectively. In the first experiment with SLAF+IDF, we achieved the BER shown by the blue circles in Fig. 15(a). Then we could further improve the transmission performance by reducing the fiber nonlinearity with the aid of a CFBG instead of IDF [36]. At the receiver, the transmitted OTDM signal was homodyne-detected with a 10 GHz optical phase-locked Nyquist LO pulse and the 64 QAM signal was demultiplexed to 10 Gbaud by using the time domain orthogonality of the Nyquist pulse. By reducing the nonlinearity with the new transmission scheme, the optimum launch power was increased from 5 dBm to 7 dBm, resulting in a 2 dB OSNR improvement after the transmission.

Figures 15(b) and (c) show the constellations of the demodulated signals obtained with the conventional and new transmission lines, respectively, each at optimum launch power, and a clear difference can be seen between them. The error vector magnitude (EVM) was successfully reduced from 6.7 % to 6.0 % and the BER was improved from 1.6 x 10^-2 to 1.0 x 10^-2 with our newly constructed transmission line.

We measured the BERs for all 128 tributaries (i.e., 1.28 Tbaud / 10 Gbaud = 128 tributaries). Figure 16 shows the measurement results. We obtained BERs below the 20 % overhead FEC threshold of 2.0 x 10^-2 for all tributaries. In this transmission, a 15.3 Tbit/s signal was successfully transmitted with a signal bandwidth of 1.47 THz, resulting in a spectral efficiency (SE) of as high as 8.7 bit/s/Hz even when the 20% FEC overhead is taken into account. These results proved that coherent Nyquist pulse OTDM transmission is highly advantageous for realizing an ultrahigh speed and a high spectral efficiency simultaneously.
The attractive features of Nyquist pulses that we have described in previous sections are expected to be advantageous not only for achieving extremely high bit rates beyond 10 Tbit/s/ch but also for realizing a WDM transmission at a 1 Tbit/s channel capacity over a long distance. In the WDM transmissions at higher than 1 Tbit/s/ch reported so far [18-20], the transmission distances are limited to less than 1000 km. Here we show a 1.28 Tbit/s/ch x 10 WDM transmission of as long as 1500 km at a symbol rate of 320 Gbaud that was achieved using non-coherent optical Nyquist pulses [37].

Figure 17 shows our experimental setup for a 10 ch, 1.28 Tbit/s (320 Gbaud polarization-multiplexed DQPSK)
Nyquist pulse OTDM-WDM transmission. As a pulse source for a channel under test (CUT), we used a 40 GHz MLFL, whose output pulse was DQPSK modulated at 40 Gbaud and bit-interleaved to 320 Gbaud with an OTDM emulator followed by polarization multiplexing. It was then shaped into optical Nyquist pulses with a roll-off factor $\alpha = 0$ by using a pulse shaper (#3). The waveform of the generated 320 Gbaud Nyquist OTDM signal is shown in Fig. 18. It can be seen that the pulses overlap greatly but there is no interference at each symbol location every 3.125 ps, corresponding to 320 Gbaud, where we carried out optical sampling for demultiplexing. There is a variation in the peak amplitude, which is caused by overlapping between adjacent Nyquist pulses, but this does not affect the transmission performance as the data is extracted at the non-overlapping points every 3.125 ps.

In parallel, 9 loading dummy channels were generated from an optical comb generator [38], whose spectrum was broadened over a bandwidth of 3.5 THz in the C-band with HNL-DFF. After OTDM and polarization multiplexing, the spectrum was shaped into a flattop profile with a 350 GHz guard band by using the pulse shaper (#2), where the guard band was kept open for the CUT. The other part of the spectrum was sliced into 9 channels with a channel spacing of 350 GHz, in which different delays were employed to remove the correlation between channels. The CUT and the dummy channels were finally combined at a pulse shaper (#3). We also generated a tone signal to deliver the clock from a CW-LD, which was intensity modulated at 10 GHz. The optical spectrum of the 10 ch, 1.28 Tbit/s WDM signal and the 10 GHz clock tone before transmission is shown in Fig. 19.

The WDM signal was then launched into a 150 km recirculating fiber loop. It was composed of three 50 km spans, where the first and second spans consist of a 25 km SLAF + 25 km IDF and the third span was a 50 km SLAF. This compensates for second- and third-order dispersions simultaneously at every loop circulation. The span losses were compensated for by EDFAs and Raman amplifiers. The residual dispersion compensation and residual gain equalization were carried out inside the loop with a pulse shaper (#4).

After the transmission, the WDM signal was demultiplexed and a clock tone signal was separated at a pulse shaper (#5). The demultiplexed CUT was separated into two orthogonal polarizations at the PBS and then OTDM demultiplexed from 320 to 40 Gbaud by using a wavelength-tunable walk-off-free NOLM [30]. The BER was measured offline using a digital oscilloscope with a sampling rate of 128 GSa/s and a bandwidth of 33 GHz and vector signal analyzer software.

The BER dependence on transmission distance is shown in Fig. 20(a). The measured BERs were below the 20% overhead FEC threshold ($2 \times 10^{-2}$) after an 1800 km transmission. Taking account of the BER variation among different WDM channels and OTDM tributaries, we measured the BER for all the WDM channels and OTDM tributaries after a 1500 km transmission. Figure 20(b) shows the corresponding BERs. BERs below $2 \times 10^{-2}$ were achieved.
for all 10 WDM channels, 8 OTDM tributaries (i.e., 320 Gbaud / 40 Gbaud = 8 tributaries), and two polarizations. As a result, a 12.8 Tbit/s signal was successfully transmitted over 1500 km. The bandwidth was 3.55 THz including 0.05 THz for the tone signal.

Although this system is not a coherent system, an SE of 3.0 bit/s/Hz has been achieved by taking an advantage of an $\alpha = 0$ Nyquist pulse and taking the 20% FEC overhead into account. A loop experiment employing a coherent Nyquist pulse is ongoing, where we expect a further increase in the SE under the same conditions as the non-coherent Nyquist transmission.

7. Conclusion

We reviewed the progress that has been made on ultrahigh-speed and digital coherent transmission over the past 20 years and described how the single-channel bit rate has increased to 10 Tbit/s and beyond with the optical Nyquist pulse. A coherent Nyquist pulse is the only pulse that enables us to realize an ultrahigh-speed of >1 Tbit/s/ch with a high spectral efficiency and a transmission distance exceeding 1500 km, which will be indispensable in next-generation backbone networks. The increase in the single-channel bit rate also contributes to a reduction in power consumption as the number of wavelength channels can be reduced. With the optimum combination granularity of OTDM and WDM, Nyquist pulses are expected to provide the possibility of realizing long-haul, single-channel multi-terabit transmission with a high spectral efficiency.
Acknowledgments

This work was supported by the JSPS Grant-in-Aid for Specially Promoted Research (26000009).

References

[1] H. G. Weber and M. Nakazawa Eds.: Ultrahigh-Speed Optical Transmission Technologies (Springer 2007).
[2] I. Kaminow, T. Li, and A. E. Willner Eds: Optical Fiber Telecommunications Volume IV A: Systems and Networks (Academic Press, 2013).
[3] M. Nakazawa, K. Kikuchi, and T. Miyazaki Eds.: High Spectral Density Optical Communication Technologies (Springer 2010).
[4] M. Nakazawa et al.: “Ultrahigh-speed “orthogonal” TDM transmission with an optical Nyquist pulse train,” Opt. Express 20 (2012) 1129.
[5] R. J. Mears et al.: “Low-noise erbium-doped fibre amplifier operating at 1.54 μm,” Electron. Lett. 23 (1987) 1026.
[6] M. Nakazawa et al.: “Efficient Er+ doped optical fibre amplifier pumped by a 1.48 μm InGaAsP laser diode,” Appl. Phys. Lett. 54 (1989) 295.
[7] I. Kaminow and T. Li Eds: Optical Fiber Telecommunications IV A and B (Academic Press, 2002).
[8] N. S. Bergano, “Wavelength division multiplexing in long-haul transoceanic transmission systems,” J. Lightwave Technol. 23 (2005) 4125.
[9] T. S. Kinsel and R. T. Denton: “Terminals for a high-speed optical pulse code modulation communication system: II. Optical multiplexing and demultiplexing,” Proc. IEEE 56 (1968) 146.
[10] T. Sakurai: “Ultrafast Photonic Device Technology in FST Project,” Europe-US-Japan Symposium on Ultrafast Photonic Technology, Chiba, Japan, 2003.
[11] E. Lach et al.: “Towards ultra-high channel bit rates,” Cost266-IST Optimist Workshop at Optical Network Design and Modelling (ONDM), Budapest, Hungary, 2003.
[12] A. Teixeira and G. M. T. Beleffi Eds.: Optical Transmission: The FP7 BONE Project Experience (Springer 2014).
[13] M. Nakazawa et al.: “1.28 Tbit/s-70 km OTDM transmission using third- and fourth-order simultaneous dispersion compensation with a phase modulator,” Electron. Lett. 36 (2000), 2027.
[14] H. G. Weber et al.: “Single channel 1.28 Tbit/s and 2.56 Tbit/s DQPSK transmission,” ECOC 2005, ThA1.2.
[15] H. C. Hansen Mulvad et al.: “Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel,” Opt. Express 18 (2010) 1438.
[16] M. Yoshida et al., “Single-channel 15.3 Tbit/s, 64 QAM coherent Nyquist pulse transmission over 150 km with a spectral efficiency of 8.3 bit/s/Hz,” Opt. Express 27 (2019) 28952.
[17] K. Schuh et al., “Single Carrier 1.2 Tbit/s transmission over 300 km with PM-64 QAM at 100 Gbaud,” OFC 2017, ThB3.5.
[18] M. Nakamura et al.: “1.3-Tbps/carrier net-rate signal transmission with 168-Gbaud PDM PS-64QAM using analogue-multiplexer-integrated optical frontend module,” ECOC 2019, Tu2.D.5.
[19] T. Kobayashi et al.: “35-Tb/s C-band transmission over 800 km employing 1-Tb/s PS-64QAM signals enhanced by complex 8 × 2 MIMO equalizer,” OFC 2019, ThB1.2.
[20] F. Buchali et al.: “1.3-Tb/s single-channel and 50.8-Tb/s WDM transmission over field-deployed fiber,” in ECOC 2019, PD1.3.
[21] F. Buchali et al.: “1.52 Tb/s single carrier transmission supported by a 128 GSa/s SiGe DAC,” in OFC 2020, ThC4.2.
[22] S. Okamoto et al.: “400 Gbit/s/ch field demonstration of modulation format adaptation based on pilot-aided OSNR estimation using real-time DSP,” IEICE Trans. Commun. E100-B (2017) 1726.