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Performance Investigation of a Cost- and Power-Effective High Nonlinearity Tolerance OFDMA-PON Scheme Based on Sub-Nyquist Sampling Rate and DFT-Spread

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ABSTRACT We investigate the performance of a cost- and power-effective high nonlinearity tolerance orthogonal frequency-division multiple access passive optical network scheme based on sub-Nyquist sampling and discrete Fourier transform spread. The analog-to-digital converter with a sampling rate below the Nyquist sampling rate is used for signal detection for each optical network unit. The complicated pre-process procedure is located in the optical line terminal. Only Low-point FFT and IDFT procedures are required in the ONU, reducing the computational complexity and power consumption in the ONU, and the sampling rate of ADC, and improve the cost- and power-efficiency effectively. Moreover, the peak-to-average power ratio is reduced effectively with the scheme. The simulation results show that the measured bit error ratio of each ONU signal well less than the forward-error correction limit of 3.8×10^{-3} is obtained after 40-km standard single mode fiber transmission.

INDEX TERMS Sub-Nyquist sampling, OFDM, DFT-spread, PAPR.

I. INTRODUCTION

Passive optical network (PON) [1]–[3] is a cost-effective solution to provide high-speed access and has been widely adopted to meet the rapid growing bandwidth requirements of end-user applications services. Increasing the capacity is a big thing and worth to massive efforts [4]–[6].

Recently, time-/wavelength-division multiplexing (TWDM) is adopted in the next generation PON stage 2 (NG-PON2) standardization to achieve an aggregate capacity of 40Gbit/s downlink transmission [7]. However, low spectral efficiency (SE) conventional on-off keying (OOK) is still adopted in NG-PON2, and the capacity per wavelength is only 10Gbit/s. Obviously, OOK is not an appropriate choice for the future PON which inevitably exceed 10Gbit/s per wavelength.

The systems beyond NG-PON2 are preferred to use advanced modulation formats with higher SE more than 1 bit/s/Hz. Orthogonal frequency-division multiplexing (OFDM) stands out among the proposed formats so far for its superior advantages, such as high SE, strong robustness to dispersion and simple distortion equalization [8]–[19]. Moreover, OFDM is transparent to modulation formats. Thanks to the advanced digital signal processing (DSP) technologies, it is easy to improve capacity through the adoption of high order quadrature amplitude modulation (QAM) for each subcarrier. The resulting high SE reduces component bandwidth requirements as well. Therefore, OFDM access (OFDMA) PON has become one of the most promising solutions for future broadband optical access networks.

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In the PON systems, a number of optical network units (ONUs) at the premises of end-users are connected to one optical line terminal (OLT) at a central office. Thus, the cost of ONUs accounts for most portion of the total system cost and should be reduced as much as possible.

OFDMA-PON is a quite flexible scheme whose subcarriers can be assigned to any ONU independently. However, the aggregate data rate will become high with multiple ONUs. According to the Nyquist sampling theorem, a sampling rate more than double the signal bandwidth is required to prevent aliasing and signal distortion. So the sampling rate of analog-to-digital converter (ADC) at each ONU is required to be high for the processing of high-speed aggregate OFDM data, even though only a small portion of the subcarriers is required, as shown in Fig.1, resulting in a waste of cost and power.

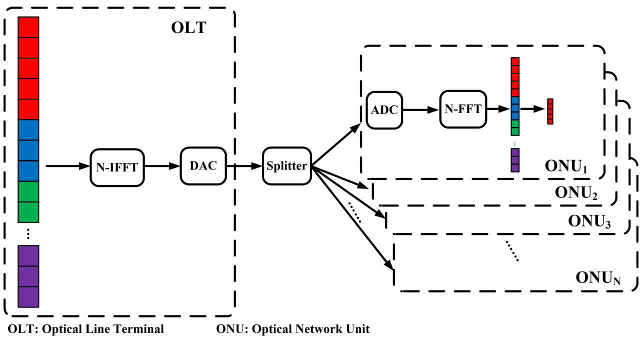

FIGURE 1. The architecture of the conventional OFDMA-PON.

A sub-Nyquist sampling scheme was proposed to reduce the required sampling rate of ADCs [20]–[22]. The ONUs in a sub-Nyquist sampling scheme are classified into several groups. The required sampling rate of ADCs would be lowered if the number of groups exceeds 1. The aggregate OFDM signals need to be pre-processed at the OLT to avoid the inter-group interference at ONUs. The desired groups are obtained by controlling sampling delays of ADCs, thereby enabling simple switching among different groups. It is easy to alter which and how many ONUs belong to a group, which greatly enhances the flexibility in bandwidth allocation. In addition, in an intensity modulation and direct-detection (IM/DD) system, the pre-processing of the sub-Nyquist sampling scheme at OLT must consider the constraints of the Hermitian symmetry of subcarriers pairs.

Another key factor should be considered is the high peak-to-average power ratio (PAPR) which deteriorates system performance, especially for the generation of OFDM signals encoded with high order QAM. High bit resolution digital-to-analog converters (DACs) and ADCs are required for the OFDM signal with high PAPR, and the signal is easily suffered from the nonlinearity of the optical and electrical components (e.g., optical modulator, fiber and RF amplifier).

Discrete Fourier transform (DFT)-spread OFDM is proposed and has already been incorporated into the uplink of the 4G mobile standard, known as long-term-evolution (LTE) [23]. Benefiting from the advantage of low PAPR, recently, it has been introduced into the IM/DD system [24]–[27].

The sub-Nuquist sampling and DFT-spread are combined for research in this paper. The signal performance is studied in IM/DD system and propagated in standard single mode fiber (SSMF). The sub-Nyquist sampling DFT-spread scheme is cost- and power-effective. Furthermore, different from the previous works, we focus on the effectiveness of the methods in the system beyond NG-PON2 with 40Gbit/s per wavelength, 40km reach, and split ratio of 1:64. Its tolerance to ADC's low bit resolution is investigated as well. The results show that it performs well in the hypothetical system and shows strong tolerance to the low bit resolution DAC/ADC. We demonstrate propagation of 13.33 Gbit/s sub-Nyquist sampling DFT-spread 16-QAM OFDM signal in IM/DD system. Simulation results show that the OFDMA-PON scheme with sub-Nyquist sampling and DFT-spread is effective to lower sampling rate at the ONUs and reduce the PAPR of signal.

The rest of the paper is organized as follows. In Section II, we analyze the principle of OFDMA-PON with sub-Nyquist sampling and DFT-spread. The structure of simulation system is described in Section III. Section IV analyzes the various simulation results. Section V is the conclusion.

II. OPERATION PRINCIPLE

In conventional OFDMA-PON, even only a small portion of the subcarriers are actually dedicated to any given ONU, the sampling rate more than double bandwidth of received signals is required to prevent spectral aliasing, which makes the system complex and uneconomical.

In the sub-Nyquist sampling scheme, OFDM subcarriers are divided equally into M parts, and an ONU in one of virtual groups is able to receive its requested data in one of these parts. The application of the sub-Nyquist sampling scheme only requires a 1/M Nyquist sampling rate and 1/M fast-Fourier transform (FFT) size in demodulation, which reduces computational complexity and power consumption effectively.

With DFT-spread, additional DFT and IDFT procedures are needed in the OLT and ONUs respectively. L/M-point DFT and IDFT are executed to reduce the PAPR of signal.

Fig. 2 outlines the principle of the sub-Nquist sampling OFDM scheme with M = 4 and N = 256. From the perspective of time domain (Fig. 2(a)), different sampling delays with interval $\Delta t = 4\Delta t_0$ are executed, where $\Delta t_0 = 2\pi/N\omega_0$ has been proved to be the best value in [20]. Different samples are obtained for ONUs in different groups.

From the perspective of frequency domain (Fig .2(b)), because of spectral aliasing caused by sub-Nyquist sampling, the subcarriers received by ADCs are linear combination of weighted sent subcarriers. For example, the received signal in 2nd subcarrier of first group is a combination of 2nd, 66th, 130th, 194th subcarriers.

The original data in 4 groups are assigned to 2nd -32nd, 34th −64th, 66th-96th, 98th-128th subcarriers respectively.

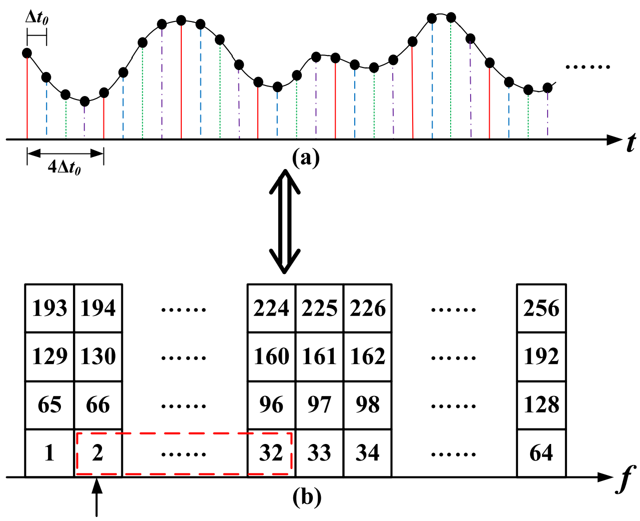

FIGURE 2. The concept of the sub-Nyquist sampling scheme.

The data in desired group could be obtained with corresponding sampling delay. For example, if the sampling delay is set to be 0, the data in first group (2^{nd}-32^{nd}) will be obtained.

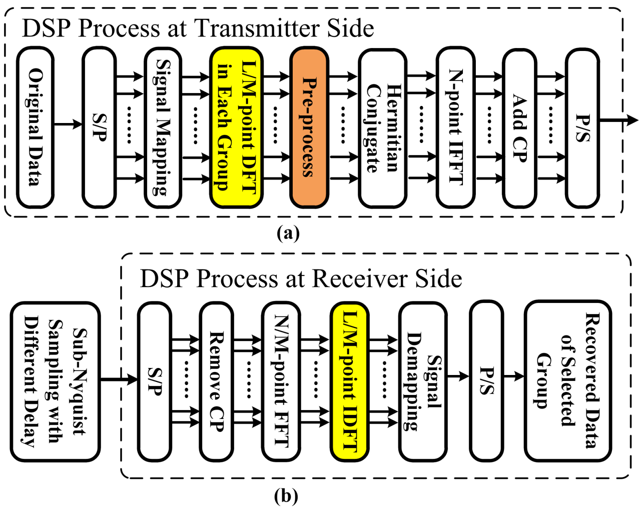

FIGURE 3. The DSP process at (a) transmitter side and (b) receiver side.

The DSP processes of sub-Nyquist sampling DFT-spread OFDM are shown in Fig. 3. Fig. 3(a) depicts the modulation process. The serial original data are first converted into L parallel channels, where L is the number of subcarriers carrying data, and mapped into L complex QAM symbols. L/M-point DFT is implemented and the symbol on each subcarrier can be spread into L/M subcarriers in the corresponding group. Pre-process is executed to compensate the spectral aliasing caused by sub-Nyquist sampling at receiver and aggregate channel response (The channel response needs to be measured in advance). Because the outputs from N-point IFFT should be real-valued, Hermitian conjugate symmetric structure is required to be constructed before IFFT. In order to avoid inter-symbol interference (ISI), cyclic prefix (CP) with appropriate length is appended in front of each IFFT output. The serial data is obtained after parallel/serial conversion and sent out for DAC to generate the electrical signal.

The corresponding demodulation process at receiver is shown in Fig. 3(b). The received signal is sampled with sub-Nyquist sampling rate and different sampling delays are adopted for different groups. Conventional DSP process is implemented for signal demodulation, the main difference is the size of FFT and IDFT reduce to N/M and L/M respectively. Another difference is that the channel estimation and equalization procedure is not required in the receiver, which reduces the computational complexity effectively. Furthermore, only 3 procedures marked in color are different from those in conventional OFDMA-PON. Therefore, it does not need much modification for upgrading from the existing conventional OFDMA-PON.

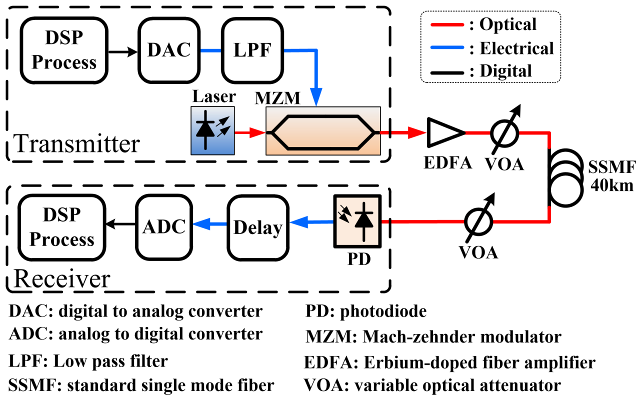

FIGURE 4. Simulation setup for sub-Nyquist sampling DFT-spread OFDM.

III. SIMULATION SETUP

Fig. 4 shows the simulation setup for the sub-Nyquist sampling DFT-spread OFDM system. The red, blue and black lines represent the optical, electrical and digital signals respectively. The DSP process, such as digital signal modulation and demodulation is implemented with Matlab. The system modules, such as electrical/optical modules, optical fiber links, are simulated with VPItransmissionMaker.

The details of the system are as follows, the sampling rate Fs=10GSa/s is set in the system. The number of pre-designed data-carring subcarriers is up to 128 in the transmitter. However, several subcarriers cannot be used because of the need for oversampling. The reason is that the zero-order hold characteristic of DAC will create an image above the Nyquist frequency (Fs/2). Therefore, only 96 subcarriers are used to carry data and 16-QAM is encoded on each subcarrier. The data-carrying subcarriers are separated into 4 groups and the 24-point DFT outputs of 4 groups are assigned to the corresponding subcarriers. Hermitian conjugate symmetric structure is constructed to generate real-value signal and the final IFFT size is 256. CP with 32 samples is added to avoid ISI. The net data rate of 13.33 Gb/s (10G $\times$ 4 $\times$ 96/256 $\times$ 256/288) is achieved. At the start of the simulation, 10 training symbols (TSs) are used to obtain the channel response which is used for pre-processing. The processed digital signal is loaded to a DAC with 8-bit resolution. The OFDM band image introduced by the DAC is removed by a low pass filter (LPF). The DAC output with appropriate amplitude is loaded to a Mach-Zehnder modulator (MZM) to generate the optical OFDM signal.

40km dispersion uncompensated SSMF is used as the transmission link in the simulation, whose parameters are set as follows, the attenuation, dispersion index, nonlinear index and effective core area of fiber are 0.2dB/km, 16ps/nm/km, 2.6×10^{-20}m^2/W and 80×10^{-12}m^2 respectively. Variable optical attenuator (VOA) and Erbium-doped fiber amplifier (EDFA) are used to adjust the launch power into fiber.

The received optical power (ROP) at receiver side is controlled by another VOA. The optical signal is converted to electrical signal by the direct detection of a photodiode (PD). A delay module is used to control the sampling delay, hence selecting the desired group. The delayed PD outputs are sampled with an 8-bit resolution ADC and processed with offline in the Matlab program.

IV. RESULTS AND DISCUSSIONS

The indicators like receiver sensitivity, nonlinearity tolerance are utilized to evaluate the performance of sub-Nyquist sampling DFT-spread OFDM system.

The PAPR of OFDM signal without DFT-spread is 13.1dB, and the PAPR reduced to 10.5dB with the added DFT-spread process, proving the effectiveness of DFT-spread for PAPR reduction.

A. RECEIVER SENSITIVITY ANALYSIS

The launce power into fiber is fixed at 8dBm for the investigation of receiver sensitivity performance. The launch power is selected by concerning of both power penalty and nonlinearity. At receiver side, the ROP varies from −10dBm to −4dBm by adjusting the VOA.

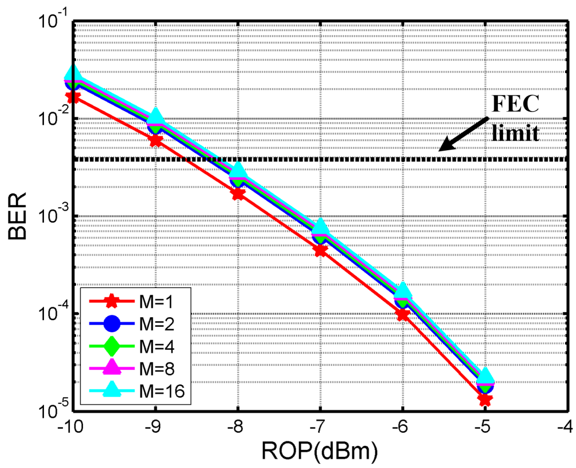

FIGURE 5. BER performance with different ROP.

Fig. 5 shows the BER performance with different ROP. The BERs of each ONU is measured using a bit-by-bit comparison as functions of the received power. The group number M is set to be 1, 2, 4, 8 or 16 for each simulation respectively, where M=1 means no sub-Nyquist sampling, and the system is same with conventional one. The average BER of all ONUs depicted in Fig. 5 show that the sub-Nyquist sampling DFT-spread OFDM has good receiver sensitivity performance. The OFDM system is error-free when the ROP is larger than −5dBm. At the FEC limit, the minimum ROP is about $-8.5d$Bm. The BER performances are similar with different M, which confirms that the sub-Nyquist sampling DFT-spread scheme can reduce the requirement of ADC sampling rate effectively, as well as the DSP computational complexity at ONUs. The performance penalty with different M could be ignored. It should be noted that, although a larger M is helpful to reduce the sampling rate and computational complexity, it also limits the maximum capacity of each ONU and reduces the number of usable subcarriers. The additional unusable subcarriers is M−3, like the 33rd,65th,97th subcarriers in Fig. 2

B. NONLINEARITY TOLERANCE ANALYSIS

The influence of nonlinearity effect will gradually increase with the increasing of the launch power into fiber, and serious nonlinear distortion will be caused. Because of low PAPR, the sub-Nyquist DFT-spread OFDM is expected to have strong nonlinearity tolerance. We investigated the nonlinearity tolerance performance in this part. The launce power into fiber is adjusted from 16dBm to 22dBm by the EDFA and VOA at transmitter side. The ROP is fixed at −2dBm.

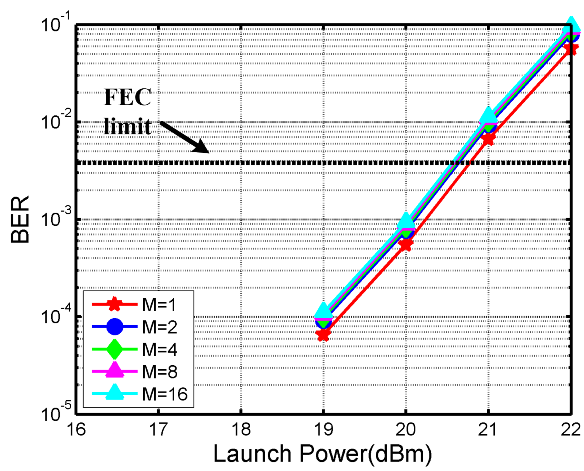

FIGURE 6. BER performance with different launch power.

The BER performance with different launch power is shown in Fig. 6. The results show that the performance of sub-Nyquist sampling DFT-spread OFDM is error-free when launch power lower than 19dBm, which means the sub-Nyquist sampling DFT-Spread OFDM has strong nonlinearity tolerance. The maximum launch power into fiber is larger than 20dBm at the FEC limit. The results prove that sub-Nyquist sampling DFT-spread has strong nonlinearity tolerance and large acceptable launch power, which makes it suitable for the system with a large number of ONUs.

C. PON DOWNSTREAM SETUP

The trade-offs in speed, distance, and split ratios should be balanced in NG-PON2 systems for various applications. A typical parameter combinations should be met, 40 Gbit/s downstream capacity and 20 km reach with at least 1:64 split. The single wavelength transmission rate is 10 Gbit/s in the NG-PON2 with TWDM.

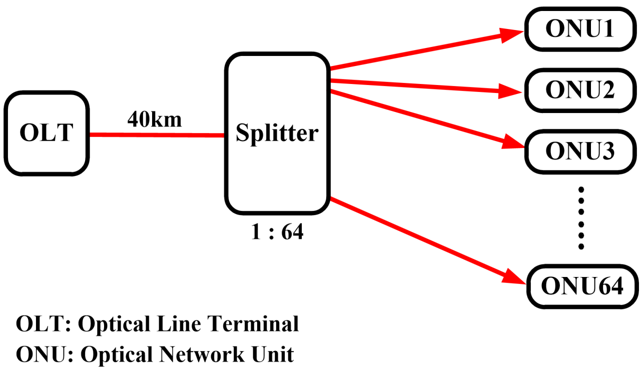

FIGURE 7. PON downstream setup.

A PON downstream setup as shown in Fig.7 is considered in this paper. The fiber link between OLT and ONU is 40 km, and the split ratio is 1:64. The single wavelength net data rate is 13.33Gb/s.

The VOA at the receiver side is fixed at 18dB to simulate the 1:64 splitter for simplicity. The launch power varies from 17dBm to 21dBm. Other parameters are the same as previous simulation.

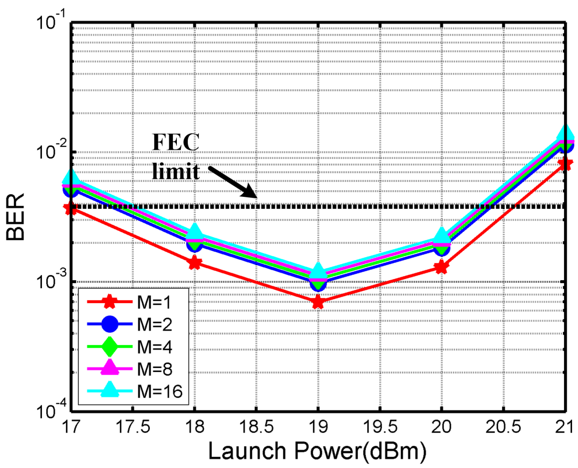

FIGURE 8. PON downstream performance.

Both noise and nonlinearity will influence the system performance. The results in Fig. 8 show that the sub-Nyquist sampling DFT-Spread OFDM could meet the requirement of FEC limit with launch power from 18dBm to 20dBm. In addition, the system performances with different M do not show significant difference, proving the effectiveness of sub-Nyquist sampling DFT-spread OFDM.

D. DAC/ADC RESOLUTION ANALYSIS

In the practical system, not only the sampling rate, but also the bit resolution of DAC/ADC should be considered. The signal nonlinearity distortion will be caused with low bit resolution, and the system performance will be deteriorated seriously. However, extra high bit resolution will increase the cost of the system, as well as the computational complexity. Therefore, it is important to fix an appropriate bit resolution by considering both facts. We investigate the system performance with different bit resolution of DAC/ADC in this part. The launce power is fixed at 19dBm, and ROP is fixed −7dBm. The resolution of DAC/ADC varies from 4-bit to 12-bit.

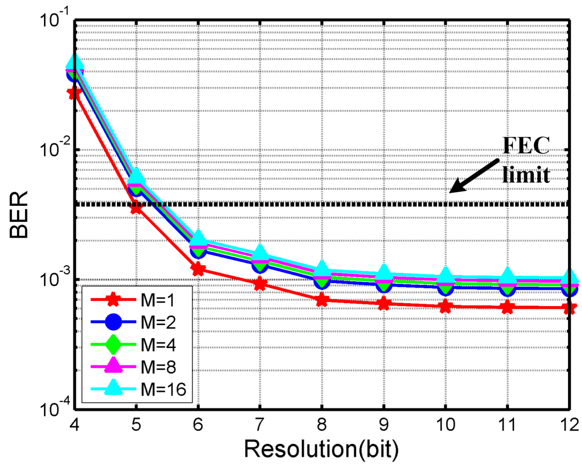

FIGURE 9. BER performance with different resolution.

The results depicted in Fig. 9 show that when the bit resolution is 4-bit or 5-bit, the system is seriously affected by the nonlinearity distortion. When 6-bit resolution is implemented, the FEC limit requirement could be met for all group number, which means that sub-Nyquist sampling DFT-spread OFDM performs well with low bit resolution DAC/ADC. The nearly best performance could be obtained when the resolution achieves 8-bit. And the system performance does not improve significantly with further increasing bit resolution. Therefore, the 8-bit resolution is a reasonable choice for the practical system.

V. CONCLUSION

In this paper, the performance of sub-Nyquist sampling DFT-spread OFDM scheme in an IM/DD system is investigated. The scheme with sub-Nyquist sampling makes it possible to lower the requirements of the ADCs sampling rate and reduce the computational complexity of the DSP at ONUs. The ONUs are divided into M groups, and using ADCs operating at 1/M of the Nyquist sampling rate. An ONU can easily alter the group to which it belongs by altering the sampling delay of the ADC, enhancing the flexibility of bandwidth allocation. Moreover, the PAPR could be reduced effectively by DFT-spread, thereby improving the nonlinearity tolerance. The scheme represents good receiver sensitivity and robustness to low-resolution nonlinearity distortion of DAC/ADC.

The results demonstrate that an ONU using an ADC operating at Nyquist sampling rate is able to receive the downstream data without significant performance degradation. The research results show that sub-Nyquist sampling DFT-spread OFDM performs well in PON system and could be regarded as a promising candidate for the system beyond NG-PON2.

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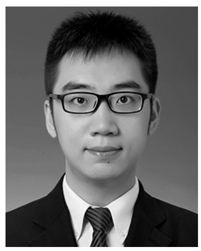

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