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A 20GHz-Band Optical-Fiber-Feed 1-Bit Bandpass Delta-Sigma Direct Digital RF Transmitter Using First Image Component of the QSFP28 Module Output

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Abstract

In this paper, we firstly demonstrate a 20-GHz 1-bit bandpass delta-sigma (BP-DS) direct digital RF transmitter using 25GbE optical fiber link. By utilizing the first image component of the QSFP28 module output, RF signal at 20 GHz band is extracted from 1-bit BP-DS data stream whose the fundamental RF signal component is at 6.45 GHz band. From 5Mbps-QPSK signal (f_c=19.33 GHz) transmission measurement, as a result, the output power of -28.6 dBm, SNR of 45.9 dB, EVM of 2.6% and ALCR$\leq$-39.7 dBc are obtained in the 2^{nd} Nyquist zone.

1 Introduction

In recent years, digital beamforming (DBF) transmitter which can offer higher spectrum efficiency and large coverage than conventional transmitter has been studied for higher microwave frequency/millimeter-wave frequency applications such as beyond 5G/6G fully digital massive MIMO (multiple input multiple output) and next generation high throughput satellite (HTS) in super high frequency (SHF) band [1]. DBF transmitter is consisted of multiple transmitters and antennas. Consequently, compact and low cost transceiver becomes a key issue.

To realize the miniaturization of transmitter, digital RF technology which can replace RF analog circuit by digital signal processing has been developed and applied to below 6 GHz wireless system. As one type of digital RF transmitter, 1-bit BP-DS transmitter can remove the up-converter and realize the high dynamic range by its noise shaping characteristic which is very attractive for DBF system [2].

To overcome the Nyquist limit and generate the RF signal beyond the Nyquist frequency (that is 1/2 of sampling clock frequency f_s), the utilization of the folded image component in high order Nyquist zones of 1-bit BP-DS signal has been proposed as direct digital RF transmitter [3].

Meanwhile, since the 1-bit signal is very suitable for optical-fiber-feed configuration [4]. In some research works, commercial (Small Form-factor Pluggable) SFP+ optical modules for 10GbE were studied to transmit RF signal generated by the fundamental component of 1-bit BP-DS signal in the 1^{st} Nyquist zone via optical fiber and showed the feasibility for distributed MIMO system [5, 6].

In our previous works, we have demonstrated the capability of 10GbE SFP+ module to transmit RF signal generated by the first image component of 1-bit BP-DS signal in the 2^{nd} Nyquist zone and measured the DBF transmitter consisted of 10GbE SFP+ modules as both electrical-to-optical (E/O) module and optical-to-electrical (O/E) module, single-mode fibers (SMF) and RF front-ends [7, 8]. It has been confirmed that the proposed DBF transmitter could achieve great performance at 7.5 GHz-band which is in the 2^{nd} Nyquist zone of 1-bit signal at the sampling frequency of 10 Gbps.

However, to generate RF signal in the high SHF band around 20 GHz, the 10GbE SFP+ module is not suitable for direct digital RF transmitter because of its low sampling frequency. The specific description will be presented in Section II.

In this paper, to generate RF signal in the high SHF band around 20 GHz, we demonstrate a 1-bit BP-DS direct digital RF transmitter using 25GbE optical fiber link. The 25GbE QSFP28 module with an internal clock and data recovery (CDR) circuits instead of 10GbE SFP+ module is used. The first image component in the 2^{nd} Nyquist zone around 20 GHz of 1-bit BP-DS signal at the module output is measured. Compared to 10GbE SFP+ module with the low sampling frequency (10 Gbps), because of the increased sampling frequency (25 Gbps), the problem of low sampling frequency mentioned above can be solved.

This paper is organized as followed. The configuration of the proposed 20GHz-band 1-bit BP-DS direct digital RF transmitter using 25GbE QSFP28 module fed by optical fiber is described in section II. The measurement setup and results are shown in section III. Finally, conclusions are presented in section IV.

2 Configuration of the proposed 20GHz-band 1-bit BP-DS direct digital RF transmitter using 25GbE QSFP28 module fed by optical fiber

The conventional digital RF transmitter with n-bits digital-to-analog converter (DAC) is shown in Figure 1. Because of the Nyquist limit, only the fundamental component in the 1^{st} Nyquist zone, which is below the half of sampling frequency, f_{sn}, is used to generate RF signal. For example, when n=10, the maximum frequency of RF signal is only 500 MHz.

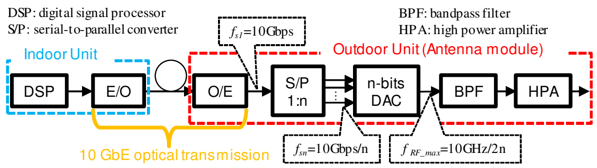


Figure 1. Conventional digital RF transmitter

To generate RF signal in higher frequency band, the digital RF transmitter using 1-bit BP-DS modulator is studied [2]. The configuration is shown in Figure 2. Since the 1-bit BP-DS signal is generated by DSP and converted to analog signal by 1-bit DAC, the maximum frequency of RF signal is improved to 5 GHz, which is n times higher than conventional digital RF transmitter using n-bits DAC.

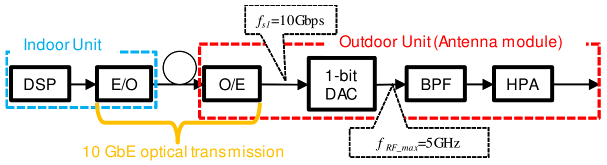


Figure 2. Digital RF transmitter using 1-bit BP-DS modulator

To overcome the Nyquist limit, in our previous research [7], we have proposed direct digital RF transmitter which the first image component in the 2^{nd} Nyquist zone of 1-bit BP-DS signal is used to generate RF signal directly at 7.5 GHz band with the sampling frequency of 10 Gbps. As described in Figure 3, the maximum frequency of RF signal is further improved to 10 GHz. However, if we want to generate RF signal in the high SHF band around 20 GHz by 10GbE SFP+ module, the higher order image components must be used, such as in the 4^{th} or 5^{th} Nyquist zone. Since the image components of 1-bit signal attenuate severely in SINC function as shown in Figure 3, the high output power and signal-to-noise ratio (SNR) can not be obtained because of the low sampling frequency. For higher sampling frequency, in this paper, 25GbE QSFP28 module with an internal CDR circuit is used.

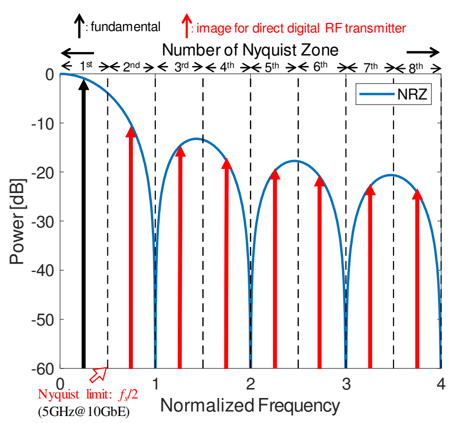


Figure 3. Spectrum of 1-bit signal in NRZ code

The proposed 20GHz-band 1-bit BP-DS direct digital RF transmitter is shown in Figure 4. Since the sampling frequency of 25GbE QSFP28 module is 25.78 Gbps, higher than that of 10GbE SFP+ module, it can generate RF signal around 20 GHz by its first image component in the 2^{nd} Nyquist zone of 1-bit signal.

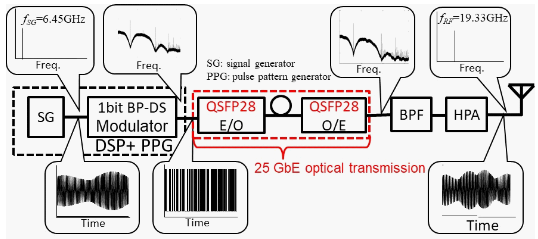


Figure 4. Proposed 1-bit BP-DS direct digital RF transmitter using QSFP28 module

3 Measurement setup and results

In this section, the measurement setup will be presented first. Then the measurement result, such as eye pattern, SNR, adjacent channel leakage power ratio (ACLR) and error vector magnitude (EVM), will be described.

3.1 Measurement setup

The measurement setup is shown in Figure 5, as well as the manufacturer and model numbers of measurement devices. In the digital domain, 6.45 GHz modulated RF signal (5Mbps-QPSK, Nyquist filter: Root Raised Cosine, roll-off 0.3) is generated and then input to 1-bit BP-DS modulator. The signal is 1-bit quantized at 25.78 Gbps. For noise shaping, 5th-order BP digital filter is used. This digital signal processing is done as off-line processing by using MATLAB. Then the 1-bit data stream generated in off-line processing is applied to the PPG (Anritsu, M18020A). The differential voltage swing of 1-bit signal is 800 mV_{pp}. The electrical 1-bit signal is fed to QSFP28 E/O module (Aim, CFORTH-QSFP28-100G-CWDM4) via SMA/QSFP28 convert module (Hitech Global, HTG-QSFP28-MSMP) and then is transmitted by 5-meter SMF to the other QSFP28 O/E module. The output signal of the QSFP28 O/E module is observed by digital oscilloscope (80GS/s) (Keysight, DSO-X 96204Q). A 5-dB optical attenuator is inserted to avoid saturation of QSFP28 O/E module.

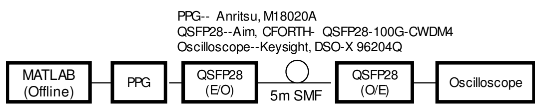
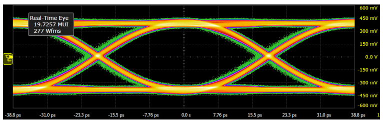


Figure 5. Measurement setup

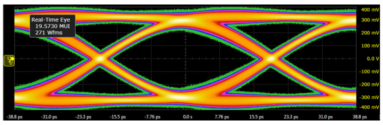
3.2 Measurement results

3.2.1 Eyepattern

Eye patterns and jitter of the transmitted 1-bit signal are measured via the optical fiber link. Figure 6a shows the eye pattern of the output signal of PPG and Figure 6b shows the eye pattern of the output signal of QSFP28 O/E module, respectively. Table 1 summarizes the measured results of jitter and eye opening. From the Figure 6 and Table 1, the fundamental component of 1-bit signal is transmitted with a good performance in the proposed transmitter.



(a) PPG



(b) QSFP28 O/E module

Figure 6. Eye pattern of output signal

Table 1. Measurement result of eye pattern and jitter.

	PPG	QSFP28 O/E
RMS jitter [ps]	1.97	2.11
Eye Width [ps]	26.8(69.1%)	26.1(67.3%)
Eye Height [V]	0.5(73.5%)	0.34(60.7%)

3.2.2 Output power, SNR, ACLR, and EVM

The waveforms of 1-bit signal of the PPG and QSFP28 O/E module is measured by oscilloscope. Then to calculate SNR and ACLR, the fast fourier transform (FFT) is conducted by MATLAB offline. To demodulate the QSPK signal, the vector signal analyzer (VSA) in oscilloscope is used to calculate the EVM. The overall spectrum of output signal of PPG is shown in Figure 7. Then its enlarged spectrum in the 1^{st} Nyquist zone is shown in Figure 8. Figure 9 shows the constellation of modulated signal in the 1^{st} Nyquist zone. As a result, Power=-7.7 dBm, SNR=55.0 dB, ACLR$\leq$-39.1 dBc and EVM=0.4% in the 1^{st}Nyquist zone (5Mbps-QPSK, f_c=6.45 GHz) are obtained.

The overall spectrum of output signal of QSFP28 O/E module is shown in Figure 10. Then its enlarged spectrums in the 1^{st} and 2^{nd} Nyquist zone are shown in Figure 11. Figure 12 shows the constellation of modulated signal in the 1^{st} and 2^{nd} Nyquist zone. As a result, Power=-9.4 dBm, SNR=58.0 dB, ACLR$\leq$-44.2 dBc, EVM=0.8% in the 1^{st}

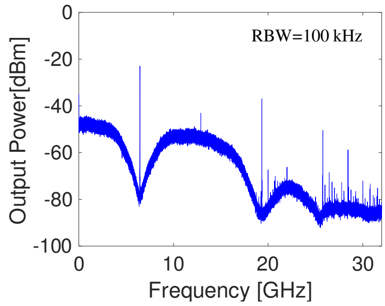


Figure 7. Overall spectrum of output signal of PPG

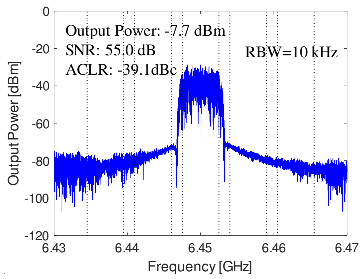


Figure 8. Enlarged spectrum of output signal of PPG in the 1^{st} Nyquist zone

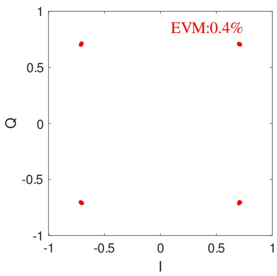


Figure 9. Constellation of 5Mbps QPSK at PPG output in the 1^{st} Nyquist zone

Nyquist zone (5Mbps-QPSK, f_c=6.45 GHz) and Power=-28.6 dBm, SNR=45.9 dB, ACLR$\leq$-39.7 dBc, EVM=2.6% in the 2^{nd} Nyquist zone (5Mbps-QPSK, f_c=19.33 GHz) are obtained, respectively. Because of the internal CDR function in the 25GbE QSFP28 module, the first image component of 1-bit signal has a good performance. The results are summarized in Table 2.

Table 2. Measurement result of output power, SNR, ACLR and EVM.

	PPG at 1^{st} NZ	QSFP28 O/E at 1^{st} NZ	QSFP28 O/E at 2^{nd} NZ
Power	-7.7 dBm	-9.4 dBm	-28.6 dBm
SNR	55.0 dB	58.0 dB	45.9 dB
ACLR	-39.1 dBc	-44.2 dBc	-39.7 dBc
EVM	0.4%	0.8%	2.6%

NZ: Nyquist Zone

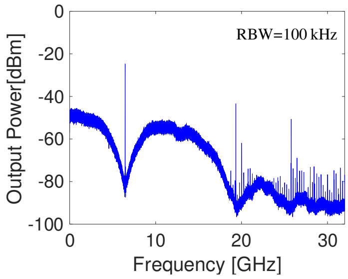
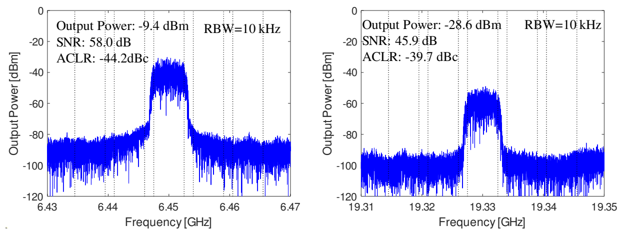
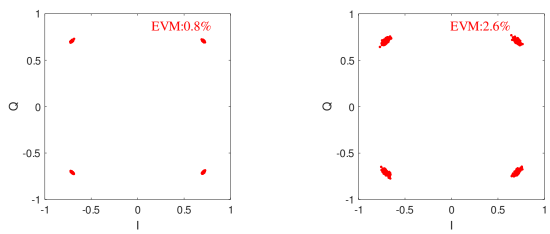


Figure 10. Overall spectrum of output signal of QSFP28 O/E module



(a) 1^{st} Nyquist zone **(b)** 2^{nd} Nyquist zone

Figure 11. Enlarged spectrum of output signal of QSFP28 O/E module



(a) 1^{st} Nyquist zone **(b)** 2^{nd} Nyquist zone

Figure 12. Constellation of 5Mbps QPSK at QSFP28 O/E module output

4 Conclusion

In this paper, we demonstrate a 20-GHz 1-bit bandpass delta-sigma (BP-DS) direct digital RF transmitter using 25GbE optical fiber link. Because of the higher sampling frequency of 25GbE QSFP28 module with an internal CDR circuit than that of 10GbE SFP+ module, the RF signal in the high SHF band around 20 GHz can be extracted beyond the Nyquist limit by using the first image component in the 2^{nd} Nyquist zone of 1-bit BP-DS signal. From 5Mbps-QPSK signal (f_c=19.33 GHz) transmission measurement, as a result, the output power of -28.6 dBm, SNR of 45.9 dB, EVM of 2.6% and ALCR$\leq$-39.7 dBc are obtained in the 2^{nd} Nyquist zone.

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