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Virtual-Carrier-Assisted 64QAM Millimetre-Wave Signal Generation Using Low-Resolution Digital-to-Analog Converter

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Abstract *We experimentally demonstrate a radio frequency digital resolution enhancer (RF-DRE) to mitigate quantization noise of 30 GHz 12 Gb/s 64QAM signal. By using RF-DRE, BER of 4-bit DAC quantized signal is improved from 6.88e-3 to 1.49e-3, and 5-bit DAC exhibits similar performance to 8-bit DAC. ©2022 The Author(s)*

Introduction

The millimetre-wave (mm-wave) communication has been an attractive technique for the fifth generation (5G) mobile communication systems [1]. The simple and cost-effective mm-wave signal generation is important for practical implementation. The photonic-assisted technique is a promising solution for a simple and cost-effective mm-wave signal generation [2], which can reduce the bandwidth requirement on the transmitter side. In particular, the virtual-carrier-assisted mm-wave signal generation technique shows the potential for the simplest structure. In this scheme, the virtual carrier is generated in the digital signal processing (DSP) module together with the signal sideband, and thus no additional devices are required. After heterodyne detection in photodetector (PD), the optically upconverted mm-wave signal can be obtained. The virtual-carrier-assisted mm-wave signal generation scheme has received extensive attention and has been widely investigated [3-5].

However, the introduction of the virtual carrier places high requirements on the resolution of the digital-to-analog converters (DACs). Low-resolution DACs bring high quantization noise in the presence of a virtual carrier [6,7], leading to a low signal-to-noise ratio (SNR). Besides, high-resolution DACs come with high costs. Therefore, there is a trade-off between cost and SNR. To cope with this problem, the quantization noise shaping technique is a promising solution, which can improve SNR while using low-resolution DACs. The Delta-Sigma modulation technique has been widely used for quantization noise shaping [8]. Besides, the digital resolution enhancer (DRE) algorithm [9-11] is also proposed to mitigate the quantization distortion effects. However, these schemes can only push the quantization noise from the baseband to the high-frequency range. Obviously, it is not suitable for the virtual-carrier-assisted mm-wave signal generation scheme, which needs to mitigate the quantization noise at the radio frequency range.

In this paper, we have proposed and experimentally demonstrated a radio frequency digital resolution enhancer (RF-DRE) algorithm to mitigate the quantization noise at the target radio frequency for the virtual-carrier-assisted mm-wave signal generation system. By introducing a bandpass filter as the reference for the RF-DRE algorithm, we can design the quantization errors and shape its spectrum inversely to the bandpass filter. By this means, the quantization noise at the target RF frequency range can be mitigated. We have demonstrated a 30 GHz virtual-carrier-assisted mm-wave transmission of 12 Gb/s 64QAM signals over 25 km standard signal mode fiber (SSMF). With the help of the proposed RF-DRE algorithm, 5-bit DAC quantized mm-wave signal shows a similar transmission performance to that of the 8-bit DAC quantized mm-wave signal. And the measured bit error rate (BER) of the 4-bit DAC quantized signal can be improved from 6.88e-3 to 1.49e-3.

Principle

Fig. 1 shows the schematic diagram of the proposed RF-DRE scheme. Firstly, each digital sample $x(n)$ is quantized by a soft quantization module to obtain different DAC quantization output possibilities. In this paper, we utilize three soft quantization possibilities: $x_{SQ}(n) = [x_q(n) - \Delta, x_q(n), x_q(n) + \Delta]$, where $x_q(n)$ is the quantized value which has the smallest Euclidean distance from $x(n)$, and Δ is the DAC stepsize. The soft quantization error can be calculated as $q(n) = x_{SQ}(n) - x(n)$. Therefore, there will be three soft quantization errors: $q_1(n)$, $q_2(n)$ and $q_3(n)$. The quantization noise design module will choose the desired quantization error from three possibilities. During this process, a bandpass filter is utilized as the reference to calculate the effective quantization error, which can be expressed as:

$$q_{eff}(n) = h(n) * q(n) = \sum_{l=0}^{L-1} h(l)q(n-l), \quad (1)$$

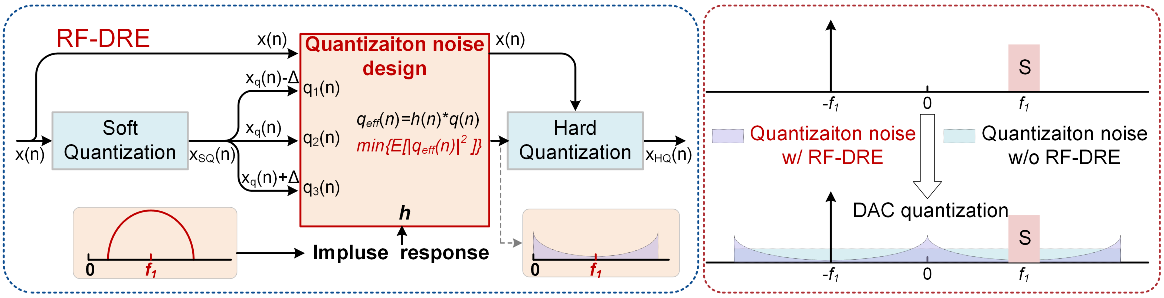

Fig. 1: The schematic diagram of the proposed RF-DRE scheme.

where $h(n)$ is the impulse response of the bandpass filter, $*$ represents the convolution operation, and L is the tap number of $h(n)$. The goal of the quantization noise design module is to minimize the Mean-Squared-Error, which can be expressed as:

$$MSE = E\left(\left|q_{eff}(n)\right|^2\right) = \frac{1}{N}\sum_{n=0}^{N-1}\left|q_{eff}(n)\right|^2, \quad (2)$$

where N is the length of the input digital samples. Obviously, each soft quantization error for each input digital sample will be chosen to calculate the MSE, leading to unacceptable computation complexity. To cope with this problem, the Viterbi algorithm [11] can be introduced to significantly reduce the computation complexity. When MSE is minimized, the spectral response of the corresponding optimal quantization error sequence will be the inverse to the used bandpass filter. Therefore, the quantization noise at the target radio frequency range can be mitigated. Finally, the optimal quantization error sequence is fed to the hard quantization module to generate the output digital sample.

Experimental Setup

Fig. 2 shows the experimental setup of the virtual-carrier-assisted mm-wave transmission system. In the transmitter, the generated signal sideband and virtual carrier are located at 13 GHz and -17 GHz, respectively. Therefore, the crosstalk between the symmetric sidebands can be avoided. Noting that a 12 Gb/s 64QAM sideband signal is generated in our experiment. A 5-tap bandpass filter is used in our RF-DRE algorithm, and the bandpass frequency range of this bandpass filter is 12 GHz-18 GHz. The quantization process is implemented in MATLAB to emulate the impacts of different resolution DACs. Then, the driving signal after quantization is loaded into an arbitrary waveform generator (AWG, Keysight M8195A). The output electrical signal with an optimized peak-to-peak voltage of 400 mV is boosted by an electrical amplifier (EA, Centellax OA3MHQM4). Subsequently, a single polarization IQ modulator (IQM, iXblue MXIQER-LN-30) is applied for modulation. A 100 kHz linewidth external cavity laser with a wavelength of 1550 nm is served as an optical source.

After 25 km SSMF propagation, the optical signal is amplified by an erbium-doped optical fiber amplifier (EDFA). The optical bandpass filter (OBPF) placed after the EDFA is used to remove the out-of-band amplified spontaneous emission noise. A variable optical attenuator (VOA) is placed before the PD to adjust the received optical power (ROP). Finally, the optical signal is detected by the PD, and the 30 GHz mm-wave electrical signal can be obtained. The detected 30 GHz mm-wave electrical signal is captured by a digital sampling oscilloscope (DSO, Tektronix DPO 73304D) for the offline process. The offline DSP has been shown in Fig. 2.

Results and Discussion

Fig. 3(a) shows the spectrum of the driving signal

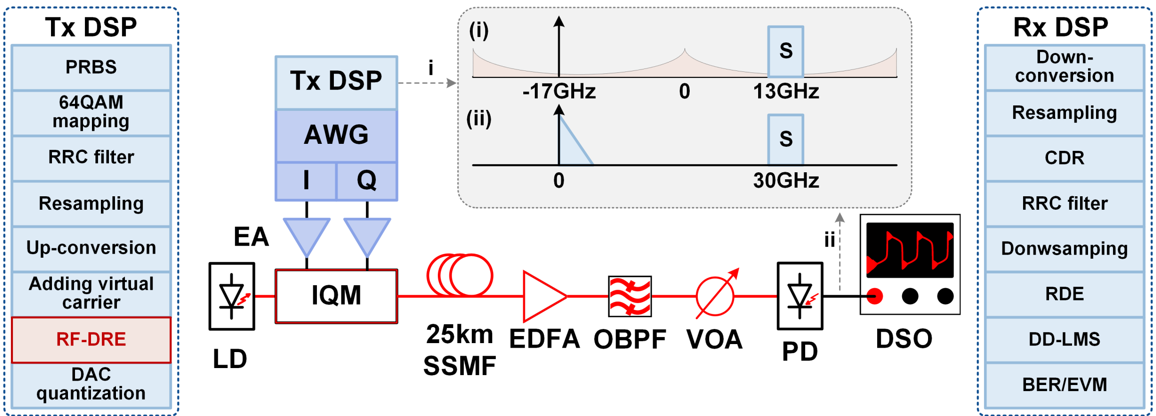

Fig. 2: The experimental setup of the virtual-carrier-assisted mm-wave transmission system.

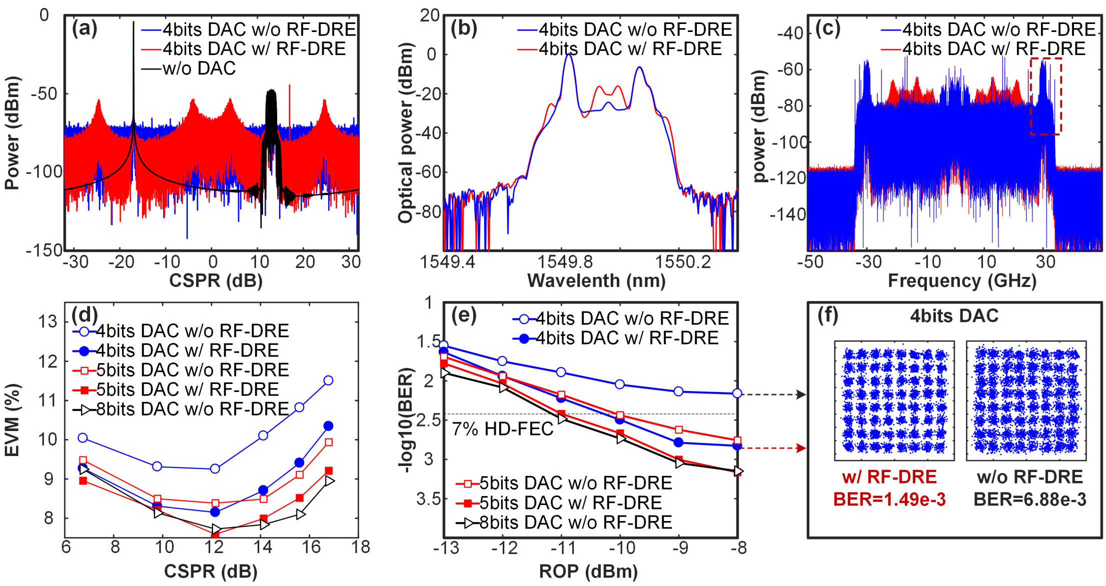

Fig. 3: Experimental results of the virtual-carrier-assisted mm-wave signal transmission system. (a) The electrical spectrum of the generated driving signal. (b) The optical spectra before PD. (c) The electrical spectrum of the received 30 GHz mm-wave signal. (d) The measured EVM vs CSPR. (e) The measured BER vs ROP. (f) The received 64QAM constellations when ROP is -8 dBm.

at the transmitter. When 4-bit DAC is applied for quantization, the SNR of the driving signal becomes worse. When the RF-DRE algorithm is applied, the noise in the signal sideband and the virtual carrier can be mitigated. Therefore, the SNR of the driving signal can be improved when the RF-DRE algorithm is applied in the presence of a low-resolution DAC. Fig. 3(b) shows the measured optical spectra before the PD when 4-bit DAC is applied. Fig. 3(c) shows the spectrum of the detected 30 GHz mm-wave signal. The above results prove that the proposed RF-DRE algorithm can push the quantization noise from the target RF frequency range to the undesired out-of-band, and the optically upconverted 30 GHz mm-wave signal can be obtained.

Fig. 3(d) shows the measured EVM performance of the received signal. Noting that the ROP is fixed at -5 dBm in this test. It can be observed that the EVM performance of 4-bit DAC quantized signal with RF-DRE can be improved similar to that of 5-bit DAC quantized signal. The EVM performance of a 5-bit DAC quantized signal with RF-DRE can also be improved similar to that of an 8-bit DAC quantized signal. The optimal carrier-to-signal power ratio (CSPR) for this system is around 12.15 dB. Noting that higher CSPR means higher power of the virtual carrier, which indicates that the signal sideband will be more sensitive to the quantization noise. Therefore, the EVM performance degrades rapidly when CSPR is higher than 12.15 dB. Fig. 3(e) shows the BER performance of the received signal at different ROPs. Noting that the CSPR is fixed at 12.15 dB in this test. The BER performance of the 4-bit DAC quantized signal with RF-DRE is similar to that of the 5-bit DAC quantized signal. The BER performance of the 5-bit DAC quantized signal with RF-DRE is similar to that of the 8-bit DAC quantized signal. For the 4-bit DAC quantized signal with -8 dBm ROP, the BER performance can be improved from 6.88e-3 to 1.49e-3, which is below the 7% hard-decision forward error correction (HD-FEC) threshold of 3.8e-3 as shown in Fig. 3(f).

Conclusions

We have demonstrated a virtual-carrier-assisted 30 GHz mm-wave transmission of 12 Gb/s 64QAM signals over 25 km SSMF. By shaping the quantization noise from the target RF frequency range to the undesired out-of-band through the proposed RF-DRE algorithm, the transmission performance of the mm-wave signal can be significantly improved. When applying the proposed RF-DRE algorithm, 5-bit DAC can exhibit similar performance to 8-bit DAC, and the BER performance of the 4-bit DAC quantized mm-wave signal can be improved from 6.88e-3 to 1.49e-3. Therefore, low-resolution DAC can be used for mm-wave signal generation using the RF-DRE algorithm. Furthermore, lower resolution DAC has the potential to be applied if a lower modulation format signal is used.

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