81.37-Gbps 2×2 MIMO 60-GHz OFDM-RoF System Employing I/Q Nonlinear Compensation Filtering Algorithm

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Abstract: We demonstrate 2x2 MIMO 60-GHz RoF system with nonlinear compensation. The proposed I/Q Volterra nonlinear compensation not only improves data rate up to 81.37Gbps but also extends wireless distance to 42 meters with data rate of >70Gbps.

1. Introduction

With the ever-changing nature of wireless communication, millimeter waves (MMW) and multiple-input-multiple-output (MIMO) stand out because of providing wider bandwidth and performing higher spectral efficiency, respectively. Therefore, MMW with wider bandwidth, such as V-band (57-64GHz), W-band (75-110GHz), and THz-band, have attracted a lot of attentions due to larger spectrum to provide multi-Gbps services [1-3]. However, higher frequency signals will lead to higher propagation loss. Hence, we need more signal power to improve wireless distance, which gives rise to nonlinear distortion from power amplifier. Besides, OFDM signals have higher PAPR which will also cause more nonlinear distortion. To achieve the best performance of signal transmission with high PAPR over a RoF channel, nonlinearities generated from both optical (e.g. optical modulators) and electrical components (e.g. power amplifiers and mixers) have to be carefully managed.

Volterra series are widely used for modeling nonlinear system, and nonlinear distortion can be compensated [4-5]. MMW signal suffers from I/Q imbalance because of its large bandwidth after electrical up-conversion. Hence, I/Q MIMO nonlinear compensation for MMW signals is required to provide more data rate and longer wireless distance [6-7]. In this paper, we propose 2x2 60-GHz MIMO system with I/Q Volterra compensation which can mitigate nonlinear distortion mainly caused by electrical power amplifier (PA) and compensate I/Q imbalance interference. With the proposed I/Q Volterra compensator, we demonstrate a 10-m 60-GHz wireless transmission with the data rate of more than 80 Gbps. Furthermore, we can extend wireless distance up to 42 meters, and the data rate can be still more than 70 Gbps.

2. Concept of I/Q Volterra and Nonlinear MIMO system compensation

There are two main distortions of our optical/wireless system as shown in Fig. 1. One is nonlinear distortion, and the other is I/Q imbalance intereference after electrical MIMO up-conversion. The nonlinear distorsions are mainly generated from electrical-to-optical (E-O) conversin using Mach-Zehnder modulator, power amplifier before wireless transmission, and down-conversion after wireless conversion. Among them, the power amplifier causes the most significant nonlinearity.

For the MIMO system, the nonlinearity come from all inupt signals. $\boldsymbol{s(t)}$ is the MIMO input singal and can be express as:

$$s(t) = \sum_{n=1}^{N} a_n s_n(t) \tag{1}$$

where N is the number of input MIMO signals. After optical/wireless MIMO system, the received signals can be expressed as [4-5]:

$$x_r(t) = \sum_{k=0}^{K} \sum_{n_1=1}^{N} \cdots \sum_{n_{2k+1}=1}^{N} \sum_{m_1=0}^{M} \cdots \sum_{m_{2k+1}=0}^{M} w^{(r)}{}_{2k+1}(m_1, \ldots, m_{2k+1}) \prod_{i=1}^{k+1} a_{n_i} s_{n_i}(t-m_i) \prod_{i=k+2}^{2k+1} a^{*}{}_{n_i} s_{n_i}{}^{*}(t-m_i) \tag{2}$$

where $x_r(t)$ is the r-th receiver signal, $w^{(r)}$ is the r-th impulse response, K and M represent the nonlinear order and memory depth, respectively. We apply Volterra model and adaptive filter to approximate the nonlinearity. The Winer model of the Volterra series is utilized and expressed as [4-5]:

$$z_r(t) = \sum_{k=0}^{K} \sum_{n_1=1}^{N} \cdots \sum_{n_{k+1}=n_k}^{N} \sum_{n_{k+2}=1}^{N} \cdots \sum_{n_{2k+1}=n_{2k}}^{N} \sum_{n_{k+1}=n_k}^{N} \sum_{m_1=0}^{M} \cdots \sum_{m_{k+1}=m'_k+1}^{M} \cdots \sum_{m_{k+2}=0}^{M} \cdots \sum_{m_{2k+1}=m'_{2k+1}}^{M} h^{(r)}{}_{2k+1}(n_1, \ldots, n_{2k+1}, m_1, \ldots, m_{2k+1}) \prod_{i=1}^{k+1} s_{n_i}(t-m_i) \prod_{i=k+2}^{2k+1} s_{n_i}{}^{*}(t-m_i) \tag{3}$$

Because MMW signals have the wide bandwidth, the I/Q imbalance is inevitable. Fig. 2 shows an I/Q Volterra filter which can be derived from Volterra filter I/Q imbalance compensation .The received signal $x(t)$ is modeled with Volterra to obtain $z(t)$.

The real part and the imaginary part of $z(t)$ are used to assess the influence of the I/Q signal, and the coefficient extends to four times, thereby compensating for I/Q imbalance. Finally we get the compensation $y(t)$.

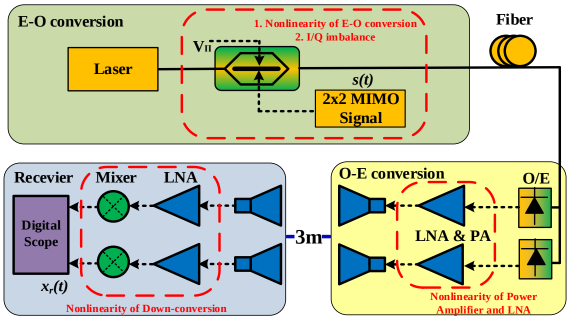
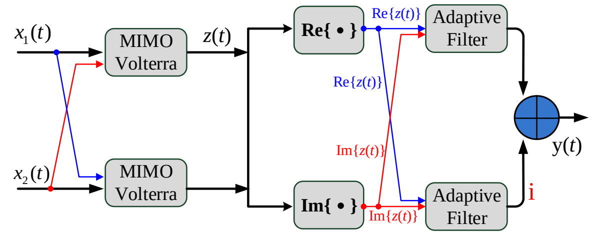


Fig. 1. Distortions of RoF System.



$$\begin{bmatrix} \mathrm{Re}\{y(t)\} \\ \mathrm{Im}\{y(t)\} \end{bmatrix} = \begin{bmatrix} W_{RR} & W_{IR} \\ W_{RI} & W_{II} \end{bmatrix} \begin{bmatrix} \mathrm{Re}\{z(t)\} \\ \mathrm{Im}\{z(t)\} \end{bmatrix}$$

Fig. 2. Functional diagram of I/Q Volterra filter

3. Experiment Result and Discussion

Fig. 3 presents the experiment setup of proposed 60-GHz OFDM RoF system employing 2x2 MIMO technology, using mixer for the down-conversion of RF signals. The baseband OFDM signals were generated by an arbitrary waveform generator (AWG) with the sampling rate of 12 GSample/s. The length of inverse fast Fourier transform (IFFT) was 1024, and cyclic prefix was set to 1/32 of IFFT length. Then, the BB IQ signals were up-converted to 21 GHz by an IQ mixer before being combined with sinusoidal waves 39.5 GHz. The combined signal was used to drive a dual-parallel Mach-Zehnder modulator (DP-MZM), which was biased at $V_{\pi/2}$ and V_{π} to suppress the optical carrier and let signal achieve single-sideband.-Following 10-km single-mode fiber (SMF) transmission. An optical interleaver was used to separate two signals, such that the optical signal mainly consisted of a modulated OFDM signal and an RF tone with a frequency difference of 60.5 GHz. Two V-band RF signals were generated by photo-detector. After 3-m wireless transmission, two signals were down-converted and captured by an oscilloscope with 80-GSample/s. The signals were demodulated by offline digital signal processing, including the MIMO equalizer and I/Q volterra conpensation. The bit-error-rate (BER) was measured by error counting.

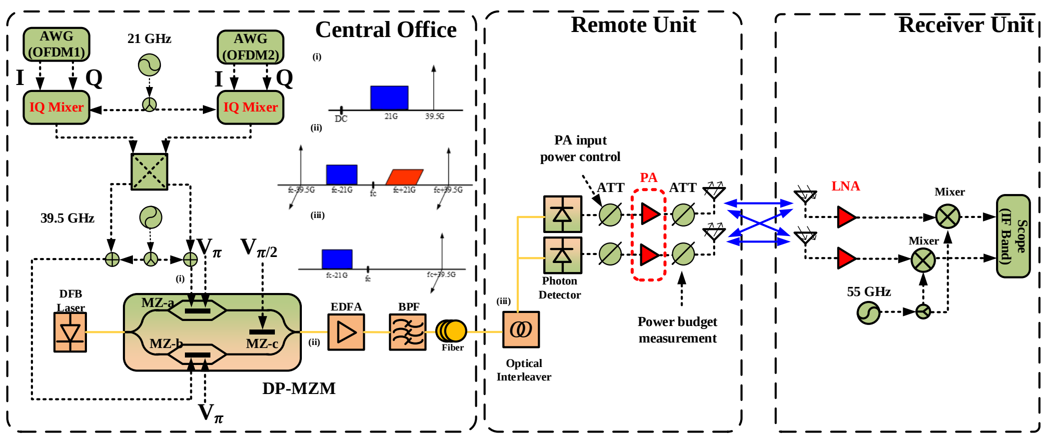


Fig. 3. Experiment setup V-Band RoF system with Volterra compensation.

Since MMW signals have higher wireless propagation loss, the power amplifier before transmitting antenna is operated in nonlinear region to get higher output power. The gain and P1dB of the PA are 22 dB and 15 dBm, respectively. Two electrical attenuators before and after PAs are utilized to control PA input power and measure extra power budget for wireless transmission, respectively. In our 2x2 MIMO optical/wireless system with 3m wireless distance, as the PA input power increases from -18.5 dBm to -9.5 dBm, signal-to-noise ratios (SNRs) of MIMO signals will decreases due to PA nonlinearity as shown Fig. 4. When PA input power is less than -18.5 dBm, the SNR trend will also decrease due to thermal noise. The attenuations after PAs can give more power budget for longer wireless distance. Hence, we use PA input power of -18.5 dBm as reference level for SNR (i.e. 21.5 dB) and power budget comparisons.

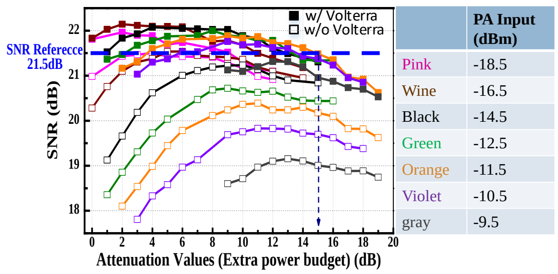


Fig. 4. Extra Power at different input powers of the transmitter amplifier.

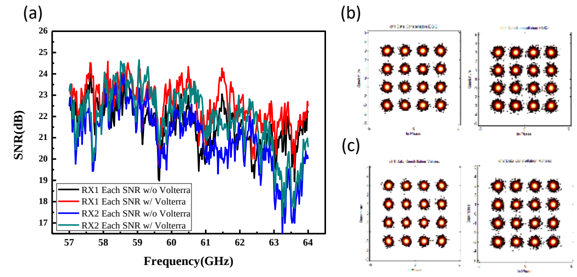


Fig. 5 (a) SNR of each OFDM subcarrier (b) Constellation w/o Volterra compensation (c) Constellation w/ Volterra compensation

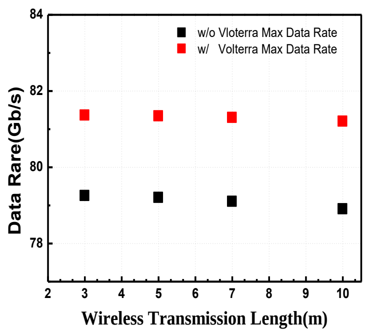


Fig. 6. The maximum date rate of different wireless transmission length.

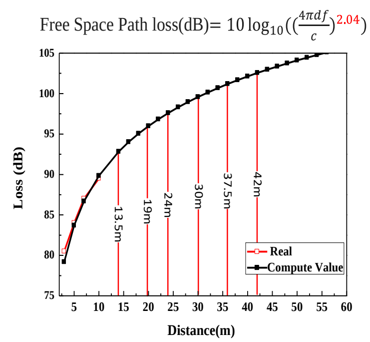


Fig. 7. Experimental and model results of 60-GHz path loss

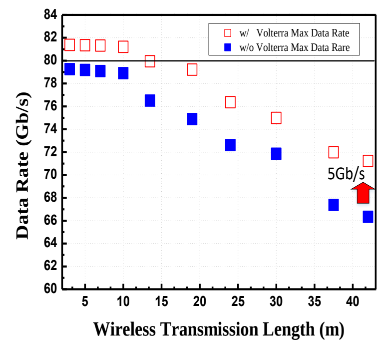


Fig. 8. Maximum data rate of longer wireless transmission length

With proposed I/Q Volterra compensation, PA nonlinear distorton can be obviously mitigated as shown in Fig. 4. When the PA input power is -16.5 dBm, the SNR can reach the maximum value of 22.07 dB, resulting in maxium transmission capacity. As PA input power is -11.5 dBm, we can get the maximum extra power budget of 15 dB for longer distance. Fig. 5 shows the SNR of each OFDM subcarrier and the corresponding constellations when PA input power is -16.5 dBm. After I/Q Volterra compensation, OFDM subcarrier SNR can be improved and the constellations become more clear.

The power and bit loadings based on bit error rate of 10^{-3} are utilized to achieve the maximum wireless capacity. Fig. 6 shows the maximum data rate with 3 to 10 meters wireless transmission. The PA input power is -16.5 dBm. With Volterra compensation, the data rate improvement can be more than 2 Gbps. The maximum data rate of 81.37 Gbps with 3m wirless distance can be achieved. The data rate with 10 m wireless distance is still higher than 80 Gbps. Fig. 7 shows experimental and model results of 60-GHz path loss. If the wireless distance is more than 10 m, we need to emulate it by attenution loss. The maximum data rates are still higher than 70 Gbps when the wireless distance is up to 42 meters as shown in Fig. 8.

4. Conclusion

I/Q Volterra nonlinearity compensation of 2x2 MIMO optical/wireless system at 60 GHz is proposed. Not only the maximum capacity is improved, but also the wireless distance is extended. With OFDM bit-loading algorithm and the nonlinearity compensation, the data rate of 81.37 Gbps can be achieved with 10km fiber and 3m wireless transmission. The maximum data rates can reach more than 70 Gbps when the wireless distance is up to 42 meters

5. References

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