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# 140 Gbps Photonics-Aided THz Wireless Communication Around 400 GHz Band Based on Artificial Neural Network Equalizer

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***Abstract*—We propose and experimentally verify a 400 GHz photonic-aided THz wireless communication system enabled by an artificial neural network (ANN) equalizer. The bit error rate (BER) performance is studied at different THz carrier frequencies from 370 GHz to 430 GHz. In addition, by means of using the piecewise learning rate approach, the ANN equalizer can improve the BER performance by approximate one order of magnitude, as compared with the traditional least mean square linear equalizer. We verify the BER performance at different baud rates from 32 GBd to 38 GBd in 390 GHz THz band. The results show that the piecewise learning rate enabled ANN equalizer can achieve a net rate of 140 Gbps after transmission over 20 km standard single mode fiber and 1 m wireless distances.**

***Keywords*—nonlinear equalizer; THz wireless communication; artificial neural network; optical fiber and wireless transmission**

## I. Introduction

With the emergence of new services and scenarios such as human-computer interaction, ubiquitous connectivity, and intelligent IoT, the demand for bandwidth and capacity for wireless communication has grown rapidly in recent years. Traditional frequency bands have gradually been unable to meet people's communication needs. The expansion of communication frequencies to THz bands (with a frequency range from 300 GHz to 10 THz) is an irreversible trend. The photonics-aided THz communication system can not only support distributed coverage based on the optical fiber networks, but also offer ultra-high bandwidth and ultra-large capacity. As a result, it will provide excellent solutions for new services and scenarios in the B5G and 6G eras. To date,

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many photonics-aided wireless communication systems have been implemented at the THz band [1-3]. For example, Ref. [1] has demonstrated a line rate of 132 Gbps signal transmission through polarization division multiplexing technique at 450 GHz link. While the rate of single polarization corresponds to 66 Gbps. Additionally, the signal transmissions with line rates of 128 Gbps at 300 GHz [2] and 400 GHz [3] over 0.5 m wireless distance have also demonstrated under the soft-decision forward error correction (SD-FEC) threshold of $2\times10^{-2}$. For the high-speed and large-capacity photonics-aided THz wireless communication systems, the linear and nonlinear distortions caused by the photoelectric components and the fiber-wireless hybrid channels are the major constraint to further improve the system performance. Therefore, the proper equalizer is necessary.

An already established equalizer is the nonlinear Volterra equalizer. It is widely used to compensate the linear and nonlinear distortions in fiber-wireless hybrid channels [4]. However, the Volterra equalizers, especially those involving higher-order kernels for the equalization of complex and hybrid channels, usually lead to a quite high complexity [5]. Another alternative equalizer approach is the application of machine learning techniques such as artificial neural network (ANN). As a nonlinear function, ANN can characterize the nonlinear behavior of the overall system, thus it is regarded as an efficient equalizer to compensate the linear and nonlinear distortions. In recent years, the ANN-based equalizer has been successfully demonstrated in the high-speed optical transmission systems [6, 7] and fiber-wireless integrated systems such as below 60 GHz radio-over-fiber link [8, 9]. Nevertheless, the use of ANN for nonlinear equalization is rarely involved in photonics-aided THz wireless communication systems, in which severe linear and nonlinear distortions exist due to the high-speed signal transmission over the fiber-wireless hybrid channels.

In this paper, we proposed an ANN equalizer with the piecewise learning rates (LRs) for the photonics-aided THz wireless communication system. The performance of the proposed ANN equalizer is verified by the experiment on 38 GBd 16-quadrature amplitude modulation (16QAM) signal with 20 km standard single-mode fiber (SSMF) transmission and 1 m wireless transmission at the 390 GHz band. The results show that a line rate of 152 Gbps (net rate of 141.4 Gbps) has been achieved under the hard-decision forward error correction (HD-FEC) threshold of $3.8\times10^{-3}$. The ANN equalizer can improve the bit error rate (BER) performance by about one order of magnitude.

## II. Experimental Setup

The experimental setup is shown in Fig. 1. At the transmitting DSP, as shown in Fig. 1(a), the binary bit sequence with the length of more than $10^5$ is first mapped into 16QAM symbols. After upsampled by four samples per symbol, a root-raised-cosine (RRC) filtering with a roll-off factor of 0.1 is performed. Then this signal is generated via the arbitrary waveform generator (AWG) by resampling to 92 GSa/s. One external cavity laser (ECL1) with the wavelength of 1549.315 nm produces continuous wavelength light waves. The generated 16QAM signal is fed into an IQ modulator for electro-optic conversion. The bias of IQ modulator is set to null point to suppress the optical carrier. And then the output optical signal is transmitted over 20 km standard single-mode fiber (SSMF) after amplified by an Erbium-doped fiber amplifier (EDFA1). A variable optical attenuator (VOA1) is used to adjust the optimal incident optical power before SSMF. After 20 km fiber transmission, the optical signal is coupled with the light waves generated by another ECL (ECL2). Both of the two ECLs have a linewidth of less than 100 kHz, while the center frequency of ECL2 is 370 ~ 430 GHz smaller than that of the ECL1. Fig. 1 (b) shows the combined optical spectra. Afterwards, the second EDFA (EDFA2) and VOA (VOA2) are used to amplify and adjust the optical power prior to photo-electric conversion, respectively. An antenna-integrated optical mixer module (AIPM, NTT IOD-PMAN-13001) as shown in Fig. 1(c), which integrates a uni-traveling carrier photodiode (UTC-PD) and a bow-tie or log-periodic antenna, is used to convert the optical signal to THz wave. After 1 m wireless transmission, the corresponding THz signal is received by a 25 dBi horn antenna (HA). Two THz lens with the diameter and focal length of 10 cm and 20 cm, respectively, are used to collimate THz wave.

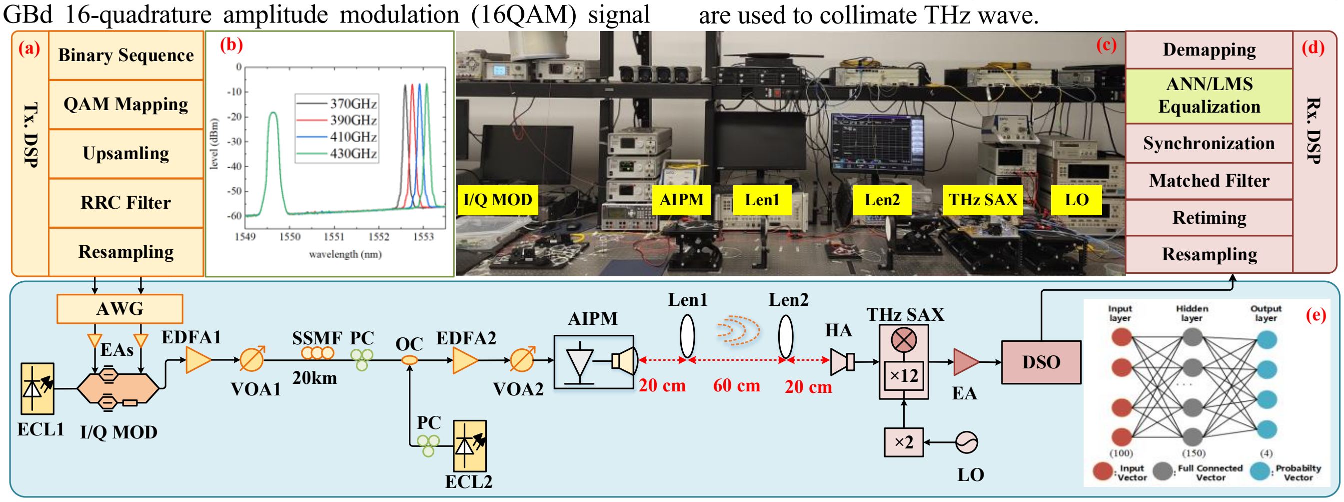


Figure 1. Experimental setup of photonics-aided THz wireless transmission system over 20 km SSMF and 1m wireless distance. (a) Tx.DSP; (b) Spectra of the optical local oscillator and optical signal after OC; (c) experimental photo; (d) Rx. DSP; (e) construction of ANN equalizer.

At the receiver, in order to down-convert the THz signal into a lower-frequency intermediate frequency (IF) signal, we adopt a THz spectrum analyzer extender (THz SAX), which contains a THz mixer, a frequency multiplier up to 12 times, and several IF amplifiers. Noting that a prior frequency doubling operation is used to increase the frequency of the electrical local oscillator (LO) input to SAX module. We set the frequencies of input LO as 14.583 GHz, 15.417 GHz, 16.25 GHz, 17.083 GHz for 370 GHz, 390 GHz, 410 GHz and 430 GHz links in the experimental setup, respectively. Thus, the frequencies of the output IF signal are about 20 GHz for all the cases. Then this IF signal is amplified by an electric amplifier (EA) and finally is captured by a 128 GSa/s digital storage oscilloscope (DSO). Afterwards, the digital sampled signal is processed in the receiving (Rx.) DSP. As shown in Fig. 1(d), the Rx. DSP process includes resampling, retiming, matched filter, synchronization, equalization, demapping and so on. For channel equalization, the proposed ANN equalizer as shown in Fig. 1(e) is used to compensate the nonlinear degradations of this photonics-aided THz wireless communication system. When does not adopt using ANN equalizer, the results of commonly used least mean square (LMS) equalizer are also exhibited for performance comparison in this paper.

## III. Results and Discussion

We first measure the transmission performance at different THz bands around 400 GHz. By adjusting the center wavelength of ECL2, the generated THz signal with the frequency varying from 370 GHz to 430 GHz can be obtained in turn. Fig. 2(a) shows the BER performance versus received optical power (ROP) prior to the AIPM for 26 GBd 16QAM signal at 370 ~ 430 GHz band. It can be seen that, the 390 GHz band has exhibited the best transmission performances. The spectrum of received IF signal for 390 GHz band is shown in Fig. 2(b) when the ROP is fixed at 12 dBm. Therefore, 390 GHz is selected as the main frequency band in the following.

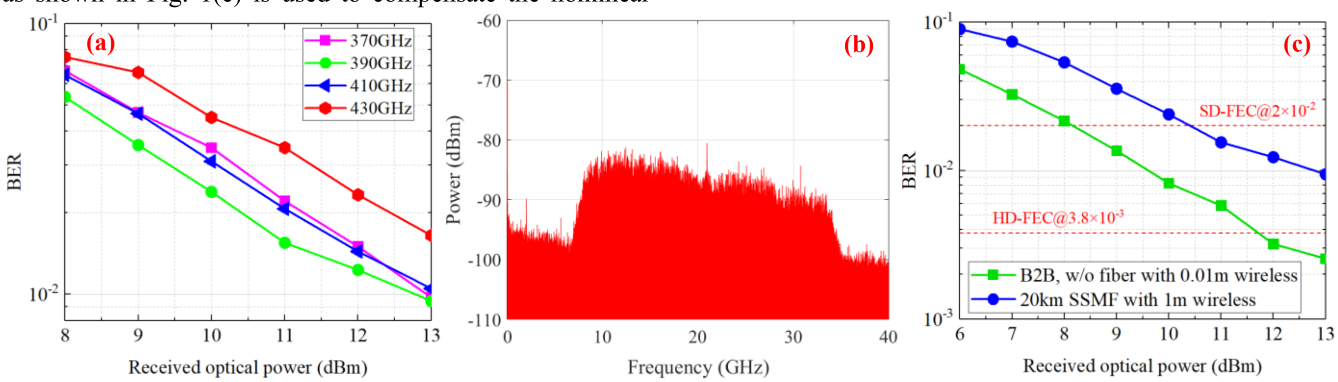


Figure 2. (a) BER performance versus ROP with different THz bands; (b) spectrum of the received IF signal with the ROP of 12 dBm; (c) BER performance versus ROP at the B2B and optical fiber transmission cases.

Then, we compare the BER performance for 26 GBd 16QAM signal versus ROP at the back-to-back (B2B) case (i.e., without fiber and 0.01m wireless transmission) and 20 km SSMF with 1 m wireless transmission case, as shown in Fig. 2(c). It can be seen that, at the SD-FEC threshold with the BER of $2\times10^{-2}$, the ROP sensitivity degradation caused by 20 km fiber and 1 m wireless transmission is more than 2 dB.

As mentioned above, the transmission of high-speed signal in photonics-aided THz communication system suffers from all kinds of linear and nonlinear impairments, due to the photoelectric components and the fiber-wireless hybrid channels [10]. In order to reconstruct the information from a distorted signal in our system, the ANN equalizer model shown in Fig. 1(e) is employed. It consists of a three-layer network with the number of neurons (100, 150, 4). The rectified linear units is used as the activation function for hidden layer, while the classification decision in output layer depends on calculated probability value. The whole data with more than $2^{18}$ symbols are divided into training set and test set with the ratio of 75:25. And the max-norm weight constraint is used to prevent overfitting.

In terms of optimization algorithm, the piecewise LR approach is used in our training process. At the beginning of training, in which corresponds to a low accuracy of the ANN equalizer, a large LR is used to speed up the gradient update. When the accuracy of ANN model reaches 90%, reduce the step size of the gradient update to make the model converge to the global optimal value. Fig. 3 shows the BER performance of 34 GBd 16QAM signal for different LR cases. For the first case, i.e., using a fixed LR of $4\times10^{-5}$, the ANN model has not searched the global optimal value, leading to a severe BER transmission performance. On the other hand, when we directly adopt a large fixed LR of $4\times10^{-5}$, a significant improvement of the BER performance can be observed. However, after combining the two different LRs with a critical point of 90% accuracy, that is, the piecewise LR approach is used, the ROP sensitivity at the 7% HD-FEC threshold can be further improved by about 0.7 dB.

Finally, based on the piecewise LR approach, we evaluate the performance of 16QAM signal for 20 km SSMF and 1 m wireless transmission under different baud rate cases. The results are shown in Fig. 4. Firstly, whether the ANN equalizer is used or not, the BER performance degrades with the increase of baud rate. This is because the higher the baud rate, the more serious the various impairments to the signal in the same transmission system. Secondly, when the 16QAM signals are demodulated without the ANN equalizer, i.e., using the LMS based linear equalizer instead, the BERs of

16QAM signals with the baud rate from 32 GBd to 38 GBd are all around the 20% SD-FEC threshold. On the contrary, after using the proposed ANN equalizer, a significant BER improvement can be exhibited. Especially, at the fixed ROP of 13 dBm, the established ANN equalizer can improve the BER by more than one order of magnitude approximately, as compared with traditional LMS equalizer. At this time, the line rate of this THz system is 152 Gbps (38×4) under the 7% HD-FEC threshold, which corresponds to a net rate of 141.36 Gbps. This proofs the valid compensation of the proposed ANN equalizer for the impairments of 400 GHz photonics-aided THz transmission system.

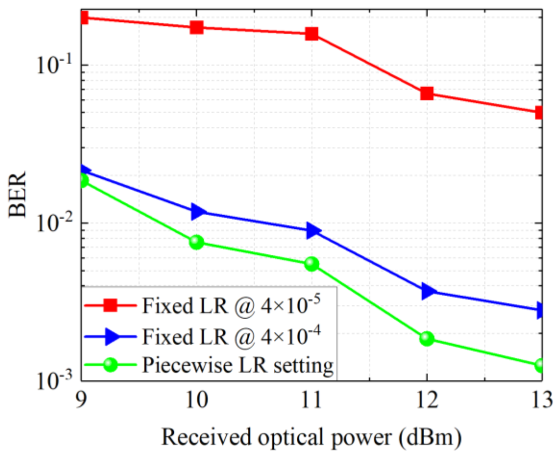


Figure 3. BER versus ROP curves with different learning rates (LR) cases.

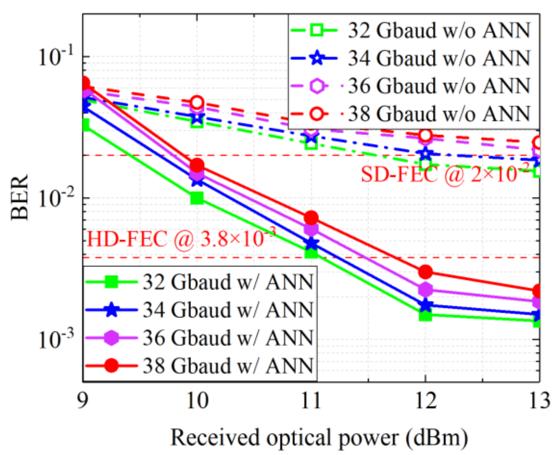


Figure 4. BER performance versus ROP with (w/) and without (w/o) ANN equalizer under different baud rate cases.

## IV. Conclusion

In conclusion, this paper has proposed and demonstrated an ANN equalizer enabled photonics-aided THz wireless communication system at around 400 GHz band. Based on the proposed ANN equalizer with piecewise LR, we can achieve a THz link with a net rate of more than 140 Gbps on a single wavelength and polarization when transmission over 20 km SSMF and 1m wireless distances. As compared with the traditional LMS equalizer, the proposed ANN equalizer can achieve approximate one order of magnitude of performance improvement. This scheme significantly enhances the performance of the photonics-aided 400 GHz THz wireless communication system, which will have a great use stage in the beyond 5G and 6G eras.

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