# Resilient MMW-RoF Network Enabled by Implementation of Tomlinson-Harashima Precoding

**Shuyi Shen, You-Wei Chen, Qi Zhou, Shuang Yao, Rui Zhang, Yahya Alfadhli, and Gee-Kung Chang**
*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA.*
*ssyzoe@gatech.edu*

**Abstract:** Tomlinson-Harashima precoding is proposed to relax the requirements of device bandwidth, linearity, and power consumption for resilient MMW-RoF network. A 16.8-dB BER improvement is experimentally demonstrated by the proposed precoding scheme subjecting to bandlimited operations.
**OCIS codes:** (060.5625) Radio frequency photonics; (060.2330) Fiber optics communications

## 1. Introduction

With the wide spectrum available and support for high traffic demand, radio-over-fiber (RoF) in millimeter-wave (MMW) band is widely used to provide high-speed seamless fiber-wireless access [1-4]. RoF is transparent to services and allows for light-weight and low-complexity optical-to-electrical (O/E) field nodes [3]. The channel response of MMW links is more static and flat compared to conventional low-frequency wireless links. As a wireless access scheme, MMW-RoF can establish effective communication links in the urban area where pulling fiber cable is cost-prohibitive, making it a popular option for mobile fronthaul, backhaul or last-mile access [2-4]. However, applications of MMW-RoF should not be restricted to that. MMW-RoF link can serve as the critical communication bridge when the fiber network is damaged subjecting to natural disasters, or when geographical restriction limits the communication [4]. In these cases, receivers and the relay nodes with low complexity and low power consumption are desirable. Furthermore, as link-recovery schemes or back-up links, such MMW-RoF links are usually anticipated to operate with devices having limited bandwidth and less optimal linearity performance.

Tomlinson-Harashima precoding (THP) is a non-linear equalization scheme to remove inter-symbol interference (ISI). It was first introduced to address the error propagation issue in decision feedback equalizers (DFE). As a pre-equalization scheme, THP is suitable for channels that are time-invariant or slowly time-varying [5]. By introducing a modulo function in the precoding process, THP offers lower peak and average power, as well as lower peak-to-average-power ratio (PAPR), compared to other pre-equalization methods. THP has found its applications in optical networks such as inter-data center networks and intensity modulation/direct detection (IM/DD) PAM4 transmissions, providing improved anti-chromatic dispersion (CD) capability and tolerance to bandlimited devices [6, 7].

In this paper, we propose THP for bandlimited MMW-RoF links. THP is feasible with the static channel characteristics of MMW. As a precoding scheme, THP shifts the receiver complexity to the transmitter, in line with the low-complexity relay/receiver requirement in resilient networks. Furthermore, THP can achieve pre-equalization with low PAPR operation, which relaxes the requirement of device linearity. On the other hand, THP-aided MMW-RoF link exhibits improved performance under the impact of bandlimited devices. In this paper, THP for a MMW-RoF link with 50-*km* fiber transmission is experimentally demonstrated. Compared to DFE-precoder, THP-aided MMW-RoF achieves 16.8-dB better bit error rate (BER) under bandlimited operation.

## 2. Operating Principles

In this paper, THP based on minimum-mean-square-error (MMSE) DFE is implemented for the MMW-RoF link. The principle of conventional DFE is shown in Fig. 1(a). $a_k$ is the original symbol from the symbol set of *M*-quadrature amplitude modulation (*M*-QAM). $x_k$ is the transmitted symbol before channel $H(z)$. $F(z)$ is the feed forward equalizer (FFE), which will reduce to impulse response if $H(z)$ is minimum phase. This is usually the case for MMW-RoF wireless channel, as the directivity of MMW, especially when aided by beamforming technologies, assures the line-of-sight (LoS) connection [8]. $B(z)$ is the feedback filter to remove ISI. $\hat{a}_k$ is the recovered symbol after hard decision. For conventional DFE precoding as shown in Fig. 2(b), the feedback filter $B(z)$ is moved to the transmitter. When $H(z)$ is minimum phase, the receiver of conventional DFE precoding reduces to a slicer. For THP, in addition to $B(z)$ a modulo-*2L* process is inserted to reduce the peak and average power penalty in the transmitter as shown in Fig.1(c), where $L = \sqrt{M}$. In the receiver side, a corresponding modulo process is added as well to restore the data from the nonlinear operation of THP.

In conventional DFE precoding, the transmitted signal $x_k$ is generated from the original data $a_k$ filtered by $M^{-1}(z)$, where $M(z) = B(z) + 1$, and the impulse response of $M^{-1}(z)$ is $f_k$. This is not advisable due to signal enhancement, which can greatly increase the average and peak power of the signal by a factor of $\sum_0^{\infty}|f_k|^2 > 1$ [5]. As an example, a DEF precoded quadrature-phase-shift-keying (QPSK) signal is presented in Fig. 1(d). In THP, by applying modulo-$2L$ to $w_k$ as indicated in Fig. 1(c), we yield $x_k = w_k \ modulo\ 2L$. As a result, $x_k$ is bounded in the range of $(-L, L)$ and the average power of $x_k$ is kept approximately the same as $a_k$, as shown in Fig. 1(e). Comparing the transmitted symbols shown in Fig.1(d) and (e), it can be seen that THP confines the $x_k$ amplitude within $(-L, L)$, providing lower peak and average power. In the receiver side, the channel-distorted symbol $y_k$ can be pushed back to $(-L, L)$ by the corresponding modulo-$2L$ process.

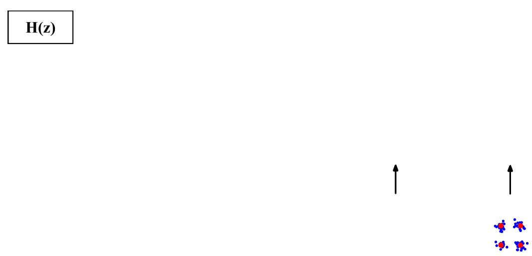



Fig. 1. Signal processing flow diagram of (a) DFE; (b) DFE pre-equalizer; (c) THP. Constellation of $x_k$: (d) DFE precoder; (e) THP.

## 3. Experimental Setup

The experimental setup is shown in Fig. 2. MMW is generated via the optical-carrier-suppression (OCS) modulation. 60-*GHz* wavelength separation is achieved by a Mach-Zehnder modulator (MZM) biased at the null point modulated by a 30-*GHz* radio-frequency (RF) source. From Fig. 2(a), it can be seen that optical carrier suppression of more than 15 dB is achieved. The electrical signal generated by an arbitrary waveform generator (AWG) is modulated to the optical carrier by the second MZM biased at the linear region. After amplified by an erbium-doped fiber amplifier (EDFA), the modulated optical signal is transmitted through 50-*km* standard single mode fiber (SSMF) before detected by a photodetector (PD) at the MMW relay node. In the relay node, the RoF signal is converted to MMW signal, amplified and then transmitted by a 15-dBi horn antenna (HA). After MMW transmission, the signal is received by another HA and down-converted to baseband, captured by an oscilloscope followed by offline digital signal processing. The experimental results of BER versus the received optical power (ROP) at the receiver side for both back-to-back (B2B, with MMW transmission) and 50-*km* fiber transmission are shown in Fig. 2(b).

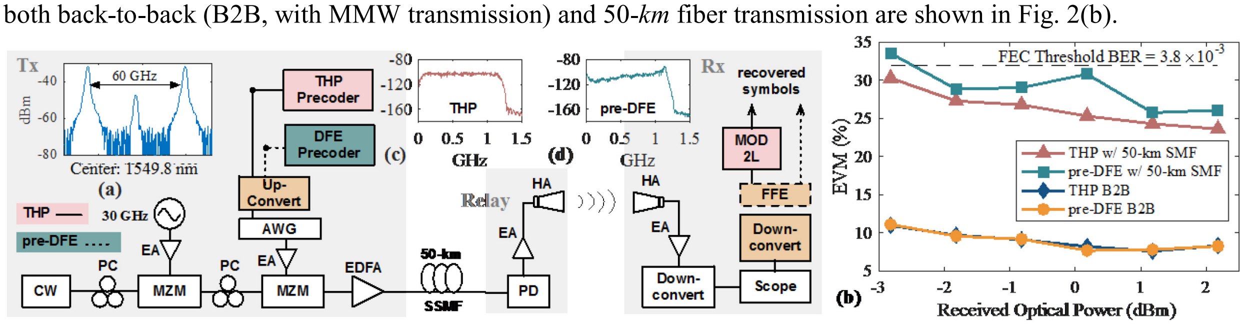



Fig. 2. Experimental setup. (a) Optical spectrum of optical MMW carrier; (b) BER vs. received optical power at the receiver. PSD of the signal after: (c) THP precoder; (d) DFE precoder.

In the experiment, the precoded QPSK signal is first up-converted to the carrier frequency $f_c$, which changes with respect to the signal baud rate in order to accommodate the signal within limited system bandwidth. The system bandwidth is limited by the commercial envelop detector for down-conversion in the receiver end, with the nominal bandwidth of 1 *GHz*. In the experiment, baud rates under bandlimited operation are investigated. For each baud rate, 50 *MHz* is reserved in the DC region to avoid baseband noise.

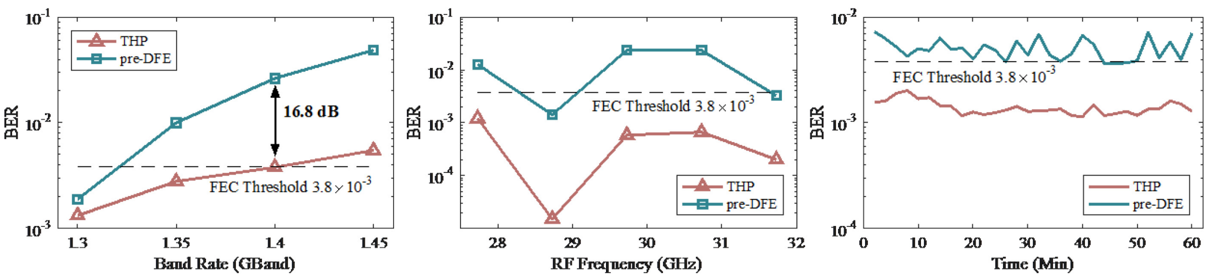
## 4. Experimental Results

From Fig. 2(b), it can be seen that after 50-*km* fiber transmission, THP can achieve lower BER performance than DFE precoder. While in B2B scenario, both achieve similar BER-vs-ROP performance. This indicates the anti-CD capability of THP. The power spectral density (PSD) of the QPSK signal precoded by THP and DFE, $x_k$, is shown in Fig. 2(c) and (d), respectively. It can be seen that THP signal exhibits a flat PSD as regular QPSK signals, whereas the PSD of the DFE-precoded signal is severely distorted with respect to the channel response.

To evaluate the achievable data capacity of a receiver bandwidth-limited system, the BER with respect to increasing baud rate is investigated with experimental results shown in Fig. 3(a). For all baud rates, the ROP is fixed at 2 dBm, the RF frequency is 28.83 *GHz*. Given the system bandwidth of 1 *GHz*, the performance of baud rates from 1.3 GBaud to 1.45 GBaud are investigated. It can be seen that for all baud rates tested, THP-coded signal achieves better BER performance. At 1.4 GBaud, THP signal provides $3.8 \times 10^{-3}$ BER while the BER of DFE-precoded signal is $2.6 \times 10^{-2}$. BER is improved by 16.8 dB, more than one order of magnitude.

The experimental results of BER versus RF frequency are shown in Fig. 3(b). For all RF frequencies, the baud rate is fixed at 1.3 GBaud, the ROP is fixed at 2 dBm. For RF frequency varying from 27.73 *GHz* to 31.73 *GHz*, the THP signal maintains the BER below the forward error correction (FEC) threshold of $3.8 \times 10^{-3}$, whereas the DFE-precoded signal fluctuates around the threshold.

One reason that the importance of THP was under-estimated until recently is that, channel information is required at the transmitter side. As a result, THP is considered not suitable for fast-changing wireless channels subjecting to none-line-of-sight (NLoS) paths. However, THP can be a good fit for our applications since the channel in MMW-RoF links is more static. To validate this point, we tested the BER performance of THP and DFE-precoded signals for one-hour time period, with the ROP of 2 dBm, the RF frequency at 28.83 *GHz*, and the baud rate of 1.3 GBaud. For every two minutes, the received signal is captured and analyzed. Throughout the experiment, the THP precoder uses the same channel information obtained at the beginning of the testing. The experimental results are shown in Fig. 3(c). Within one-hour duration, THP maintains the BER below FEC threshold.




(a) (b) (c)

Fig. 3. Experimental results. (a) BER vs. baud rate. (b) BER vs. RF frequency. (c) BER measurement over one-hour time period.

## 5. Conclusion

We have proposed a THP-aided MMW-RoF link for resilient networks. The THP-aided MMW-RoF link provides low-complexity relay nodes and receiver that are suitable for link-recovery or back-up purposes. Compared to DFE precoding, THP provides low peak and average power for the transmitted signal. In both bandlimited operation and 50-*km* SSMF transmission which incurs CD, experimental results have shown that THP provides better BER performance than DFE precoder. A 16.8-dB BER improvement of THP with respect to DFE precoder is experimentally demonstrated for the receiver bandwidth-limited system. The stability of THP precoder in the MMW-RoF link is also experimentally validated over the time period of one hour. THP provides stable BER performance for MMW-RoF links, allowing for system devices with limited bandwidth, linearity, and power consumption, which fits the needs of resilient networks.

## References


[1] S. Rommel, M. Heck, J. J. V. Olmos, and I. T. Monroy, "mm-Wave Wireless Communications based on Silicon Photonics Integrated Circuits," Korean-Danish Photonics Workshop at KAIST, 2015.

[2] A. Lebedev et al., "Feasibility study and experimental verification of simplified fiber-supported 60-GHz picocell mobile backhaul links," IEEE Photonics Journal, vol. 5, no. 4, 7200913, Aug. 2013

[3] Chang, G.-K., and Cheng, L., "Fiber-wireless integration for future mobile communications," Radio and Wireless Symposium, pp. 16-18, 2017.

[4] Kawanishi, T., Kanno, A., & Freire, H. S. "Wired and Wireless Links to Bridge Networks: Seamlessly Connecting Radio and Optical Technologies for 5G Networks," IEEE Microwave Magazine, vol.19, no.3, pp.102-111, 2018.

[5] Barry, J.R., Lee, E.A. and Messerschmitt, D.G., 2012. "Digital communication,". Springer Science & Business Media.

[6] K. Matsumoto et al. "On the impact of Tomlinson-Harashima precoding in optical PAM transmissions for intra-DCN communication," Th3D.7, OFC 2018.

[7] N. Kikuchi et al. "Application of Tomlinson-Harashima Precoding (THP) for Short-Reach Band-Limited Nyquist PAM and Faster-Than-Nyquist PAM Signaling,", W1J.2, OFC 2018.

[8] K. Lyu, Z. Rezki, M.-S. Alouini, "Accounting for Blockage and Shadowing at 60-GHz mmWave Mesh Networks: Interference Matters,", IEEE International Conference on Communications, pp.676-680, May 2018.