Mitigation of Dispersion-Induced Power Fading in Broadband Intermediate-Frequency-over-Fiber Transmission using Space-Time Block Coding

Jinwoo Park[1], Joungmoon Lee[1], Inho Ha[1] and Sang-Kook Han[1*]

[1]*Department of Electrical & Electronic Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, South Korea*

**skhan@yonsei.ac.kr*

Abstract: STBC with optical I-Q modulator for dispersion-induced power fading mitigation is proposed and experimentally demonstrated in broadband IFoF system. 9.5GHz bandwidth IFoF signal transmission with 8.5% EVM in fading-affected band of 50km transmission was demonstrated. © 2024 The Author(s)

1. Introduction

Data traffic has been growing for years, and as a result transmission capacity has become increasingly important in the discussion of new communication standards such as beyond 5G and 6G. In particular, as mobile data traffic grows, recent research is focusing on increasing the transmission capacity of mobile fronthaul to keep up with rising demand. Digital radio-over-fiber (RoF) based on the common public radio interface (CPRI) was used in the existing mobile fronthaul interface. However, it has a key drawback of bandwidth inefficiency because traffic amplification occurs in the process of optical binary modulation [1]. Therefore, bandwidth-efficient mobile fronthaul schemes based on analog radio-over-fiber (A-RoF) is recently attracting attention. Especially, intermediate-frequency over fiber (IFoF) based 5G and b5G mobile fronthaul link is promising because of its advantages in bandwidth efficiency, low latency and high flexibility to support various communication specifications [2]. Despite its advantages, high propagation losses during transmission are a major challenge for broadband IFoF research. Chromatic dispersion in optical fiber transmission causes group velocity difference between the upper sideband and lower sideband of the broadband analog signal. Two sidebands destructively interfere, causing radio frequency (RF) power fading in a certain frequency range. This effect of 1st order chromatic dispersion becomes more critical as modulation frequency and transmission distance increases [3]. At 20km, the maximum transmission distance of mobile fronthaul in the 5G standards, RF deep fading theoretically occurs at approximately 14GHz. The signal modulation bandwidth of the existing IFoF transmission scheme is limited to the frequency of the deep fading frequency range.

In this paper, we devised a novel broadband IFoF transmission link to mitigate the effects of dispersion-induced power fading. We proposed space-time block coding (STBC) utilizing an in-phase/quadrature (IQ) modulator to the optical fiber link to avoid destructive interference between two sidebands. We further experimentally demonstrate optical STBC using IQ modulator with 10GHz multiband IFoF signal with 50km-fiber transmission, showing that our proposed scheme is scalable to long-distance and broad-band mobile fronthaul links for 5G and beyond.

2. Principle of Operation

STBC, which is also known as Alamouti code, is a simple multiple-input-single-output (MISO) transmission diversity scheme without sacrificing data rate mainly applied in wireless communication. STBC primarily operates by transmitting orthogonal data set over two consecutive timeslots with two transmitters. In the first timeslot, the data is modulated and transmitted through the transmitter according to a specific pattern. In the subsequent timeslot, the data is again modulated and transmitted, but with one of the transmitter phase-shifted to achieve orthogonality between the signals. This orthogonality is a key feature of the STBC, as it simplifies the decoding process at the receiver. For the first transmitter, signal s_{2k-1} and s_{2k} is assigned for a consecutive timeslot t_{2k-1} and t_{2k}. And, for the second transmitter, signal $-s_{2k}^*$ and s_{2k-1}^* assigned for the same timeslots t_{2k-1} and t_{2k} which include conjugates with phase shift. The conjugate and 180-degree phase shift ensure orthogonality between the signal sets of two transmitters. The signal generated in each transmitter goes through the channel h_1 and h_2. When the receiver gets signals through the channel, it can get $h_1 \cdot s_{2k-1} + \mathrm{h}_2 \cdot s_{2k}$ for t_{2k-1} and $h_1 \cdot s_{2k}^* + \mathrm{h}_2 \cdot s_{2k-1}^*$ for t_{2k}. Due to the phase shift and conjugates, the interference terms add up to zero, resulting in the orthogonality of the received signal [4, 5]. In traditional wireless communication, antennas are used as the transmitter and receiver. Our proposed technique utilizes an IQ-modulator as the STBC modulator and coder, and photodetector (PD) as a receiver.

The basic principle of using phase shift and conjugates to ensure orthogonality is applied to optical STBC with an IQ-modulator. Signal set $[s_{2k-1}\ s_{2k}]$ and phase-shifted $[-s_{2k}\ s_{2k-1}]$ are assigned to I (in-phase) and Q (quadrature) arm or modulator. The conjugating process is done by matching the optical phase difference between in-phase and quadrature components. For the timeslot t_{2k-1}, signal s_{2k-1} of I and s_{2k} of Q is modulated and coupled with 90°-phase difference. Therefore, if the half-wave voltage of I and Q arm $V_{\pi I} = V_{\pi Q} = V_{\pi}$, electric fields can be expressed as $E_{2k-1} = \exp\left(j\frac{s_{2k-1}}{V_{\pi I}} + j\frac{\pi}{4}\right) + \exp\left(j\frac{s_{2k}}{V_{\pi Q}} - j\frac{\pi}{4}\right)$ for t_{2k-1} and $E_{2k} = \exp\left(\frac{s_{2k}}{V_{\pi I}} + j\frac{\pi}{4}\right) + \exp\left(-\frac{s_{2k-1}}{V_{\pi Q}} - j\frac{\pi}{4}\right)$ for t_{2k}. The expression $\exp(j\frac{\pi}{4})$ and $\exp(-j\frac{\pi}{4})$ describes the phase difference between I and Q. These electric fields are transmitted through a dispersive fiber channel with a transfer function $H = \exp[-j\frac{D\lambda^2 L}{4\pi c}\omega_s^2]$, with fiber dispersion coefficient D, wavelength of the optical carrier λ, length of the fiber L, speed of light c and RF signal frequency ω_s. After transmission, electric fields (1) and (2) are received with photodetector by square-law detection process that expressed as $i(t) = |E(t)|^2$. Since the DC component is blocked and the second-order component is negligible, output photocurrent can be approximately driven as $i(t) \propto \cos(\frac{D\lambda^2 L}{4\pi c})$. Since we used an IQ modulator, the phase difference between two signals of each arm is $\frac{\pi}{2}$. This results in the following if the photocurrent from one arm is expressed proportional to $\cos(\frac{D\lambda^2 L}{4\pi c})$, then the photocurrent of another arm can be written in the formula proportional to $\sin(\frac{D\lambda^2 L}{4\pi c})$. Therefore, each signal transmitted over the cos- and sin-channel is detected by photodetector. Based on the orthogonality of trigonometric functions the deep fading region of each channel response can be filled in with another. After the receiving and decoding process is done, the signal has a spectrum as it is transmitted over the flattened channel $\sqrt{H^2 + H^{2*}}$, where the dispersion-induced power fading is eliminated.

3. Experiments and results

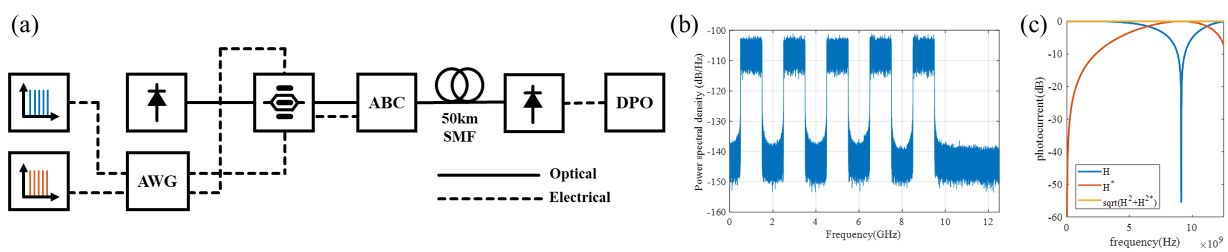

Fig. 1. (a) Experimental setup for IQ-modulator based IFoF system (b) Power spectral density of transmitted IFoF signal (c) Frequency response of channel H, $H^*$and $\sqrt{H + H^*}$ for fiber length L=50km

Fig. 1. (a) shows the experimental setup of the proposed IQ-modulator based IFoF system. At the transmitter, STBC-aided signal sets are fed into an arbitrary waveform generator (AWG). The power spectral density (PSD) of the IFoF-orthogonal frequency division multiplexing (OFDM) signal is depicted in Fig. 1. (b). Quadrature Amplitude Modulation (QAM) signal modulated in 16 levels is carried on 1500 subcarriers, with 240kHz subcarrier spacing. Due to the high PAPR of the IFoF-OFDM signal, clipping is conducted with a clipping ratio $\sigma = 6$dB. The clipping process helps ensure a dynamic range of modulation with regard to the transfer curve of the IQ modulator to avoid unexpected nonlinear effects. Also, the frequency bands of the signal are set as 0.5~1.5, 2.5~3.5, 4.5~5.5, 6.5~7.5 and 8.5~9.5GHz. These '1GHz signal band-1GHz guard band' settings are also intentionally designed to minimize 2nd and 3rd intermodulation components (IMD2 and IMD3) considering the nonlinear property of devices such as an IQ modulator and RF amplifiers. Those IFoF parameters were set to be optimal to exclude as much as possible nonlinear issues that are not the target of this research. The entire bandwidth is set as 9.5GHz because the RF frequency response of AWG was limited to 11GHz. The configured signal is fed to IQ modulator with automatic bias controller (ABC) to ensure quadrature operation of the I and Q arms and the phase difference between them. The problem with transmitting a moderate bandwidth signal is that it is difficult to prove the concept because deep fading occurs in 14GHz band when the signal is transmitted over a fiber of 20km length, which is the target distance for existing mobile fronthaul. Instead of using local oscillators, the setup was configured to increase the length of optical fiber to 50km to shift the region of deep fading to lower frequency bands. When the transmission distance is increased to 50km, the theoretical frequency response of channel H, orthogonal channel H, and decoded response $\sqrt{H^2 + H^{*2}}$ can be figured as Fig 1. (c). The deep fading is observed at 9.1GHz, making it difficult to receive and demodulate the 5th band of signal described in Fig 1. (b). In this experiment, we transmitted and received IFoF signals with STBC in a 50km system setup. Also, a series of processes involving demodulation and decoding were conducted to extract the original QAM signal. Through this, we aimed to confirm that the STBC using an IQ modulator mitigates the effects of dispersion-induced power fading. The PSD of the deep fading region was compared

with the transmission experiment using the usual Mach-Zehnder modulator (MZM) and the error vector magnitude (EVM) of 16QAM signal was measured.

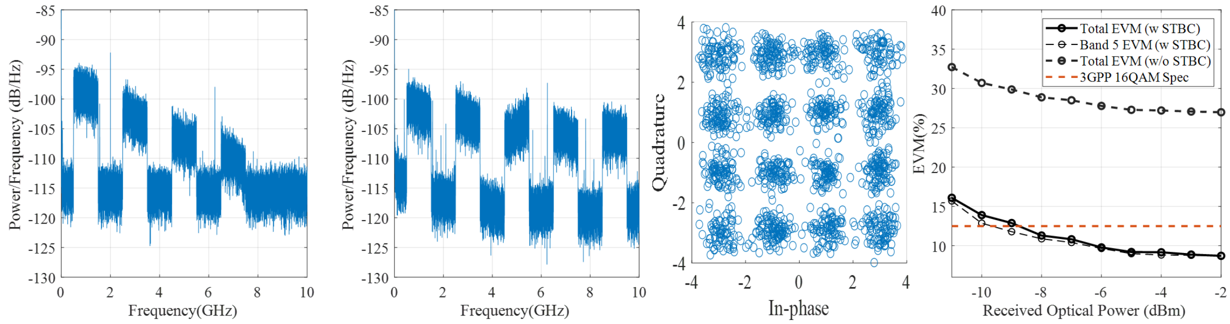

Fig. 2. (a) PSD of IFoF signal without STBC (b) PSD of IFoF signal with STBC
(c) Constellation of demodulated 16QAM of band5 (ROP = -11dBm) (d) EVM of IFoF signal with and without STBC

Fig. 2. (a) and (b) show the received PSD of IFoF signal over 50km fiber transmission without and with STBC. For the Fig. 2. (a), it shows the 5th band of signal almost faded so that the demodulation process became meaningless. On the contrary, despite the long-distance transmission, the 5th band of the IFoF signal is not affected by dispersion-induced power fading. The 5th band of the signal with the proposed technique succeeded in demodulating the 16QAM signal, as shown in the constellation of Fig. 2. (c). After decoding and 1-tap equalizing to calibrate phase noise caused by oscilloscope and RF devices, EVM was calculated and plotted according to the received optical power as Fig. 2. (d). EVM under 12.5%, the 3GPP 16QAM specification, was achieved with received optical power over -8dBm for the total band with STBC. Moreover, if the received optical power is sufficient, EVM is reduced by 8%. We can see that the total EVMs are saturated over 25%, because the band 5 was critically affected by dispersion-induced power fading so that EVMs are calculated about 100%. Unfortunately, in the experimental condition, three factors have contributed to the non-flattening of the PSD. One is the frequency response of AWG, which causes PSD to be unflattened even in the back-to-back transmission. Another is the quadrature bias voltage of I and Q, V_I and V_Q, have a little difference. It was not large enough to affect the success of the technique, but it created a slight imbalance in the transfer function of the orthogonal signal set. The other factor was large nonlinear components generated from a modulator and RF devices. As shown in Fig. 2. (a), the noise floor of the 1st band is raised by the nonlinear component. These IMD2 and IMD3 components lower the SNR of the signal, slightly raising the total average EVM, as depicted in Fig. 2. (d). However, despite these degradation factors of the experiment, the proposed STBC technique using an IQ modulator worked as theorized. It was verified that communication is sufficiently possible under the condition that the received optical power is secured. Also, since this experiment was conducted in a 50km environment due to equipment limitations, it can be expected to be more effective in an actual IFoF link environment where a local oscillator and an adder are utilized.

4. Conclusion

In this work, space-time block coding with IQ modulator for mitigation of dispersion-induced power fading in the multiband IFoF transmission system is proposed and experimentally demonstrated. Based on the orthogonality ensured with STBC, IFoF signal with 9.5GHz bandwidth is successfully transmitted and received through a dispersive optical fiber link with EVM under 12.5% for the received optical power over -8dBm, achieving about 8.5% EVM with sufficient optical power. The results obtained in this study show that the proposed IFoF transmission system is applicable to longer-distance or broader-bandwidth mobile fronthaul links for the beyond 5G and next-generation network system.

5. References

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