28-GHz RoF Link Employing Optical Remote Heterodyne Techniques with Kramers–Kronig Receiver

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Abstract. We propose and demonstrate a 28-GHz optical remote heterodyne RoF link using KK receiver for the first time. An optical SSB modulated signal is obtained utilizing an IQ modulator and two free-running lasers. Due to its minimum phase property, KK algorithm can be adopted to reconstruct the complex 16-QAM signal from the received intensity signal. This scheme is effective in eliminating the SSBI penalty introduced by square-law detection. Through the use of the KK receiver, the power penalty caused by the 80 km SSMF transmission is found to be less than 1 dB with digital CDC post processing. The KK-based receiver can also provide about 2 dB advantage over the traditional receiver at the 7% HD-FEC threshold in the case of 28 GBaud rate transmission over 80 km fiber. Furthermore, as the baud rate increases, the benefit of KK receiving scheme is more obvious and superior than that of the traditional receiving scheme.

Keywords: Millimeter-wave · Radio-over-fiber (RoF) · Optical heterodyning
Fiber optics communication

1 Introduction

Radio over fiber (RoF) technique can offer a strong and cost-effective solution on enhancing the system capacity and mobility of wireless links. It can make the network structure more flexible by using fibers to connect the central office (CO) with numerous simplified base stations (BSs). Among different schemes, optical remote heterodyne technique provides a promising and low-cost solution for RoF transmission [1–3]. In optical remote heterodyne, the modulated signal light is coupled with an optical local oscillator (LO) at the centralized CO (not at the BSs) and each BS is only responsible for O/E, E/O, filtering and amplification of the signal.

At the receiving side of an optical remote heterodyne direct-detection (DD) RoF system, a conventional receiver generally requires a microwave LO and an electric mixer for down conversion. In addition, this solution cannot eliminate the DD-induced signal-to-signal interference (SSBI) without extra signal processing techniques [4, 5]. In contrast, the recently proposed approach named Kramers–Kronig (KK) algorithm

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can fully reconstruct the complex field signal from the detected photocurrent amplitude waveform with a low digital signal processing (DSP) complexity, assuming that the signal is a single-sideband and minimum phase signal [6–9]. As a result, the microwave LO and electric mixer can be avoided at the receiver. Moreover, the KK-based approach is able to alleviate the SSBI very well [10].

In this paper, we report and demonstrate a 28-GHz RoF link employing optical remote heterodyne techniques with Kramers–Kronig receiver. It is worth highlighting that the 28-GHz is considered in this paper instead of the widely investigated 60-GHz because higher distances can be achieved even in nonline-of-sight (NLOS) transmission [2] for 28-GHz systems plus better choices on available devices for future 5G operating frequency. Optical remote heterodyne techniques and single-ended photodiode (PD) with KK reception scheme for 16-quadrature amplitude modulation (QAM) signal reconstruction are combined to achieve the low-cost and efficient scheme for 28-GHz RoF link. Furthermore, to the best of our knowledge, this is for the first time to adopt KK reception scheme in ROF systems. The paper is organized as follows. Section 2 explains the fundamental principles of the proposed scheme and the simulation results are presented and discussed in Sect. 3. Section 4 gives the conclusion.

2 Scheme of Proposed Remote Heterodyne RoF Link with Kramers–Kronig Receiver

The schematic of the proposed remote heterodyne RoF link with KK receiver is shown in Fig. 1. At the CO transmitter, a suppressed carrier double sideband (SC-DSB) signal is generated by modulating 16-QAM baseband data onto a continuous wave (CW) laser utilizing an IQ modulator. Afterwards, the SC-DSB signal light is coupled with a carrier from the LO, then an optical single sideband signal (OSSB) is obtained in this case. By controlling the carrier signal power ratio (CSPR) and adjusting the signal bandwidth (proportional to baud rate) and RF frequency (namely the frequency difference between the CW laser and the LO), we can make the SSB signal satisfy the minimum phase signal condition, which is an indispensable condition for adopting the KK algorithm.

At the BS, the photocurrent signal (see inset (iii) in Fig. 1) which is obtained using a single-ended PD for heterodyne detection, is wireless transmitted via a pair of antennas after amplification. At the receiver, the received signal is converted into digital signal by an analog-to-digital converter (ADC), and is fed to the DSP for offline processing finally.

Suppose that the complex signal $s(t)$ is a conventional bandwidth-limited 16-QAM small signal with a bandwidth of B, then the SSB signal can be described as

$$y(t) = A + s(t)\exp(j2\pi f_{RF} t) \quad (1)$$

where A is constant and represents the amplitude of the carrier, $f_{RF} = f_C - f_{LO}$ is the radio frequency. It can be shown that $y(t)$ is a minimum phase signal when $f_{RF} \geq B$ and $|A|$ is large enough compared to $|s(t)|$ [7].

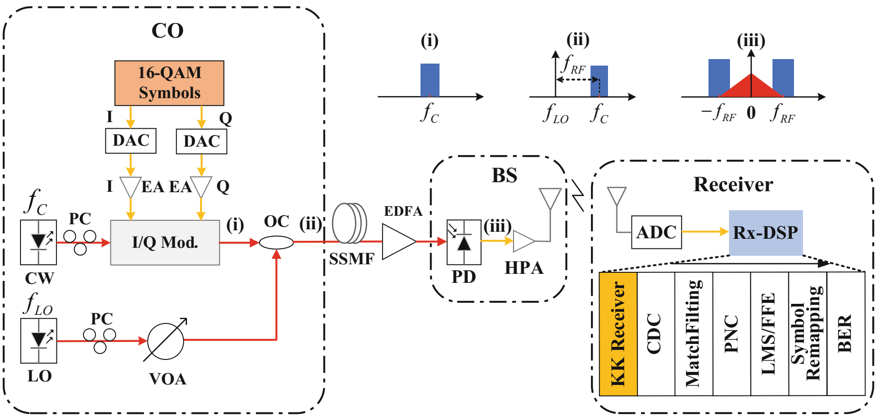

Fig. 1. Schematic of system setup. Insets: (i) modulated SC-DSB signal. (ii) OSSB minimum phase signal generated by coupling the SC-DSB signal with a carrier from the LO. (iii) photocurrent signal with DC and SSBI after square-law detection. PC: polarization controller. EA: electric amplifier. OC: optical coupler. EDFA: Erbium-doped optical fiber amplifier. HPA: high-power amplifier.

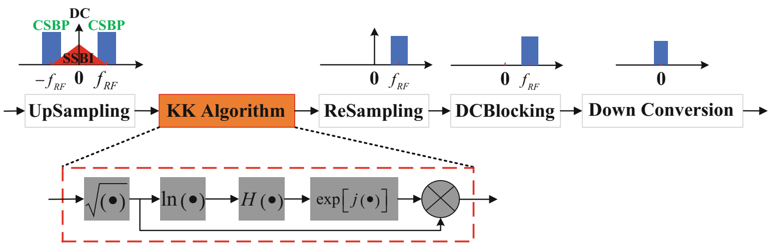

Fig. 2. DSP flow of KK reception scheme

After transmission and square-law detection, the photocurrent signal can be written as

$$I(t) = |A|^2 + 2\Re e[s(t)\exp(j2\pi f_{RF} t)] + |s(t)|^2 \tag{2}$$

where $\Re e[x]$ stands for the real part of x. In the Eq. (2), the first and second terms are the direct current (DC) and the desired carrier-signal beating products (CSBP), the third term is the SSBI.

The process of DSP of KK receiver is shown in Fig. 2. KK algorithm reconstructs the complex field signal from its detected amplitude

$$E_s(t) = \left\{\sqrt{I(t)}\exp[j\varphi(t)] - A\right\}\exp(-j2\pi f_{RF} t) \tag{3}$$

$$\varphi(t) = \frac{1}{2} p.v. \int_{-\infty}^{+\infty} \frac{\ln[I(t')]}{\pi(t - t')} dt' = H\left\{\ln\left[\sqrt{I(t)}\right]\right\} \tag{4}$$

where $\varphi(t)$ is the phase part of the minimum phase signal, $p.v.$ refers to the Cauchy's principal value of the integral [7, 9]. The term $H\{\bullet\}$ represents Hilbert transform operation.

Since KK scheme can directly reconstruct the complex waveform of the detected photocurrent signal, and hence avoids the SSBI introduced by square-law detection as mentioned above. Therefore, we can adopt a simple and cost-effective pure-digital receiver solution at the receiver in optical remote heterodyne RoF systems. On the other hand, if the traditional receiving scheme is used, it firstly requires a microwave LO and an electric mixer for down conversion. Secondly, the performance of the system is seriously degraded in the case of CSBP and SSBI overlapping. In summary, the KK reception scheme has a significant advantage from either the overall cost or system performance when compared to the conventional reception solution.

3 System Setup and Results

We have demonstrated the proposed remote heterodyne RoF link with KK receiver utilizing co-simulation through industry standard VPI-Transmission Maker and MATLAB. The system setup is shown in Fig. 1. It should be noted that in practical applications, the signal obtained from PD should be wireless transmitted via a pair of antennas. In our simulation experiment, however, we have omitted the antenna part for simplicity because this is not the focus of this article.

The CO transmitter consists of a CW laser at 1552.524 nm, a free-running LO at 1552.749 nm and an IQ modulator fed by two DACs for data generation and modulation. Both lasers have a linewidth of 1 MHz and 11 dBm output optical power, and their wavelength difference corresponds to 28-GHz in frequency, as shown in Fig. 1 inset (ii). The modulation format is 16-QAM at 4 samples-per-symbol. Root-raised cosine (RRC) filters with a roll-off factor of 0.1 are used for Nyquist pulse-shaping. The IQ modulator is biased at its transmission null point and generates an optical SC-DSB signal. Afterwards, we obtain the OSSB by coupling with the carrier generated by the LO. In order to prove the effectiveness of the KK receiver, we consider an 80 km link over standard single mode fiber (SSMF). The attenuation coefficient of the SSMF is set at 0.2 dB/km. Other parameters of SSMF include dispersion coefficient D of 16 ps/nm/km, and nonlinear index of $2.6 \times 10^{-20} \mathrm{m}^2/\mathrm{W}$.

At the BS, we use a single-ended PD which has a responsivity of 0.84 A/W and dark current of 0.43 nA to conduct heterodyne beating detection. A variable optical attenuator (VOA) is placed before the PD in order to adjust the received optical power (ROP). Then the obtained photocurrent is fed to the DSP for offline processing after ADC at the receiver. Firstly, a KK-based receiver reconstructs the complex field signal from the photocurrent amplitude directly, then chromatic dispersion compensation (CDC) is carried out by digital post-processing. It is necessary and indispensable for laser phase noise compensation (PNC) since both the CW laser and LO have a linewidth of 1 MHz. After matched filtering, channel equalization based on least-mean-square (LMS) with feed forward equalizer (FFE) are applied. Finally, the bit error rate (BER) is calculated following symbol decision and remapping.

In order to ensure good system performance, the CSPR is set to about 9 dBm. Figure 3a shows the BER curves of the 28-GHz 16-QAM SSB signal with 28 GBaud symbol rate for two cases in RoF optical remote heterodyne system. One is optical back-to-back (B2B) transmission and the other is 80 km SSMF transmission. It can be seen that the hardware-decision pre-forward error correction (HD-FEC) BER lower than 3.8×10^{-3} can be achieved at a ROP of –13.3 dBm for B2B case and –12.5 dBm for 80 km transmission case. Obviously, the power penalty caused by the 80 km SSMF is less than 1 dB.

Figure 3b compares the BER performance between the KK reception scheme and

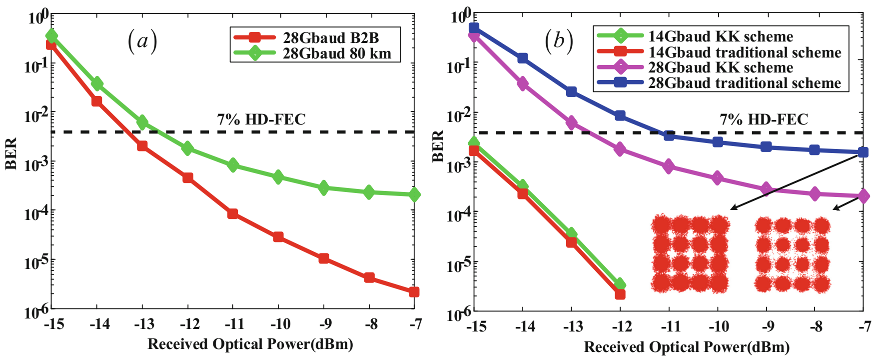

Fig. 3. The BER performance of 28-GHz 16-QAM RoF system. (a) 28 GBaud for B2B and 80 km SSMF. (b) 80 km SSMF transmission in contrast of KK receiver and traditional receiver for 14 GBaud and 28 GBaud 16-QAM signal.

the conventional reception scheme at different baud rates after 80 km SSMF transmission. In the case of 14 GBaud rate, the BER results of two receiving schemes are almost the same, because CSBP and SSBI have no overlap in this case. On the other hand, the KK scheme has about 2 dB advantage over the traditional scheme at 28 GBaud rate case, which exists a partial overlap between CSBP and SSBI. The insets in Fig. 3b are shown the constellation diagrams of two reception schemes at a ROP of —7 dBm, respectively. Qualitative comparison between these two figures shows that KK receiving solution brings significant improvement in the signal quality. Moreover, as the signal's baud rate increases, there exists more serious signal degradation caused by SSBI and the KK receiving scheme shows higher performance gain than that of the traditional receiving scheme.

4 Conclusions

In this paper, we propose and demonstrate a 28-GHz RoF link employing optical remote heterodyne techniques with KK Receiver. The simulation results reveal that the power penalty caused by the 80 km SSMF can be reduced to less than 1 dB with digital CDC post processing. Moreover, when compared with traditional receiver, the receiver sensitivity has improved about 2 dB at the 7% HD-FEC threshold for 28 GBaud 16-QAM signal transmission over 80 km SSMF by using KK receiver. In summary, the KK reception scheme has a significant advantage from either the overall cost or system performance compared to the conventional reception solution. It is thus a promising candidate for the future 5G millimeter wave radio access network applications.

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References

1. Insua, I.G., Plettemeier, D., Schäffer, C.G.: Simple remote heterodyne RoF system for Gbps wireless access. In: International Topical Meeting on Microwave Photonics, pp. 1–4. IEEE, Valencia, Spain (2009)
2. Latunde, A.T., Milosavljevic, M., Kourtessis, P., et al.: OQAM-OFDM RoF with IM-DD remote heterodyne 28 GHz upconversion for 5G millimeter RANs. In: International Conference on Transparent Optical Networks, pp. 1–4. IEEE, Trento, Italy (2016)
3. Omomukuyo, O., Thakur, M.P., Mitchell, J.E.: Simple 60-GHz MB-OFDM Ultrawideband RoF System Based on Remote Heterodyning. IEEE Photonics Technol. Lett. **25**(3), 268–271 (2013)
4. Lin, C.T., Chiang, S.C., Li, C.H., et al.: V-band gapless OFDM RoF system with power detector down-conversion and novel Volterra nonlinear filtering. Opt. Lett. **42**(2), 207–210 (2017)
5. Li, Z., Erkilinc, M.S., Galdino, L., et al.: Comparison of digital signal-signal beat interference compensation techniques in direct-detection subcarrier modulation systems. Opt. Express **24**(25), 29176–29189 (2017)
6. Chen, X., Antonelli, C., Chandrasekha, S., et al.: 218-Gb/s single-wavelength, single-polarization, single-photodiode transmission over 125-km of standard singlemode fiber using Kramers-Kronig detection. In: Optical Fiber Communications Conference and Exhibition, pp. 1–3. Optical Society of America, Los Angeles, USA (2017)
7. Mecozzi, A., Antonelli, C., Shtaif, M.: Kramers-Kronig Coherent Receiver. Opt. **3**(11), 1220 (2016)
8. Shu, L., Li, J., Wan, Z., et al.: Single-Lane 112-Gbit/s SSB-PAM4 Transmission With Dual-Drive MZM and Kramers-Kronig Detection Over 80-km SSMF. IEEE Photonics J. **9**(6), 1–9 (2017)
9. Fan, S.J., Zhuge, Q.B., et al.: Twin-SSB direct detection transmission over 80 km SSMF using Kramers-Kronig Receiver. In: European Conference on Optical Communication, pp. 1–3. IEEE, Gothenburg, Sweden (2017)
10. Li, Z., Erkilinc, M.S., Shi, K., et al.: SSBI Mitigation and the Kramers-Kronig Scheme in Single-Sideband Direct-Detection Transmission With Receiver-Based Electronic Dispersion Compensation. J. Lightwave Technol. **35**(10), 1887–1893 (2017)