Simplified Coherent Photonics-aided W-band Fiber-mmW Integrated System with Adaptive Kramers-Kronig Scheme

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Abstract *We demonstrate a simplified, coherent W-band fiber-mmW integrated system with an envelope-detector at user-end for complex-signal detection, enabled by the adaptive KK algorithm. Over 3.5-dB sensitivity improvement with 60-Gbps 16-QAM signal through 20-km SSMF and 1-m 94-GHz wireless is achieved at the 3.8E-3 BER threshold.*

Introduction

With the increasing demand for wireless communication in applications such as IoT and Smart Cities in the upcoming 6G network, the mmW frequency band has gained attention due to its greater available bandwidth (30~300 GHz). Photonics-aided mmW technology is widely studied due to its ability to integrate with existing networks and combine the benefits of optical fiber and mmW communication [1]. Compared with all-electronic mmW technology, photonics-aided mmW has the ability to be integrated with existing communication networks, and also combines the advantages of both optical fiber and mmW communication [1-5]. As illustrated in Fig. 1, in a radio access network (RAN), the optical signal generated by the central unit/distributed unit (CU/DU) is transmitted through the optical fiber, and coupled with another laser before delivering to the remote unit (RU) at the base station (BS). The mmW is then generated by photonics-aided method through a photodiode (PD) by heterodyne mixing, and transmitted to various user-end (UE) mobile terminals for signal reception and further processing.

Complex signals with quadrature amplitude modulation (QAM) formats are commonly used in optical fiber and wireless communication systems to increase capacity. However, detecting these signals requires coherent reception, typically based on optical or electrical mixers or hybrids, which can increase system complexity. In previous study, the Kramers–Kronig scheme has been proposed in optical communication systems to simplify the receiver based on a single PD [6-10]. In photonics-aided mmW systems, the IQ modulated optical signal is converted to an mmW signal directly after the fiber transmission. In [9], a tone is inserted at the transmitter, so the wireless UE-side receiver can use a simple envelope detector (ED), and down-

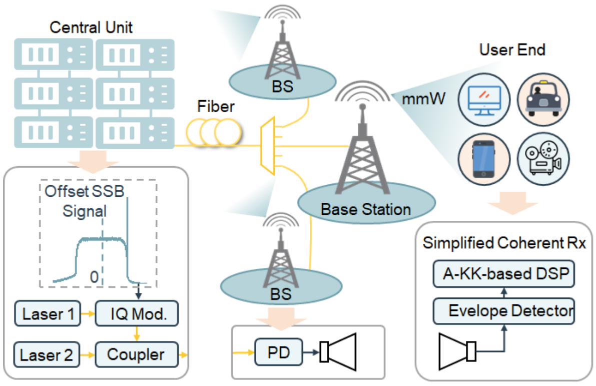

Fig. 1: Simplified coherent W-band fiber-mmW integrated communication system.

conversion to obtain baseband signals, enabling complex signal reception in UE-side mobile terminals with much lower cost. Generally, square-law detection inevitably results in signal-to-signal beat interference (SSBI). However, past KK scheme can introduce error when the system does not fully satisfy square-law detection, especially when there exists nonlinearity in the system [9].

In this paper, we demonstrate a simplified, coherent W-band fiber-mmW integrated system with an envelope-detector at UE-side for complex-signal detection. To facilitate signal recovery at the receiver, we apply digital signal processing (DSP) to add a pilot tone at the edge of the signal spectrum without using additional laser source, as illustrated in Fig. 1. An adaptive KK (A-KK) method is utilized to mitigate the impact of SSBI by considering the nonlinearity of the entire mmW system response, and then coherent DSP is utilized for complex signal recovery. Both QPSK and 16-QAM signals are studied in the system, and over 3.5-dB sensitivity improvement with 60-Gbps 16-QAM signal through 20-km SSMF and 1-m 94-GHz wireless is achieved at the 3.8E-3 BER threshold.

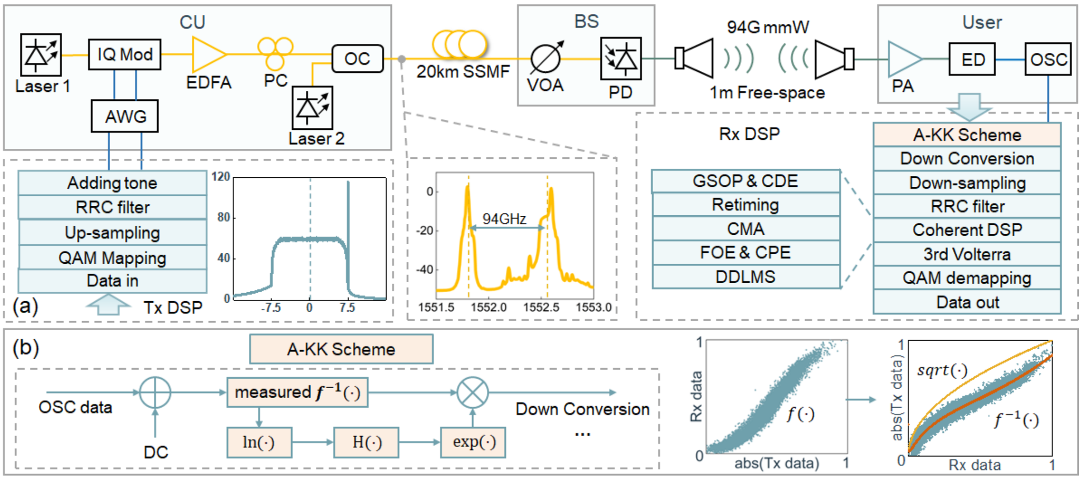

Fig. 2: (a) Experimental setup of simplified coherent photonics-aided fiber-mmW integrated system with (b) A-KK scheme.

Principle and Experimental Setup

Square-law detection is characterized by a photocurrent that is proportional to the input optical power, denoted as $i = RP_{in}$, where R represents the responsivity of PD. Assuming that optical field of the signal can be represented as $E = E_0 + s(t) \cdot e^{-j\pi ft}$, where E_0 corresponds to the tone and $s(t)$ is the signal, the resulting photocurrent after PD can be expressed as::

$$i(t) = R[E_0^2 + E_0 s(t)e^{-j\pi ft} + E_0 s^*(t)e^{j\pi ft} + |s(t)|^2] \quad (1)$$

Where the term $|s(t)|^2$ represents the SSBI, which is here eliminated by A-KK scheme.

In IQ modulation, the bias voltage of the modulator should be set in its linear operating region. Assuming the absence of nonlinearities during modulation, detection, and transmission, the detected photocurrent is proportional to the optical power, which is the square of the electric field amplitude. Therefore, in an ideal condition, we consider $i \propto |s_T(t)|^2$. Therefore, previous KK scheme uses the square root of the photocurrent to recover the amplitude information of the transmitted signal. However, in practice, due to modulator limitation, PD saturation and fiber nonlinearity, the proportionality between the photocurrent and the signal amplitude squared may not be strictly satisfied, and a nonlinear relationship $i = f(|s_T(t)|)$ may arise. Therefore, in our A-KK scheme, we use recover the signal amplitude by Eq. 2, and the phase of the signal can then be restored using the KK relationship shown in Eq. (3):

$$|s_T'(t)| = f^{-1}(i(t)) \quad (2)$$

$$\phi(t) = H(\ln(|s_T'(t)|)) \quad (3)$$

Where $H(\cdot)$ represents Hilbert transform. For the measurement of the nonlinear relationship f, we perform the amplitude-to-amplitude (AM-AM) measurement between the absolute value of transmitted signal and received signal, and then use the least squares (LS) algorithm for curve fitting, as shown in the inset of Fig. 2(b).

The setup of our simplified coherent fiber-mmW integrated system is depicted in Fig. 2. At the transmitter, the signal is mapped into QAM constellations and up-sampled, and passed through a root-raised cosine (RRC) filter before appended with a pilot located at the spectral edge. The signal, which is generated by an arbitrary waveform generator (AWG), is modulated onto a laser by an IQ modulator. After passing through an erbium-doped fiber amplifier (EDFA) and a polarization controller (PC), the modulated optical signal is coupled with another laser beam with a frequency difference of 94 GHz to generate the mmW signal. The output optical power is controlled by a variable optical attenuator (VOA) before the optical signal is detected by a PD to

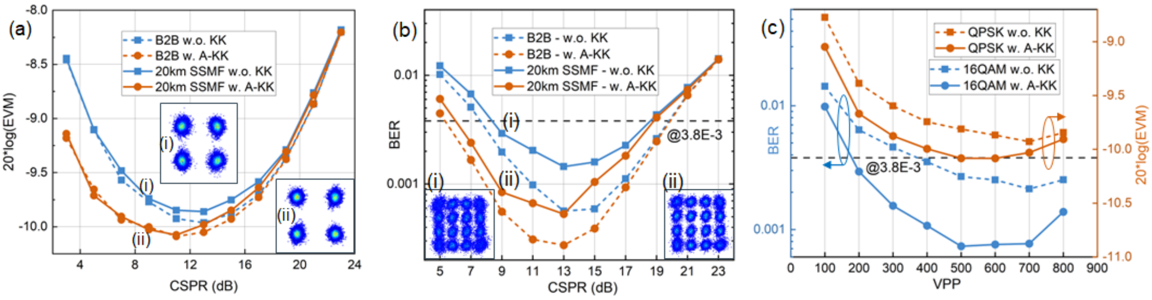

Fig. 3: Parameters affecting the performance of A-KK scheme: (a) EVM as a function of CSPR for 12.5-Gbaud QPSK signal, (b) BER as a function of CSPR for 12.5-Gbaud 16-QAM signal and (c) EVM/BER as a function of VPP.

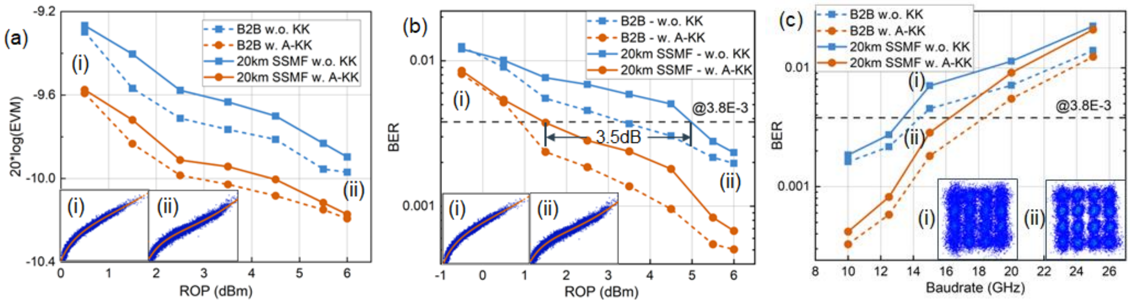

Fig. 4: Experimental results for B2B and 20-km SSMF transmission: (a) EVM as a function of ROP for 12.5-Gbaud QPSK signal, (b) BER as a function of ROP for 12.5-Gbaud 16-QAM signal and (c) BER as a function of baudrate for 16-QAM

generate the mmW signal, which is then transmitted and received through a pair of antennas. After propagating through free space for 1-m, the received mmW signal is amplified by a power amplifier (PA) and detected by an ED for offline signal recovery. The A-KK scheme is employed in the DSP to mitigate SSBI, and the signal is down-converted, down-sampled, and filtered by a matched RRC filter before state-of-the-art coherent DSP. The entire system achieves a simplified coherent fiber-mmW integrated communication, and the A-KK scheme is utilized for better signal recovery.

Experimental Results

The phase recovery method employing A-KK scheme relies heavily on the value of carrier-to-signal power ratio (CSPR). In this work, the influence of CSPR and peak-to-peak voltage (VPP) on the experimental system is examined and the power budget enhancement of the system utilizing the A-KK scheme is investigated.

Fig. 3(a) shows the relationship between error vector magnitude (EVM) and CSPR for 12.5-Gbaud QPSK signal. The dashed line represents back-to-back (B2B) transmission, while the solid line represents transmission over a 20-km standard single-mode fiber (SSMF). Although A-KK scheme can bring improvements, the EVM is generally larger when CSPR is low due to imperfect detection. When CSPR is high, the A-KK scheme cannot bring significant improvement. The same trend is seen in Fig. 3(b), which shows the BER performance of 12.5-Gbaud 16-QAM signal as a function of CSPR. Combining the results of Fig. 3(a) and 3(b), we can conclude that the overall system performance is optimal with a CSPR between 9 and 13 dB. In our system, carrier generation is performed in offline DSP, and the sum of the carrier and signal power is constant (provided by Laser 1), meaning that a high CSPR leads to a low signal power. Therefore, a CSPR of 9 dB is selected for subsequent analysis. Fig. 3(c) shows the impact of VPP on the system performance for QPSK and 16-QAM signals. Insufficient signal-to-noise ratio (SNR) or nonlinear effects cause the BER to increase when the VPP is too small or too large, respectively. By using the A-KK scheme, the BER performance is enhanced, and the VPP required to achieve the lowest BER is reduced from 700 to 500 mV, indicating the effectiveness of the proposed scheme in energy conservation.

The EVM and BER performance for 12.5-Gbaud QPSK and 16-QAM signals as a function of received optical power (ROP) is presented in Fig. 4(a) and (b), respectively. Our results demonstrate that the A-KK scheme significantly enhances the BER performance of the system. Even when ROP ≥ 5.5 dBm in the presence of severe nonlinear interference, the A-KK algorithm shows effective signal recovery performance for both B2B and 20-km SSMF transmission scenarios. As for 16-QAM signal, taking 3.8e-3 as the BER threshold, the A-KK scheme can improve the power budget by ~3.5 dB for 20-km SSMF transmission. Fig. 4(c) shows the relationship between BER and the symbol rate of the 16-QAM signal, with a CSPR of 9 dB and ROP of 5.5 dBm. The insets show the constellation points solved after A-KK-based DSP for small and large baud rates, respectively. In this case, more than 15-Gbaud of transmission over 20-km SSMF and 1-m wireless can be achieved.

Conclusions

A simplified, coherent W-band fiber-mmW integrated system with an envelope-detector at user-end for complex-signal detection is proposed, enabled by the adaptive KK algorithm. Over 3.5-dB sensitivity improvement with 60-Gbps 16-QAM signal through 20-km SSMF and 1-m 94-GHz wireless is achieved at the 3.8E-3 BER threshold.

Acknowledgements

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