Application of Kramers–Kronig receiver in SSB-OFDM-RoF link

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Received September 21, 2018; accepted November 23, 2018; posted online December 28, 2018

We propose and investigate the use of a Kramers–Kronig (KK) receiver in a single sideband orthogonal frequency division multiplexing radio over fiber (SSB-OFDM-RoF) link based on an optical remote heterodyne solution. This scheme is effective in eliminating the signal-to-signal beating interference introduced by square-law detection of a photo-detector in an SSB-OFDM-RoF link. We extensively study the influences of different carrier-to-signal power ratios (CSPRs), laser linewidths, and transmission distances on our proposed scheme. It is proved that the KK-based receiver can reduce optimal CSPR by more than 5 dB and provide about 1.1 dB gain over the conventional mixer-based receiver scheme with CSPR of 11 dB after 75 km fiber transmission.

OCIS codes: 060.5625, 060.2330, 060.2840.

doi: 10.3788/COL201917.010605.

Radio over fiber (RoF) technology has been extensively studied due to its numerous advantages, such as broad bandwidth, low attenuation, and flexibility for wireless links in recent years. RoF combined with optical remote heterodyne technology[1–3], where the modulated signal light is coupled with an optical carrier generated by a local oscillator (LO) at the central station (CS), and no LO is required at the base station (BS), further simplifies the BS and greatly reduces the overall cost of the system. Among different modulation schemes, orthogonal frequency division multiplexing (OFDM), especially the single sideband (SSB) OFDM, has attracted much attention in RoF systems because of its high spectral efficiency, good tolerance to dispersion effects and multipath fading[4,5].

In OFDM-RoF systems, as is well known, heterodyne detection has a simpler structure and lower cost than coherent detection based on a balanced photo-detector (PD) because it requires only one single-ended PD. However, the signal-to-signal beating interference (SSBI) will be introduced by square-law detection of the PD. Without SSBI cancellation processing, the SSBI may deteriorate the system performance considerably. Generally, there are two common methods to obtain intermediate frequency or baseband from the RF signal; one is using a power detector, such as a Schottky diode[6,7], and the other is employing an electric mixer[8]. For the mixer scheme, an extra high-power LO is necessary, which makes the receiver more complex and expensive. On the other hand, a power detector scheme does not need the LO, but an electric RF tone (usually produced at the transmitter) along with the information-bearing signal is needed for square-law detection, which increases the transmitter complexity and decreases the power efficiency. Furthermore, none of the two methods can remove the SSBI term if no additional measures are used. Solutions to SSBI elimination include a guard-band between the carrier and signal bands so that the SSBI term falls into a separate frequency range to the signal–carrier beat term[6], the iterative SSBI estimation and cancellation technique[9,10], Volterra nonlinear equalizer[11,12], and selective subcarrier encoding in OFDM systems[8,13]. For these approaches, either spectral efficiency is reduced or system complexity is increased. Instead of depending on extra techniques to eliminate SSBI, the recently proposed approach named the Kramers–Kronig (KK) algorithm can fully reconstruct the complex signal from the detected amplitude of the photocurrent and is able to alleviate the SSBI very well[14–17]. In the previous report, the KK-based receiver was mainly used for a data center interconnection system. We believe that it is also advantageous to use a KK receiver in the RoF link for wireless and optical access networks.

In this Letter, we propose and investigate the application of the KK receiver in an SSB-OFDM-RoF link based on optical remote heterodyne solution. This scheme can accurately reconstruct the complex baseband signal in the digital domain from the RF signal, while effectively removing the SSBI term. Since the perturbation to the signal introduced by the nonlinear SSBI term is eliminated by KK operation, further signal processing, like electrical chromatic dispersion compensation (ECDC), can be performed at the receiver. The key advantages of the proposed KK receiver-based SSB-OFDM-RoF scheme are listed in the following: (1) simplify the system structure and reduce the complexity of transceiver, since some hardware devices, such as power detector, electric mixer, and microwave LO, are avoided; (2) significantly improve the system performance and effectively eliminate the SSBI term introduced by square-law detection of the PD.

The schematic of the proposed optical remote heterodyne SSB-OFDM-RoF link based on the KK receiver is shown in Fig. 1. At the CS, the information-bearing OFDM signal is modulated onto a continuous wave (CW) laser by using optical carrier suppression (OCS) modulation. Then, the signal light is coupled with an optical carrier from the LO to obtain the optical SSB-OFDM signal. Note that the central frequencies of the CW and LO are f_C and f_{LO}, respectively. The minimum phase signal, which is the necessary and sufficient condition for the KK algorithm[14], can be fulfilled by controlling the frequency difference of the two lasers, the signal bandwidth, and the carrier-to-signal power ratio (CSPR). At each BS, an RF signal with a central frequency located at $f_{\mathrm{RF}} = f_C - f_{\mathrm{LO}}$ can be obtained with a single-ended PD through heterodyne beating detection. It is worth mentioning that we can extract the optical carrier for uplink photoelectric modulation, which avoids using additional lasers at each BS, but this is not the focus of this Letter, so it is not given in Fig. 1. Finally, after wireless transmission by a pair of antennas, the complex OFDM baseband signal is reconstructed with SSBI cancellation utilizing the KK-based approach at the receiver side.

In order to reach the minimum phase condition for the OFDM signal, the CSPR should be larger than the peak-to-average power ratio (PAPR) of the information-bearing signal[18]. Since the OFDM signal has a high PAPR in general, which not only reduces the efficiency of linear power amplifiers, but also degrades the performance of the OFDM-RoF transmission link, it is therefore necessary to adopt the PAPR reduction method. In this Letter, the crest factor reduction (CFR) method is used for PAPR reduction[19]. Suppose that the complex signal $s(t)$ is a conventional bandwidth-limited OFDM signal with a bandwidth of B, then the baseband signal after clipping can be expressed as

$$c_i(t) = \begin{cases} s_i(t) & (|s_i(t)|^2 \le T), \\ \sqrt{\frac{T}{|s_i(t)|^2}} \cdot s_i(t) & (|s_i(t)|^2 > T), \end{cases} \tag{1}$$

where $T = R_C \cdot P_m$ is the threshold of peak power, P_m is the average power of the unclipped OFDM signal, and R_C is the ratio of the clipping level to the average power.

After OCS modulation and coupling with an optical carrier, the output optical SSB-OFDM signal is given by

$$\begin{aligned} E_{\mathrm{out}} &= E_{\mathrm{LO}} + E_s(t) \\ &= [A + c(t)\exp(j2\pi f_{\mathrm{RF}} t)] \cdot \exp(j2\pi f_{\mathrm{LO}} t), \end{aligned} \tag{2}$$

where A is a constant and represents the amplitude of the optical carrier generated by the LO. It can be shown that $y(t) = A + c(t)\exp(j2\pi f_{\mathrm{RF}} t)$ is a minimum phase signal when $f_{\mathrm{RF}} \ge B$ and $|A|$ is large enough compared to the peak of $|c(t)|$[14].

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

$$i(t) = \eta\{|A|^2 + 2\Re e[A \cdot c(t)\exp(j2\pi f_{\mathrm{RF}} t)] + |c(t)|^2\}, \tag{3}$$

where η denotes the responsivity of the PD, $\Re e[x]$ stands for the real part of x. In Eq. (3), the first and second terms are the direct current (DC) and the desired carrier–signal beating product (CSBP). The third term is the undesired SSBI term (schematically depicted in red in Fig. 1(e) with the CSBP indicated in green).

Afterwards, the photocurrent signal is amplified and fed to a pair of antennas. This process can be modeled as

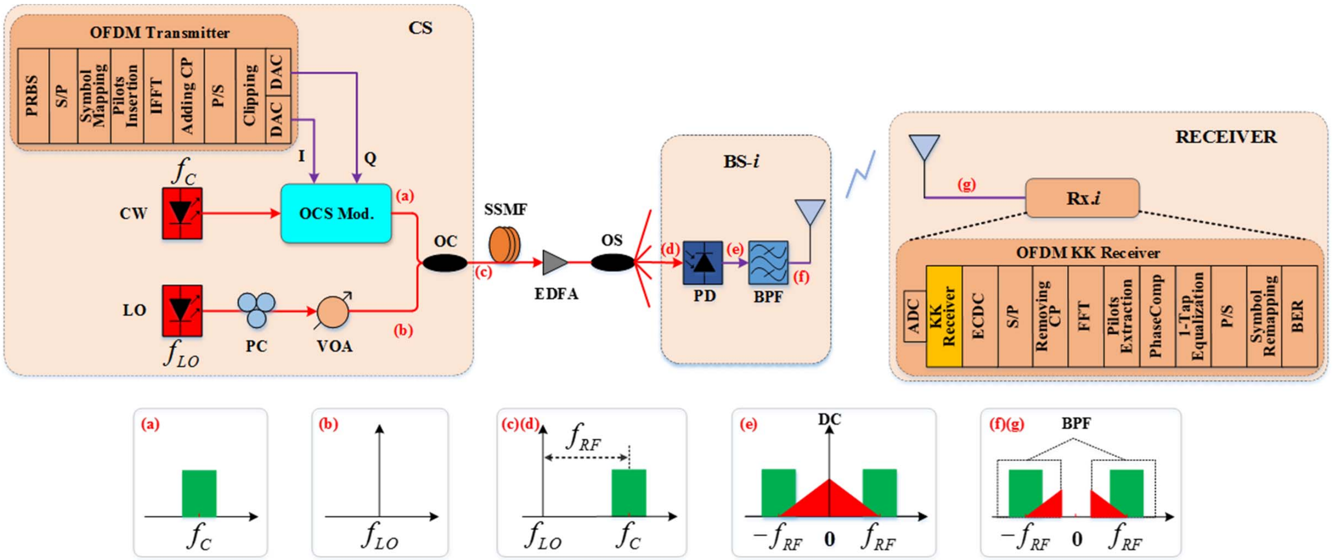

Fig. 1. Schematic of the proposed optical remote heterodyne SSB-OFDM-RoF link based on the KK receiver. S/P, serial-to-parallel; P/S, parallel-to-serial; DAC, digital-to-analog converter; PC, polarization controller; OC, optical coupler; OS, optical splitter; EDFA, erbium-doped optical fiber amplifier; ADC, analog-to-digital converter.

band-pass filtering (BPF), where the DC and part of the SSBI outside the operating band of antennas are removed [as depicted in Fig. 1(f)]. That is, the RF signal can be described as

$$i_{\mathrm{RF}}(t) = i(t) * h(t), \tag{4}$$

where $h(t)$ represents the transfer function of the BPF, and $*$ denotes the convolution operation.

Figure 2 shows the signal processing flow of the KK receiver. The KK receiver reconstructs the original baseband signal from the RF signal by

$$\varphi(t) = \frac{1}{2}p.v.\int_{-\infty}^{+\infty}\frac{\ln[I_{\mathrm{RF}}(t')]}{\pi(t-t')}\mathrm{d}t' = H\left\{\ln\left[\sqrt{I_{\mathrm{RF}}(t)}\right]\right\},$$

$$s'(t) = \left\{\sqrt{I_{\mathrm{RF}}(t)}\exp[j\varphi(t)] - M\right\}\exp(-j2\pi f_{\mathrm{RF}}t), \tag{5}$$

where $I_{\mathrm{RF}}(t)$ is equal to $i_{\mathrm{RF}}(t)$ plus an appropriate virtual carrier [as shown in Fig. 2(b)], $\varphi(t)$ and M are the phase and mean of the minimum phase signal restored by the KK algorithm, respectively, and $p.v.$ refers to Cauchy's principal value of the integral. The term $H\{\cdot\}$ represents the Hilbert transform operation.

In theory, the KK receiver can accurately recover the baseband signal from the RF signal, and the SSBI introduced by the PD's square-law detection, as mentioned above, can be effectively alleviated.

In the following, we evaluate the performance of the proposed optical remote heterodyne SSB-OFDM-RoF link base on the KK receiver, utilizing co-simulation through industry standard VPI Transmission Maker (VPI TM 9.1) and MATLAB. The simulation setup is the same as Fig. 1 except for the antennas. The wavelengths of the CW laser and LO are set to 1552.524 and 1552.749 nm, respectively, where a 28 GHz RF signal can be obtained by heterodyne beating detection. A pseudo-random bit sequence (PRBS) with the length of 2^{20} is mapped into 16 quadrature amplitude modulation (QAM) and the symbol rate is 28 GBaud. The fast Fourier transform (FFT) size of the OFDM signal is 512, 480 subcarriers are used for signal transmission, and the rest are filled with zero. In addition, one pilot subcarrier is inserted between every 10 data subcarriers for equalization purposes, and a cyclic prefix (CP) ratio of 1/64 is adopted. The net bit rate of the 16-QAM OFDM signal is about 94 Gb/s. The CFR method is used to reduce the PAPR of the OFDM signal. We consider a 75 km standard single mode fiber (SSMF) link to demonstrate the effectiveness of the KK receiver. The attenuation coefficient of the SSMF is set at 0.2 dB/km. Other parameters of the SSMF include a dispersion coefficient of 16 ps/(nm · km), dispersion slope of 0.08 $\mathrm{ps/(nm^2 \cdot km)}$, and nonlinear index of 2.6×10^{-20} $\mathrm{m^2/W}$. At the BS, heterodyne beating detection is achieved by a single-ended PD, which has a responsivity of 0.84 A/W and a dark current of 0.43 nA. After BPF, the RF OFDM signal contaminated by SSBI is received and sampled at the receiver side. Then, the KK-based receiver reconstructs the complex baseband signal from the RF OFDM amplitude, as depicted in Fig. 2. ECDC, CP removal, FFT, pilot extraction, phase compensation, and equalization are carried out in turn for OFDM signal recovery and performance evaluation.

By setting the peak threshold to be six times that of the average power of an unclipped OFDM signal, the PAPR reduces from the original 11.2 dB to 7.8 dB after CFR clipping. With an optimized optical modulation index of 0.11 and launch power of 0 dBm, the signal-to-noise ratio (SNR) versus different CSPRs is evaluated for back-to-back (B2B) transmission, as shown in Fig. 3. There is a trade-off between the SSBI and the additive white Gaussian noise (AWGN). A larger CSPR means a smaller signal power when the total power (signal power plus optical carrier power) is fixed. For the conventional mixer-based scheme, the SSBI term dominates system performance before reaching the optimal CSPR, so the SNR performance increases as CSPR increases because the SSBI decreases with the increase of CSPR. In contrast, the KK receiver scheme can distinctly reduce the optimal CSPR because it can effectively eliminate the SSBI. It is found that the optimal CSPR is 15 dB for the KK scheme and 20 dB for the mixer scheme, respectively. Obviously, the optimal CSPR is reduced by 5 dB through the use of the KK receiver, and there is a 1.4 dB SNR improvement with an optimized CSPR compared to the conventional mixer scheme.

We further investigate the effect of laser linewidths on the bit error rate (BER) versus received optical power (ROP) for 16-QAM and 64-QAM signals after 75 km SSMF transmission using the optimized CSPR. As shown in Fig. 4, it is found that our system has the ability to support high-order modulation formats, and narrow linewidth (less than or equal to 0.1 MHz) lasers are required to obtain a good performance for both 16-QAM and 64-QAM signals while keeping the same linewidth of the LO and

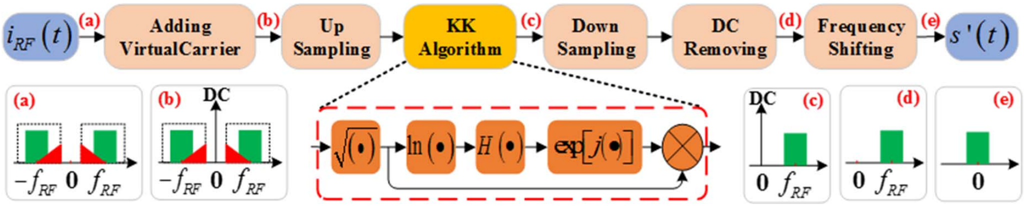

Fig. 2. Signal processing flow of the KK receiver. The baseband signal can be extracted from the RF signal by the KK receiver; meanwhile, the SSBI is effectively eliminated.

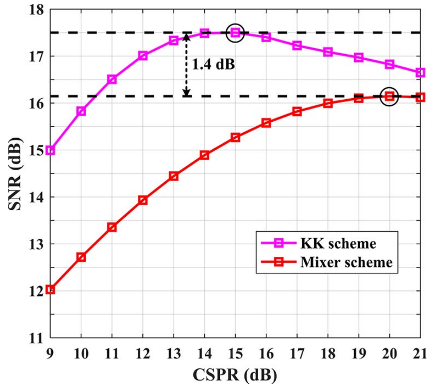

Fig. 3. SNR versus the CSPR, where the launch power remains constant and the ROP is fixed at 0 dBm for B2B transmission.

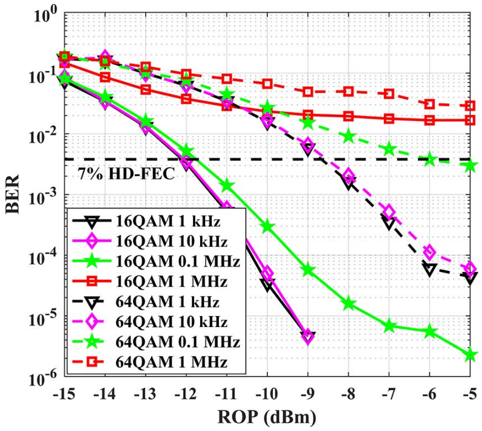

Fig. 4. BER versus ROP with different laser linewidths for 16-QAM and 64-QAM signals after 75 km SSMF transmission.

CW lasers. Obviously, the laser linewidths have a remarkable influence on the performance of the system. This is mainly because the OFDM signal is sensitive to the frequency offset and phase noise for heterodyne beating detection. Therefore, we set the linewidths of two lasers to 100 kHz for the following research.

Figure 5 shows the BER performance versus ROP over different SSMF lengths without CDC and with receiver-side DSP-based CDC. It is observed that without CDC, the maximum SSMF transmission length is 50 km for the BER to stay below the 7% hard-decision forward error correction (HD-FEC) threshold (3.8×10^{-3}). Instead, after CDC operation, the BER results for different transmission distances (even for 100 km) are significantly improved and are basically consistent with the B2B scenario. Obviously, there is no power penalty caused by less than 100 km SSMF transmission in our SSB-OFDM-RoF system while utilizing the post-CDC technique, which does not require prior knowledge of the link dispersion at the CS transmitter compared to pre-CDC method.

Lastly, we compare the BER performance of a 94 Gb/s SSB-OFDM signal between the KK scheme and the conventional mixer-based receiver scheme for different

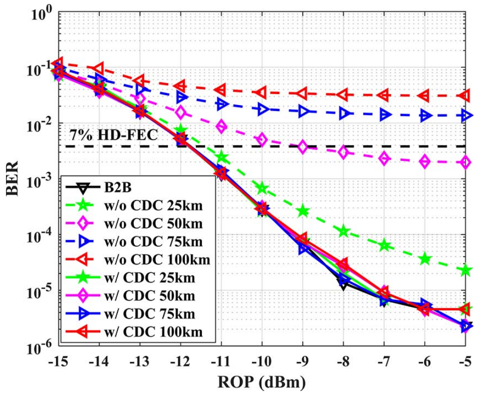

Fig. 5. BER versus ROP curves with different SSMF lengths with and without CDC for 16-QAM signal.

CSPRs after 75 km SSMF transmission. Since the 16-QAM OFDM subcarriers closer to the optical carrier are deteriorated by the SSBI, the benefit of the KK receiver scheme is notably superior than that of the mixer-based scheme, as depicted in Fig. 6. It can be observed that the KK scheme can provide about 0.4 and 1.1 dB gain over the mixer-based scheme at the 7%

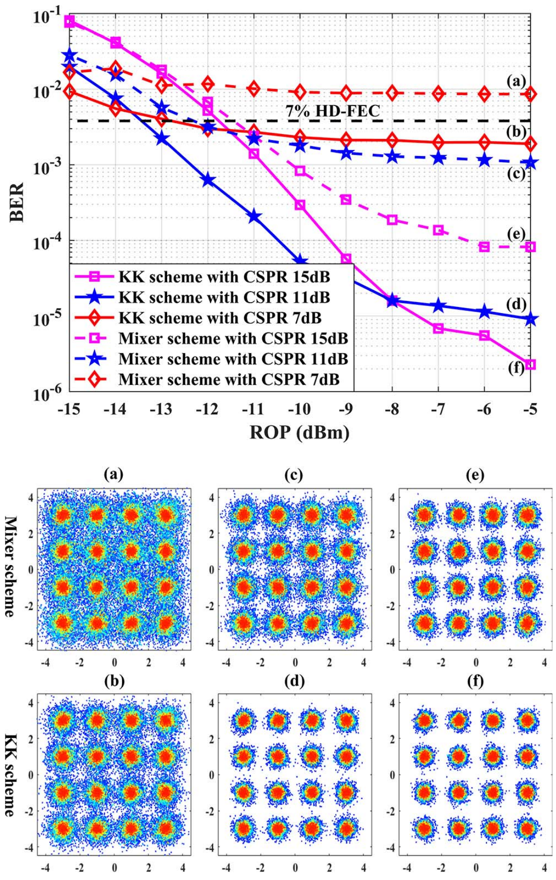

Fig. 6. BER performance comparison of the KK scheme and mixer-based scheme with 94 Gb/s 16-QAM SSB-OFDM signal. Constellation diagrams for the mixer-based scheme with CSPR of (a) 7 dB, (c) 11 dB, (e) 15 dB, and KK scheme with CSPR of (b) 7 dB, (d) 11 dB, (f) 15 dB at ROP of −5 dBm.

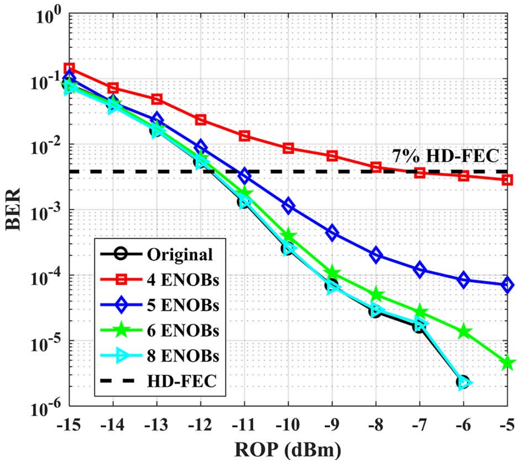

Fig. 7. BER versus ROP with different ENOBs of DAC and ADC.

HD-FEC threshold with the CSPR of 15 and 11 dB, respectively. A higher gain can be obtained when CSPR is further reduced, attributing to the effective elimination of SSBI by the KK receiver. Moreover, when the CSPR is set to 7 dB (smaller than the PAPR of 7.8 dB), the KK scheme can also reduce the BER from about 3×10^{-2} to below the 7% HD-FEC threshold, though the minimum phase condition is not rigorously fulfilled in this case. On the other hand, the system performance is dominated by the noise at low ROP, so the BER performance decreases as CSPR increases. However, for increased ROP, where the SSBI dominates over the noise, the BER performance increases with increased CSPR for the conventional mixer-based scheme. For the KK scheme, the minimum phase condition is better satisfied with increased CSPR, resulting in the BER performance also being improved. Finally, it should be emphasized that the SSBI and CSBP only partially overlap, and the signal degradation is not serious in our system. The KK receiver can provide more remarkable and superior performance improvement than the mixer-based receiver when further increasing the baud rate, where the signal degradation caused by SSBI is significantly aggravated.

The effective number of bit (ENOB) of the digital-to-analog converter (DAC) and analog-to-digital converter (ADC) is an important parameter to consider in practice. Moreover, the performance of the KK scheme is sensitive to the ENOBs, so we further study the impact of the ENOBs of the DAC and ADC with the results given in Fig. 7. For simplicity, we take the same bit resolution for both the DAC and ADC. It can be seen that eight or more ENOBs can achieve the same performance as the original signal, whilst six ENOBs introduce little performance degradation. In addition, the logarithm appearing in Eq. (5) introduces spectral broadening, which necessitates digital upsampling of the received signal. The effect of the resampling rate on the performance of the KK receiver can refer to Ref. [16].

We have investigated and demonstrated an SSB-OFDM-RoF link employing the optical remote heterodyne technique with a KK receiver. The obtained results show that the CSPR, laser linewidths, ENOBs of the ADC and DAC, and resampling rate before the KK algorithm play important roles on the signal's transmission performance. With the help of post-CDC after the KK algorithm, no power penalty is observed after even 100 km SSMF transmission in our proposed SSB-OFDM-RoF scheme. In addition, the benefit of the KK receiver scheme is notably superior than that of the conventional mixer-based scheme, attributing to the effective elimination of SSBI by the KK algorithm.

This work was supported by the National Natural Science Foundation of China (Nos. 61420106011 and 61471088) and the Fundamental Research Funds for the Central Universities (No. ZYGX2016J014).

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