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LETTER

Study of signal separation and demodulation techniques considering IQ imbalance by stored data batch signal processing

Yudai Mita, Yuta Hiraoka, Tomofumi Hikasa, Shigeru Tomisato, Satoshi Denno, and Kazuhiro Uehara

Abstract With the arrival of the IoT era, the problem of interference has become even more serious, and the challenge is to establish techniques for separating and demodulating collide signals. To achieve this, we are conducting research on stored data batch signal processing technology using short-time Fourier transform (STFT). In this paper, we used a feature quantity demodulation method proposed as a method for stored data batch signal processing to evaluate the effect of IQ imbalance, which is a factor in signal degradation in the transmitter, on signal separation and demodulation performance. Furthermore, we proposed a receiver configuration that estimates the amount of degradation due to IQ imbalance from the extracted feature quantities and compensates for the signal degradation. Computer simulation results confirmed that the proposed compensation method can improve signal separation and demodulation performance when degraded by IQ imbalance.

Keywords: stored data batch signal processing, short-time Fourier transform, IQ imbalance, IQ Imbalance compensation

Classification: Wireless Communication Technologies

1. Introduction

With the advent of the IoT era, the problem of interference has become even more serious, and separation and demodulation of collide signals has become a challenge. However, conventional channel separation methods using a band-pass filter cannot separate and demodulate collide signals. To solve this problem, we are studying signal separation and demodulation technologies using stored data batch signal processing [1]. Through this, we aim to separate and demodulate IoT/M2M terminal signals that have collided or interfered. In stored data batch signal processing, the power and phase components on the center frequency of the desired signal are extracted as features using the short-time fourier transform (STFT). STFT can generally obtain time resolution without loss of symbol information by making the window width sufficiently short compared to the symbol length. STFT can then be used for signal analysis. The center frequency of the desired signal is then detected from the spectrum obtained by signal analysis using STFT, and the complex spectrum showing the power and phase components on the center frequency is extracted. The extracted components are considered to be the controlled power and phase components on the center frequency of the reference signal obtained by STFT of the unmodulated signal, and these are extracted as feature values. The equation used for feature extraction is shown in Eq. (1), (2) and (3).

$$Y(\omega,\tau)=\int_{-\infty}^{\infty} w(t-\tau)\,y(t)\,e^{-j\omega t}dt+\int_{-\infty}^{\infty} w(t-\tau)\,n(t)\,e^{-j\omega t}dt\,, \quad (1)$$

$$G_c(\omega,\tau)=\int_{-\infty}^{\infty} w(t-\tau)\,e^{-j(\omega-\omega_c)t}dt\,, \quad (2)$$

$$\sqrt{pe^{j\varphi}}=\frac{Y(\omega_c,\tau)}{G_c(\omega,\tau)}\,, \quad (3)$$

where $y(t)$ is the received signal, $n(t)$ is the noise, $p(t)$ is received power, $\varphi(t)$ is the phase, f_c is the center frequency, and ω_c is the angular velocity on the center frequency. By performing STFT with the window function $w(t)$, the complex spectrum $Y(\omega,\tau)$ of the received signal at time τ in Eq. (1) can be obtained. Note that $\omega_c=2\pi f_c$. where $g_c(t)$ is a reference signal generated based on the center frequency of the desired signal and $G_c(\omega,\tau)$ is the complex spectrum on the center frequency f_c of the unmodulated signal obtained by STFT of the reference signal. From the ratio of the components $Y(\omega_c,\tau)$ and $G_c(\omega,\tau)$ on the center frequency f_c of the spectrum obtained by Eq. (1), (2) a spectrum $\sqrt{p(t)}$ representing the power of the feature and a spectrum $e^{j\varphi}$ representing the phase are obtained. We have proposed a feature demodulation method that uses the extracted feature quantities as they are to perform demodulation, which can reduce the amount of calculations compared to conventional demodulation methods using synchronous detection, etc., and evaluated the performance of various modulation methods [2, 3].

On the other hand, previous studies on signal separation and demodulation have not considered signal degradation factors caused by the characteristics of the transceiver. In actual wireless communication systems, the characteristics of transmitters and receivers are not ideal, and imperfections and variations cause amplitude and phase errors, which degrade signals and affect signal separation and demodulation. In this paper, we consider IQ imbalance, which is a signal degradation factor that occurs in quadrature modulators, and evaluate its influence on signal separation and demodulation performance when using the feature quantity demodulation method. Furthermore, we estimate the amount of degradation due to IQ imbalance from the extracted feature quantities, propose a receiver configuration that compensates for the deterioration, and verify its

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[1] Graduate School of Natural Science and Technology,
Okayama University,
Okayama-shi, Okayama, 700-8530 Japan

[a] mitayudai@s.okayama-u.ac.jp

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effectiveness.

2. IQ imbalance

IQ imbalance is a signal degradation factor that occurs in quadrature modulators. In this study, we evaluated the signal separation and demodulation performance of the proposed method by considering IQ imbalance in the desired signal using Eq. (4).

$$s_{iq}(t)=\mathrm{Re}\left(s(t)\right)\cdot 10^{\frac{I_a}{40}}\cdot e^{-jI_p\left(\frac{\pi}{360}\right)}+j\,\mathrm{Im}\left(s(t)\right)\cdot 10^{-\frac{I_a}{40}}\cdot e^{jI_p\left(\frac{\pi}{360}\right)},\quad (4)$$

where *s(t)* is the modulated signal, $s_{iq}(t)$ is the modulated signal considering IQ imbalance, I_a is the amplitude imbalance, I_p is the phase imbalance, Re() is the I component of the term in brackets, and Im() is the Q component of the term in brackets [4].

In this study, we proposed a receiver configuration that estimates the degradation due to IQ imbalance at the receiver using the extracted feature quantities and compensates for the signal degradation. To perform the estimation, a pilot signal, which is a known signal between the transmitter and receiver, was inserted into the transmitted data. From the pilot signal and the feature quantity extracted, the estimated amplitude imbalance $\hat{I}_a$ and phase imbalance $\hat{I}_p$ were obtained using the following equations.

$$\hat{I}_p=\frac{-2\left(\sqrt{p}e^{j\varphi}\right)^2+\sqrt{\left(\sqrt{p}e^{j\varphi}\right)^2-4\,\mathrm{Re}\left(s(t)\right)\mathrm{Im}\left(s(t)\right)\left(\mathrm{Re}\left(\sqrt{p}e^{j\varphi}\right)\mathrm{Im}\left(\sqrt{p}e^{j\varphi}\right)-\mathrm{Re}\left(s(t)\right)\mathrm{Im}\left(s(t)\right)\right)}}{2\,\mathrm{Re}\left(s(t)\right)\mathrm{Im}\left(s(t)\right)},\quad (5)$$

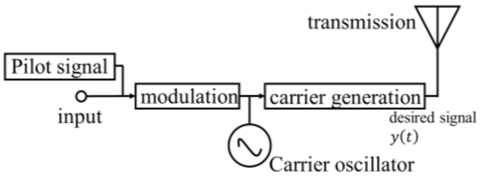
$$\hat{I}_a=\left|40\log 10\left(\frac{\mathrm{Re}\left(\sqrt{p}e^{j\varphi}\right)\mathrm{Im}\left(s(t)\right)+\mathrm{Im}\left(\sqrt{p}e^{j\varphi}\right)\mathrm{Im}\left(s(t)\right)\tan\left(\frac{\hat{I}_p\pi}{360}\right)}{\mathrm{Im}\left(\sqrt{p}e^{j\varphi}\right)\mathrm{Re}\left(s(t)\right)+\mathrm{Re}\left(\sqrt{p}e^{j\varphi}\right)\mathrm{Re}\left(s(t)\right)\tan\left(\frac{\hat{I}_p\pi}{360}\right)}\right)\right|,\quad (6)$$

where *s(t)* is the modulated signal and $\sqrt{p}e^{j\varphi}$ is the extracted feature quantity. Using the estimated value of amplitude imbalance and phase imbalance obtained in Eqs. (5) and (6), after demodulating the signal, the received signal is compensated using the following equation.

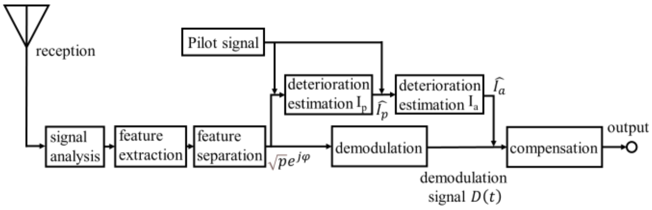
$$D_c(t)=\left(\frac{\mathrm{Re}\left(C_t\right)}{10^{\frac{\hat{I}_a}{40}}\cos\left(\frac{\hat{I}_p\pi}{360}\right)}+j\frac{\mathrm{Im}\left(C_t\right)}{10^{-\frac{\hat{I}_a}{40}}\cos\left(\frac{\hat{I}_p\pi}{360}\right)}\right),\quad (7)$$

$$C_t=\mathrm{Re}\left(D(t)\right)e^{j\left(\frac{\hat{I}_p\pi}{360}\right)}+j\,\mathrm{Im}\left(D(t)\right)e^{-j\left(\frac{\hat{I}_p\pi}{360}\right)}$$

where *D(t)* is the demodulated signal and $D_c(t)$ is the compensated signal. A block diagram of the proposed IQ imbalance compensation system is shown in Fig. 1.



(a) Transmitter



(b) Receiver

Fig. 1 Block diagram of IQ imbalance compensation system

3. Evaluation index

In this paper, we used overlapped bandwidth ratio (OBR) as an evaluation index for signal separation and demodulation performance. OBR is defined as the ratio of the overlapping portion of the desired signal and the occupied bandwidth of the interference signal to the occupied bandwidth of the desired signal. Note that the occupied bandwidth is the frequency width that includes 99% of the power. In computer simulation, the bit error rate (BER) characteristics were evaluated when varying the OBR. The larger the OBR that can separate and demodulate, the higher the signal separation and demodulation performance, because the desired signal can be separated and demodulated even if the superimposition of interfering signals is large. The OBR value for which BER is 10^{-3} or less, which can achieve almost error-free performance by applying error control technology, was used as the reference value to enable signal separation and demodulation.

We also evaluated the degree of deviation of signal points during modulation between a signal without degradation and a signal with IQ imbalance considered using error vector magnitude (EVM) [%].

4. Simulation results

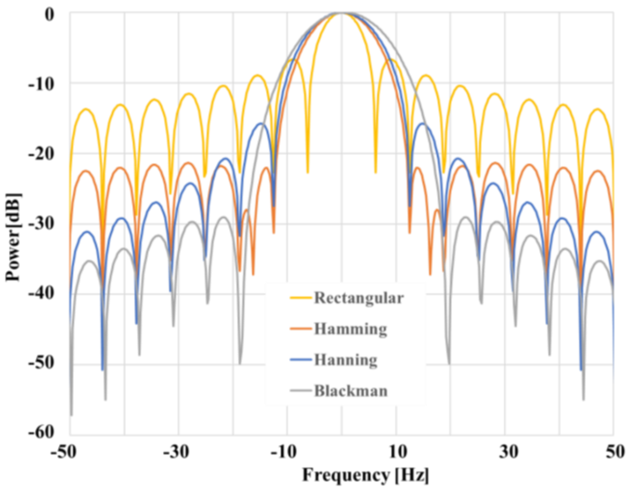
We evaluated the signal separation and demodulation performance using the feature quantity demodulation method when compensating for signal degradation due to IQ imbalance. Simulation conditions are shown in Table I. IQ imbalance compensation was performed in two patterns, one in which 2 symbols/s out of a symbol rate of 64 symbols/s was used as a pilot signal, and the other in which 4 symbols/s was used as a pilot signal, and the signal separation and demodulation performance was evaluated. Figure 2 (a) shows the spectra of various window functions when performing STFT. It is necessary to select an optimal window to perform signal separation and demodulation based on the trade-off between main lobe width and side lobe level. When affected by IQ imbalance, high signal separation and demodulation performance can be obtained by using a rectangular window when performing STFT when the signal degradation is small, and a Hamming window when the signal degradation is large. This has been confirmed in previous research [5].

Figure 2 (b) shows the signal separation and demodulation performance of the feature quantity demodulation method when considering an amplitude imbalance of 3 dB and a phase imbalance of 20° (EVM, 24.8%), and Fig. 2 (c) shows the performance when considering an amplitude imbalance of 7 dB and a phase imbalance of 45° (EVM, 58.6%). In Fig. 2 (b), the best signal separation and demodulation performance was obtained with the rectangular window without compensation, and separation and demodulation were possible with an OBR of 85.4%. When the pilot signal was 2 symbol/s, the OBR for signal separation and demodulation was 85.8%, which was almost the same as the signal separation and demodulation performance without compensation, but when the pilot signal was 4 symbol/s, the OBR for signal separation and demodulation became possible at 87.0%, and OBR improved by approximately 1.6% compared to the case without compensation. In Fig. 2 (c), signal separation and demodulation were impossible without compensation, but signal separation and demodulation became possible with compensation, and the highest performance was obtained using the Hamming window. In this case, signal separation and demodulation became possible with an OBR of 69.1% when the pilot signal was 2 symbols/s, and an OBR of 69.8% when the pilot signal was 4 symbols/s. Simulation results show that the more pilot signals were used, the better the OBR was able to separate and demodulate signals.

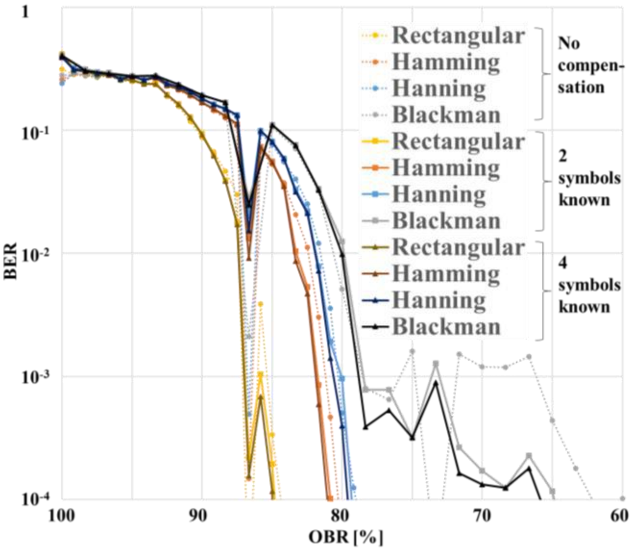
Figure 2 (d) summarizes the OBR values that can be separated and demodulated under various signal degradation conditions. In addition to Figs. 2(c) and (d), the cases with EVM of 14.5% (amplitude imbalance, 2 dB; phase imbalance, 10°) and EVM of 43.2% (amplitude imbalance, 7 dB; phase imbalance, 45°) are considered. The horizontal axis is the EVM when signal degradation by IQ imbalance is considered, and the vertical axis is the OBR. Signal separation and demodulation performance is improved by applying the proposed compensation technique, and when the pilot signal is 2 symbols/s, signal separation and demodulation is possible with compensation using a rectangular window compared to without compensation when considering an amplitude imbalance of 5 dB and phase imbalance of 35° (EVM, 43.2%) OBR improved up to 64.5%.In the case of 4 symbols/s, the OBR that enables signal separation and demodulation improved up to 65.2% when compensation was performed using a rectangular window compared to when no compensation was performed when considering an amplitude imbalance of 5 dB and a phase imbalance of 35°.

Table I Simulation conditions

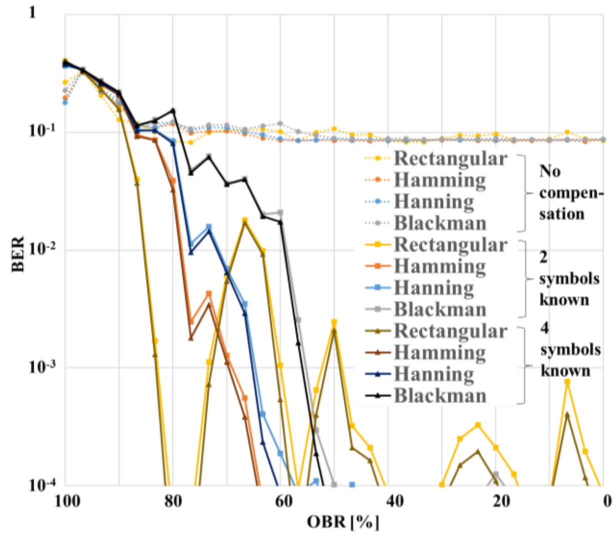
Modulation system	QPSK
Center frequency of the desired signal	1000 Hz
Occupied bandwidth	1200 Hz
Symbol rate	64 symbol/s
FFT size	8192 points
Window function	Rectangle, Hamming, Hanning, Blackman
Window width	32 sample lengths
Window shift width	16 sample lengths
Sampling rate	8192 Hz
Propagation environment	AWGN
E_b/N_0	7 dB
D/U	0 dB



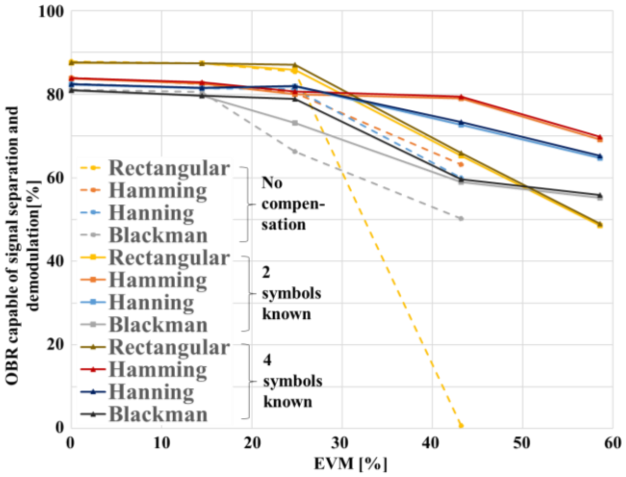
(a) Spectrum of window function when performing STFT



(b) Signal separation and demodulation performance when considering 3dB amplitude imbalance and 20° phase imbalance (EVM, 24.8%)



(c) Signal separation and demodulation performance when considering 7 dB amplitude imbalance and 45° phase imbalance (EVM, 58.6%)



(d) OBR values that can be separated and demodulated under various signal degradation conditions

Fig. 2 Signal separation and demodulation performance

5. Conclusion

In examining a technique for separating and demodulating colliding signals using feature quantity demodulation, which is a method of stored data batch signal processing, we evaluated the effects of signal degradation due to IQ imbalance caused by the characteristics of a quadrature modulator using computer simulations. Furthermore, we estimated the amount of deterioration due to IQ imbalance from the extracted feature quantities, proposed a receiver configuration that compensates for it, and evaluated the signal separation and demodulation performance. We confirmed that compensation improves signal separation and demodulation performance and increases the OBR that can be separated and demodulated. We also confirmed that even in cases where signal separation and demodulation are impossible without compensation, signal separation and demodulation become possible with compensation.

Future works include evaluation under various propagation path conditions, consideration of compensation techniques for other degradation factors such as filter distortion caused by transmitter/receiver characteristics, and verification of computer simulation results through actual measurements.

Acknowledgments

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