Proposal of a Quadrature SSB Modulation Scheme for Wireless Communication Systems

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***Abstract*—Recent wireless communication systems strongly require modulation scheme with higher spectral efficiency. In this paper, we propose a new modulation scheme, i.e., the Quadrature Single Side Band (Q-SSB) modulation scheme, which orthogonally multiplexes two SSB signals and it has twice spectral efficiency. Under Additive White Gaussian Noise (AWGN) channel environment, the Bit Error Rate (BER) performance of the Quadrature Phase-Shift Keying (QPSK) based Q-SSB signal, i.e., two independent Amplitude-Shift Keying SSB (ASK-SSB) signals, is superior by 3.5dB in Carrier-to-Noise Ratio (CNR) in comparison to the same data rate and the same occupied bandwidth of 16 Quadrature Amplitude Modulation (16QAM) signal. A key idea of our Q-SSB modulation scheme is to introduce a power-domain multiplexing type of Non-Orthogonal Multiple Access (NOMA) technique for removing the Hilbert transform terms from in-phase and quadrature components in the receiver side.**

Keywords-SSB; Hilbert; Quadrature; NOMA; Multiplexing.

I. INTRODUCTION

Recently, the demand of wireless communication system has been increasing with the spread of smartphones, digital terrestrial broadcastings, and wireless Local Area Network (LANs). Frequency resources are depleted in the Ultra High Frequency (UHF) and Super High Frequency (SHF) bands used by many wireless systems, so the high-priority issue for next wireless systems is a revolutionary modulation scheme with higher spectral efficiency. Here, to improve spectral efficiency, we propose the combination of the SSB scheme and the quadrature modulation scheme.

The Single Side Band (SSB) system sends data at half of the occupied bandwidth compared with the Double Side Band (DSB) system. The SSB signal can be made by combination of Hilbert transformation and quadrature multiplexing, which causes in-phase addition of one sideband and cancellation of the opposite sideband. The SSB system, however, is only effective scalar modulation, such as an Amplitude-Shit Keying (ASK) modulation.

On the other hand, the quadrature modulation, which is a typical DSB modulation, employs the two carrier waves of the same frequency which are out of phase with each other by 90°. The transmitted signal is created by quadrature multiplexing the two carrier waves. The SSB modulation has a single data rate and a single sideband and the quadrature modulation has a double data rate and double sidebands. As a result, the both have same spectral efficiency. Here, if we incorporate the SSB modulation with the quadrature modulation, twice spectral efficiency will be expected.

Unfortunately, since both modulations use the same signal processing of quadrature multiplexing, it is not independent each other. Thus, a lossless demodulation cannot be performed analytically. The in-phase component includes I-data and the Hilbert transform of Q-data, and the quadrature component includes Q-data and the Hilbert transform of I-data in the receiver side. Those Hilbert transform terms cannot be removed analytically if this goes on. In fact, several recent researchers have investigated the SSB modulation. For example, the research in [1]-[3] successfully transmitted SSB signal using the turbo equalization technology in the receiver side. We present our proposed system that can solve the problem about Hilbert transform terms in the transmission side.

A key idea of our Q-SSB modulation scheme is to introduce a power-domain multiplexing type of Non-Orthogonal Multiple Access (NOMA) technique for removing the Hilbert transform terms from in-phase and quadrature components in the receiver side [4]. Thus, on the receiver side, IQ-data can be demodulated by estimating the amplitude of data [5].

In this paper, we confirmed Bit Error Rate (BER) performances in both of the Q-SSB NOMA signal, and the multiplexed Q-SSB NOMA signals. We also confirmed that under Additive White Gaussian Noise (AWGN) channel environment the BER performance of the Quadrature Phase-Shift Keying (QPSK) based Q-SSB NOMA signal is superior by 3.5dB in Carrier-to-Noise Ratio (CNR) in comparison to the same data rate and the same occupied bandwidth of 16QAM signal.

The remainder of this paper is organized into sections as follows: Section 2 explains a method of DSB modulation, and Section 3 explains how SSB modulation is performed. Section 4 presents our proposed system that uses Q-SSB NOMA modulation, and explains how to multiplex two data in the proposed system. Section 5 presents the performance evaluation and simulation results of the proposed scheme. Finally, we conclude the paper in Section 6.

II. DSB MODULATION

Amplitude Modulation (AM) is a technique that multiplies carrier wave into the information signal, and change the

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amplitude of the transmission signal in proportion to the size of the information signal. A transmission signal S(t) in a general AM method can be represented as

$$S(t) = A[1 + k \cdot m(t)] \cdot cos(2\pi f_c t + \varphi), \quad (1)$$

where A is the signal amplitude, k is the modulation index $(0 \leq k \leq 1)$, f_c is the carrier frequency, and φ is the phase of the carrier. A general envelope waveform of AM method has m(t) waveform centered around $\pm A$ amplitude.

Next, consider the transmission spectrum of AM method. Note that multiplication on the time axis is the convolution on the frequency axis, and the Fourier transform of (1) is represented as

$$\begin{aligned} S(f) &= [\delta(f) + M(f)] \otimes \frac{1}{2}[\delta(f - f_c) + \delta(f + f_c)] \\ &= \frac{1}{2}[\delta(f - f_c) + M(f - f_c)] \\ &\quad + \frac{1}{2}[\delta(f + f_c) + M(f + f_c)]. \end{aligned} \quad (2)$$

Here, to simplify (2), $A = 1, k = 1$, and $\varphi = 0$. Thus, by multiplying the carrier wave, the baseband signal is shifted to the carrier wave band. A spectrum diagram showing this state is shown in Figure 1.

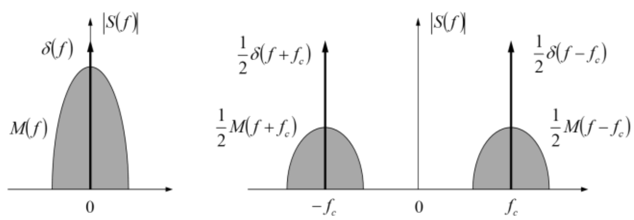


Figure 1. Spectrum diagram of AM method

As an example, consider the case of $m(t) = cos\, 2\pi f_m t$. If $\varphi = 0$ is set, (1) is rewritten as

$$\begin{aligned} S(t) &= A(1 + 2\pi f_m t) \cdot cos\, 2\pi f_c t \\ &= A\, cos\, 2\pi f_c t + \frac{A}{2} cos\, 2\pi (f_c - f_m) t \\ &\quad + \frac{A}{2} cos\, 2\pi (f_c + f_m) t. \end{aligned} \quad (3)$$

In (3), the first term represents a carrier wave component. The second and third terms are components of the information signal m(t).

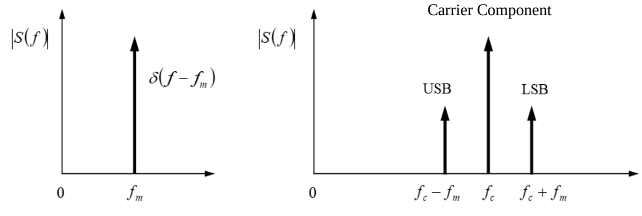


Figure 2. Spectrum of DSB modulation

The lower frequency component than the carrier wave in the second term is called Lower Side Band (LSB), and the higher frequency component than the carrier wave in the third term is called Upper Side Band (USB). As shown from Figure 2, a spectrum is generated at a location separated by $\pm f_m$ from the carrier frequency f_c. In this way, a method of moving an information signal to a carrier band and performing communication using LSB and USB is called Double Side Band (DSB) modulation method.

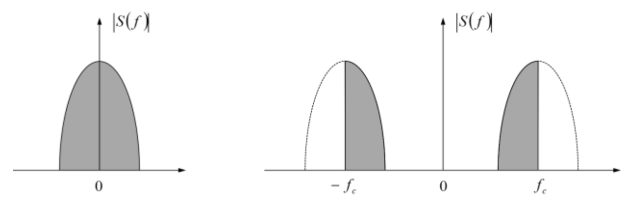
III. SSB MODULATION

We present how SSB modulation is performed, by explaining about the characteristic of SSB modulation and Hilbert transformation.

A. The characteristic of SSB modulation

In the previous section, we described that the DSB system performs communication using both the left and right sidebands centered on the carrier frequency. However, as can be seen from (3), since the LSB and USB contain the same information, all information transmission is possible by using only one of the LSB and USB. In this way, a method for performing communication using only one sideband is called Single Side Band (SSB) modulation method.

Figure 3 shows the SSB transmission spectrum by LSB. Here, the negative frequency region is also shown as an arithmetic expression, but only the positive frequency region appears as a real signal. Compared to the DSB method the greatest feature of the SSB method is that the frequency occupation band is halved [6].



(a) Base band signal (b) SSB signal

Figure 3. SSB transmission spectrum using LSB

B. Hilbert transformation

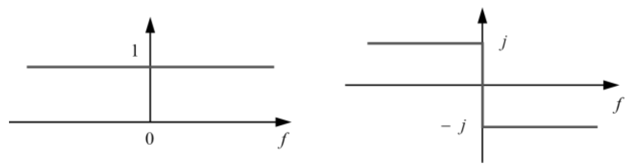
A method of generating an SSB signal using two $\pi/2$ phase shifters is called the Phase Shift Method. As one of the phase shifters, generating the signal $\hat{x}(t)$ whose phase is shifted $\pi/2$ from the input signal $x(t)$ is called Hilbert transform, and is represented as

$$\hat{x}(t) = H[x(t)] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau. \quad (4)$$

Here, the frequency characteristic of Hilbert transformation $H(\omega)$ is represented as

$$\hbar(t) \Leftrightarrow H(\omega) = \begin{cases} -j = exp(-j\pi/2)\ (\omega > 0) \\ +j = exp(+j\pi/2)\ (\omega < 0). \end{cases} \quad (5)$$

The Hilbert transformation delays $\pi/2$ at positive frequencies, and advances $\pi/2$ at negative frequencies. Also, the amplitude characteristic is constant regardless of the frequency. Figure 4 shows the conversion characteristics [7].



(a) Amplitude characteristic (b) Phase characteristic

Figure 4. Hilbert transformation characteristics

The following explains about the repeatability of Hilbert transformation. First, (6) is obtained by expressing (5) of the Hilbert transformation in the form of Fourier transform and combining them into one equation. That is represented as

$$\hat{X}(\omega) = -j\, sgn(\omega) \cdot X(\omega), \tag{6}$$

where the $sgn(\omega)$ is a sign function. The value of this function is 1 at positive frequency and is -1 at negative frequency. Therefore, when the Hilbert transform is performed again on the signal that has been conducted Hilbert transformation, the equation is represented as

$$\begin{aligned}\hat{\hat{X}}(\omega) &= \{-j\, sgn(\omega)\} \times \{-j\, sgn(\omega) \cdot X(\omega)\} \\ &= -X(\omega),\end{aligned} \tag{7}$$

and the signal inverting the original signal is output. Thus, the Hilbert transformation has repeatability. Moreover, it is a linear transform, and the equation is represented as

$$\begin{aligned}H[m(t) \pm n(t)] &= H[m(t)] \pm H[n(t)] \\ &= \hat{m}(t) \pm \hat{n}(t).\end{aligned} \tag{8}$$

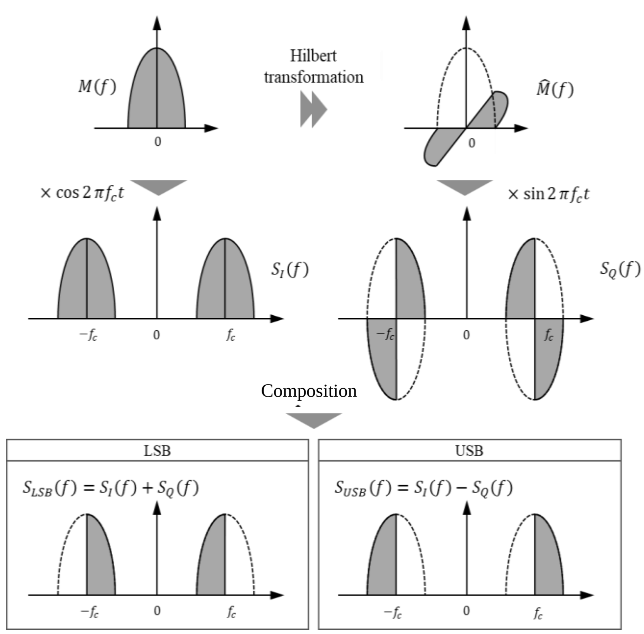


Figure 5. Generation method of SSB modulation signal

Figure 5 shows the spectrum transition in the SSB signal generation circuit. In Figure 5, $S_{USB}(t)$ *and* $S_{LSB}(t)$ of transmitted signal at this time is represented as

$$S(t) = m(t) \cdot cos\, 2\pi f_c t \pm \hat{m}(t) \cdot sin\, 2\pi f_c t, \tag{9}$$

where $m(t)$ is the modulation signal and $\hat{m}(t)$ is the Hilbert transformation of $m(t)$. In (9), when the second term is added, SSB modulation by LSB is performed. And when the second term is subtracted, SSB modulation by USB is performed. As shown from (9), the modulation signal can be restored by multiplying $cos\, 2\pi f_c t$ on the receiver side, and can demodulate SSB modulation signal [8].

IV. PROPOSED METHOD

In this section, we present our proposed system that uses Q-SSB NOMA modulation, and explain how to multiplex two data in the proposed system.

A. The method of Q-SSB NOMA modulation

The conventional Q-SSB modulation scheme considered the transmission method in which the phases of I-data and Q-data differ by 90° as shown in Figure 6. The transmission signal of the conventional method is expressed as

$$\begin{aligned}S_u(t) = &\left\{I_u(t) + \widehat{Q_u}(t)\right\} cos\, 2\pi f_c t \\ &+ \left\{-\widehat{I_u}(t) + Q_u(t)\right\} sin\, 2\pi f_c t.\end{aligned} \tag{10}$$

From (10), it is possible to extract I-data by multiplying $cos\, 2\pi f_c t$, and to extract Q-data by multiplying $sin\, 2\pi f_c t$. However, the BER performance is extremely deteriorated because the extra Hilbert component cannot be removed analytically.

Therefore, as shown in Figure 6, we introduce the method like NOMA that adds two data with different amplitudes on the same frequency. Here, our proposed system is different from the real NOMA method. We use the term of NOMA to help understand that two data have different amplitudes on the same frequency. The demodulation method on the receiving side uses the original method using amplitude estimation. The transmission signal of our proposed method in the case of USB is expressed as

$$\begin{aligned}S_u(t) = &\left\{I_u(t) + \frac{1}{2} Q_u(t)\right\} cos\, 2\pi f_c t \\ &+ \left\{-\widehat{I_u}(t) - \frac{1}{2}\widehat{Q_u}(t)\right\} sin\, 2\pi f_c t.\end{aligned} \tag{10}$$

I-data and Q-data can be extracted by multiplying $cos\, 2\pi f_c t$. In the case of LSB, the transmission signal is expressed as

$$\begin{aligned}S_l(t) = &\left\{I_l(t) + \frac{1}{2} Q_l(t)\right\} cos\, 2\pi f_c t \\ &- \left\{-\widehat{I_l}(t) - \frac{1}{2}\widehat{Q_l}(t)\right\} sin\, 2\pi f_c t.\end{aligned} \tag{11}$$

Figure 7 shows Q-SSB modulation circuit. Here, the modulation signal on the I-data is $I(t)$, and the modulation

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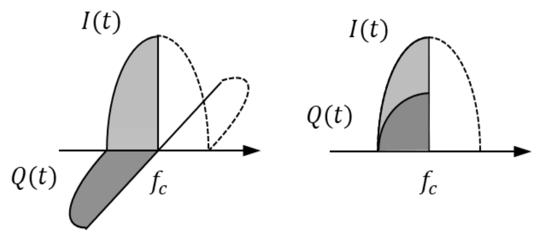
signal on the Q-data is $Q(t)$. USB is adopted as the sideband. As shown from Figure 7, Q-data is halved after QPSK mapping, and $S(t)$ is configured as (10).

Figure 8 shows the amplitude combinations of IQ data on the receiver side.



(a) Conventional method (b) Proposed method

Figure 6. Comparison between conventional method and proposed method

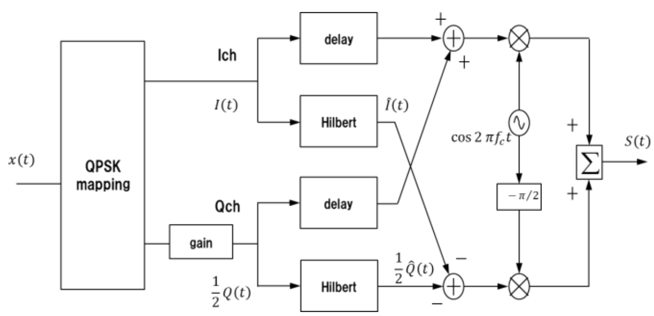


Figure 7. Q-SSB modulation circuit

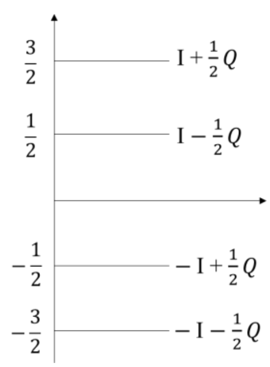


Figure 8. Amplitude of quadrature SSB received signal

As mentioned in the introduction, our system estimates the amplitude of $\left\{I_u(t)+\frac{1}{2}Q_u(t)\right\}$ on the receiver side. Since our system introduces QPSK modulation, the value of I-data and Q-data is 1 or -1. So, the amplitude of $\left\{I_u(t)+\frac{1}{2}Q_u(t)\right\}$ is represented as in Figure 8. The quadrature signals can be demodulated by the distinction of each amplitude in Figure 8.

B. The method of multiplexing Q-SSB NOMA modulation

In the previous section, we described the modulation method of SSB signal. However, it is a method to suppress the sideband on the opposite side, putting information on LSB or USB with one carrier wave.

In this paper, we put different information on LSB and USB at the same carrier frequency and perform data transmission by multiplexing method. From (10) and (11), the signal obtained by adding different information on USB and LSB is represented as

$$S(t)=\left\{I_u(t)+\frac{1}{2}Q_u(t)+I_l(t)+\frac{1}{2}Q_l(t)\right\}\cos 2\pi f_c t \\ +\left\{-\widehat{I_u}(t)-\frac{1}{2}\widehat{Q_u}(t)+\widehat{I_l}(t)+\frac{1}{2}\widehat{Q_l}(t)\right\}\sin 2\pi f_c t. \quad (12)$$

Then, the spectrum of the multiplexed SSB signal can be represented as Figure 9.

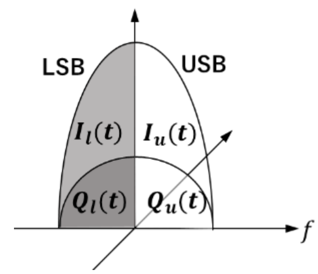


Figure 9. Spectrum of multiplexed SSB signal

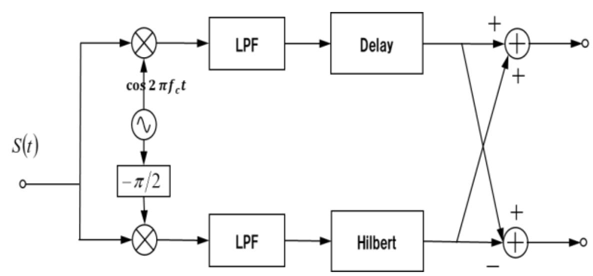


Figure 10. Demodulation circuit of multiplexed SSB signal

On the receiver side, our proposed system uses the demodulation circuit as show in Figure 10. In the upper part of Figure 10, $S(t)$ of (12) is multiplied by $\cos 2\pi f_c t$, and passed through LPF. That is represented as (13). In the lower part of Figure 10, $S(t)$ of (12) is multiplied by $\sin 2\pi f_c t$, and passed through LPF. That is represented as (14). And the signal when the Hilbert transformation is performed on (14) is represented as (15). The USB signal is extracted by adding (13) and (15), and IQ data is obtained by the amplitude estimation.

$$S_{cos}(t)=I_u(t)+\frac{1}{2}Q_u(t)+I_l(t)+\frac{1}{2}Q_l(t) \quad (13)$$

$$S_{sin}(t)=-\widehat{I_u}(t)-\frac{1}{2}\widehat{Q_u}(t)+\widehat{I_l}(t)+\frac{1}{2}\widehat{Q_l}(t) \quad (14)$$

$$\hat{S}_{sin}(t)=I_u(t)+\frac{1}{2}Q_u(t)-I_l(t)-\frac{1}{2}Q_l(t) \quad (15)$$

Similarly, the LSB signal is extracted by subtracting (13) and (15), and IQ data is obtained by the amplitude estimation.

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V. Performance Evaluation by Simulation

In this paper, we confirmed BER performances in both of the Q-SSB NOMA signal which have data on only USB, and the Multiplexing Q-SSB NOMA signals. And we confirmed that the BER performance of the QPSK based Q-SSB NOMA signal is superior by 3dB in CNR in comparison to the same data rate and the same occupied bandwidth of 16QAM signal.

A. Simulation specification

Table 1 shows the simulation tables used in this study. Our proposed system performs on the simulation by using MATLAB/Simulink. Figure 11 shows the block diagram of the Q-SSB NOMA system. Figure 12 shows the block diagram of the Multiplexing Q-SSB NOMA system. We have evaluated the utility of Q-SSB NOMA signal by measuring its BER performance and spectrum. We also confirmed the advantage of proposal compared to the conventional Q-SSB modulation method in Figure 6.

TABLE I. SIMULATION SPECIFICATION.

Primary Modulation	QPSK
Secondary Modulation	SSB
Data Rate	2 Mbps
Carrier Frequency	16 MHz
Data Size	Single Carrier
Transmitted Sample Rate	128Mbps
Received Sample Rate	512Mbps

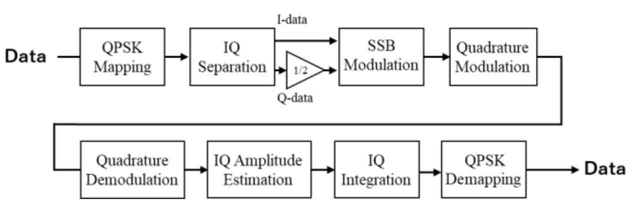

Figure 11. Block diagram of Q-SSB NOMA system

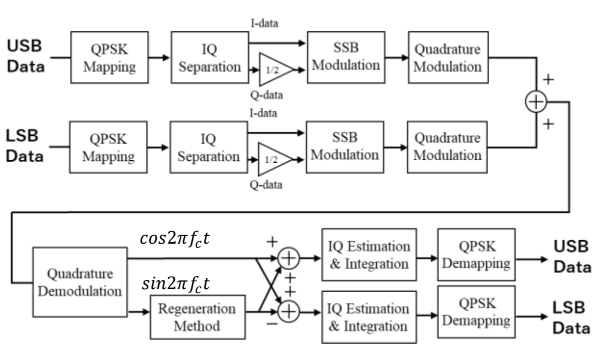

Figure 12. Block diagram of Multiplexing Q-SSB NOMA system

B. Simulation result (Q-SSB NOMA signal)

Figure 13 shows the spectrum of Q-SSB NOMA signal. Figure 14 shows the BER performance of the conventional Q-SSB modulation method (a) and our proposed Q-SSB modulation method (b) shown in Figure 6. Figure 15 compares the BER performance of DSB QPSK transmission or DSB 16QAM transmission with the BER performance of Q-SSB QPSK transmission.

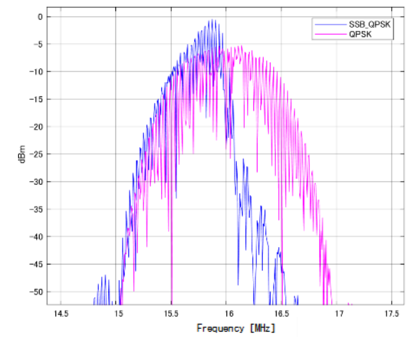

Figure 13. Spectrum of Q-SSB NOMA system

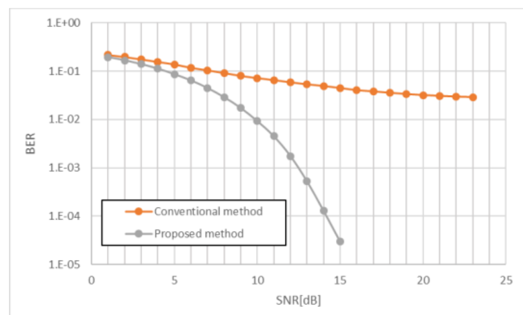

Figure 14. BER performance of conventional method and proposed method

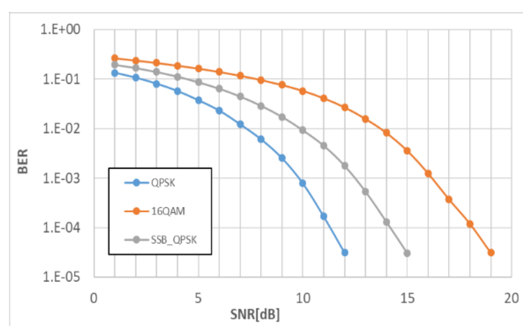

Figure 15. BER performance of Q-SSB NOMA system

As can be seen from Q-SSB NOMA modulation spectrum, compared to QPSK modulation spectrum, the part of the opposite sideband is suppressed by about 30dB by the Hilbert transformation process. And it expresses that Q-SSB NOMA signal can be transmitted using only one sideband.

As shown in Figure 14, it can be confirmed that our proposed method has the BER performance of 7.5dB better than the conventional method. This is because the conventional method uses a complicated demodulation method to remove an extra Hilbert component, whereas the proposed method can demodulate only by amplitude estimation without considering the Hilbert component.

As can be seen from 15, the SSB method that can send 4-bit data using two transmissions simultaneously has the BER performance of 3.5dB better than the DSB method that sends 4-bit data using 16QAM. The reason why the BER performance of Q-SSB QPSK transmission is 2.5dB worse than DSB QPSK transmission is considered to be the penalty when IQ data transmitted by NOMA is separated by the amplitude estimation method.

C. *Simulation result (Multiplexing Q-SSB NOMA signal)*

Figure 16 shows the spectrum of Multiplexing Q-SSB NOMA signal. Figure 17 compares the BER performance of the Q-SSB signal with data only on USB and the BER performance when each of USB and LSB signals are extracted from Multiplexing Q-SSB signal.

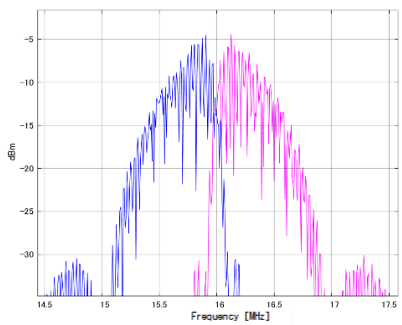

Figure 16. Spectrum of Multiplexing Q-SSB NOMA system

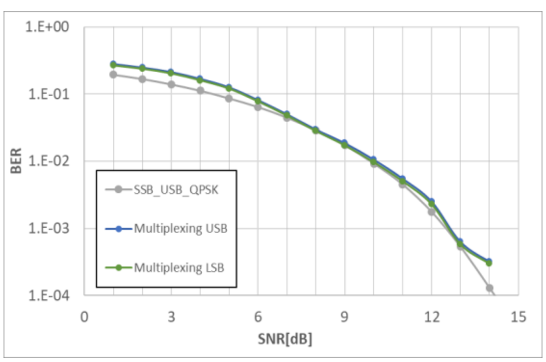

Figure 17. BER performance of Multiplexing Q-SSB NOMA system

As can be seen from Figure 16, each sideband part suppresses the opposite sideband by the Hilbert transformation process, so that two QPSK transmissions can be performed simultaneously using different data on USB and LSB.

In Figure 17, the BER performance of the Multiplexing Q-SSB signal may be slightly more deteriorated than Q-SSB signal with data on only one sideband. But that is due to the regenerating method to adjust Hilbert components, and their BER performances are almost not change. DSB 16QAM transmission and Q-SSB NOMA QPSK transmission sends 4 bits per symbol. Therefore, it was confirmed that the Multiplexing Q-SSB NOMA signal is superior to 16QAM transmission in terms of BER performance.

VI. Conclusion

We have proposed the Q-SSB NOMA modulation scheme to generate the quadrature SSB modulation signal with half of frequency band. It has been confirmed that under AWGN channel environment the BER performance of the QPSK based Q-SSB NOMA signal is superior by 3.5dB in CNR in comparison to the same data rate and the same occupied bandwidth of 16QAM signal. We are going to improve better the BER performance of the QPSK based Q-SSB NOMA signal. Additionally, we proposed improving the frequency efficiency of single carrier transmission. Therefore, we are going to improve the frequency efficiency of multicarrier transmission by combining the OFDM method and the Q-SSB modulation method.

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