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A New Design of SC-FDE Structure for Jammer Attack

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We propose a new single carrier - frequency domain equalization (SC-FDE) transmission structure to reduce degradation of data reception performance when a high-power narrow band intentional or non-intentional interference exists. In the conventional SC-FDE structure, channel estimation is performed in the time domain and then converted into frequency domain channel estimate. When there is a high power narrow band jammer or interference, time domain channel estimation is very challenging due to the high power jammer. To relieve from this difficulty, we propose a new SC-FDE transmission structure that can estimate frequency-domain channel directly without intermediate stage for time-domain channel estimation. Compared to the conventional structures, the proposed one has a common cyclic prefix (CP) for both pilot and data while the conventional techniques have only CP for data. The performance improvement of the proposed structure under narrow band jammers is verified through computer simulation. According to the results, it is confirmed that the proposed structure significantly improves the receiver performance compared to the conventional structure when jammer exists.

Keywords: SC-FDE; Channel estimation; Narrow band jammer; Frequency domain equalization; Frame structure

I. INTRODUCTION

In multipath fading environments, orthogonal frequency division multiplexing (OFDM) and single carrier frequency domain equalization (SC-FDE) are widely used for commercial and military communications (Czylwik, 1999; Hwang *et al.*, 2004). Both methods can perform simple frequency domain channel equalization in channel environments with multipath components (Hwang *et al.*, 2004). Both systems use the cyclic prefix (CP) to prevent the interference between transmission blocks. CP also has a function to convert linear convolution between the transmitted signal and the channel into circular convolution, which enables frequency domain equalization. Since OFDM has a higher peak-to-average power ratio (PAPR) than SC-FDE, OFDM signals are burdensome to the power amplifier. In addition, OFDM is sensitive to the carrier frequency offset (Yan *et al.*, 2016). However, OFDM is very useful for multiple access by allocating different subcarriers to different users. For those reasons, OFDM is used for a downlink and SC-FDE is used for an uplink of cellular systems (Falconer *et al.*, 2002). SC-FDE is also used in military communications because communication is usually point-to-point and frequency-division multiple access is difficult to implement without base stations.

The communication environment considered in this paper is a situation where communication is performed by the SC-FDE signaling in the military environments. An important consideration in military communication is the ability to improve reception performance as well as to resist enemy's intentional radio wave attacks. If the communication frequency is exposed to the enemy, it is possible to make an interference signal of large power, called jammer (Zhu *et al.*, 2016), and to be able to communicate reliably in these situations is very important in military communications. In the case of OFDM, they are multiplexed on subcarriers to transmit information. Therefore, even if several subcarriers are affected by the narrow band jammers, information of the remaining subcarriers can be properly received. However, the SC-

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FDE is weaker than OFDM for narrow band jammer attack because the transmission signal is a wideband single carrier (Shahriar *et al.*, 2015).

In order to overcome these weaknesses, this paper proposes a new SC-FDE transmission frame structure that enables reliable reception even in the presence of narrow band jammer. Specifically, compared to the conventional structures, the proposed one has a common CP for both pilot and data while the conventional techniques have CP for only data. Once the transmission structure is changed into the proposed scheme, the receiver does not use a special algorithm to remove jammer at the receiver. The existing researches for removing jammers require recognition of some information for the jammers and remove those based on the information. However, the proposed technique does not need to determine whether the jammers exist. The reception structure naturally removes the narrow band jammers. More specifically, in the conventional SC-FDE frame structure, the receiver performs the time domain channel estimation first using the pilot and then, the channel estimate is converted into the frequency domain channel by fast Fourier transform (FFT). The equalization is completed in the frequency domain. In contrast, the proposed method performs channel estimation and channel equalization in frequency domain directly without time domain channel estimation. In the conventional method, the time domain channel estimation is difficult due to the high-power unknown jammer, and accordingly, it is difficult to obtain the frequency domain channel estimate. On the other hand, the proposed method can directly obtain the frequency domain channel even if jammer exists. The performance of the proposed method is shown through computer simulation. According to the simulation result, when there is a high power narrow band jammer, the conventional method is often impossible to receive data, while the proposed method can transfer data at the expense of some performance loss. Also shown is that the bit error ratio (BER) performance loss under jamming environments can be reduced when the direct sequence spread spectrum technique is combined with the proposed SC-FDE structure.

The composition of this paper is as follows. Section 2 describes the conventional SC-FDE structure. Section 3 describes the proposed frame structure and introduces the receiver structure. This section also explains how the proposed method can succeed in restoring data when there is a narrow band jammer. Section 4 shows the computer simulation environment and results, and conclusion is made in Section 5.

II. CONVENTIONAL SC-FDE STRUCTURE AND PROBLEM IN NARROW BAND JAMMER ENVIRONMENTS

A. Conventional SC-FDE structure

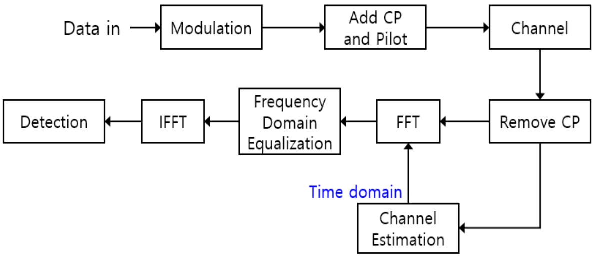

Figure 1. A block diagram of the operation process of the conventional SC-FDE systems

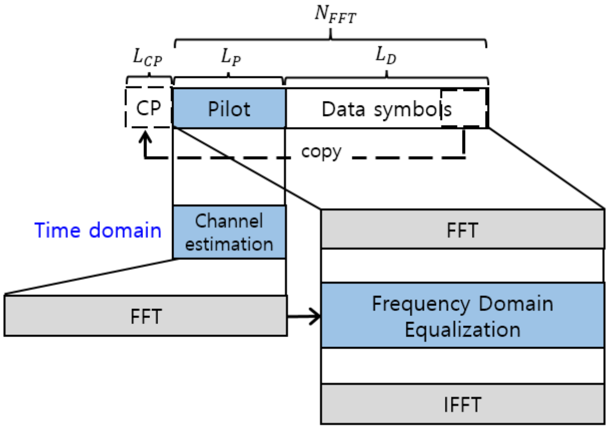

Figure 2. The conventional SC-FDE signal structure

Figure 1 is the block diagram of the operation process of the conventional SC-FDE system. First, the transmitted information is converted into complex symbols through modulation. This paper employs quadrature amplitude modulation (QAM). The modulation symbols are divided into a fixed length. This length is related to the FFT size of the frequency domain equalization at the receiver. If the length is short, the pilot and CP overheads increases. In contrast, if the length is long, the equalization performance at high-speed mobility environments decreases. Therefore, the block length should be determined by the trade-off between overhead and mobility. After that, a CP created by copying the end of data is inserted at the front of the block to prevent inter block interference. A pilot is also inserted and transmitted to help channel estimation and channel equalization at the receiver. The biggest difference from OFDM is that OFDM performs the inverse fast Fourier transform (IFFT) process at the transmitter, but the SC-FDE does not perform any IFFT process at the transmitter. Therefore, the PAPR of the SC-FDE signal is the same as conventional single carrier modulation. The only difference is the CP. The transmission signal generated through the above process is transmitted, passed through the wireless channel, and received by the receiver.

The received signal is distorted by the inter-symbol interference (ISI) in multipath environments. The ISI is severe as the signal bandwidth is wider. Compensation of this ISI at time-domain is challenging because finding the accurate channel inverse filter is demanding. SC-FDE relieve from this challenge by performing frequency-domain equalization.

The receiver first removes the CP from the received signal and performs time domain channel estimation using the pilot. The estimated time domain channel is transformed into the frequency domain through FFT. For frequency domain equalization, the data is also transformed into the frequency domain and the channel is compensated by dividing the frequency-domain received signal by the frequency-domain channel. The compensated signal is converted into the time domain signal through IFFT. Finally the data is recovered by demodulation of the time-domain signal.

The process is described in detail as follows. Figure 2 shows the conventional SC-FDE transmission signal structure (Falconer *et al.*, 2002). SC-FDE generates transmission data through a digital modulation scheme with a single carrier transmission system and the transmission structure consists of CP, pilot and data symbols. L_D is the length of a data symbol transmitted in one SC-FDE block. A pilot signal is transmitted for channel estimation and equalization. The length of the pilot is defined as L_P. The length of the pilot and data symbols is N_{FFT} and $N_{FFT} = L_P + L_D$. In order to use the frequency domain equalizer in the receiver, the CP is inserted ahead of the data block since the received signal must be in the form of a circular convolution between the channel impulse response and the transmission signal. CP is the last L_{CP} symbols of the data block. The length of N_{FFT} cannot be increased very long, because the channel must not change over the length N_{FFT} interval for operation of the frequency domain equalizer. If the channel variation is severe during this interval, equalization does not work well. Therefore, the size of N_{FFT} should be determined in consideration of the Doppler effects given by a function of the moving speed and the carrier frequency, and the pilot length L_P for channel estimation should be set to obtain sufficient channel estimation performance. Long pilot can increase the accuracy of the channel estimation while the pilot overhead increases. Considering the above conditions, the receiver performs time domain channel estimation using pilot and then converts it into a frequency domain signal through FFT. Then, the frequency domain signal is compensated for the channel distortion by frequency domain equalization. The equalized time domain signal can be obtained through IFFT of the frequency domain signal.

When the receiver receives a SC-FDE block in Figure 2, the receiver removes the CP and utilizes the pilot to perform time-domain channel estimation. Let's define the transmission signal from which the CP is removed as $x(n), n = 0, \dots, N_{FFT} - 1$ and the reception signal as $y(n), n = 0, \dots, N_{FFT} - 1$. Assume that the channel is causal and the channel length is L_h In this case, the channel impulse response can be written as $h(n), n = 0, \dots, L_h - 1$ and the received signal is as follows.

$$\begin{aligned} y(n) &= \textstyle\sum_{l=0}^{L_h-1} h(l)x(n-l) + \gamma(n) \\ &= \boldsymbol{x}^T(n)\boldsymbol{h} + \gamma(n) \end{aligned} \tag{1}$$

where

$$\boldsymbol{x}(n) = [x(n), x(n-1), \dots, x(n-L_h-1)]^T$$
$$\boldsymbol{h} = [h(0), h(1), \dots, h(L_h-1)]^T$$

$\gamma(n)$ represents Gaussian noise and $x(-1) = x(N_{FFT}), x(-2) = x(N_{FFT}-1), \dots$ by the CP.

In the received signal model of a given conventional SC-FDE structure in (1), the time-domain channel estimation is done and then frequency domain channel estimation is performed by FFT. In the received signal, $y(n), n = 0, \dots, L_P - 1$ is the pilot interval. The received pilot in this interval can be expressed as

$$\begin{aligned} &[y(0), y(1), \dots, y(L_P-1)]^T \\ &= [x^T(0), x^T(1), \dots, x^T(L_P-1)]^T h \\ &+ [\gamma(0), \gamma(1), \dots, \gamma(L_P-1)]^T \end{aligned} \tag{2}$$

and

$$y_P = X_P h + \gamma$$
$$y_P = [y(0), y(1), \dots, y(L_P-1)]^T$$

$$X_P = [x^T(0), x^T(1), \dots, x^T(L_P - 1)]^T$$
$$\gamma = [\gamma(0), \gamma(1), \dots, \gamma(L_P - 1)]^T$$

From (2), the channel estimation of the least squares method can be easily obtained. The least square estimated value of the time domain channel $\hat{h}$ is

$$\hat{h} = (X_P^H X_P)^{-1} X_P^H y_P \quad (3)$$

The frequency domain channel $\hat{H}_C(k)$ is obtained through FFT of $\hat{h}$. The channel compensation is performed in the frequency domain. For this, frequency received signal is required:

$$Y(k) = \sum_{n=0}^{N_{FFT}-1} y(n) \, exp\left(-j2\pi \frac{nk}{N_{FFT}}\right), k = 0, \dots, N_{FFT} - 1 \quad (4)$$

Channel compensation or equalization is to divide the received signal by the frequency-domain channel estimate, or $Y(k)$ is divided by $\hat{H}_C(k)$. Instead of simple division (zero-forcing equalization), minimum mean square error (MMSE) equalization is introduced to improve equalization performance in low signal to noise ratio (SNR) region.

$$\hat{X}_C(k) = \frac{Y(k)\hat{H}_C^*(k)}{|\hat{H}_C(k)|^2 + \sigma_\gamma^2} \quad (5)$$

As seen in (5), we need to estimate the variance of noise for the MMSE equalization. This paper assumes that the noise variance is given. Finally, the channel-compensated time domain signal is obtained via IFFT:

$$\hat{x}_C(n) = \sum_{k=0}^{N_{FFT}-1} \hat{X}_C(k) \, exp\left(j2\pi \frac{nk}{N_{FFT}}\right), n = 0, \dots, N_{FFT} - 1 \quad (6)$$

B. Problems of conventional SC-FDE structure in narrow band jammer environment

In military communications, however, there is a risk that the communication frequency is exposed to the jamming attack. In the conventional SC-FDE receiver, the channel is obtained in the time domain and then, the frequency domain channel is obtained. If a narrow band jammer exists, the received signal can be written as follows.

$$y(n) = x^T(n)h + I(n) + \gamma(n) \quad (7)$$

$I(n)$ represents narrow band jammer. The time domain channel estimation performance is better as the SNR is higher. If the SNR is low, the channel may not be estimated correctly. When there is a narrow band jammer, the higher the signal to interference plus noise ratio (SINR), the better the channel estimation. However, since the jammer power is similar to the received signal or may be even larger, the SINR can be 0 dB or less in such scenarios. In this case, the time domain channel estimation cannot provide reliable channel estimate unless the training signal is not very long (Haykin, 2002). Consequently, the frequency domain channel cannot be obtained as well. This results in poor channel equalization and the reception performance.

Figure 3 shows an example of time-domain channel estimation. The pilot length is 32 ($L_P = 32$). The channel impulse response is $\boldsymbol{h} = [0.80, 0.53, 0.27]$. The jammer does not exist here. The power of received signal is 10 dB higher than the power of noise, i.e., SINR = 10 dB. The ideal channel impulse response and the estimated channel is shown in Figure 3. As shown in the figure, the estimated channel is very close to the ideal channel.

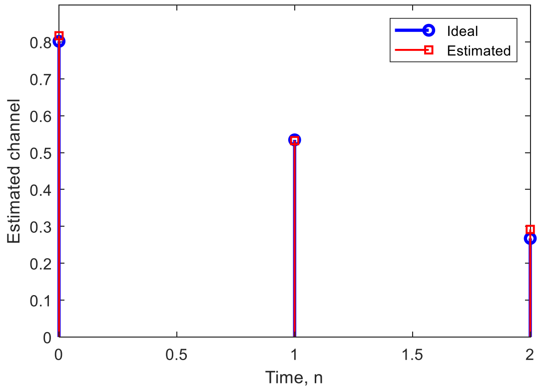

Figure 3. Time-domain estimated channel without jammer for SINR = 10 dB

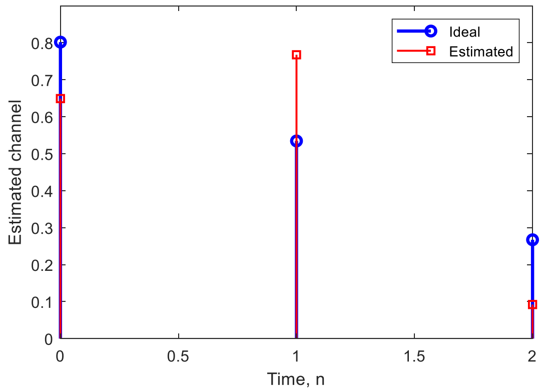

Figure 4. Time-domain estimated channel with jammer for SINR = 0 dB

On the contrary, Figure 4 shows the estimated channel impulse response when a single-tone jammer exists. Here, the power of jammer is the same as that of the received signal. Thus, we can say SINR = 0 dB. As shown in Figure 4, the estimated channel is quite different from the ideal channel, which indicates the channel estimation does not work well. This is due to the strong jammer. The channel estimation performance will be worse when the jammer is much stronger than the received signal. Those results shows that the time domain channel estimation is quite vulnerable to the strong narrow band jammers.

In frequency domain, narrow band jammer affects only a part of the bandwidth of the whole signal. That is, if the channel is estimated properly in remaining frequency excluding the narrow band jammer, channel equalization will be possible. If the received signal at the frequency where the narrow band jammer is located is nulled to '0', some of the received signals will be damaged but the jammer can be removed. Therefore, it is possible to restore the received signal from the other frequency band. In order to make such a method successful, it is necessary to establish a way to accurately estimate the frequency domain channel even in the presence of narrow band jammer. Based on this idea, the proposed method changes the frame structure so that the frequency domain channel can be obtained directly without using the time domain channel estimation.

III. PROPOSED SC-FDE TRANSMISSION

Figure 5 shows the proposed SC-FDE transmission structure. The big difference compared to the conventional structure in Figure 1 is that there is one block of pilot in the conventional structure, but in the proposed structure, the pilot is divided into three blocks. The same pilot2 signal is used before and after the data symbol. Also, the length of pilot2 is exactly the same as the CP at the front of the frame. In this structure, the CP is the CP of the pilot (pilot1+pilot2) block as well as the CP of the entire (pilot1+pilot2+data+pilot2) block. In other words, the CP of the proposed structure shares the pilot block and the entire data block.

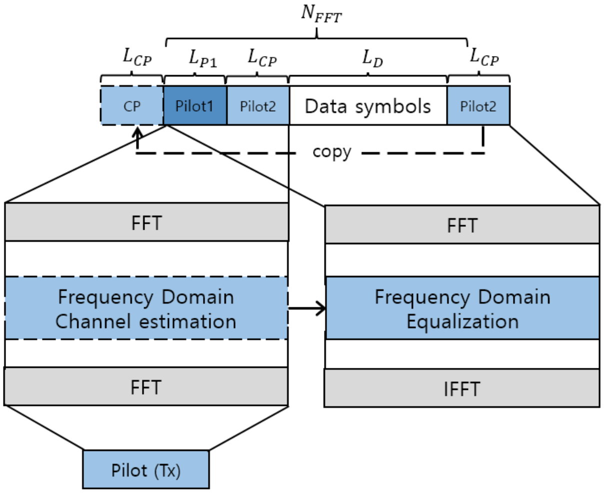

Figure 5. The proposed SC-FDE transmission structure

Due to the proposed structure, pilot2 can be the CP. By doing this, the received pilot block can be a result of circular convolution between transmitted pilot and the channel. This enables frequency domain channel estimation without time domain channel estimation as well as data symbols. A detailed explanation of this process is as follows.

Consider the (pilot1+pilot2) block after removing the CP at the receiver. Since the received (pilot1+pilot2) block is the result of circular convolution of the (pilot1+pilot2) and the channel impulse response, FFT can be directly used to find the channel in the frequency domain. Define the transmission signal of length N_{FFT} as $x(n)$ and the reception signal as $y(n)$, as in the conventional method. After removing the CP from the received signal for channel estimation, the pilot signal (pilot1+pilot2) $Y_P(k)$ in the frequency domain is obtained first.

$$Y_P(k) = \sum_{n=0}^{L_{P1}+L_{P2}-1} y(n)\, exp\left(-j2\pi\frac{nk}{N_{FFT}}\right)$$
$$, k = 0, \dots, N_{FFT}-1 \qquad (8)$$

$Y_P(k)$ represents the frequency domain pilot distorted by the channel. For channel estimation, find the ideal frequency domain characteristic of the transmission pilot signal, which is

$$X_P(k) = \sum_{n=0}^{L_{P1}+L_{P2}-1} x(n)\, exp\left(-j2\pi\frac{nk}{N_{FFT}}\right), k = 0, \dots, N_{FFT}-1 \quad (9)$$

N_{FFT} frequency domain channels can be obtained as follows (MMSE channel estimation).

$$\hat{H}_P(k) = \frac{Y_P(k)}{X_P(n)}, k = 0, \dots, N_{FFT}-1 \quad (10)$$

In order to compensate for the frequency domain channel, the frequency domain received signal is obtained in the same way as the conventional method:

$$Y(k) = \sum_{n=0}^{N_{FFT}-1} y(n)\, exp\left(-j2\pi\frac{nk}{N_{FFT}}\right), k = 0, \dots, N_{FFT}-1 \quad (11)$$

After that, compensate the channel by dividing by $\hat{H}_P(k)$.

$$\hat{X}_P(k) = \frac{Y(k)\hat{H}_P^*(k)}{|\hat{H}_P(k)|^2+\sigma_Y^2} \quad (12)$$

Finally, the channel compensated time domain received signal is obtained via IFFT as follows.

$$\hat{x}_P(n) = \sum_{k=0}^{N_{FFT}-1} \hat{X}_P(k)\, exp\left(j2\pi\frac{nk}{N_{FFT}}\right), n = 0, \dots, N_{FFT}-1 \quad (13)$$

The features of the proposed method are described as follows. In the case of the conventional method, it is impossible to directly estimate the frequency domain channel form the received signal. In order to obtain the frequency domain channel using the FFT, the received signal in the form of circular convolution between the transmission pilot signal and the channel impulse response is required. However, in the conventional structure of Figure 1, since the CP is the signal at the end of the data, not the pilot, the frequency domain channel could not be obtained directly. In the proposed structure, in contrast, the frame structure is modified so that the CP is designed to be the CP of the entire transmission block as well as the CP of the pilot block (pilot1+pilot2), which facilitates frequency domain channel estimation and equalization without the need of time-domain channel estimation. In the proposed structure, even in an environment where a narrow band jammer exists and the SINR is bad, the frequency domain channel can be obtained and equalization is also possible. In particular, if frequency domain channel is acquired when there is a narrow band jammer using the proposed structure, a large value will be observed in the frequency bins where a narrow band jammer located. However, since the frequency domain equalization is a process of dividing the received signal by the channel estimates, the effect of nulling at the jammer frequencies is naturally conducted by the equalization process. That is, even if no additional signal processing is performed to remove the jammer, the jammer removal effect can be attained naturally. In general, two steps of jammer recognition and elimination are required for jammer removal. The proposed technique, however, removes jammer without explicit recognition or determination of existence of the jammer.

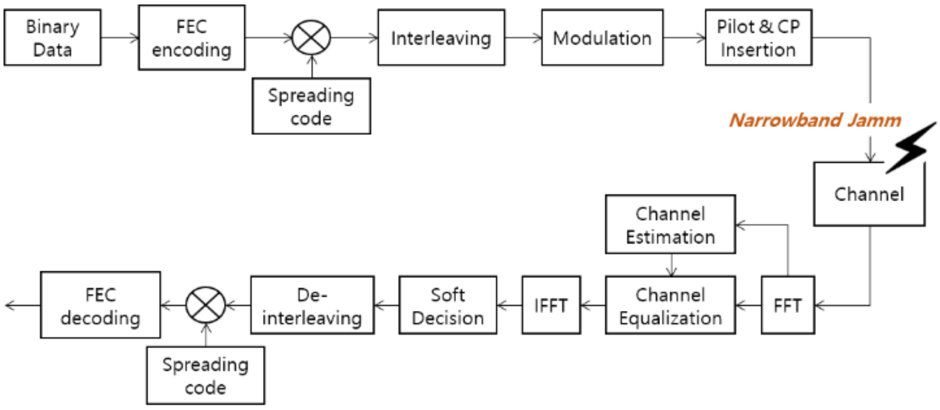

Figure 6. Simulation block diagram

IV. COMPUTER SIMULATION ENVIRONMENT AND RESULT

A. Simulation environment

The performance of the proposed SC-FDE was verified through computer simulation (Bansal & Shricastava, 2017; Jeong *et al.*, 2017). Figure 6 shows a block diagram of the SC-FDE transceiver system used in the simulation. The transmitter generates random binary data and performs forward error correction (FEC) encoding. Then, pseudo noise (PN) code is multiplied to form a direct sequence spread spectrum, and interleaving is used to mix data sequences to prevent cluster error. After modulation, CP and pilot signals are added and transmitted for inter block interference prevention and frequency domain equalization. The transmitted data is received via a communication channel, and when a narrow band jammer exists, a jamming signal is also added and received.

The receiver estimates the frequency domain channel using the previous received pilot and performs equalization. Next, log likelihood ratio (LLR) is obtained, and transmission data is restored in the order of deinterleaving, despreading, and FEC decoding. The detailed parameters used in the simulation are as follows.

Table 1. Simulation environment

Parameter	**Value**
Binary data length	384 bits
Channel code	LDCP, R=1/2
Spreading gain	1, 4
Modulation	QPSK
CP length (L_{CP})	32 symbols
Pilot length (Pilot1 + Pilot2)	128 symbols
JSR (Jammer to Signal Ratio)	0 dB
Number of jammer	1
FFT size (L_{FFT})	512

Table 1 shows the simulation environments. Binary data of 384 bits is used for the transmission message and Low-density Parity-check (LDPC) code of code rate 1/2 is used for the channel code (Li *et al.*, 2014). The spreading gain was 1 or 4 and interleaving was performed using 32x24, 64x18 matrices for each spreading gain. Modulation scheme is quadrature phase shift keying (QPSK), the CP length is set to 32 symbols and the total pilot length is set to 128 symbols. One narrow band jammer was considered and the jammer to signal ration (JSR) was fixed at 0 dB. That is, the jammer and the received signal have same environment of power. The communication channel is considered add white Gaussian noise (AWGN) and fading channel. And the FFT size is 512, the symbol rate is 2 M symbol/s.

B. Frequency domain channel estimation results when narrow band jammer exists

Figure 7 shows an example of frequency domain channel estimation. The jammer does not exist here. The power of received signal is 10 dB higher than the power of noise, i.e., SINR = 10 dB. The ideal channel impulse response and the estimated channel are all shown in Figure 3 According to the results, the estimated channel is very close to the ideal channel.

Figure 8 shows the estimated frequency domain channel when a single-tone jammer exists. Here, the power of jammer is the same as that of the received signal. Thus, we can say SINR = 0 dB. As shown in Figure 8, the estimated channel is quite similar to the ideal channel except for the jamming frequency. As shown in Figure 4, we failed to estimate the time domain channel for the same environments. However, the proposed technique enables the frequency domain channel estimation. Compare Figure 8 with Figure 7, the estimated channel response look similar. When a narrow band jammer exists, the estimated channel shows high magnitude at the jammer's frequency. What happens if the equalization is performed with this channel estimate? Since the estimated channel has high magnitude at the jammer's frequency, if we divide the frequency domain received signal by the estimated frequency domain channel, the jamming signals will be much lowered. This can be interpreted as nulling at jammer's frequency. In fact, most anti-jamming technique removes the jammer from the received signal after recognition of the existence of the jammer. The proposed technique does not need to determine or recognize whether a jammer exist or not. The jammer removal is done without any concern during the channel estimation and equalization process.

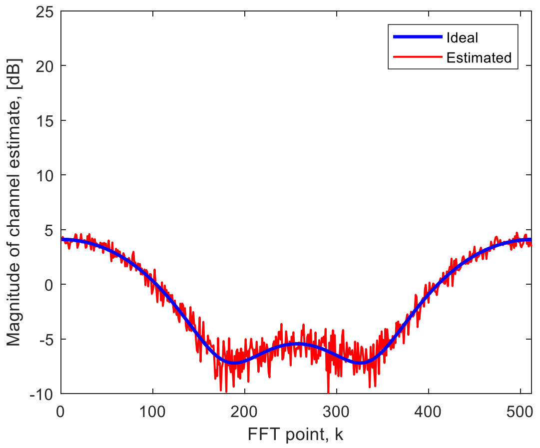

Figure 7. Frequency domain channel estimation in proposed SC-FDE structure when jammer exists

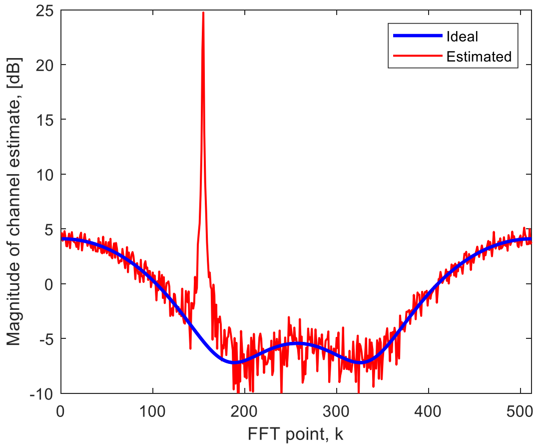

Figure 8. Frequency domain channel estimation in proposed SC-FDE structure when jammer exists

C. BER simulation

Figure 9 shows bit error rate (BER) performance of the conventional SC-FDE structure and the proposed structure according to jammer existence/nonexistence and spreading gains in AWGN environment. In the conventional method based on the time domain channel estimation, it can be confirmed that even if the SNR is large, the data cannot be restored properly. In contrast, the performance of the proposed SC-FDE structure is decreased by about 2 dB compared to the case when there is no jammer, but the BER performance is much improved compared to the conventional SC-FDE structure. Also, as the spreading gain increase from 1 to 4, the loss is decreased by about 0.5 dB compared to the no-jammer case.

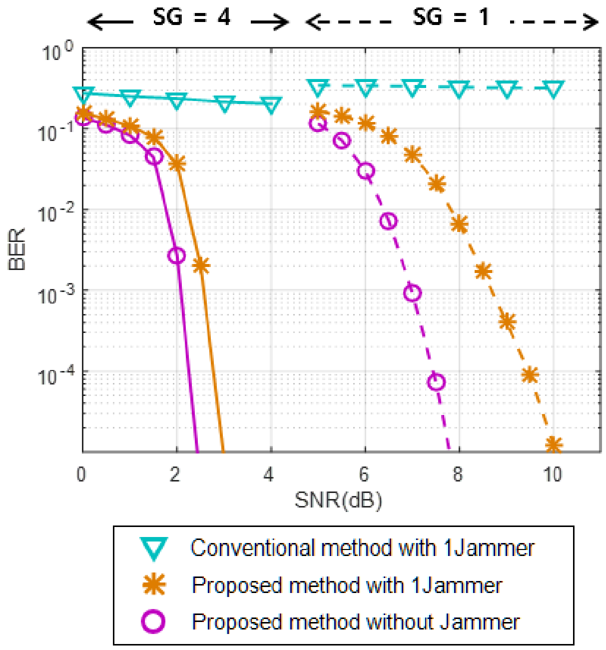

Figure 9. BER performance in AWGN channel

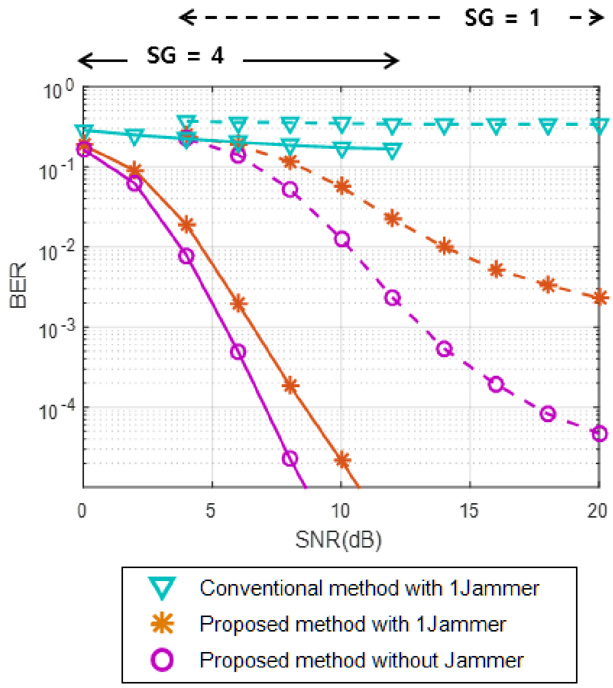

Figure 10. BER performance in fading channel

Figure 10 shows the BER performance of the proposed SC-FDE structure with and without spreading gain and jammer in the fading channel environment. The fading channel model is as follows. The 7-path model is used. The power for each multipath is [0.73, 0.031, 0.034, 0.051, 0.061, 0.042, 0.051] and the multipath delay is [0, 1.6, 3.2, 4.8, 6.4, 8.0, 9.6] μs. Each path is assumed to be a Rayleigh channel and the speed is 60 km/h (Berger, 2006). According to the simulation results, the

conventional method still does not perform data restoration properly. Also, when the proposed method with and without jammer is observed based on the BER=1E-3, the performance degradation is observed at 10 dB and 2 dB, respectively, when spreading gain is 1 and 4, respectively.
From the simulation results, it can be seen that the proposed method can be expected to provide stable reception even when there is no special signal processing in the presence or absence of narrow band jammer. Especially, if the spreading gain is large, it can be confirmed that performance deterioration can be reduced when there is a jammer.

V. CONCLUSION

In this paper, we propose a new SC-FDE transmission structure and receiver structure. The proposed method is designed to estimate the frequency domain channel without going through the time domain channel estimation. Moreover, stable reception is possible even in a narrow jammer or interference environment. Therefore, it is possible to perform stable communication even in the presence of interference or jammer by applying the method proposed in a system in which the reliability of communication is directly connected to safety, such as a military communication system or an autonomous vehicle or a drones.

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