Carrier Frequency Offset Detection Using Hierarchical Modulations for OFDM Communications

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Abstract—**In this study, we used hierarchical modulation technology to estimate the carrier frequency offset (CFO) caused by the Doppler effect. In this study, we transformed modulation within orthogonal frequency-division multiplexing into hierarchical modulation. We estimated the extent of the Doppler effect using the hierarchical modulation characteristic that the bit error rate (BER) of each level varies for differing CFO. The design developed in this study estimates the CFO and conducts hierarchical modulation of pilot signals. The receiving end estimates the CFO based on the characteristic that the BER of each level has different error rates at various CFO degrees. The simulation result showed that the actual BER was higher than the mathematically analyzed BER for each level, which resulted in overestimated CFO degrees or extents.**

Keywords- Carrier Frequency offset(CFO); Hierarchical Modulation; OFDM

I. INTRODUCTION

To satisfy the substantial amount of data transmission for the current wireless channel environments, single-carrier (single-rate) communication architectures cannot fulfill the requirements of ordinary users. To increase transmission speeds, single-carrier systems adopt a symbol time that is shorter than the channel delay spread or distribution. Therefore, single-carrier symbols are significantly influenced by the multipath interference of wireless communication environments at high transmission speeds. However, multicarrier communication transmission systems can increase symbol time at identical transmission speeds. This reduces the multipath interferences of multicarrier symbols in wireless communication environments at identical transmission speeds. Thus, in wireless communication environments, new multicarrier communication transmission systems naturally replace single-carrier communication architectures.

The basic principle of OFDM is to divide high-speed transmission data flows into several low-speed data flows. These waveforms with varying transmission speeds are orthogonal to each other on the frequency spectrum. In other words, OFDM separates the original usable bandwidth into multiple sub-bands and transmits data using subcarriers that are orthogonal to each other. Thus, OFDM can be considered a special multicarrier (multi-rate) transmission type.

The OFDM system is extremely sensitive to carrier orthogonality. However, at high moving velocities, the Doppler effect induces CFOs and results in unorthogonal carriers. This significantly influences the high-velocity-transmission performance of OFDM systems.

In Section 2, we introduce general quadrature amplitude modulation (QAM) and hierarchical QAM and explain the difference between the two modulations. In addition, we used mathematical equations to analyze the bit error rate (BER) of the two modulations under additive white Gaussian noise (AWGN) and a Doppler effect environment. We compared the advantages and disadvantages of these two modulation methods and explained the purpose of employing hierarchical modulation. In Section 3, we describe the OFDM architecture. Hierarchical modulation was used instead of general modulation. Subsequently, we introduce the (inverse) fast Fourier transform (FFT), P/S, CP, GI, and the generation method for pilot signals.

II. HIERARCHICAL MODULATION

General OFDM modulation is assumed to be 64-QAM. Every point in the constellation map or diagram was determined using 6 bits combined with Gray codes. Neighboring codes differed by 1 bit. When the overall BER attains an optimal situation, an even distribution of constellation points on the constellation map is presented. This maximizes the distance between each constellation point under the same average energy and minimizes the overall error rate. Previous scholars have proposed a method that differs from general modulation for achieving an uneven distribution of constellation points on the constellation map [1], as shown in Fig. 1. Although the overall BER increases, hierarchical modulation is advantageous for providing superior protection of relatively important information and lower protection of less important information. In this study, we integrated hierarchical modulation into the OFDM technology.

A total of three hierarchical bits exist. The protection level of each hierarchical bit differs. Level 1 bits were used to determine the large black points in Fig. 1.

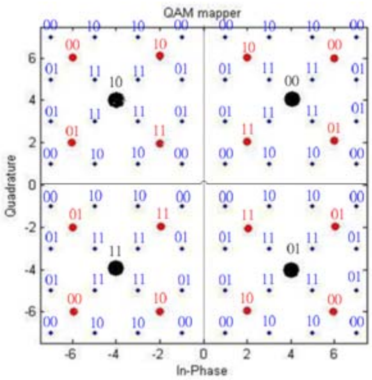

Figure 1. Hierarchical 64-QAM constellation map and Gray codes

A. Hierarchical M-QAM modulation

The 64-QAM transmits 6 bits in every subcarrier. When the used modulation transmission rate increases, the received interference becomes increasingly sensitive. Because the smaller variation range of point positions easily causes errors, the error rate increases.

For this study, we used hierarchical 64-QAM as the example, where an and bn indicated the amplitude size of the real part and the imaginary part of the nth transmission signal.

$$a_n, b_n = \pm d_2^{'}, \pm(d_2^{'} + 2d_3), \pm(2d_2 + d_2^{'}), \pm(2d_2 + 2d_3 + d_2^{'}), d_2^{'}, d_2, d_3$$

represents the distance required to completely describe the hierarchical modulation constellation points as shown in Fig. 2.

Furthermore, regarding the hierarchical 64-QAM signal average energy, the simulated average energy calculated for the constellation map was $E_s' = 2(d_2' + d_3 + d_2)^2$. However, the actual energy required to modulate every signal and the average energy were $E_s = 2(d_2' + d_3 + d_2)^2 + 2\cdot d_2^{\,2} + 2\cdot d_3^{\,2}$.

To simplify the design parameters and facilitate the calculation of error rates, we defined the two parameters $\lambda_1 = \dfrac{d_2}{d_2'}$ and $\lambda_2 = \dfrac{d_3}{d_2'}$. When the values of these two parameters were adjusted, the distribution in the constellation map varied, as shown in Fig. 8. When $\lambda_1 = 2$ and $\lambda_2 = 1$, the constellation map has an even distribution, identical to the general constellation map. When we simultaneously changed the two parameters, as shown in Fig. 3 to Fig. 5, the constellation map showed an increasingly uneven distribution. Additionally, using λ_1 and λ_2, signal frequency average energy can be shown as

$$E_s = (2(1+\lambda_1+\lambda_2)^2 + 2\cdot\lambda_1^{\,2} + 2\cdot\lambda_2^{\,2})\cdot d_2'^2 \qquad (1)$$

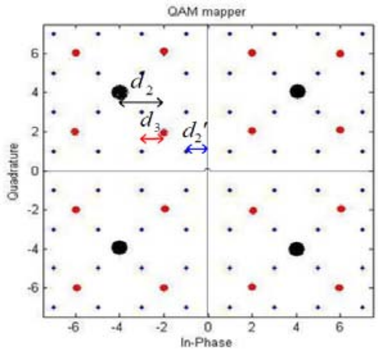

Figure 2. The hierarchical 64-QAM constellation map

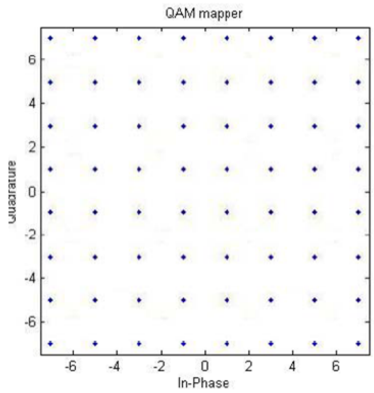

Figure 3. 64-QAM constellation map (λ1 = 2, λ1 = 1)

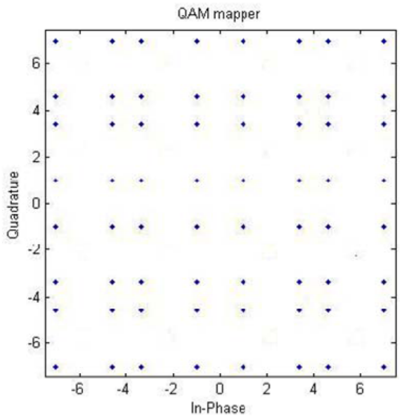

Figure 4. 64-QAM constellation map (λ1=1.8, λ2=1.2)

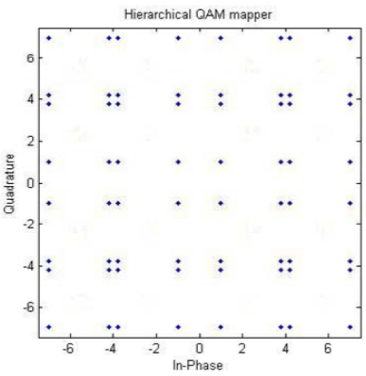

Figure 5. 64-QAM constellation map (λ1=1.6, λ2=1.4)

B. *Error rate analysis of every level bit in AWGN channels*

In an AWGN channel, the error rates are related to the distance between constellation points. Because the hierarchically modulated constellation map presents an uneven distribution, the distance between each constellation point differs. The uneven distribution is also the cause of the varying BER for each level. Considering hierarchical 64-QAM for example, three levels can be divided; the error rate protection level differs between levels.

The following equation simplifies the parameters required for calculation. a, b, and c are integrals. $N_0/2$ is the bilateral power spectrum density (PSD) of AWGN.E_s/N_0 represents signal-to-noise ratio (SNR).

After the parameters in the Erfc function are simplified, the BER of each level can be determined using the following three equations.

$$P_{b,AWGN}(i_1,64)=\frac{1}{8}[I(1,2,2,\lambda_1,\lambda_2)+I(1,2,0,\lambda_1,\lambda_2)+I(1,0,2,\lambda_1,\lambda_2)+I(1,0,0,\lambda_1,\lambda_2)]$$

(2)

$$P_{b,AWGN}(i_2,64)=\frac{1}{8}[2\cdot I(0,1,-1,\lambda_1,\lambda_2)+2\cdot I(0,1,1,\lambda_1,\lambda_2)+I(2,1,1,\lambda_1,\lambda_2)+I(2,1,3,\lambda_1,\lambda_2)$$
$$-I(2,1,3,\lambda_1,\lambda_2)-I(2,3,1,\lambda_1,\lambda_2)-I(2,3,3,\lambda_1,\lambda_2)]$$

(3)

$$P_{b,AWGN}(i_2,64)=\frac{1}{8}[4\cdot I(0,0,1,\lambda_1,\lambda_2)+2\cdot I(0,2,-1,\lambda_1,\lambda_2)+I(2,0,1,\lambda_1,\lambda_2)-2\cdot I(0,2,1,\lambda_1,\lambda_2)$$
$$-I(2,0,3,\lambda_1,\lambda_2)-2\cdot I(2,2,1,\lambda_1,\lambda_2)+2\cdot I(2,2,3,\lambda_1,\lambda_2)+I(2,4,1,\lambda_1,\lambda_2)-I(2,4,3,\lambda_1,\lambda_2)]$$

(4)

These three equations show that different λ1 and λ2 present different error rates. Fig. 6, 7, and 8 show a comparison of SNR under various hierarchical modulation with the BER of each level.

III. HARQ APPLYING HIERARCHICAL PILOT SIGNALS TO CFO ESTIMATION

In this study, we designed a hierarchical modulation method to estimate the CFO caused by the Doppler effect. The goal was to generate different protection degrees for various level bits. Therefore, if the receiving end identifies the error rate of the transmission end bits passing the channel, the current CFO severity can be accurately estimated.

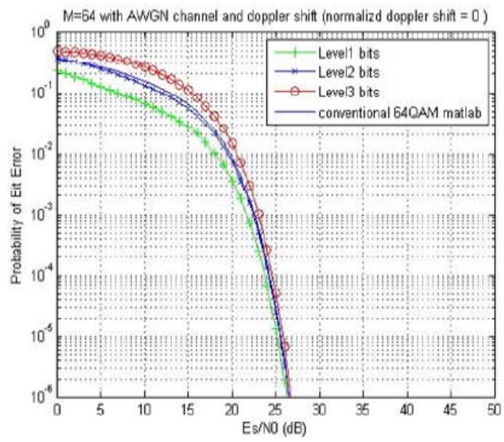

Figure 6. Error rates for each level (λ1 = 2, λ2 = 1)

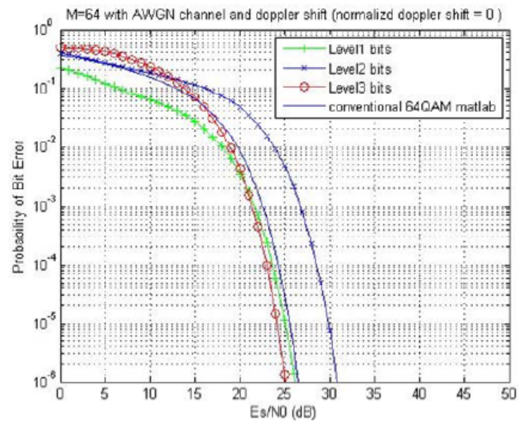

Figure 7. rror rates for each level (λ1 = 1.8, λ2 = 1.2)

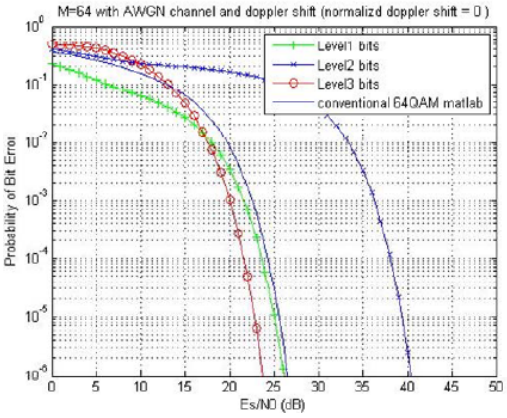

Figure 8. Error rates for each level (λ1 = 1.6, λ2 = 1.4)

For the system architecture proposed in this section, we used hierarchical modulation to modulate pilot bits. Pilot bits were a section of message or information known by the transmission and receiving ends. The receiving end can calculate the error rate of pilot bits for each level based on receiving the hierarchical pilot signals passing through the channel. We used the differing bit error rates of each level regarding the CFO caused by the Doppler effect to estimate the current CFO.

The system proposed in this study replaces the existing OFDM pilot signal with the hierarchical modulation pilot signal. Based on the characteristic that bits of each level have differing error rates for the CFO caused by the Doppler effect, we estimated the CFO severity. After we completed the estimations, feedback was sent to the original carrier for adjustment. Thus, the OFDM system can maintain orthogonality between carriers, reduce mutual interference between carriers and the system error rates, and improve system performance.

C. Transmission-end model

Fig. 9 shows the new transmission end of the OFDM system proposed in this section.

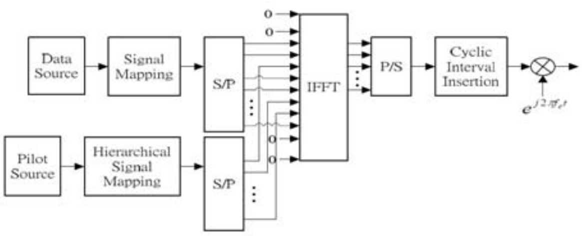

Figure 9. The OFDM system transmission end for hierarchical pilot signals

The most significant difference between the proposed technology and existing technology is the pilot signal modulation design. The purpose of incorporating pilot signals into OFDM signals is to estimate the received noise, interference, and signal attenuation degree during the transmission process. When the receiving end receives signals converted through the channel from the transmission end, the phase variation and signal attenuation degree can be estimated.

Additionally, scholars have developed the adaptive modulation method, which uses the pilot signal error rate to determine the channel quality and whether to employ QPSK, 16-QAM, or 64-QAM for current modulation.

The pilot signal designed in this study converts pilot bits through hierarchical modulation. We then used the hierarchical-modulated signals to estimate the channel variation and error rate of each level. The error rate of each level can be used to determine the quality of the current channel. Furthermore, the characteristic that the bits of each level have differing error rates for CFO can be used to estimate the CFO.

The pilot signal value of each OFDM signal was determined using the W k value. The subsequent pilot signal bits were converted into hierarchical pilot signals through hierarchical modulation. Using the hierarchical pilot signals known by the transmission and receiving ends, the receiving end can estimate the noise interference and signal attenuation degree during the transmission process to conduct signal attenuation equalization.

For the pilot bit model in this study, we used the comb type [2-4]. As shown by the pilot bit arrangement in Fig. 10, the overall architecture regularly cons pilot bits on subcarriers at certain intervals for every time before transmitting data signals on other subcarriers.

D. Receiving-end model

The operation at the receiving end is the reverse of all functions of the transmission end, facilitating signal demodulation. The OFDM baseband signal that passes through the channel first removes the CP interval. After the signal passed through the P/S converter and FFT, the signal of each subcarrier was obtained. Subsequently, we extracted hierarchical pilot signals from specific subcarriers to conduct channel estimation. Additionally, using a simple one-tap equalizer to apply gain adjustments to signals can compensate for the signal fading under the influence of the channel to prevent serious distortion of the transmission signal. Finally, a demodulator was employed to recover data bits.

In addition to the original function blocks, the new receiving end structure proposed in this chapter includes a hierarchical demodulator, an S/P converter, multiple pilot signal buffers, and a CFO estimator, as shown in Fig. 11. This enabled the different error rates of pilot signals for each level regarding CFO to be used to estimate the extent of the Doppler effect and perform correct CFO compensation.

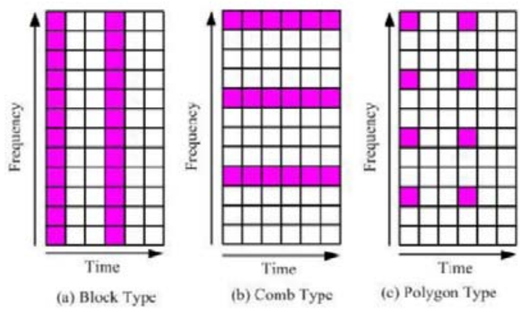

Figure 10. Arrangement of pilot bits

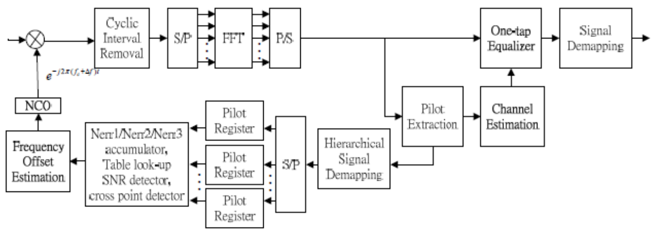

Figure 11. The OFDM system receiving end for hierarchical pilot signals

E. *CFO estimation*

General modulation presents an even distribution on the constellation map. The error rate of each level bit does not vary because of the CFO degree. However, hierarchical-modulated signals present an uneven distribution on the constellation map. Additionally, the BER of each level bit differs. In other words, hierarchical modulation results in differing protection levels for bits of each level. When the CFO was 0 dB and the SNR was less than 10 dB, the protection level for Level 3 bits was the lowest (with the highest error rate), followed by that for Level 2; Level 1 had the highest protection level. When the SNR ranged between 10 and 17 dB, the protection level from low to high (error rates from high to low) was Level 2, Level 3, and Level 1. When the SNR was higher than 17, the protection level in low-to-high sequence was Level 2, Level 1, and Level 3.

F. *SNR analysis and estimation*

The novel method proposed in this study for estimating CFO requires the SNR size to be known before estimation. Therefore, whether the signal intensity received by the mobile platform is accurate directly influences the CFO estimation performance. Thus, we propose a method that differs from the signal receiving intensity method for estimating the signal SNR. Using the fact that the BER of each level bit differs after hierarchical modulation, based on the above characteristics of the BER for each level, we designed a flowchart to realize the overall SNR estimation method.

The transmission-end OFDM signal was embedded with hierarchical-modulated pilot signals; the hierarchical modulation parameters were λ1 = 1.6 and λ2 = 1.4. Through the channel noise and interference, the receiving end temporarily stores bits of each level, and also calculates the BER of each level bit. Assuming that the Level 1 BER was Nerr1, Level 2 BER was Nerr2, and Level 3 BER was Nerr3, and so on, we used the varying BER of each level to determine the current SNR size. When Nerr3 > Nerr2 > Nerr1, the estimated SNR was between 0 and 10 dB, representing an undesirable communication quality. When Nerr2 > Nerr3 > Nerr1, and the normalized CFO was smaller than 0.12, the estimated SNR ranged between 10 and 18 dB, representing a neutral communication quality. When the normalized CFO was smaller than 0.12 and the estimated SNR was larger than 20 dB, a favorable communication quality was achieved. When Nerr2 > Nerr1 > Nerr3, the estimated SNR was greater than 20 dB, representing a favorable communication quality.

IV. SIMULATION AND RESULTS

First, we referenced the parameter specifications of LTE and 802.16m. The IFFT setting was 512 [5] The sampling frequency fs was 7.68 MHz [6. We modulated the pilot signal using the hierarchical 64-QAM (λ1 = 1.6, λ2 = 1.4) proposed in this study; the CP length was one-fourth that of the original length, as shown in Table I. Subsequently, during channel simulation, we fabricated a wireless environment with multiple paths. The receiving end showed evidence of the Doppler effect or offset caused by five types of moving velocities. The maximum Doppler shift f m at velocities of 30 km/h, 120 km/hand 500 km/h was 69.4 Hz, 277.8 Hz, 578.7 Hz, 810.2 Hz, and 1157.4 Hz, respectively. We defined the normalized Doppler shift or offset by assuming that the subcarrier interval was 1. Fig. 12, 13, and 14 show the simulation results of the 7.68MHz sampling frequency at velocities of 30 km/h, 120 km/h and 500 km/h, respectively.

TABLE I. THE DESIGN SPECIFICATIONS OF THE TRANSMISSION AND RECEIVING ENDS

System Parameter	Studied Case	Comment
Subcarrier Number	512	FFT size
Sample Frequency	7.68 Hz	
Subcarrier Spacing	15 K Hz	
Carrier Frequency	2.5 GHz	
Used Subcarriers	400	Pilot: 80; Data: 320
Guard Interval Ratio	1/4	
Constellation	QPSK, 16-QAM, 64-QAM	
Pilot Constellation	Hierarchical 64-QAM	(λ_1 = 1.6, λ_2 = 1.4)
Doppler Shift	30 km/h, 120 km/h, 500 km/h	

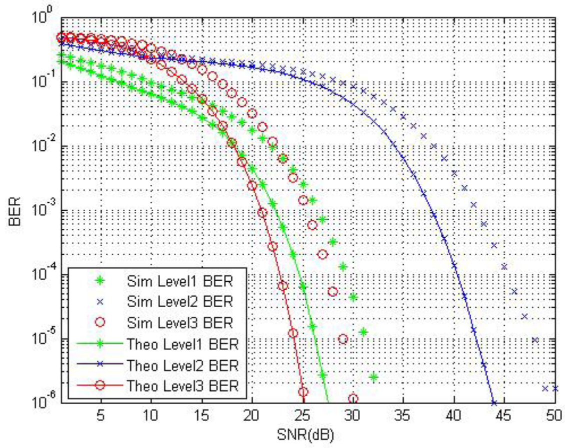

Figure 12. The BER of each level (V: 30 km/h, fs: 7.68 MHz)

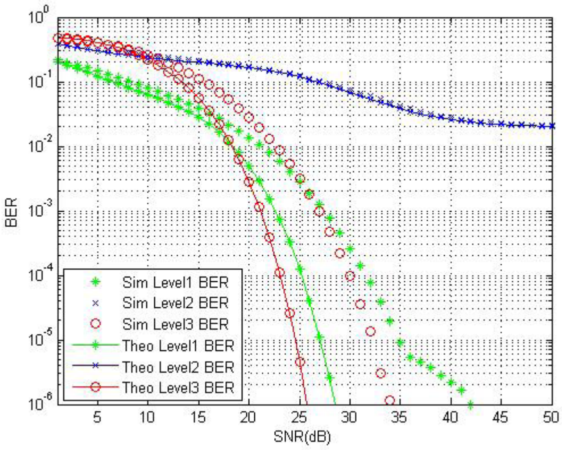

Figure 13. The BER of each level (V: 120 km/h, fs: 7.68 MHz)

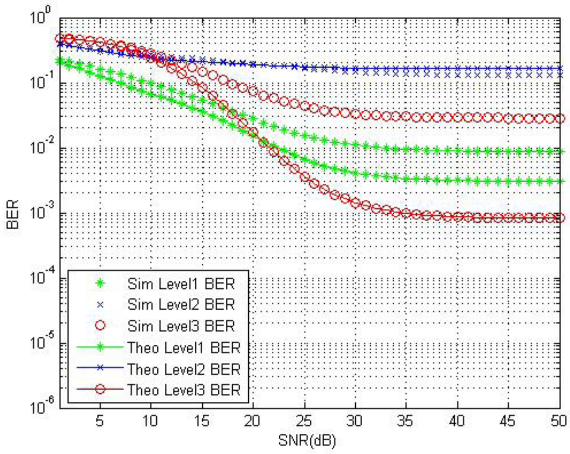

Figure 14. The BER of each level (V: 500 km/h, fs: 7.68 MHz)

V. CONCLUSION

As shown in Fig. 12, 13 and 14, the error rate performance for the simulation results was significantly inferior to that of the mathematical analysis for all given velocities. This was because the mathematical analysis proposed in this study considered only AWGN and CFO, ignoring the channel attenuation caused by multiple paths. Channel attenuation reduces the overall error rate performance of the proposed system to a degree significantly inferior to that provided by mathematical analysis. This leads to overestimations of the CFO by the receiving end compared to the actual frequency shift or offset produced by the Doppler effect. We used a flow-chart and table-referencing method based on the error rates for various levels (Nerr1, Nerr2, Nerr3) solved for in real-time by the receiving end to estimate the CFO . The results obtained when the channel SNR was assumed to be known and high are shown in Table II.

TABLE II. CFO SIMULATION RESULTS

Velocity (Km/h)	30	120	500
Doppler Shift (Hz)	69.4	277.8	1157.4
Normalized Doppler Shift	0.0046	0.0185	0.0772
Normalized Doppler Shift Based on Flowcharts	0.001~0.01	0.01~0.05	0.11~0.15
Estimated Doppler Shift (Level 1)	X	X	0.15
Estimated Doppler Shift (Level 2)	0.007	0.019	0.08
Estimated Doppler Shift (Level 3)	X	X	0.135

Table II shows that the CFO at velocities of 30 km/h and 120 km/h can be accurately estimated using flowcharts. However, at high velocities, the flowchart estimation method overestimates the overall CFO degree. We also employed Nerr1 and Nerr3 for a table comparison. Because Level 1 and Level 3 do not produce error rates between 10−1 and 10−6 at low velocities, we cannot make judgments based on received error rates. Furthermore, overestimation also occurs at high velocities. Only by using Nerr2 as the sole judgment table reference can we obtain relatively accurate judgments at low and high velocities. The reason for the inaccurate judgments at 30 km/h was that the buffer designed for the receiving end was 1 MB. The minimum receivable error rate was 10−6; thus, slight inaccuracies can occur. Because the mathematical analysis of this study considered only the influence of AWGN and CFO without considering the channel attenuation problem, the simulated error rates differed from the mathematical analysis results. This difference can cause the system to overestimate the CFO degree. Additionally, to simplify inter-carrier interference (ICI), we treated ICI as having Gaussian distribution. In other words, ICI was considered a type of AWGN. However, the actual ICI was not Gaussian distributed. Thus, this assumption could cause errors in mathematical equation analyses [7].

ACKNOWLEDGMENT

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