Derivation and Analysis of the BER Closed Form in the OFDM Communication System with IQ Imbalance

Nguyen Thanh Hieu[1] · Byung-Su Kang[2] · Kwangchun Lee[2] · Heung-Gyoon Ryu[1]

Abstract

Orthogonal frequency division multiplexing(OFDM) is very useful for the wireless communication system. However, OFDM is very sensitive to the radio frequency impairments. One of the most important major impairments is the IQ imbalance between in-phase(I) and quadrature(Q) branches in the up and down-conversion. IQ imbalance can be divided into phase and amplitude imbalances. These imbalances make constellation of signal to expand and rotate. The performance of system is severely degraded. In this paper, a closed-form for the bit error probability of the OFDM signal in IQ imbalance environment is derived in terms of the function of phase and amplitude imbalance parameters. So, it will be convenient and useful to evaluate the performance of OFDM communication system with IQ imbalance. It is confirmed that computer simulation results closely match with the results of the analytical derivation. When phase imbalance φ=20°, amplitude imbalance ε=0.1; 0.3; 0.4; 0.5, BER at 10^{-5} is severely degraded by 1.8 dB, 3.12 dB, 4.72, and 8.44 dB, respectively.

Key words : BER, OFDM, IQ Imbalance, QAM.

Ⅰ. Introduction

In recent years, orthogonal frequency division multiplexing(OFDM) has been used widely in digital wireless transmission area. It has been adopted in several communication systems such as wireless local area network(WLAN) IEEE 802.11a[1], wireless metropolitan area network(WMAN) IEEE 802.16a[2], digital audio broadcasting(DAB), digital video broadcasting(DVB-T)[3]. OFDM is also a potential candidate for four-generation (4G) mobile wireless system. OFDM divides frequency selective channel into several frequency-flat sub-channels that provides greater immunity to multi-path fading. However, OFDM is very sensitive to the impairments of radio frequency(RF) front-end. A major source of impairment is the imbalance between in-phase (I) and quadrature phase (Q) components of signal.

In this paper, we study the impact of IQ imbalance including the amplitude and phase imbalance on the OFDM system. Usually, base-band signal is up-converted to radio frequency before transmission through the antenna. In the receiver side, RF signal is down-converted to base-band. Both cosine and sine waveforms are basically used for the OFDM signal representation. Due to the several sources of inaccuracies, the phase difference between cosine and sine waveform is not exactly 90° and they do not have the same amplitude levels. Then, IQ imbalance causes severely degradation for performance of system. The effects of IQ imbalance have been investigated in the several conventional studies. In [4], [5], up-conversion, down-conversion and IQ imbalance in analog domain were introduced. The model for phase and amplitude mismatch was derived in [6]. The effect of IQ imbalance on OFDM system was investigated in [7], [8]. In [9], simulation results showed the limit of IQ imbalance in MIMO-OFDM system. The authors also designed MIMO receiver architectures that are robustness to IQ imbalance by exploiting the structure of orthogonal space-time codes. In [10], authors proposed an estimation technique for calculating the imbalance parameter. Estimated parameters are used to calibrate the receiver imbalance. IQ imbalance and several impairments which are phase noise, frequency offset are investigated in [11], [12]. In these papers, additional effects from channel estimation on IQ compensation and procedure to compensate have been considered. However, the relationship between performance degradation and IQ imbalance has not been derived in closed-form.

In this paper, we investigate the performance of OFDM communication system in the IQ imbalance environment. Closed-form for the bit error probability is proposed in the function of imbalance parameters. This equation is convenient to evaluate the performance of OFDM system with IQ imbalance. Computer simulation is carried out verify the closed-form for the bit error

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[1]Dept. of Electronic Engineering and Research Institute of Computer, Information & Communication, Chungbuk National University, Cheongju, Korea.
[2]RF Technology Team, Mobile Telecommunication Research Division, ETRI, Daejeon, Korea.

probability. We find that simulation result is very close to analytical result.

II. System Description

OFDM can be implemented efficiently by FFT and IFFT. In transmitter side, IFFT convert signal in frequency domain into signal in time domain. The simple block diagram of OFDM transmitter is illustrated in Fig. 1.

Let $X=[X_0, X_1,\cdots, X_N-1]^T$ denotes input data after serial to parallel converter (S/P). The complex base-band of OFDM signal in time domain is given by

$$x(t)=\frac{1}{N}\sum_{n=0}^{N-1}X_n e^{j2\pi\triangle ft}, 0\le t < NT \quad (1)$$

where T is the data period, NT is OFDM symbol duration, $\triangle f=\frac{1}{NT}$ is the sub-carrier spacing. After IFFT, the signal is converted in P/S converter to transmit. The sampled time domain signal $x(t)$ is sequence $x=[x_0, x_1,\cdots, x_{LN-1}]^T$. L is an integer that is larger or equal to 1, which is called as over-sampling factor. When L=1, the samples are achieved by use of Nyquist rate sampling. The "L-time over-sampled" time domain samples can be obtained as

$$x_k=\frac{1}{N}\sum_{n=0}^{N-1}X_n e^{j2\pi\frac{nk}{LN}} \qquad l=0,1,\cdots,LN-1 \quad (2)$$

That is, $x=IFFT(X)$. From now on, we consider the case L=1.

High frequency modulated signal is implemented by quadrature modulation. The real and image part of $x(t)$ are considered as in-phase (I) and quadrature (Q) components. The sine and cosine waveforms of local oscillation are required. Local oscillator(LO) creates cosine waveform for I branch, phase this signal is shifted by 90° for the Q branch. Transmitted signal has the form of

$$s(t)=I(t)\cos\omega_c t+Q(t)\sin\omega_c t \quad (3)$$

where ω_c is angle frequency of carrier. Due to the several sources of inaccuracies[6], shifting RF signal will make imbalance in two branches. The IQ imbalance is generated in the amplitude and phase, which is modeled in Fig. 2.

So, transmitted signal is represented by

$$\tilde{s}(t)=I\left(1+\frac{\varepsilon}{2}\right)\cos\left(\omega_c t+\frac{\phi}{2}\right)+Q\left(1-\frac{\varepsilon}{2}\right)\sin\left(\omega_c t-\frac{\phi}{2}\right) \quad (4)$$

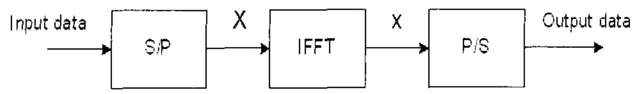


Fig. 1. Simple block diagram of OFDM transmitter.

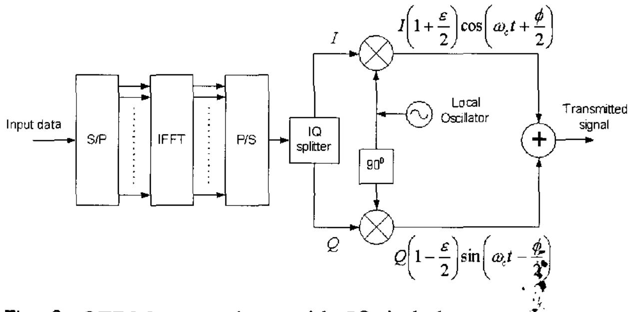


Fig. 2. OFDM transmitter with IQ imbalance.

where ε is amplitude imbalance and φ is phase imbalance between I and Q branches from the ideal case. The performance of system is degraded by IQ imbalance.

At the quadrature demodulation, received signal is multiplied by the local carrier signals $\cos\omega_c t$ and $\sin\omega_c t$ respectively. After multiplying and low-pass filtering, the signal is combined in the IQ combiner. If we assume the noise-free channel, the combined signal in complex form is

$$r(t)=\left[I\left(1+\frac{\varepsilon}{2}\right)\cos\frac{\phi}{2}-Q\left(1+\frac{\varepsilon}{2}\right)\sin\frac{\phi}{2}\right] + j\left[-I\left(1-\frac{\varepsilon}{2}\right)\sin\frac{\phi}{2}+Q\left(1-\frac{\varepsilon}{2}\right)\cos\frac{\phi}{2}\right]. \quad (5)$$

After some calculations[13], we can derive

$$r(t)=\left(\cos\frac{\phi}{2}+j\frac{\varepsilon}{2}\sin\frac{\phi}{2}\right)x(t) + \left(\frac{\varepsilon}{2}\cos\frac{\phi}{2}-j\sin\frac{\phi}{2}\right)x^*(t) \quad (6)$$

$$r(t)=a_1x(t)+a_2x^*(t) \quad (7)$$

where $x(t)=I(t)+jQ(t)$; $x^*(t)$ is conjugate of $x(t)$.

$$a_1=\cos\frac{\phi}{2}+j\frac{\varepsilon}{2}\sin\frac{\phi}{2} \quad (8)$$

and, $$a_2=\frac{\varepsilon}{2}\cos\frac{\phi}{2}-j\sin\frac{\phi}{2} \quad (9)$$

After down conversion, complex base-band signal $r(t)$ is sent to OFDM demodulation. Discrete form of $r(t)$ is found from serial to parallel $r=r[r_0, r_1,\cdots, r_{N-1}]^T$. Taking the FFT operation, we have

$$R=a_1X+a_2X^{\#} \quad (10)$$

where $R=[R_0, R_1,\cdots, R_{N-1}]^T=FFT(r)$, $X=FFT(x)=[X_0, X_1, \cdots, X_{N-1}]^T$

$X^{\#}=FFT(x^*)=[X_0^*, X^*_{N-1},\cdots, X^*_{N/2}, X^*_{N/2-1},\cdots, X_1^*]^T$

The received signal is scaled by a_1 and interfered by mirror image. The complex conjugate value is scaled by a_2. The second component is self-interference and reduces the noise margin.

Ⅲ. BER Derivation and Analysis

After up-conversion at quadrature modulation, the signal $\hat{s}(t)$ is transmitted over AWGN channel. The received signal through AWGN is expressed by

$$s_r(t) = \hat{s}(t) + n(t) \tag{11}$$

where $n(t) = n_I \cos\omega_c t + n_Q \sin\omega_c t$ and n_I and n_Q are zero-mean Gaussian random variables with variances $\sigma^2_{N_I} = \sigma^2_{N_Q} = \sigma^2_N/2$.

At the receiver, down-converted signal is obtained by multiplying with cosine and sine waveform of local oscillator at each branch and low-pass filtering(LPF). For the convenience, we assume these signals in each branch are $2\cos\omega_c t$ and $2\sin\omega_c t$ respectively. The baseband signal is represented by

$$\begin{aligned} r(t) = & LPF\Big(\Big(2\Big(I\Big(1+\frac{\varepsilon}{2}\Big)\cos\Big(\omega_c t+\frac{\phi}{2}\Big)+Q\Big(1-\frac{\varepsilon}{2}\Big)\cdot \\ & \sin\Big(\omega_c t-\frac{\phi}{2}\Big)+n_1\cos\omega_c t+n_Q\sin\omega_c t\Big)\cos\omega_c t\Big)\Big) \\ & +jLPF\Big(2\Big(I\Big(1+\frac{\varepsilon}{2}\Big)\cos\Big(\omega_c t+\frac{\phi}{2}\Big)+Q\Big(1-\frac{\varepsilon}{2}\Big)\cdot \\ & \sin\Big(\omega_c t-\frac{\phi}{2}\Big)+n_1\cos\omega_c t+n_Q\sin\omega_c t\Big)\sin\omega_c t\Big) \end{aligned} \tag{12}$$

After some calculation we have

$$\begin{aligned} r(t) = & \Big[I\Big(1+\frac{\varepsilon}{2}\Big)\cos\frac{\phi}{2}-Q\Big(1+\frac{\varepsilon}{2}\Big)\sin\frac{\phi}{2}\Big] \\ & +j\Big[-I\Big(1-\frac{\varepsilon}{2}\Big)\sin\frac{\phi}{2}+Q\Big(1-\frac{\varepsilon}{2}\Big)\cos\frac{\phi}{2}\Big]+n_I+jn_Q \end{aligned} \tag{13}$$

According to (6) and (7), (13) can be written as

$$r(t) = \alpha_1 x(t) + \alpha_2 x^*(t) + n_1 + jn_Q \tag{14}$$

where α_1 and α_2 are calculated by (8) and (9).

OFDM signal $x(t) = I(t) + jQ(t)$ is a summation of several waveforms, so that they are complex stationary Gaussian process with equal distributed, zero-mean, variances, $\sigma_I^2 = \sigma_Q^2 = \sigma^2$, independent $I(t)$ and $Q(t)$ components. We assume

$$I_1 = I(t), \quad I_2 = I(t+\tau) \tag{15}$$

$$Q_1 = Q(t), \quad Q_2 = Q(t+\tau) \tag{16}$$

The joint pdf is expressed by

$$\begin{aligned} p(I_z, I_2, Q_1, Q_2) = p(I_z, I_2)p(Q_1, Q_2) = \frac{1}{(2\pi)^2\delta^4(1-\rho^2)}\cdot \\ \exp\Big(-\frac{(I_1^2+Q_1^2)+(I_2^2+Q_2^2)-2\rho(I_1I_2+Q_1Q_2)}{2\sigma^2(1-\rho^2)}\Big) \end{aligned} \tag{17}$$

The autocorrelation of OFDM signal

$$\begin{aligned} R_{xx}(\tau) &= E\{x^*(t)x(t+\tau)\} = E\{(I_1-jQ_1)(I_2+jQ_2)\} \\ &= [R_{II}(\tau)+R_{QQ}(\tau)]+j[R_{IQ}(\tau)-R_{QI}(\tau)] \end{aligned} \tag{18}$$

Because I and Q are two independent Gaussian variables, $R_{II}(0) = R_{QQ}(0) = \sigma^2$ and $R_{IQ}(0) = R_{QI}(0) = 0$. Then $R_{xx}(0) = 2R_{II}(0) = 2\sigma^2 = \sigma_x^2$. By the same way we can compute the autocorrelation $R_{x^*x^*}(0) = 2\sigma^2 = \sigma_x^2$.

The power of desired signal can be calculated by

$$P_s = E[\alpha_1^* x^*(t)\cdot\alpha_1 x(t+\tau)]|_{\tau=0} = |\alpha_1|^2 R_{xx}(0) = |\alpha_1|^2\sigma_x^2 \tag{19}$$

Similarly, power of image component

$$P_i = E[\alpha_2^* x(t)\cdot\alpha_2 x^*(t+\tau)]|_{\tau=0} = |\alpha_2|^2 R_{x^*x^*}(0) = |\alpha_2|^2\sigma_x^2 \tag{20}$$

The ratio of interfered and desired signal is called image rejection ratio(IIR) defined by

$$IRR = \frac{P_i}{P_s} = \frac{|\alpha_2|^2}{|\alpha_1|^2} = \frac{\frac{\varepsilon^2}{4}\cos^2\frac{\phi}{2}+\sin^2\frac{\phi}{2}}{\cos^2\frac{\phi}{2}+\frac{\varepsilon^2}{4}\sin^2\frac{\phi}{2}} \tag{21}$$

This value in dB is computed by $IIR(dB)$=10log(1+ IIR).

The power of additional noise is

$$P_N = P_{N_I} + P_{N_Q} = \sigma^2_{N_I} + \sigma^2_{N_Q} = \sigma^2_N \tag{22}$$

The ratio of desired signal and interfered signal and noise is

$$\begin{aligned} SNR &= \frac{P_S}{P_i+P_N} = \frac{|\alpha_1|^2\sigma_x^2}{|\alpha_2|^2\sigma_x^2+\sigma_N^2} \\ &= \frac{|\alpha_1|^2\sigma_x^2/\sigma_N^2}{|\alpha_2|^2\sigma_x^2+\sigma_N^2+1} = \frac{|\alpha_1|^2E_s/N_0}{|\alpha_2|^2E_s/N_0+1} \end{aligned} \tag{23}$$

The bit error rate of BPSK or QPSK signal is given by $BER = Q(\sqrt{2SNR})$, where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty} e^{-\frac{t^2}{2}}\, dt$. Replacing to (23), we can have the closed form of BER.

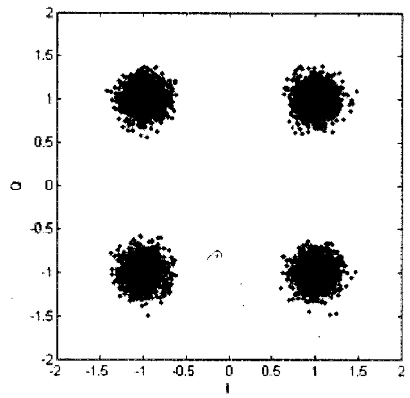
$$\begin{aligned} BER &= Q\Big(\sqrt{2\frac{|\alpha_1|^2E_b/N_0}{|\alpha_2|^2E_b/N_0+1}} \\ &= Q\Big(\sqrt{2\frac{(\cos^2\phi/2+\varepsilon^2/4\sin^2\phi/2)E_b/N_0}{(\varepsilon^2/4\cos^2\phi/2+\sin^2\phi/2)E_b/N_0+1}}\Big) \end{aligned} \tag{24}$$

If there is no IQ imbalance i.e. ε=0 and φ=0, the BER formula reduces to the simple form of BER performance of BPSK or QPSK in AWGN channel, $BER = Q(\sqrt{2E_b/N_0})$.

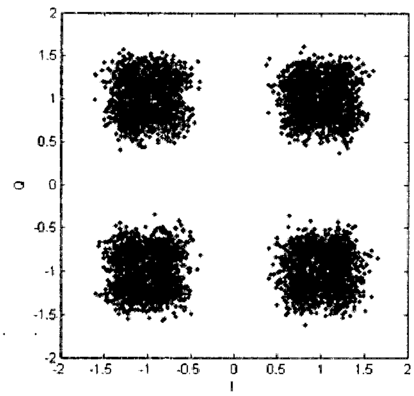
Ⅳ. Numerical Results and Discussion

The performance of OFDM system with IQ imbalance is carried out to verify the analytical results by simulation. OFDM system has the following parameters: number of sub-carrier: N=64, data constellation: QPSK.

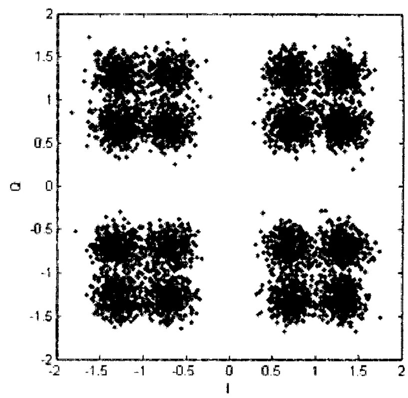
Constellation of received signal is shown in Fig. 3. When IQ imbalance is amplitude or phase imbalance respectively, constellation is extended. Otherwise, if IQ imbalance includes amplitude and phase imbalance,



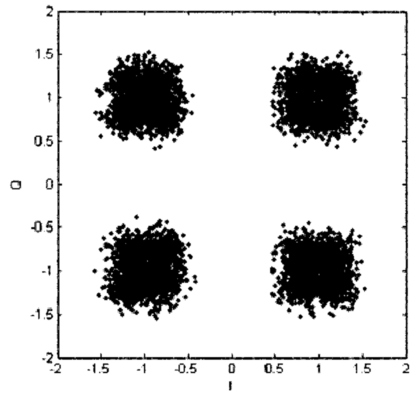
(a) Signal constellation without IQ imbalance (E_b/N_0=15 dB)



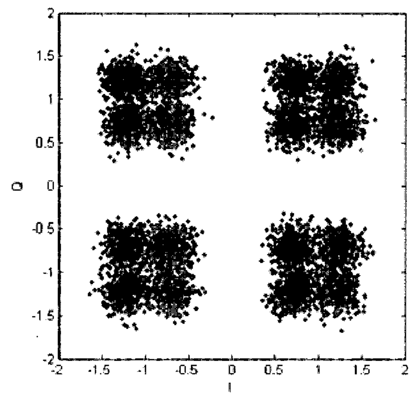
(b) Signal constellation with only amplitude imbalance ε =0.4 (E_b/N_0=15 dB)



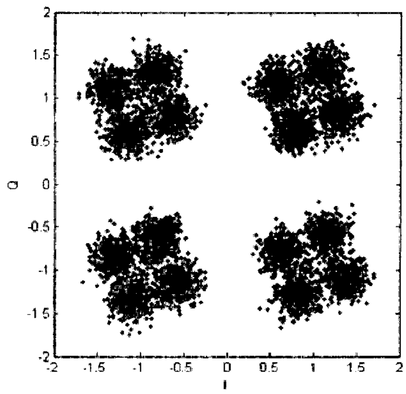
(c) Signal constellation with only amplitude imbalance ε =0.6 (E_b/N_0=15 dB)



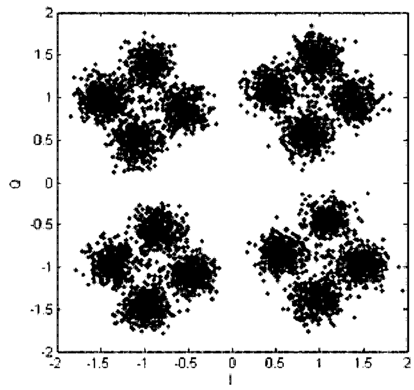
(d) Signal constellation with only phase imbalance φ=20° (E_b/N_0= 15 dB)



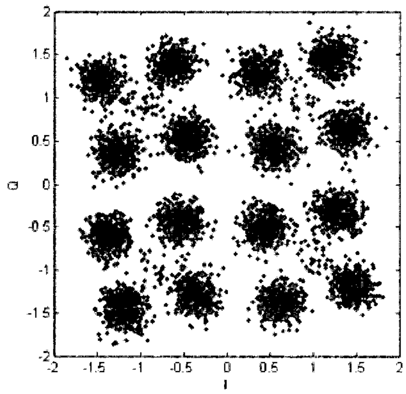
(e) Signal constellation with only phase imbalance φ=30° (E_b/N_0= 15 dB)



(f) Signal constellation with IQ imbalance ε =0.2, φ =30° (Eb/N_0= 15 dB)



(g) Signal constellation with IQ imbalance ε =0.4, φ =30° (E_b/N_0=15 dB)



(h) Signal constellation with IQ imbalance ε =0.2, φ =50° (Eb/N_0=15 dB)

Fig. 3. Constellation of OFDM signal.

constellation is not only extended but also rotated. In contrast with other RF impairments e.g. phase noise, nonlinear amplifier···, IQ imbalance has discrete value of ε and φ because constellation is rotated and divided into several parts instead of spread constellation. When the received signal excesses the decision threshold, it will make error in the received data. Obviously, IQ imbalance reduces the noise margin of system.

The self-interference (mirror image) component in the received signal makes degradation in the signal to noise ratio(SNR). The quantity of SNR degradation represented by IIR versus ε and φ is illustrated in Fig. 4. At origin $\varepsilon=0$ and $\varphi=0$, value of IIR is also equal zero and there is no degradation in SNR. The loss of SNR will increase when ε and φ increase.

Loss in SNR of OFDM system results in degradation of BER performance. Simulation of BER performance is carried out to verify analytical result in Eq. (24). Fig. 5 shows BER performance of OFDM system with only phase IQ imbalance. These curves of BER versus E_b/N_0 correspond to ideal case and phase imbalance is $\varphi=10$, 20, 25, 30° respectively. At 10^{-5}, BER is degraded by 0.45 dB, 1.66 dB, 2.8 dB, and 5 dB from ideal case 9.5 dB to 9.95 dB, 11.16 dB, 12.3 dB and 14.5 dB. Fig. 6 illustrates BER performance when only amplitude IQ imbalance is considered. Amplitude imbalance $\varepsilon=0.2$; 0.3; 0.4; 0.5 make BER is degraded by 0.5 dB, 1.08 dB, 2.05 dB, and 3.84 dB correspondingly. Fig. 7 and Fig. 8

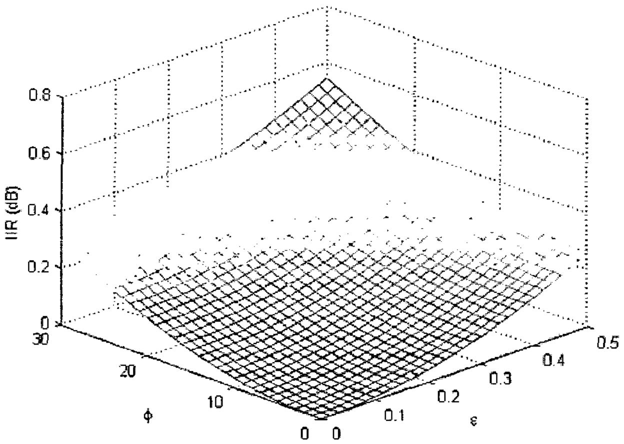


Fig. 4. Image rejection ratio (IIR) (dB).

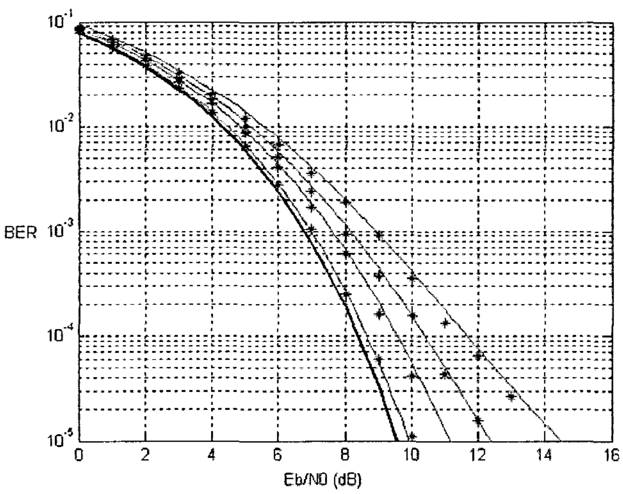


Fig. 5. BER curves (1) at $\varepsilon=0$; $\varphi=10$, 20, 25, 30°.

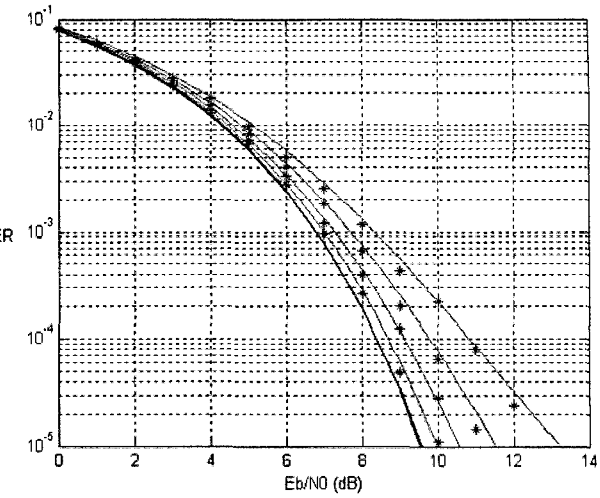


Fig. 6. BER curves (2) at $\varepsilon=0.2$; 0.3; 0.4; 0.5; $\varphi=0°$.

are BER performances when both amplitude and phase imbalance are concerned. In Fig. 7, when $\varphi=10°$, $\varepsilon=$ 0.2; 0.3; 0.4; 0.5 make BER is degraded by 0.88 dB, 1.51 dB, 2.59 dB, and 4.53 dB at 10^{-5}. In Fig. 8, when $\varphi=20°$, $\varepsilon=0.1$; 0.3; 0.4; 0.5 make BER is degraded by 1.8 dB, 3.12 dB, 4.72, and 8.44 dB. From all results of BER performance analysis and comparison, it can be confirmed that simulation results are very close to analytical results. Closed-form for probability of bit error in (24) can be used to estimate or predict the communication performance of OFDM system with IQ imbalance.

Ⅴ. Conclusion

The impairments of RF front-end make degradation in the OFDM communication system performance. The im-

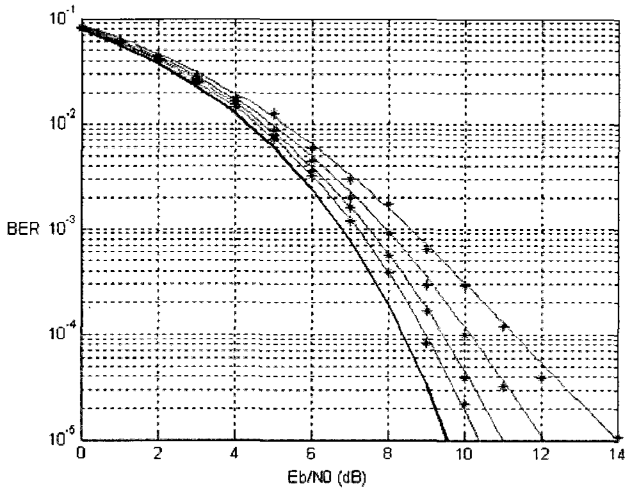


Fig. 7. BER curves (3) at $\varepsilon=0.2$; 0.3; 0.4; 0.5; $\varphi=10°$.

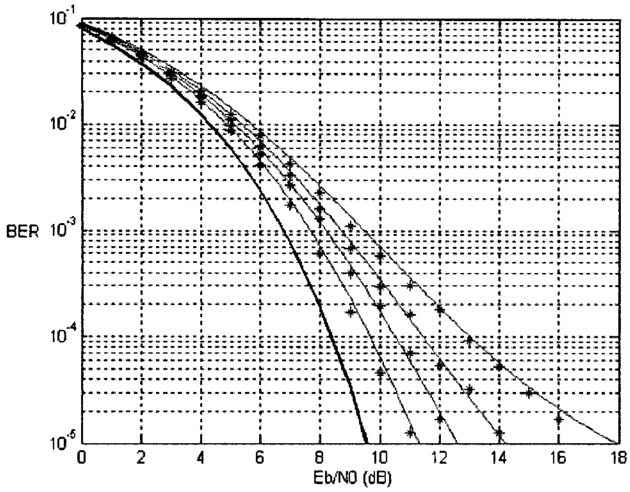


Fig. 8. BER curves (4) ε=0.1; 0.3; 0.4; 0.5; φ=20°.

balance between I and Q branches of up-conversion stage causes degradation in BER performance. In this paper, the effect of IQ imbalance is investigated. Closed-form for error probability for OFDM system with IQ imbalance is derived. Derived closed-form for bit error probability is a function of phase and amplitude imbalance parameters. This form is convenient for evaluating the performance of OFDM system with IQ imbalance. Computer simulations are carried and simulation result is very close to the analytical result. When phase imbalance φ=20°, amplitude imbalance ε=0.1; 0.3; 0.4; 0.5, BER at 10^{-5} level will is degraded by 1.8 dB, 3.12 dB, 4.72, and 8.44 dB, respectively.

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Nguyen Thanh Hieu

was born in Hanoi, Vietnam, August 25th 1977. He received the B.S. degree in the department of electronics and telecommunication from Vietnam National University in Hanoi, June 1999. He received the M.S. degree in the department of electronics and communications engineer- ing, Vietnam national university in Hanoi, June 2003. He is currently working toward Ph.D. degree in the department of electronic engineering, Chungbuk National University, Republic of Korea. From January 2000 to June 2004, he was a lecturer in the telecommunication division faculty of technology, Vietnam National University in Hanoi, Vietnam. His research interests include digital communication system, OFDM system design and nonlinearity compensation problems of OFDM and CDMA communication system.

Kwangchun Lee

received B.E. and M.E. degrees in the department of electronics from ChungAng University, Seoul, Korea in 1986 and 1988 respectively. Since 1988, he has worked for ETRI and he serves as a team leader. Current research interests include mobile communication, RF system and wireless space channel modeling.

Byung-Su Kang

received B.E. and M.E. degrees in the department of electronics from Kyungpook National University, Republic of Korea in 1997 and 1999, respectively. He joined ETRI in 1999. His main research areas are mixed-analog system design and radio frequency(RF) engineering.

Heung-Gyoon Ryu(M'88)

was born in Seoul, Republic of Korea 1959. He received the B.S. and M.S. and Ph.D. degrees in electronic engineering from Seoul National University in Seoul, Korea 1982, 1984 and 1988. Since 1988, he has been with Chungbuk National University, Korea, where he is currently a professor of department of electrical, electronic and computer engineering in Chungbuk National University. He worked as chief director of RICIC(research institute of computer, information communication center) in Chungbuk National University from March 2002 to Feb. 2004. His main research interests are digital communication systems, commuication circuit design, spread spectrum system and communication signal processing. Since 1999, he has worked as reviewer of the IEEE transaction papers. He received the '2002 ACADEMIC AWARD' from the Korea Electromagnetic Engineering Society, Korea.