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다중 접합 기반 수신기의 영상 제거비 평가 및 향상 방법

(Improvement in Image Rejection of Multi-Port Junction-based Direct Receivers)

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요 약

본 논문에서는 다중 접합 기반 수신기 (MPDR)의 영상 제거 성능을 향상시키는 반복적인 단일주파수 CW 신호 기반 I/Q 신호 재생 알고리즘을 제안한다. 이 논문에서는 MPDR 수신기의 I/Q 신호 재생이 직접변환수신기의 I/Q 부정합 보상임을 보인다. 분석을 바탕으로 I/Q 재생의 정확도를 영상 제거비로써 평가한다. 제안한 방법은 기존의 I/Q 신호 재생 방법에 비해서 20dB 이상 영상 제거비를 향상시킨다. 모의실험 결과는 제안한 방법을 이용한 MPDR 수신기의 영상 제거비가 70dB 이상임을 보이고, 비트오율 성능은 페이딩 채널 환경에서 조차도 일반적인 동기 수신기의 성능과 거의 같음을 보인다.

Abstract

This paper presents an iterative single-frequency continuous-wave signal-based I/Q regeneration method for improving image-rejection performance of multi-port junction-based direct receivers (MPDRs). This paper analyzes I/Q regeneration in MPDRs as I/Q mismatch compensation for direct conversion receivers. Based on the analysis, this paper evaluates the accuracy of I/Q regeneration in terms of the image-rejection ratio (IRR). The proposed method improves the IRR performance more than 20 dB compared to existing I/Q regeneration methods. Simulation results show that MPDRs using the proposed method can achieve an IRR of more than 70 dB, and that the bit error rate performances are almost the same as those of conventional coherent demodulators, even in fading channels.

Keywords : Multi-port junction, I/Q regeneration, image rejection, Rayleigh fading channel.

Ⅰ. 서 론

As the demand for high-speed wireless communications, various wireless communication standards have been developed or are under development, including IEEE 802.11n,[1] 4th Generation (4G) mobile communication, and IEEE 802.15.3a.[2] The band below 5GHz is heavily occupied by many communication systems and hence does not provide sufficient bandwidth for multi-Gbps wireless communication. Recently, standards have been developed that specify operation in the higher frequencies, such as the 10GHz band or the 60GHz band.[3~4] CMOS radio-frequency integrated circuit (RFIC) is widely used in communications at frequencies below 5GHz. However, for higher frequency communications, monolithic microwave integrated circuits (MMICs) or multi-port (e.g., five- or six-port) junction-based direct receivers (MPDRs)

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using passive microwave components may be used.* MPDRs have the following advantages compared with conventional receivers using active devices. First, the use of passive devices provides improved wideband characteristics. Second, the power consumption is reduced due to the use of passive microwave components, such as directional couplers and power dividers. Third, hardware imperfections and wideband characteristics can be improved by calibrating the multi-port junction.[6-7] However, there have been no direct and quantitative methods but bit error rate (BER) to measure the performances of MPDRs.[5, 8~10]

This paper, first, theoretically analyzes impairment of MPDRs and examines the relationship between impairment and I/Q imbalance. Based on the analysis, the image-rejection ratio (IRR) can be used to measure the degree of impairment of MPDRs. A new impairment compensation, i.e., I/Q regeneration, method is proposed to improve the IRR performance of MPDRs.** In Section 2, the impairment of MPDRs is analyzed. And, the relationship between impairment and I/Q imbalance is examined. An iterative single-frequency CW signal-based I/Q regeneration method is proposed in Section 3. In Section 4, the IRR and the BER performances of MPDRs using the proposed method are evaluated. Finally, conclusions are presented in Section 5.

Ⅱ. Impairment of MPDRs and I/Q Imbalance

Fig. 1 shows the block diagram of an MPDR. As shown in Fig. 1, two ports in a multi-port junction are connected with $r(t)$ and $c(t)$, respectively. In the remaining three ports, $r(t)$ and $c(t)$ are additively mixed using diode and low-pass filter (LPF). It is written as

$$\begin{aligned} &P_i(t) = \\ &A^2|\alpha_i|^2/2 + |\beta_i|^2/2 \cdot \left(I_m^2(t) + Q_m^2(t)\right) \\ &+ 2A|\alpha_i\beta_i| \cdot \left(I_m(t)\cos(\phi_o - \phi_i) + Q_m(t)\sin(\phi_o - \phi_i)\right) \end{aligned} \quad (1)$$

In (1), $|\alpha_i|$ and $|\beta_i|$ denote the attenuation values for $c(t)$ and $r(t)$, and $\angle\alpha_i$ and $\angle\beta_i$ are the phase-shift values for $c(t)$ and $r(t)$, respectively. $I_m(t)$ and $Q_m(t)$ are transmitted I- and Q-channel signals, respectively. ϕ_0 denotes the phase difference between $c(t)$ and $r(t)$. And, ϕ_i is the difference between the phase-shift values, i.e., $\angle\beta_i - \angle\alpha_i$. In (1), it is shown that $P_i(t)$ is linearly correlated with $I_m(t)$ and $Q_m(t)$. Hence, $I_m(t)$ and $Q_m(t)$ can be regenerated in terms of the linear combination $P_i(t)$.[8] It is written as

$$\begin{aligned} I_r(t) &= a_{I1}P_1(t) + a_{I2}P_2(t) + a_{I3}P_3(t) \\ Q_r(t) &= a_{Q1}P_1(t) + a_{Q2}P_2(t) + a_{Q3}P_3(t) \end{aligned} \quad (2)$$

where $I_r(t)$ and $Q_r(t)$ denote the regenerated I- and Q-channel signals, respectively. a_{Ii}, a_{Qi} (i=1,2,3) are the I/Q regeneration parameters. These parameters must be determined in order to regenerate the I- and Q-channel signals from $P_i(t)$. When the multi-port junction is ideal, $I_r(t)$ and $Q_r(t)$ must be identical to $I_m(t)$ and $Q_m(t)$, respectively. By inserting (1) in (2), a_{Ii}, a_{Qi} (i=1,2,3) are written as

$$\begin{aligned} a_{I2} &= -\frac{|\alpha_1\beta_1|}{|\alpha_2\beta_2|}\frac{\sin(\phi_3-\phi_1)}{\sin(\phi_3-\phi_2)}a_{I1} + \frac{1}{2A|\alpha_2\beta_2|}\frac{\sin\phi_3}{\sin(\phi_3-\phi_2)} \\ a_{I3} &= \frac{|\alpha_1\beta_1|}{|\alpha_3\beta_3|}\frac{\sin(\phi_2-\phi_1)}{\sin(\phi_3-\phi_2)}a_{I1} - \frac{1}{2A|\alpha_3\beta_3|}\frac{\sin\phi_2}{\sin(\phi_3-\phi_2)} \\ a_{Q2} &= -\frac{|\alpha_1\beta_1|}{|\alpha_2\beta_2|}\frac{\sin(\phi_3-\phi_1)}{\sin(\phi_3-\phi_2)}a_{Q1} + \frac{1}{2A|\alpha_2\beta_2|}\frac{\cos\phi_3}{\sin(\phi_3-\phi_2)} \\ a_{Q3} &= \frac{|\alpha_1\beta_1|}{|\alpha_3\beta_3|}\frac{\sin(\phi_2-\phi_1)}{\sin(\phi_3-\phi_2)}a_{Q1} - \frac{1}{2A|\alpha_3\beta_3|}\frac{\cos\phi_2}{\sin(\phi_3-\phi_2)} \end{aligned} \quad (3)$$

However, in reality, attenuation values and phase-shift values in multi-port junctions may deviate from the expected values due to process variation such that the regenerated signals may

* The six-port junction-based direct receiver was proposed in 1994.[5]

** Impairment compensation for MPDRs is designated as the I/Q regeneration.

become different from transmitted signals. When $|\alpha_i|$ and $|\beta_i|$ are changed to $|\alpha_i(1+\Delta\alpha_i)|$ and $|\beta_i(1+\Delta\beta_i)|$, respectively, and ϕ_i is changed to $(\phi_i+\Delta\phi_i)$, then the regenerated I- and Q-channel signals are changed as follows:[11]

$$\begin{aligned} I_r'(t) &= (1+\delta_{Ii})I_m(t)+\delta_{Iq}Q_m(t) \\ &= A_I\cdot\left(I_m(t)\cos\phi_I+Q_m(t)\sin\phi_I\right) \\ Q_r'(t) &= \delta_{Qi}I_m(t)+(1+\delta_{Qq})Q_m(t) \\ &= A_Q\cdot\left(-I_m(t)\sin\phi_Q+Q_m(t)\cos\phi_Q\right) \end{aligned} \tag{4}$$

where

$$\begin{aligned} \delta_{Ii} &= \frac{2A|\alpha_1\beta_1||a_{I1}|}{\sin(\phi_3-\phi_2)}\begin{pmatrix} \sin(\phi_3-\phi_2)\left((\Delta\alpha_1+\Delta\beta_1)\cos\phi_1-\Delta\phi_1\sin\phi_1\right) \\ -\sin(\phi_3-\phi_1)\left((\Delta\alpha_2+\Delta\beta_2)\cos\phi_2-\Delta\phi_2\sin\phi_2\right) \\ +\sin(\phi_2-\phi_1)\left((\Delta\alpha_3+\Delta\beta_3)\cos\phi_3-\Delta\phi_3\sin\phi_3\right) \end{pmatrix} \\ &+\frac{1}{\sin(\phi_3-\phi_2)}\begin{pmatrix} (\Delta\alpha_2+\Delta\beta_2)\cos\phi_2\sin\phi_3 \\ -(\Delta\alpha_3+\Delta\beta_3)\sin\phi_2\cos\phi_3 \\ +(\Delta\phi_3-\Delta\phi_2)\sin\phi_2\sin\phi_3 \end{pmatrix} \\ \delta_{Iq} &= -\frac{2A|\alpha_1\beta_1||a_{I1}|}{\sin(\phi_3-\phi_2)}\begin{pmatrix} \sin(\phi_3-\phi_2)\left((\Delta\alpha_1+\Delta\beta_1)\sin\phi_1+\Delta\phi_1\cos\phi_1\right) \\ -\sin(\phi_3-\phi_1)\left((\Delta\alpha_2+\Delta\beta_2)\sin\phi_2+\Delta\phi_2\cos\phi_2\right) \\ +\sin(\phi_2-\phi_1)\left((\Delta\alpha_3+\Delta\beta_3)\sin\phi_3+\Delta\phi_3\cos\phi_3\right) \end{pmatrix} \\ &-\frac{1}{\sin(\phi_3-\phi_2)}\begin{pmatrix} \Delta\phi_2\cos\phi_2\sin\phi_3-\Delta\phi_3\sin\phi_2\cos\phi_3 \\ +\left((\Delta\alpha_2+\Delta\beta_2)-(\Delta\alpha_3+\Delta\beta_3)\right)\sin\phi_2\sin\phi_3 \end{pmatrix} \\ \delta_{Qi} &= \frac{2A|\alpha_1\beta_1||a_{Q1}|}{\sin(\phi_3-\phi_2)}\begin{pmatrix} \sin(\phi_3-\phi_2)\left((\Delta\alpha_1+\Delta\beta_1)\cos\phi_1-\Delta\phi_1\sin\phi_1\right) \\ -\sin(\phi_3-\phi_1)\left((\Delta\alpha_2+\Delta\beta_2)\cos\phi_2-\Delta\phi_2\sin\phi_2\right) \\ +\sin(\phi_2-\phi_1)\left((\Delta\alpha_3+\Delta\beta_3)\cos\phi_3-\Delta\phi_3\sin\phi_3\right) \end{pmatrix} \\ &+\frac{1}{\sin(\phi_3-\phi_2)}\begin{pmatrix} \Delta\phi_3\cos\phi_2\sin\phi_3-\Delta\phi_2\sin\phi_2\cos\phi_3 \\ +\left((\Delta\alpha_2+\Delta\beta_2)-(\Delta\alpha_3+\Delta\beta_3)\right)\cos\phi_2\cos\phi_3 \end{pmatrix} \\ \delta_{Qq} &= -\frac{2A|\alpha_1\beta_1||a_{Q1}|}{\sin(\phi_3-\phi_2)}\begin{pmatrix} \sin(\phi_3-\phi_2)\left((\Delta\alpha_1+\Delta\beta_1)\sin\phi_1+\Delta\phi_1\cos\phi_1\right) \\ -\sin(\phi_3-\phi_1)\left((\Delta\alpha_2+\Delta\beta_2)\sin\phi_2+\Delta\phi_2\cos\phi_2\right) \\ +\sin(\phi_2-\phi_1)\left((\Delta\alpha_3+\Delta\beta_3)\sin\phi_3+\Delta\phi_3\cos\phi_3\right) \end{pmatrix} \\ &+\frac{1}{\sin(\phi_3-\phi_2)}\begin{pmatrix} (\Delta\alpha_3+\Delta\beta_3)\cos\phi_2\sin\phi_3 \\ -(\Delta\alpha_2+\Delta\beta_2)\sin\phi_2\cos\phi_3 \\ +(\Delta\phi_3-\Delta\phi_2)\cos\phi_2\cos\phi_3 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} A_I &= \sqrt{(1+\delta_{Ii})^2+\delta_{Iq}^2} \\ \phi_I &= \tan^{-1}\frac{\delta_{Iq}}{1+\delta_{Ii}} \\ A_Q &= \sqrt{\delta_{Qi}^2+(1+\delta_{Qq})^2} \\ \phi_Q &= -\frac{\pi}{2}+\tan^{-1}\frac{1+\delta_{Qq}}{\delta_{Qi}} \end{aligned} \tag{5}$$

Equations (4)-(5) show that when the attenuation and phase-shift values for a multi-port junction deviate from the designed values due to the process variation, the regenerated I- and Q-channel signals have an I/Q imbalance. Based on the analysis provided in this paper, the IRR can be used to measure the accuracy of I/Q regeneration for MPDRs. In this paper, we simulate the IRR performance of existing I/Q regeneration methods, which is shown in Table 1. Table 1 shows that MPDRs using existing I/Q regeneration methods may achieve an IRR of between 30 dB and 50 dB. Compared with the IRR performance of conventional receivers using I/Q imbalance compensation methods, performance is degraded by about 20dB.[13~17]

표 1. 기존 I/Q 재생성 방법의 IRR 모의 성능

Table 1. Simulated IRR performance of existing I/Q regeneration methods.

I/Q regeneration methods	IRR
Huang [8]	50 dB
Huang [9]	30 dB
Hentschel [12]	45 dB
Park [10]	38 dB

Ⅲ. Iterative Single-Frequency CW Signal-based I/Q Regeneration Method for MPDRs

To improve the IRR performance of MPDRs, we propose an iterative single-frequency CW signal-based I/Q regeneration method. The proposed method utilizes the symmetry characteristics of the single-frequency CW signal similar to the single-frequency CW signal-based I/Q regeneration method. In the single-frequency CW signal-based I/Q regeneration method, each processing step is performed once.*** In contrast, the proposed method

*** In [10], it was shown that the single-frequency CW signal-based I/Q regeneration method has three processing steps. In the first processing step, the initial I/Q regeneration parameters are determined by using the symmetry characteristics of a single-frequency CW signal. In the second iterates the second and third processing step. In the proposed method, the second processing in the i-th iteration is written as

$$\begin{aligned} I_{r,i,2nd}(t) &= I_{r,i-1,3rd}(t)\cos\theta_i + Q_{r,i-1,3rd}(t)\sin\theta_i \\ Q_{r,i,2nd}(t) &= Q_{r,i-1,3rd}(t)\cos\theta_i - I_{r,i-1,3rd}(t)\sin\theta_i \end{aligned} \quad (6)$$

where $I_{r,i-1,3rd}(t)$ and $Q_{r,i-1,3rd}(t)$ denote the regenerated I- and Q-channel signals after completing the third processing steps in the (i-1)-th iteration, respectively. $I_{r,i,2nd}(t)$ and $Q_{r,i,2nd}(t)$ are the regenerated I- and Q-channel signals after completing the second processing steps in the i-th iteration, respectively. And, θ_i is the phase difference between the major axis of the elliptic-type trajectory diagram and the x-axis. And, the third processing in the i-th iteration is written as

$$\begin{aligned} I_{r,i,3rd}(t) &= I_{r,i,2nd}(t) \\ Q_{r,i,3rd}(t) &= A_i \cdot Q_{r,i,2nd}(t) \end{aligned} \quad (7)$$

where A_i denotes the ratio of the magnitude of the major axis of the elliptic-type trajectory diagram to the magnitude of the minor axis of the elliptic-type trajectory diagram.

As shown in Table 1, since the estimation of I/Q regeneration parameters of the single-frequency CW signal-based I/Q regeneration method is not perfect, when the single-frequency CW signal is transmitted, another elliptic-type trajectory diagram of the regenerated signal is created and the MPDR still has an I/Q imbalance. In the proposed method, by iterating (6) and (7), the trajectory diagram becomes closer to a circle and the IRR performance is improved.

processing step, the regenerated signal is rotated to align the major axis of the elliptic-type trajectory diagram with the x-axis. In the third processing step, the Q-channel signal in the regenerated signal is scaled to align the regenerated signal with the transmitted single-frequency CW signal.

Ⅳ. Performance Evaluation

Fig. 2 shows the simulated spectrum of 64-constellation quadrature amplitude modulation (64-QAM) with the proposed method. Fig. 2 shows that a MPDR using the proposed method may achieve an IRR of about 70 dB, which is more than 20dB better than existing I/Q regeneration methods. And, the IRR performance of MPDRs using the

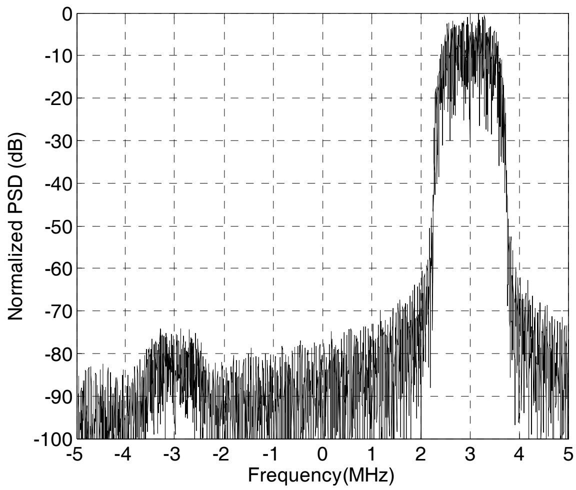

그림 2. ·제안 구조를 적용한 64진 직교 진폭 변조 스펙트럼 모의실험 결과

Fig. 2. ·Simulated 64-QAM spectrum with the proposed method.

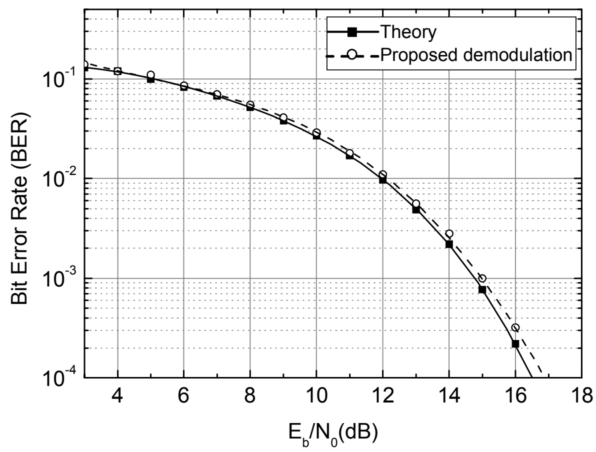

그림 3. 백색 가우시안 잡음 채널에서의 64진 직교 진폭 변조 비트오율 모의실험 결과

Fig. 3. Simulated BER performance of 64-QAM in an AWGN channel.

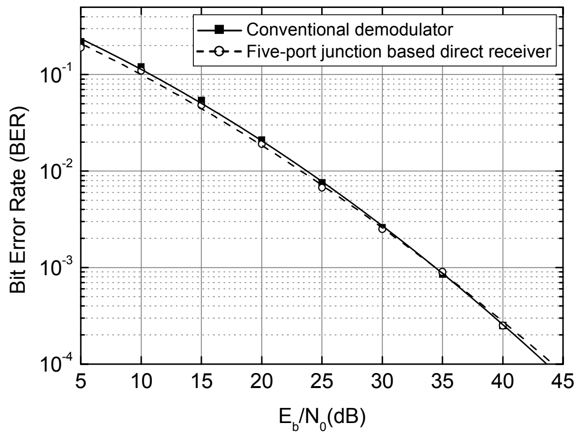

그림 4. 느린 레일리 페이딩 채널에서의 64진 직교 진폭 변조 비트오율 모의실험 결과

Fig. 4. Simulated BER performance of 64-QAM in a slow Rayleigh fading channel.

proposed method is better than or equal to that of conventional receivers using I/Q imbalance compensation methods. Fig. 3 shows the simulated BER performance of 64-QAM in an AWGN channel. Fig. 4 shows the simulated BER performance of 64-QAM in a slow Rayleigh fading channel with normalized fade rate of $f_dT=3\times10^{-2}$.[19]**** Simulation results show that the BER performances of MPDRs using the proposed method are almost the same as those of conventional coherent demodulators, even in slow Rayleigh fading channels.

V. Conclusions

This paper has analyzed the relationship between impairment of MPDRs and I/Q imbalance. Then, based on the analysis, this paper has evaluated the IRR performance of existing I/Q regeneration methods for MPDRs and showed that they have degraded performance compared to the I/Q imbalance compensation methods. An iterative single-frequency continuous-wave signal-based I/Q regeneration method has been proposed to improve the IRR performance of MPDRs. Simulation results have shown that using the proposed method, the IRR and the BER performances of MPDRs become better than or equal to those of conventional coherent demodulators.

**** The Rayleigh fading channel model is generated according to Jakes′ model.[18]

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