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다중 접합 기반 수신기의 I/Q 재생성과 I/Q 부정합의 정량적 분석

(A Quantitative Analysis of I/Q Regeneration and I/Q Mismatch in Multi-Port Junction-based Direct Receivers)

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요 약

본 논문에서는 새로운 해석을 통해서 RFIC에서 사용하는 범용 I/Q 부정합 보상기를 사용하여 다중 접합 기반 수신기에서 I 채널과 Q 채널 정보 신호를 생성할 수 있음을 증명한다. 이 증명으로 다중 접합 기반 수신기를 기존의 RFIC 기반 시스템에 추가적인 디지털 신호 처리 기능 없이 집적할 수 있다. 이 논문에서는 다중 접합기의 I/Q 재생성 파라미터의 정확도와 I/Q 부정합 사이의 관계를 분석하고, 추정 결과와 모의 실험 결과가 거의 일치함을 보인다.

Abstract

This paper proves that multi-port junction-based direct receivers (MPDRs) can regenerate I- and Q-channel signals accurately by using conventional I/Q mismatch compensation. This proof enables MPDRs to be integrated into existing RFIC based systems without additional digital signal processing. This paper analyzes the relationship between accuracy of I/Q regeneration parameters and degree of I/Q mismatch, and shows that the estimation results and the simulation results are almost the same.

Keywords : 5-포트 접합, I/Q 신호 재생성, I/Q 부정합 보정

Ⅰ. Introduction

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].

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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]. In addition, due to the development of various wireless communication standards, portable wireless communication terminals must be able to support several wireless communication standards. Since digital signal processing allows for the possibility of supporting a data rate between several

Mbps and Gbps via pipelining and parallel processing techniques, it is easy to support multiple communication standards on the same digital signal processor. However, it may not be efficient to support multiple communication standards on the same radio-frequency integrated circuit (RFIC) as the operating band and bandwidth strongly depend on process technology. CMOS RFIC is widely used in communications at frequencies below 5GHz. However, for higher frequency communications, monolithic microwave integrated circuits (MMICs) or multi-port junction-based direct receivers (MPDRs) using passive microwave components may be used[5-6]. Multi-port (e.g., five- or six-port) junction-based direct receivers have the following advantages compared with conventional receivers using active devices. First, the power consumption is reduced due to the use of passive microwave components, such as directional couplers and power dividers. Second, the use of passive devices provides improved wideband characteristics compared to those of conventional receivers. It is worth noting that wideband characteristics are important in high-speed communications. Third, hardware imperfections and wideband characteristics can be improved by calibrating the multi-port junction[7-8]. However, MPDRs have the following disadvantages compared with conventional receivers which use active devices. First, the MPDRs require at least three analog-to-digital converters (ADCs). Second, I/Q regeneration is required to regenerate the I- and Q-channel signals from the power signals of a multi-port junction. Since the MPDRs require additional components, there have been difficulties combining them with existing RFICs in existing RFIC based systems.

This paper presents new interpretations of MPDRs and shows that MPDRs can be used directly in existing RFIC based systems. We first prove that I/Q regeneration in MPDRs is identical to I/Q mismatch compensation for RFICs. This leads us to a new interpretation that MPDRs can regenerate I- and Q-channel signals accurately only by using two ADCs and conventional I/Q mismatch compensator that are extensively used in existing RFIC based systems.

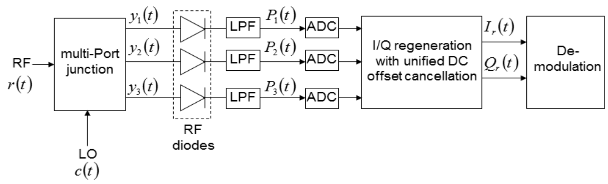


그림 1. MPDR 구조도

Fig. 1. Block diagram of an MPDR.

In Section II, it is proved that a MPDR with imperfect I/Q regeneration parameters can be modeled as a non-ideal direct conversion quadrature demodulator in which the I- and Q-paths have a phase and gain mismatch. In Section III, it is analyzed the relationship between the accuracy of the I/Q regeneration parameters and the degree of I/Q mismatch. Finally, conclusions are presented in Section IV.

Ⅱ. I/Q Regeneration in MPDRs and I/Q Mismatch

Fig. 1 shows the block diagram of an MPDR. Let the modulated carrier signal be written as

$$s(t) = \mathrm{Re}\{m(t)e^{j\omega_c t}\} \tag{1}$$

where ω_c denotes the carrier frequency and Re{x} denotes the real part of x. $m(t)$ denotes the information signal and is written as

$$m(t) = I_m(t) + jQ_m(t) = A_m(t)e^{j\phi_m(t)} \tag{2}$$

The received signal can be expressed as

$$\begin{aligned} r(t) &= s(t) + n(t) = \mathrm{Re}\{m(t)e^{j\omega_c t}\} + n(t) \\ &= A_m(t)\cos(\omega_c t + \phi_m(t)) + n(t) \end{aligned} \tag{3}$$

where $n(t)$ denotes additive white Gaussian noise (AWGN) with two-sided spectral density $N_0/2$. The receiver LO signal is written as*

$$c(t) = \mathrm{Re}\left\{A e^{j(\omega_c t + \phi_0)}\right\} = A\cos(\omega_c t + \phi_0) \quad (4)$$

where ϕ_0 denotes the phase difference between $c(t)$ and $r(t)$. As shown in Fig. 1, two ports in a five-port junction are connected with $r(t)$ and $c(t)$, respectively. The remaining three ports output the signal, which is the linear sum of $r(t)$ and $c(t)$ with each attenuation and phase-shift values. It is written as

$$\begin{aligned} y_i(t) = &|\alpha_i| A\cos(\omega_c t + \phi_0 + \angle\alpha_i) \\ &+ |\beta_i| A_m(t)\cos(\omega_c t + \phi_m(t) + \angle\beta_i) \\ &+ |\beta_i| n(t), \qquad i = 1,2,3 \end{aligned} \quad (5)$$

where $|\alpha_i|$ and $|\beta_i|$ are 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. In the power detection and low pass filtering of $y_i(t)$, $r(t)$ and $c(t)$ are additively mixed such that the received signal $r(t)$ is down-converted to the baseband[10]. Then, the low-pass filtered power signal of $y_i(t)$ ($P_i(t)$ in Fig. 1) is written as

$$\begin{aligned} &P_i(t) = (y_i(t))^2 = \\ &\frac{A^2|\alpha_i|^2}{2} + \frac{|\beta_i|^2}{2}\left(I_m^2(t) + Q_m^2(t)\right) + w_i(t) \\ &+ 2A|\alpha_i\beta_i| \cdot \left(I_m(t)\cos(\phi_o - \phi_i) + Q_m(t)\sin(\phi_o - \phi_i)\right) \\ &\text{where} \\ &\qquad \phi_i = \angle\beta_i - \angle\alpha_i \end{aligned} \quad (6)$$

In (6), $w_i(t)$ is the contribution of channel noise, in which the AWGN is altered by the power detector diode, and $A^2|\alpha_i|^2/2$ and $|\beta_i|^2(I_m^2(t)+Q_m^2(t))/2$ are the rectified signals of $c(t)$ and $r(t)$, respectively. In (6), it is shown that the low-pass filtered power signal $P_i(t)$ is linearly correlated with the transmitted I- and Q-channel signals. Hence, the transmitted I- and Q-channel signals can be regenerated in terms of the linear combination of the low-pass filtered power signals[10]. It is written as

$$\begin{aligned} I_r(t) &= a_{I1}P_1(t) + a_{I2}P_2(t) + a_{I3}P_3(t) \\ Q_r(t) &= a_{Q1}P_1(t) + a_{Q2}P_2(t) + a_{Q3}P_3(t) \end{aligned} \quad (7)$$

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 the power signals of a multi-port junction.

To examine the influence of a non-ideal multi-port junction, let us assume the following conditions: (a) the I/Q regeneration parameters are ideal, (b) the DC offset, i.e. $A^2|\alpha_i|^2/2$, is removed, (c) the amplitude of the LO signal, A, is much greater than 1**, (d) ϕ_0 in (4) is equal to 0, and (e) the channel has no noise. Since A>>1, the power of the rectified signals of $r(t)$ may be much smaller than that of the desired signal component such that it can be removed in (6). When the multi-port junction is ideal, $I_r(t)$ and $Q_r(t)$ must be identical to the transmitted I- and Q-channel signals $I_m(t)$ and $Q_m(t)$, respectively. By inserting (6) in (7), $I_r(t)$ is written as

$$\begin{aligned} I_r(t) = &2AI_m(t)\begin{pmatrix} a_{I1}|\alpha_1\beta_1|\cos\phi_1 \\ + a_{I2}|\alpha_2\beta_2|\cos\phi_2 \\ + a_{I3}|\alpha_3\beta_3|\cos\phi_3 \end{pmatrix} \\ &- 2AQ_m(t)\begin{pmatrix} a_{I1}|\alpha_1\beta_1|\sin\phi_1 \\ + a_{I2}|\alpha_2\beta_2|\sin\phi_2 \\ + a_{I3}|\alpha_3\beta_3|\sin\phi_3 \end{pmatrix} \\ = &I_m(t) \end{aligned} \quad (8)$$

From (8), we find

* In general, the frequency and phase of the LO signal differ from those of the carrier of the received signal. In [9], it was shown that when the single-frequency CW signal is used, the carrier frequency recovery can be completed prior to I/Q regeneration. It is assumed herein that only the carrier phase of the LO signal differs from that of the carrier of the received signal.

** This is expected because, in general, the LO signal power is much greater than the received signal power.

$$2A\begin{pmatrix} a_{I1}\left|\alpha_1\beta_1\right|\cos\phi_1 \\ +a_{I2}\left|\alpha_2\beta_2\right|\cos\phi_2 \\ +a_{I3}\left|\alpha_3\beta_3\right|\cos\phi_3 \end{pmatrix}=1$$
$$\begin{pmatrix} a_{I1}\left|\alpha_1\beta_1\right|\sin\phi_1 \\ +a_{I2}\left|\alpha_2\beta_2\right|\sin\phi_2 \\ +a_{I3}\left|\alpha_3\beta_3\right|\sin\phi_3 \end{pmatrix}=0 \qquad (9)$$

The I channel regeneration parameters satisfying (9) are written as

$$\begin{aligned} a_{I2} &= -\frac{\left|\alpha_1\beta_1\right|}{\left|\alpha_2\beta_2\right|}\frac{\sin(\phi_3-\phi_1)}{\sin(\phi_3-\phi_2)}a_{I1} \\ &\quad +\frac{1}{2A\left|\alpha_2\beta_2\right|}\frac{\sin\phi_3}{\sin(\phi_3-\phi_2)} \\ a_{I3} &= \frac{\left|\alpha_1\beta_1\right|}{\left|\alpha_3\beta_3\right|}\frac{\sin(\phi_2-\phi_1)}{\sin(\phi_3-\phi_2)}a_{I1} \\ &\quad -\frac{1}{2A\left|\alpha_3\beta_3\right|}\frac{\sin\phi_2}{\sin(\phi_3-\phi_2)} \end{aligned} \qquad (10)$$

Since (10) has two equations and three unknowns, there is an infinite set of I channel regeneration parameters, and the two regeneration parameters are expressed in terms of another regeneration parameter. Qr(t) is written as

$$\begin{aligned} Q_r(t) &= 2AI_m(t)\begin{pmatrix} a_{Q1}\left|\alpha_1\beta_1\right|\cos\phi_1 \\ +a_{Q2}\left|\alpha_2\beta_2\right|\cos\phi_2 \\ +a_{Q3}\left|\alpha_3\beta_3\right|\cos\phi_3 \end{pmatrix} \\ &\quad -2AQ_m(t)\begin{pmatrix} a_{Q1}\left|\alpha_1\beta_1\right|\sin\phi_1 \\ +a_{Q2}\left|\alpha_2\beta_2\right|\sin\phi_2 \\ +a_{Q3}\left|\alpha_3\beta_3\right|\sin\phi_3 \end{pmatrix} \\ &= Q_m(t) \end{aligned} \qquad (11)$$

From (11), we find

$$\begin{pmatrix} a_{Q1}\left|\alpha_1\beta_1\right|\cos\phi_1 \\ +a_{Q2}\left|\alpha_2\beta_2\right|\cos\phi_2 \\ +a_{Q3}\left|\alpha_3\beta_3\right|\cos\phi_3 \end{pmatrix}=0$$
$$-2A\begin{pmatrix} a_{Q1}\left|\alpha_1\beta_1\right|\sin\phi_1 \\ +a_{Q2}\left|\alpha_2\beta_2\right|\sin\phi_2 \\ +a_{Q3}\left|\alpha_3\beta_3\right|\sin\phi_3 \end{pmatrix}=1 \qquad (12)$$

The Q channel regeneration parameters which satisfy (12) are written as

$$\begin{aligned} a_{Q2} &= -\frac{\left|\alpha_1\beta_1\right|}{\left|\alpha_2\beta_2\right|}\frac{\sin(\phi_3-\phi_1)}{\sin(\phi_3-\phi_2)}a_{Q1} \\ &\quad +\frac{1}{2A\left|\alpha_2\beta_2\right|}\frac{\cos\phi_3}{\sin(\phi_3-\phi_2)} \\ a_{Q3} &= \frac{\left|\alpha_1\beta_1\right|}{\left|\alpha_3\beta_3\right|}\frac{\sin(\phi_2-\phi_1)}{\sin(\phi_3-\phi_2)}a_{Q1} \\ &\quad -\frac{1}{2A\left|\alpha_3\beta_3\right|}\frac{\cos\phi_2}{\sin(\phi_3-\phi_2)} \end{aligned} \qquad (13)$$

However, in reality, attenuation values and phase-shift values in multi-port junctions may deviate from the expected values due to process variation. Let us assume that $|\alpha_i|$ 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, $P_i(t)$ is changed as follows:

$$\begin{aligned} P'_i(t) &= \frac{A^2\left|\alpha_i(1+\Delta\alpha_i)\right|^2}{2} \\ &\quad +\frac{\left|\beta_i(1+\Delta\beta_i)\right|^2}{2}\left(I_m^2(t)+Q_m^2(t)\right)+w_i(t) \\ &\quad +\begin{pmatrix} 2A\left|(\alpha_i(1+\Delta\alpha_i))(\beta_i(1+\Delta\beta_i))\right| \\ \cdot\begin{pmatrix} I_m(t)\cos(\phi_o-\phi_i-\Delta\phi_i) \\ +Q_m(t)\sin(\phi_o-\phi_i-\Delta\phi_i) \end{pmatrix} \end{pmatrix} \end{aligned} \qquad (14)$$

and the regenerated I- and Q-channel signals are changed as follows:

$$\begin{aligned} I'_r(t) &= a_{I1}P'_1(t) + a_{I2}P'_2(t) + a_{I3}P'_3(t) \\ Q'_r(t) &= a_{Q1}P'_1(t) + a_{Q2}P'_2(t) + a_{Q3}P'_3(t) \end{aligned} \tag{15}$$

where (10) and (13) are used for aIi, aQi (i=1,2,3). By inserting (14) in (15), I'r(t) and Q'r(t) are written as

$$\begin{aligned} Q'_r(t) &= \\ & 2A|\alpha_1\beta_1|a_{Q1}\begin{pmatrix} |(1+\Delta\alpha_1)(1+\Delta\beta_1)|\cos(\phi_1+\Delta\phi_1) \\ -|(1+\Delta\alpha_2)(1+\Delta\beta_2)|\dfrac{\sin(\phi_3-\phi_1)}{\sin(\phi_3-\phi_2)}\cos(\phi_2+\Delta\phi_2) \\ +|(1+\Delta\alpha_3)(1+\Delta\beta_3)|\dfrac{\sin(\phi_2-\phi_1)}{\sin(\phi_3-\phi_2)}\cos(\phi_3+\Delta\phi_3) \end{pmatrix} I_m(t) + \begin{pmatrix} |(1+\Delta\alpha_2)(1+\Delta\beta_2)|\dfrac{\cos\phi_3}{\sin(\phi_3-\phi_2)}\cos(\phi_2+\Delta\phi_2) \\ -|(1+\Delta\alpha_3)(1+\Delta\beta_3)|\dfrac{\cos\phi_2}{\sin(\phi_3-\phi_2)}\cos(\phi_3+\Delta\phi_3) \end{pmatrix} I_m(t) \\ & -2A|\alpha_1\beta_1|a_{Q1}\begin{pmatrix} |(1+\Delta\alpha_1)(1+\Delta\beta_1)|\sin(\phi_1+\Delta\phi_1) \\ -|(1+\Delta\alpha_2)(1+\Delta\beta_2)|\dfrac{\sin(\phi_3-\phi_1)}{\sin(\phi_3-\phi_2)}\sin(\phi_2+\Delta\phi_2) \\ +|(1+\Delta\alpha_3)(1+\Delta\beta_3)|\dfrac{\sin(\phi_2-\phi_1)}{\sin(\phi_3-\phi_2)}\sin(\phi_3+\Delta\phi_3) \end{pmatrix} Q_m(t) - \begin{pmatrix} |(1+\Delta\alpha_2)(1+\Delta\beta_2)|\dfrac{\cos\phi_3}{\sin(\phi_3-\phi_2)}\sin(\phi_2+\Delta\phi_2) \\ -|(1+\Delta\alpha_3)(1+\Delta\beta_3)|\dfrac{\cos\phi_2}{\sin(\phi_3-\phi_2)}\sin(\phi_3+\Delta\phi_3) \end{pmatrix} Q_m(t) \end{aligned} \tag{16}$$

If it is assumed that $|\Delta a_i|<<1$ and $|\Delta\phi_i|<<|\phi_i|$, then $I'_r(t)$ and $Q'_r(t)$ can be approximated as

$$\begin{aligned} I'_r(t) &\approx \\ & \left(1 + \frac{2A|\alpha_1\beta_1|a_{I1}}{\sin(\phi_3-\phi_2)} \begin{pmatrix} \sin(\phi_3-\phi_2)((\Delta\alpha_1+\Delta\beta_1)\cos\phi_1 - \Delta\phi_1\sin\phi_1) \\ -\sin(\phi_3-\phi_1)((\Delta\alpha_2+\Delta\beta_2)\cos\phi_2 - \Delta\phi_2\sin\phi_2) \\ +\sin(\phi_2-\phi_1)((\Delta\alpha_3+\Delta\beta_3)\cos\phi_3 - \Delta\phi_3\sin\phi_3) \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} \right) I_m(t) \\ & + \left(-\frac{2A|\alpha_1\beta_1|a_{I1}}{\sin(\phi_3-\phi_2)} \begin{pmatrix} \sin(\phi_3-\phi_2)((\Delta\alpha_1+\Delta\beta_1)\sin\phi_1 + \Delta\phi_1\cos\phi_1) \\ -\sin(\phi_3-\phi_1)((\Delta\alpha_2+\Delta\beta_2)\sin\phi_2 + \Delta\phi_2\cos\phi_2) \\ +\sin(\phi_2-\phi_1)((\Delta\alpha_3+\Delta\beta_3)\sin\phi_3 + \Delta\phi_3\cos\phi_3) \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 \\ +((\Delta\alpha_2+\Delta\beta_2)-(\Delta\alpha_3+\Delta\beta_3))\sin\phi_2\sin\phi_3 \end{pmatrix} \right) Q_m(t) \\ Q'_r(t) &= \\ & \left(\frac{2A|\alpha_1\beta_1|a_{Q1}}{\sin(\phi_3-\phi_2)} \begin{pmatrix} \sin(\phi_3-\phi_2)((\Delta\alpha_1+\Delta\beta_1)\cos\phi_1 - \Delta\phi_1\sin\phi_1) \\ -\sin(\phi_3-\phi_1)((\Delta\alpha_2+\Delta\beta_2)\cos\phi_2 - \Delta\phi_2\sin\phi_2) \\ +\sin(\phi_2-\phi_1)((\Delta\alpha_3+\Delta\beta_3)\cos\phi_3 - \Delta\phi_3\sin\phi_3) \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 \\ +((\Delta\alpha_2+\Delta\beta_2)-(\Delta\alpha_3+\Delta\beta_3))\cos\phi_2\cos\phi_3 \end{pmatrix} \right) I_m(t) \\ & + \left(1 - \frac{2A|\alpha_1\beta_1|a_{Q1}}{\sin(\phi_3-\phi_2)} \begin{pmatrix} \sin(\phi_3-\phi_2)((\Delta\alpha_1+\Delta\beta_1)\sin\phi_1 + \Delta\phi_1\cos\phi_1) \\ -\sin(\phi_3-\phi_1)((\Delta\alpha_2+\Delta\beta_2)\sin\phi_2 + \Delta\phi_2\cos\phi_2) \\ +\sin(\phi_2-\phi_1)((\Delta\alpha_3+\Delta\beta_3)\sin\phi_3 + \Delta\phi_3\cos\phi_3) \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} \right) Q_m(t) \end{aligned} \tag{17}$$

Equation (17) has the following characteristics. First, from (9) and (12), $A|a_1\beta_1|a_{I1}$ and $A|a_1\beta_1|a_{Q1}$ are not much different from 1. Second, ϕ_2 and ϕ_3 must not be the same due to removing one output port in a multi-port junction. This means that $sin(\phi_3-\phi_2)$ is not equal to 0. Third, all coefficients have Δa_i, $\Delta\beta_i$, or $\Delta\phi_i$ (i=1,2,3). By analyzing these three characteristics, we find that all coefficients, except the constant 1 in (17), are much less than 1. Hence, (17) is represented as

$$
\begin{aligned}
I_r'(t) &= (1+\delta_{Ii})I_m(t)+\delta_{Iq}Q_m(t) \\
&= A_I\cdot\left(I_m(t)\cos\phi_I+Q_m(t)\sin\phi_I\right) \\
Q_r'(t) &= \delta_{Qi}I_m(t)+(1+\delta_{Qq})Q_m(t) \\
&= A_Q\cdot\left(-I_m(t)\sin\phi_Q+Q_m(t)\cos\phi_Q\right)
\end{aligned}
\tag{18}
$$

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} \\
&\quad+\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} \\
&\quad-\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} \\
&\quad+\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} \\
&\quad+\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}
\tag{19}
$$

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

In (19), δ_{Ii} and δ_{Iq} denote the erroneous weights for the I- and Q-channel information signals due to the imperfect I-channel regeneration parameters, respectively. δ_{Qi} and δ_{Qq} represent the erroneous weights for the I- and Q-channel information signals due to the imperfect Q-channel regeneration parameters, respectively. Using A_I and A_Q of (19), we define the common gain and gain mismatch between A_I and A_Q. These are written as

$$A_{common} = \frac{\sqrt{(1+\delta_{Ii})^2 + \delta_{Iq}^2} + \sqrt{\delta_{Qi}^2 + (1+\delta_{Qq})^2}}{2}$$
$$A_{mismatch} = 2\frac{\sqrt{(1+\delta_{Ii})^2 + \delta_{Iq}^2} - \sqrt{\delta_{Qi}^2 + (1+\delta_{Qq})^2}}{\sqrt{(1+\delta_{Ii})^2 + \delta_{Iq}^2} + \sqrt{\delta_{Qi}^2 + (1+\delta_{Qq})^2}} \quad (20)$$

Also, using ϕ_I and ϕ_Q of (19), we are able to define the phase offset and phase mismatch between ϕ_I and ϕ_Q. These are written as

$$\phi_{offset} = \frac{\tan^{-1}\frac{\delta_{Iq}}{1+\delta_{Ii}} + \left(-\frac{\pi}{2} + \tan^{-1}\frac{1+\delta_{Qq}}{\delta_{Qi}}\right)}{2}$$
$$\phi_{mismatch} = \tan^{-1}\frac{\delta_{Iq}}{1+\delta_{Ii}} - \left(-\frac{\pi}{2} + \tan^{-1}\frac{1+\delta_{Qq}}{\delta_{Qi}}\right) \quad (21)$$

Equations (17)-(21) show that when the attenuation and phase-shift values for a multi-port junction deviate from the designed values due to fabrication errors, the regenerated I- and Q-channel signals have an I/Q mismatch compared with the transmitted signals. Hence, an MPDR with imperfect I/Q regeneration parameters can be modeled as a non-ideal direct conversion quadrature demodulator in which there are gain and phase mismatches between the I and Q channels. This means that I/Q regeneration in an MPDR performs two functions simultaneously. First, it generates the transmitted I- and Q-channel information signals from the power signals of a multi-port junction. Second, it compensates the I/Q mismatch due to the non-ideal attenuation and phase-shift values.

Based on the analysis provided in this paper, these two functions can be separated. Furthermore, remarkably, MPDRs can be integrated into existing RFIC based systems without additional digital signal processing because the I/Q mismatch compensation function in I/Q regeneration is identical to that in existing RFIC based systems. This enables the development of a multiple-standard radio transceiver with a wide frequency operating range from hundreds MHz to tens of GHz.

Ⅲ. Relationship between Imperfect I/Q Regeneration and I/Q Mismatch

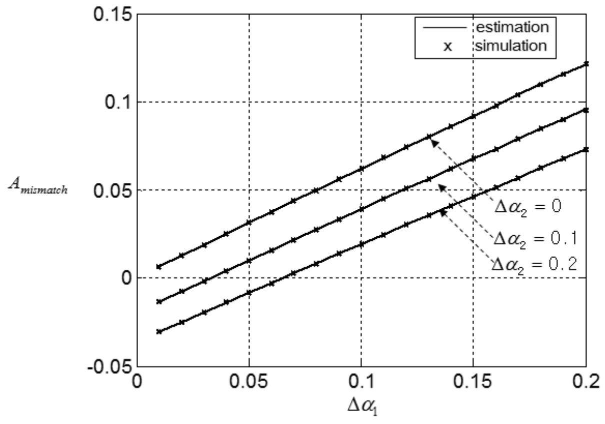
In this section, we examine the relationship between imperfect I/Q regeneration and I/Q mismatch in an MPDR using (19)-(21).* In (19)-(21), we find that the gain and phase mismatches are related to the sum of $\Delta\alpha_i$ and $\Delta\beta_i$ (i=1,2,3) and not to the individual values of $\Delta\alpha_i$ and $\Delta\beta_i$. Hence, when the sum of $\Delta\alpha_i$ and $\Delta\beta_i$ (i=1,2,3) remains constant, i.e., $\Delta\alpha_i+\Delta\beta_i=C$ (constant), the gain and phase mismatches do not change regardless of $\Delta\alpha_i$.

An MPDR has no gain or phase mismatches when the sum of $\Delta\alpha_i$ and $\Delta\beta_i$ (i=1,2,3) for each output port is the same, i.e., $(\Delta\alpha_1+\Delta\beta_1)=(\Delta\alpha_2+\Delta\beta_2)=(\Delta\alpha_3+\Delta\beta_3)=(\Delta\alpha+\Delta\beta)$, and when $\Delta\phi_i$ (i=1,2,3) is equal to 0. In this case, (19) is represented as

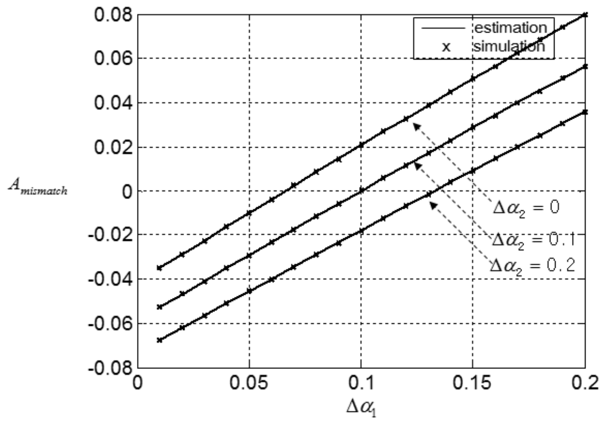
$$\begin{aligned}\delta_{Ii} &= (\Delta\alpha + \Delta\beta)\\ \delta_{Iq} &= 0\\ \delta_{Qi} &= 0\\ \delta_{Qq} &= (\Delta\alpha + \Delta\beta)\end{aligned} \quad (22)$$

By inserting (22) in (20) and (21), we find that there are no gain or phase mismatches. Also, an MPDR has no gain or phase mismatches when Δϕi

* For analysis, the following junction parameters are used : α_1=1, α_2=1, α_3=1, β_1=1, β_2=1, β_3=1, $\phi_1=\pi/6$, $\phi_2=2\pi/3$, and $\phi_3=4\pi/3$.



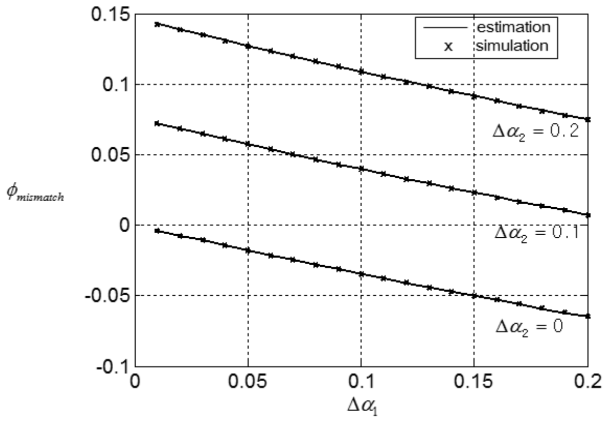
(a)



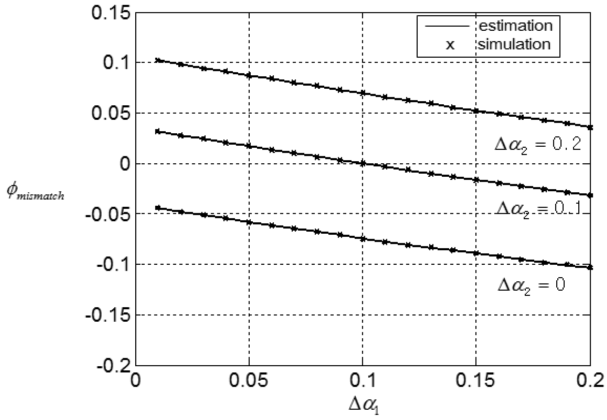
(b)

그림 2. Δa_i (i=1,2,3)와 이득 부정합의 관계

Fig. 2. The relationship between Δa_i (i=1,2,3) and gain mismatch (a) Δa_3 =0 and (b) Δa_3 =0.1.



(a)



(b)

그림 3. Δa_i (i=1,2,3)와 위상 부정합의 관계

Fig. 3. The relationship between Δa_i (i=1,2,3) and phase mismatch (a) Δa_3 =0 and (b) Δa_3 =0.1.

(i=1,2,3) of each output port is the same, i.e., $\Delta\phi_1=\Delta\phi_2=\Delta\phi_3=\Delta\phi$, and when the sum of Δa_i and $\Delta\beta_i$ (i=1,2,3) is equal to 0. In this case, (19) is represented as

$$\begin{aligned} \delta_{Ii} &= 0 \\ \delta_{Iq} &= -\Delta\phi \\ \delta_{Qi} &= \Delta\phi \\ \delta_{Qq} &= 0 \end{aligned} \tag{23}$$

By inserting (23) in (20) and (21), we find that there are no gain or phase mismatches.

Fig. 2 and Fig. 3 show the relationships between Δa_i (i=1,2,3) and the gain and phase mismatch, respectively.* Fig. 2 shows that, to decrease the gain mismatch, there must be a proportional relationship among the values of Δa_i (i=1,2,3). Fig. 3 shows that, to decrease the phase mismatch, there must be a proportional relationship between Δa_1 and Δa_2, as well as an inversely proportional relationship between Δa_1 and Δa_3. Fig. 4 and Fig. 5 show the relationships between $\Delta\phi_i$ (i=1,2,3) and the gain and phase mismatch, respectively. Fig. 4 shows that, to decrease the gain mismatch, there must be a proportional relationship between $\Delta\phi_1$ and $\Delta\phi_2$, as well as an inversely proportional relationship between $\Delta\phi_1$ and Δ

* Since both the gain and phase mismatches are related to the sum of Δa_i and $\Delta\beta_i$, we change Δa_i while $\Delta\beta_i$ remains zero.

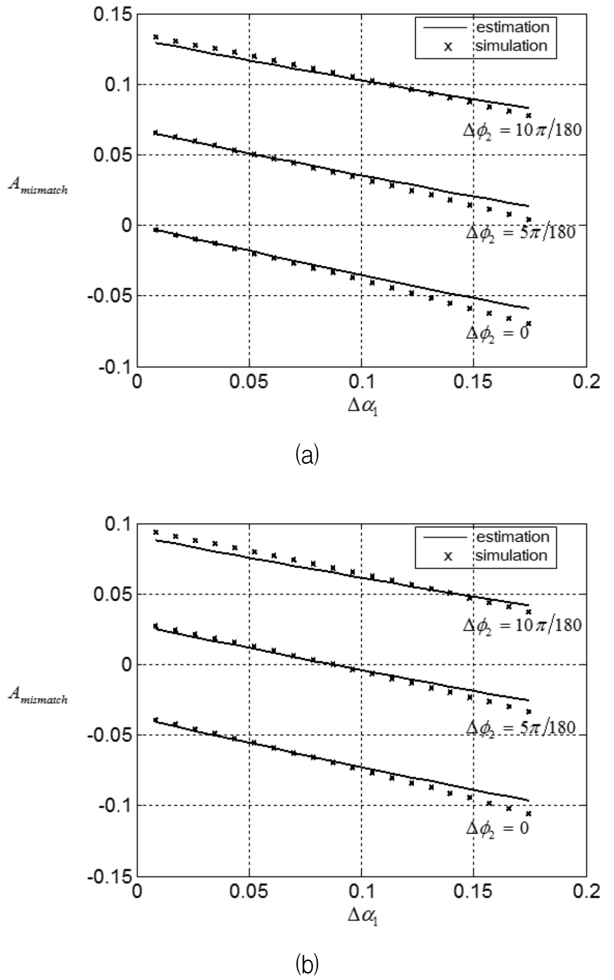


그림 4. $\Delta\phi_i$ (i=1,2,3)와 이득 부정합의 관계
Fig. 4. The relationship between $\Delta\phi_i$ (i=1,2,3) and gain mismatch (a) $\Delta\phi_3$ =0 and (b) $\Delta\phi_3$ =5π/180.

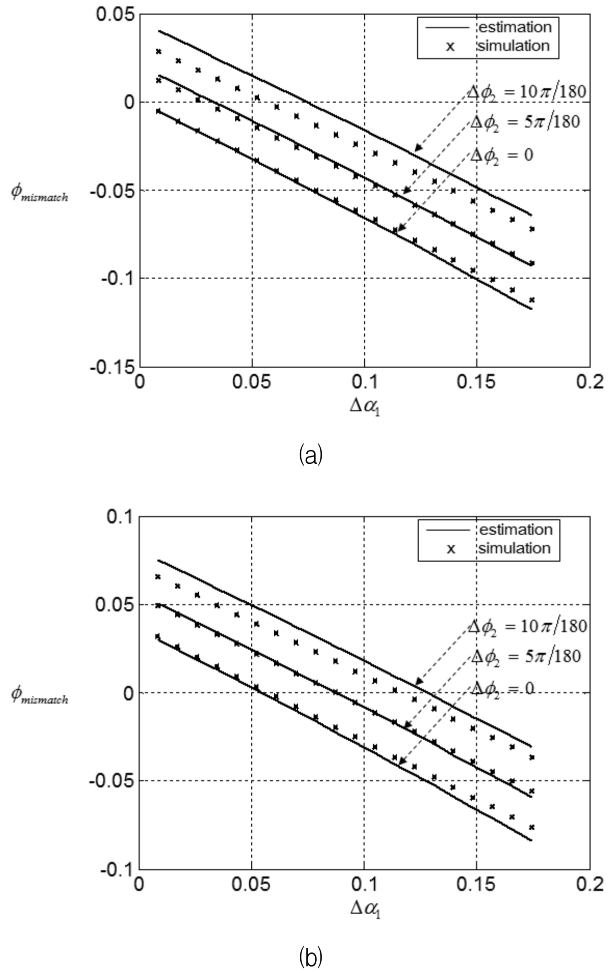


그림 5. $\Delta\phi_i$ (i=1,2,3)와 위상 부정합의 관계
Fig. 5. The relationship between $\Delta\phi_i$ (i=1,2,3) and phase mismatch (a) $\Delta\phi_3$ =0 and (b) $\Delta\phi_3$ =5π/180.

ϕ_3. Fig. 5 shows that, to decrease the phase mismatch, there must be a proportional relationship among the values of $\Delta\phi_i$ (i=1,2,3). In addition, the simulation results for gain and phase mismatch are shown in Fig. 2-Fig. 5. It is worth noting that the estimation results using (19)-(21) and the simulation results are almost the same.

Ⅳ. Conclusions

This paper has presented that MPDRs can regenerate I- and Q-channel signals accurately by using the conventional I/Q mismatch compensator. We have proved that imperfect I/Q regeneration in MPDRs causes an I/Q mismatch. The relationship between the accuracy of I/Q regeneration parameters and the degree of I/Q mismatch has been analyzed. Based on the analysis and simulation, it has been shown that gain and phase mismatches are related to a multi-port junction structure.

References

[1] IEEE P802.11n/D7.0, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 5: Enhancements for Higher Throughput, Sep. 2008.
[2] IEEE 802.15 WPAN High Rate Alternative PHY

Task Group 3a (TG3a). [Online]. Available: http://www.ieee802.org/15/pub/TG3a.html.
[3] IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a (TG4a). [Online]. Available: http://www.ieee802.org/15/pub/TG4a.html.
[4] IEEE 802.15 WPAN High Rate Alternative PHY Task Group 3c (TG3c). [Online]. Available: http://www.ieee802.org/15/pub/TG3c.html.
[5] Ji Li, R. G. Bosisio, and Ke Wu, "A Six-Port Direct Digital Millimeter Wave Receiver," *1994 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1659-1662.
[6] S. Kim, N. Kim, and Y. Kim, "I/Q channel regeneration in 6-port junction based direct receiver," *J. of Institute of Electronics Engineers of Korea*, Vol. 40, No. 7, pp. 222-225, Jun. 2003.
[7] G. F. Engen, "The Six-Port Reflectometer: An Alternative Network Analyzer," *IEEE Trans. Microw. Theory Tech.*, pp. 1075-1080, Dec. 1977.
[8] G. F. Engen, "Calibrating the Six-Port Reflectometer by Means of Sliding Terminations," *IEEE Trans. Microw. Theory Tech.*, pp. 951-957, Dec. 1978.
[9] H. C. Park, H. Lim, and J. Yu, "Unified DC Offset Cancellation and I/Q Regeneration with Carrier Phase Recovery in Five-Port Junction based Direct Receivers," *J. of Institute of Electronics Engineers of Korea*, Vol. 44-TC, No. 6, pp. 64-70, Jun. 2007.
[10] T. Hentschel, "The Six-Port as a Communications Receiver," *IEEE Trans. Microw. Theory Tech.*, Mar. 2005, pp. 1039-1047.
[11] X. Huang, D. Hindson, M. Léséleuc, and M. Caron, "I/Q-Channel Regeneration in 5-Port Junction based Direct Receivers," *1999 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 169-173.

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