직접 변환 수신기에서 Early-Late 위상 보상기를 사용한 위상 오차 보정

김영완*

Phase Offset Correction using Early-Late Phase Compensation in Direct Conversion Receiver

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요 약

최근 무선통신시스템에서 직접변환 트랜시버 또는 IF 샘플링 SDR 기반 수신기가 일반적인 트랜시버 구조에 상응하여 설계되어지고 있다. 일반적인 AFC/APC 보상 회로가 기저 대역에서 RF 입력 신호와 국부발진 신호의 주파수 및 위상 오차를 보정할지라도 직접변환 수신 구조에서는 주요한 열화 요소로 작용한다. 일반적인 보상 회로의 제한적인 동작 영역과 기저 대역에서의 I/Q 채널의 불 평형을 용이하게 보상할 수 있도록 RF 입력 신호단에서 주파수 및 위상 오차를 보정하는 방법을 본 논문에서 제안한다. RF 입력단에서 고정된 주파수 및 위상 오차 이외에 변화하는 주파수 및 위상 오차를 제안된 early-late 보상기에 의해 효과적으로 보상할 수 있다. RF 입력단에서의 주파수 및 위상 오차의 보정으로 직접변환 수신기의 기저 대역에서의 기존 주파수 및 위상 오차 보정 회로는 간단히 설계할 수 있으며 미세한 오차 보정 구조로 용이하게 이용할 수 있다.

ABSTRACT

In recent wireless communications, direct conversion transceiver or IF sampling SDR-based receivers have being designed as an alternative to conventional transceiver topologies. In direct conversion receiver architecture, the frequency/phase offset between the RF input signal and the local oscillator signal is a major impairment factor even though the conventional AFC/APC compensates the service deterioration due to the offset. To cover the limited tracking range of the conventional method and effectively aid compensation scheme in terms of I/Q channel imbalances, the frequency/phase offset compensation in RF-front end signal stage is proposed in this paper. In RF-front end, the varying phase offset besides the fixed large frequency/phase offset are corrected by using early-late phase compensator. A more simple frequency and phase tacking function in digital signal processing stage of direct conversion receiver is effectively available by an ingenious frequency/phase offset tracking method in RF front-end stage.

키워드

Phase Offset Correction, Direct Conversion Receiver, Early-Late Phase Compensation

Ⅰ. Introduction

The direct conversion principle can meet the

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ever-increasing demand for realization of low power, fully integrated and portable transceivers. This new type transceiver is a cost effective alternative to conventional heterodyne architecture counterpart, which requires an expensive and non-integrated RF and IF filters. Many workers have presented results emphasizing the usefulness of the direct conversion topologies in digital communication systems[1],[2]. However, though the direct conversion technology provides advantages of compact communication architecture, low power consumption and flexibility to adopt the SDR-based multi-modulation schemes, there are some problems to overcome in direct conversion topologies, which are main problems affecting direct conversion receiver(DCR)[3],[4]. Many researches to overcome those problems, which are DC offset, I/Q channel gain and phase imbalances and even-order inter-modulations, have been presented in the literatures [4],[5]. These research results are mainly compensation algorithms of gain and phase imbalances occurring in I/Q channel of quadrature demodulator architecture. To compensate the service deterioration due to these imperfect factors, the compensation algorithms are mainly processed in baseband signal processing stage. However, the frequency and phase offset between the RF input signal and the local oscillator signal is a major impairment factor in direct conversion receiver besides conventional hetero-dyne receivers. The frequency and phase offsets have been covered by automatic frequency and phase tracking circuit in the conventional hetero-dyne receiver.

The frequency and phase instability of local oscillator signal, however, may be increased and it can be more difficult to track the offset in conditions of some processing data rate as the input RF signal frequency is increased. Therefore, though the common automatic frequency and phase tracking circuits can be utilized in direct conversion receiver, the frequency and phase offset in direct conversion receiver may not be compensated by the conventional automatic frequency/phase tracking loops. In general, this phenomenon can be occurred even in conventional hetero-dyne receiver by a limited tracking range or white noise enhancement in wide-tracking range[6].

In RF-front end stage, the frequency and phase offset can be compensated by advanced digital signal processing techniques. By an ingenious frequency and phase offset tracking method in RF signal input stage, a more simple frequency/phase tacking function can be designed to provide the fine tuning in digital signal processing stage of direct conversion receiver. Based on the digital signal processing techniques in RF-front end, the frequency/phase offset compensation method between the RF input signal and the local oscillator signal is proposed in this paper.

In RF-front end, the varying phase offset besides the fixed large frequency and phase offset are corrected by using an early-late phase compensator. It is possible to process the sampled RF signal by advanced IF sampling and related semi-conductor techniques. To improve the compensation performance in low signal-to-noise ratio channel, the signal-to- noise ratio is enhanced by the accumulator in RF input signal stage. The new frequency and phase offset compensator in RF-front stage corrects the offsets very well even in low signal-to-noise channel. The proposed architecture can be integrated in a customized on-chip for direct conversion receiver as well as conventional IF sampling architecture. The validity and compensation performance of the proposed topology is verified by system simulations.

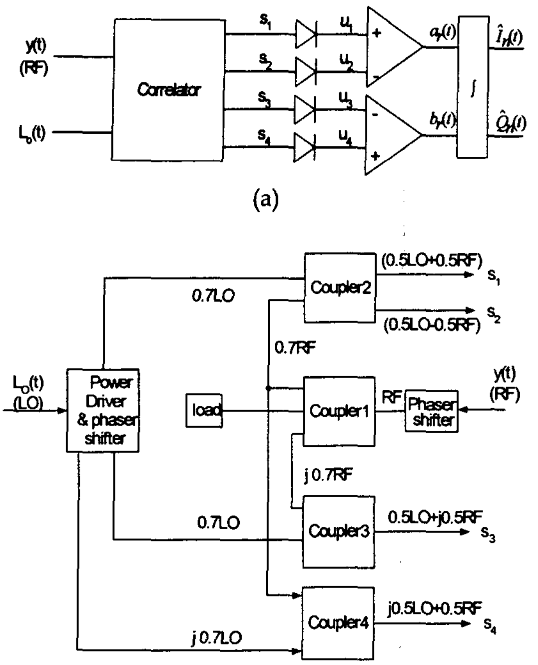
II. Phase Correction Model using Early-Late Compensator

1. Effect due to Phase Offset

In direct conversion receiver, though the conventional direct conversion topology is usually used, the six-port topology can be used as shown in Fig. 1[2].

The input RF signal may be expressed by

$$y(t) = a_n A\cos(2\pi f_c t+\theta) + b_n A\sin(2\pi f_c t+\theta) + \eta(t) \tag{1}$$



(a)

(b)

Fig 1. Six-port direct conversion receiver, (a) diagram of six-port and (b) diagram of phase correlator.

where f_c denotes a carrier signal frequency, A is amplitude of an input signal, $[a_n, b_n]$ expresses the transmitting symbol signal of I/Q channel and θ is the phase offset of a RF input signal.

The RF input signal (1) can be re-written by

$$y(t) = y_1\varphi_1(t) + y_2\varphi_2(t) + n(t)$$

$$\varphi_1(t) = \sqrt{\frac{2}{T_s}}\cos(2\pi f_c t + \theta)$$

$$\varphi_2(t) = \sqrt{\frac{2}{T_s}}\sin(2\pi f_c t + \theta) \qquad (2)$$

where T_s denotes the symbol duration of transmission signal.

In case of phase offset θ, the output signals of power detector from Fig. 1 are expressed by

$$u_1 = (|L_o(t)|^2 - |y(t)|^2 + 2j|L_o(t)||y(t)|\sin\theta)/4$$

$$u_2 = (-|L_o(t)|^2 + |y(t)|^2 + 2j|L_o(t)||y(t)|\sin\theta)/4$$

$$u_3 = (-|L_o(t)|^2 - |y(t)|^2 - 2|L_o(t)||y(t)|\cos\theta)/4$$

$$u_4 = (|L_o(t)|^2 + |y(t)|^2 - 2|L_o(t)||y(t)|\cos\theta)/4 \qquad (3)$$

where $L_O(t)$ is the local oscillator signal that may be expressed by $\cos(2\pi f_c t)$.

From Fig. 1, the output signals through the adder are also written by

$$a_r(t) = |\cos(2\pi f_c t)| \times |y(t)| \times \cos(\theta)$$

$$b_r(t) = |\sin(2\pi f_c t)| \times |y(t)| \times \sin(\theta) \qquad (4)$$

Therefore, the n-th symbol signals of the recovered transmission signal are deduced as follow:

$$\hat{I}_n = \int_{(n-1)Ts}^{nTs} |\cos(2\pi f_c t)| \times |y(t)| \times \cos(\theta)\, dt$$

$$\hat{Q}_n = \int_{(n-1)Ts}^{nTs} |\sin(2\pi f_c t)| \times |y(t)| \times \sin(\theta)\, dt \qquad (5)$$

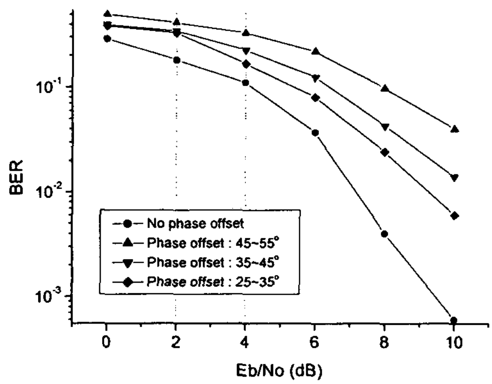


Fig 2. The effects due to the phase offsets for DQPSK.

It is seen from (5) that the recovered signals are affected by phase offset between the RF input signal and the local oscillator signal. The degradation performances due to phase offsets are shown in Fig. 2.

It is known that the effect due to phase offset is larger as the phase offset is increased. It is also clear that the phase offset has a significant effect on the service performance. Therefore, it is necessary to effectively compensate the phase offset in RF front-end stage.

2. Phase Offset Correction

To compensate the phase offset between a RF input signal and a local oscillator signal, the phase offset correction using the early-late phase compensator in RF front-end stage is used as shown in Fig. 3. In Fig. 3, the phase offset n-th symbol may be expressed by between a local oscillator signal and a RF input signal is estimated in an early-late phase compensator. The estimated phase error is applied as additional phase signal to the local oscillator. Therefore, the phase offset is compensated by the feedback phase signal of the early-late phase compensator. To estimate the phase offset, the local oscillator signal is generated as signal components of $\cos(2f_c t)$ and $\sin(2f_c t)$ by 90° phase shifter. These signal are used to recover the I/Q channel signals, respectively. Also, the signal components of the local oscillator signal are generated as an early and a late signal with phase shifting factor(α) of the early-late phase shift unit, respectively. From Fig. 3, the early-late phase shifted signals are sampled with sampling rate of $K=T_c/T_s$, $T_c=1/f_c$ and the k-th sampled signals of n-th symbol may be expressed by

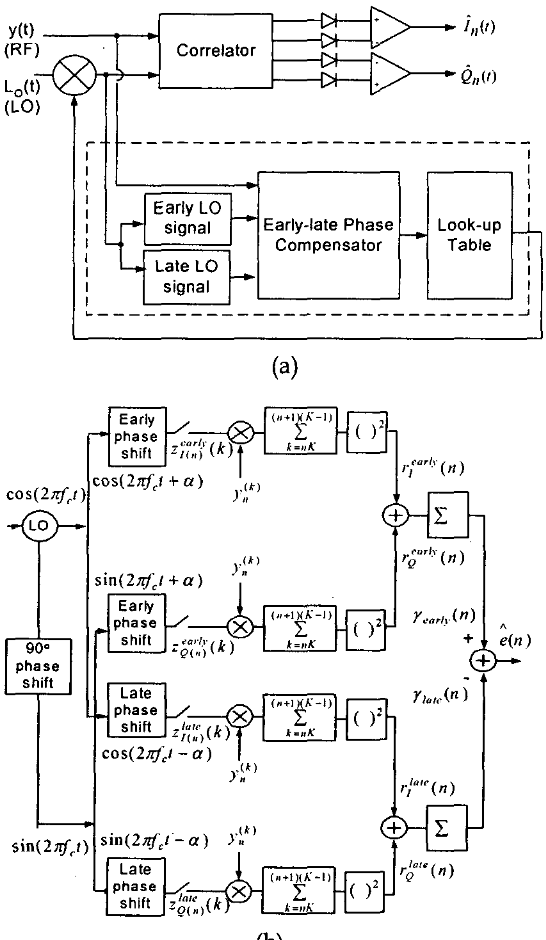


Fig 3. (a) Block diagram of phase offset correction using the early-late phase compensator and (b) early-late phase compensator.

$$z_{I(n)}^{early}(k)=\cos(2\pi\frac{nk}{K}+\alpha)$$
$$z_{Q(n)}^{early}(k)=\sin(2\pi\frac{nk}{K}+\alpha)$$
$$z_{I(n)}^{late}(k)=\cos(2\pi\frac{nk}{K}-\alpha)$$
$$z_{Q(n)}^{late}(k)=\sin(2\pi\frac{nk}{K}-\alpha) \tag{6}$$

These sampled signals of (6) are added as symbol unit after multiplication with the RF input signal and the added signals are multiplied by itself as follows:

$$\gamma_I^{early}(n)=[\sum_{k=nK}^{(n+1)(K-1)}\tilde{z}_{I(n)}^{early}(k)]^2$$
$$\gamma_Q^{early}(n)=[\sum_{k=nK}^{(n+1)(K-1)}\tilde{z}_{Q(n)}^{early}(k)]^2$$
$$\gamma_I^{late}(n)=[\sum_{k=nK}^{(n+1)(K-1)}\tilde{z}_{I(n)}^{late}(k)]^2$$
$$\gamma_Q^{late}(n)=[\sum_{k=nK}^{(n+1)(K-1)}\tilde{z}_{Q(n)}^{late}(k)]^2 \tag{7}$$

where $\tilde{z}(k)$ denotes the multiplied signal of a sampled RF input signal of (1) and a sampled local oscillator signal (6).

The multiplied I/Q channel signals (7) have the correlation information between the early-late local oscillator signal and the RF input signal with phase error. Therefore the phase offset can be estimated by using the correlation values. To more accurately estimate the phase offset, the correlation values for I/Q channel are used in estimation of the phase offset. From Fig. 3, the multiplied I/Q channel signals are added for early and late signals, respectively.

$$\gamma_{early}(n) = \gamma_I^{early}(n) + \gamma_Q^{early}(n)$$
$$\gamma_{late}(n) = \gamma_I^{late}(n) + \gamma_Q^{late}(n) \tag{8}$$

Using all the correlation information for I/Q channel signals from (8), the phase error can be estimated from difference between early and late correlation values:

$$\hat{e}(n) = \gamma_{early}(n) - \gamma_{late}(n) \tag{9}$$

It is clear that the estimated correlation of $\hat{e}(n)$ gets the information of phase error.

To find an actual phase error corresponding to the estimated correlation values of (9), the look-up table following the early-late phase compensator is required as shown in Fig. 3. The look-up table is generated by using the same method with the early-late phase compensator. The theoretical correlation values corresponding to phase offsets of RF input signals, which may be the measured data, are memorized in look-up table unit.

For the look-up table generation, the phase-shifted local oscillator signals from (6) can be expressed by

$$lo_I^{early}(k) = \sum_{k=0}^{(K-1)} \cos(2\pi \frac{k}{K} + \alpha)$$
$$lo_I^{late}(k) = \sum_{k=0}^{(K-1)} \cos(2\pi \frac{k}{K} - \alpha)$$
$$lo_Q^{early}(k) = \sum_{k=0}^{(K-1)} \sin(2\pi \frac{k}{K} + \alpha)$$
$$lo_Q^{late}(k) = \sum_{k=0}^{(K-1)} \sin(2\pi \frac{k}{K} - \alpha) \tag{10}$$

Assuming that the data in I/Q channels are transmitted as $a_n = 1$ and $b_n = 1$, the RF input signal of n-th symbol with phase error θ can be written by

$$\tilde{y}_n^{(k)} = \sum_{k=0}^{(K-1)} [\cos(2\pi f_c nk/K + \theta) + \sin(2\pi f_c nk/K + \theta)] + \eta(n) \tag{11}$$

Then, the correlation functions for phase error estimation are also expressed by

$$\gamma_{\tilde{y}}^{early}(n) = \frac{1}{K} \sum_{k=0}^{K-1} [lo_I^{early}(k) + lo_Q^{early}(k)] \times \tilde{y}_n^{(k)}$$
$$\gamma_{\tilde{y}}^{late}(n) = \frac{1}{K} \sum_{k=0}^{K-1} [lo_I^{late}(k) + lo_Q^{late}(k)] \times \tilde{y}_n^{(k)} \tag{12}$$

From (12), the theoretical phase errors corresponding to (9) are deduced by

$$e(n) = \gamma_{\tilde{y}}^{early}(n) - \gamma_{\tilde{y}}^{late}(n) \tag{13}$$

Using (13), the look-up table can be generated as shown in Table 1. The look-up table was generated under conditions of phase error unit of 10° and phase shifting factor α of $\pi/6$. The correlation values of phase error estimation functions were normalized as an amplitude unit of 1.

Table 1. Look-up table

Phase error	$\gamma_{\tilde{y}}^{early}(n)$	$\gamma_{\tilde{y}}^{late}(n)$	$e(n)$
0°	0.866	0.866	0
10°	0.766	0.9397	-0.1736
20°	0.6428	0.9848	-0.342
30°	0.5	1	-0.5
40°	0.342	0.9849	-0.6428
50°	0.1736	0.9397	-0.766
60°	0	0.866	-0.866
70°	-0.1736	0.766	-0.9397
80°	-0.342	0.6428	-0.9848
90°	-0.5	0.5	-1
-10°	0.9397	0.766	0.1736
-20°	0.9848	0.6428	0.342
-30°	1	0.5	0.5
-40°	0.9848	0.342	0.6428
-50°	0.9397	0.1736	0.766
-60°	0.866	0	0.866
-70°	0.766	-0.1736	0.9397
-80°	0.6425	-0.342	0.9848
-90°	0.5	-0.5	1

The phase error differences to compensate the phase offsets may be occurred between the estimated phase errors and theoretical values from (9) and (13). Therefore, the actual phase error to compensate the phase offset is estimated by comparing the estimated phase error, $\hat{e}(\theta)$ and theoretical phase error, $e(\theta)$:

$$\hat{\theta} = \arg\min_{\theta} |e(\theta) - \hat{e}(\theta)| \tag{14}$$

where $\hat{\theta}$ is an actual phase error to compensate the phase offset and is a value that minimizes the absolute value of $f\{e(\theta) - \hat{e}(\theta)\}$.

Then, the phase-compensated signal is fed to the local oscillator of the six-port direct conversion receiver:

$$L_O'(t) = \cos(2\pi f_c t + \hat{\theta}) \tag{15}$$

In estimation of phase offset between the RF input signal and the local oscillator signal, however, the phase offset is estimated every N-symbols block. In fact, it is not possible to estimate the phase offset every symbol unit because of the delay of the early-late phase compensator. To compensate the slowly varying phase error in N-symbols block, also, the early-late phase compensator corrects the phase error in N-symbols block by using the recursive method:

$$\hat{e}(n+1) = (1-\rho)\cdot\hat{e}(n) + \rho\cdot\hat{e}(n+1) \tag{16}$$

where ρ is the weighting factor less than 1, which is a value between $\hat{e}(n)$ and $\hat{e}(n+1)$.

III. Accumulation for White Noise

The phase error is compensated by using the early-late phase compensator that estimates the correlation between a local oscillator signal and a RF input signal with the fixed or varying phase offset. The input RF signal is fed to the early-late phase compensator with noise component as shown in (1). The correlation values are influenced by additive white gaussian noise feeding to the RF signal port. To estimate the accurate phase offset, it is important to diminish the effect of additive white gaussian noise. The early-late phase compensator with accumulator, which reduce the effect of additive white gaussian noise, is shown in Fig. 4.

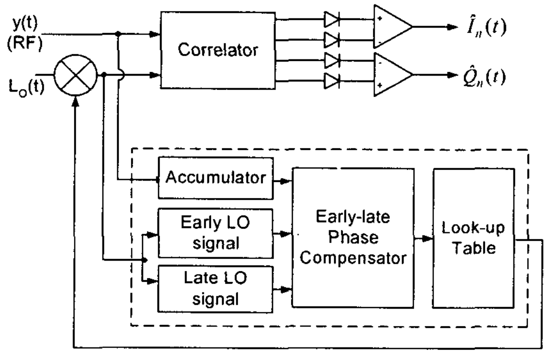


Fig 4. Block diagram of phase offset correction with accumulator.

As shown in Fig. 4, the RF input signal is fed to the early-late phase compensator through the accumulator. The RF symbol signal is accumulated as the accumulation length of N-symbols. The accumulator adds each symbol of accumulated N-symbols signal. Then, the effect of additive white gaussian noise can be mitigated by the accumulator.

The accumulator performs the accumulation as an unit of N-symbols of the RF signal that was sampled as K sampling rate per symbol:

$$\hat{y} = \sum_{n=0}^{N}\sum_{k=0}^{K} y(nkTs) \tag{17}$$

IV. System Simulation and Performance

1. Performance of Accumulator in the Presence of White Noise

The performances of accumulator dependent on the accumulation length N are shown in Fig. 5, which have conditions of 2 dB SNR.

It is shown from Fig. 5 that accumulator reduces the additive white gaussian noise component by accumulation. Also, it is clear that the effect of noise cancellation is enhanced as the accumulation length N is increased.

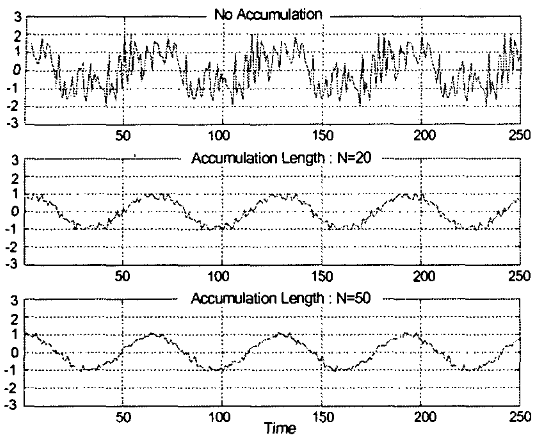


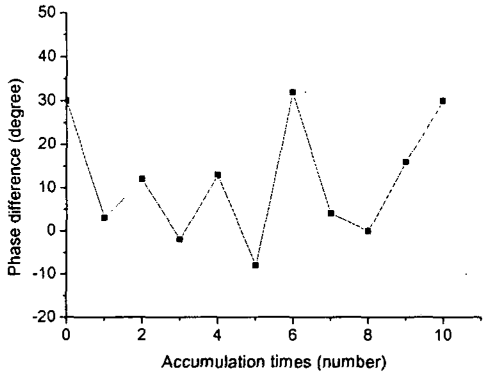
Fig 5. RF signal waveform dependent on the accumulation length N (SNR=2 dB).

To find the influence of accumulation length according to signal-to-noise ratios, the phase differences between the real phase error and the estimated phase error were simulated under conditions of DQPSK modulation and phase shifting factor α of $\pi/6$. Fig. 6 shows the phase error difference dependent on the accumulation length at SNR of 2 dB. In low SNR signal, the phase error difference is fluctuated in large range as the accumulation times are increased. On the other hand, the fluctuation may be mitigated as the accumulation length is increased. However, the accumulation times can be decreased in case of the signal with more high SNR. Fig. 7 shows a good phase error estimation performance even condition of low accumulation times in case of the SNR signal of 4 dB.

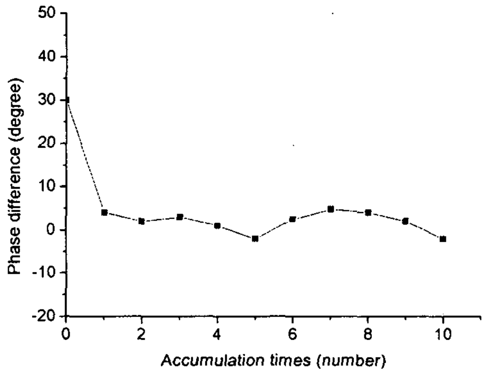
In compared with Fig. 6, it is shown that the phase offset in high SNR signal is more accurately estimated even accumulation times less than that of low SNR signal. Therefore, the phase error difference can be negligible even case of the low accumulation length, if the RF input signal with high SNR is fed to the accumulator.

2. Performance of Early-late Compensator for Phase Correction

The performances of the proposed early-late phase compensator using an accumulator are



(a)

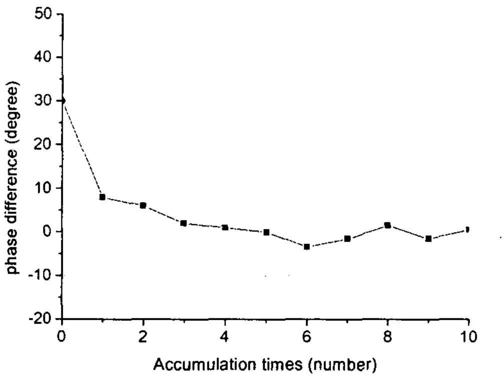


(b)

Fig 6. Phase difference performance dependent on accumulation times at SNR of 2 dB, (a) accumulation length =1 and (b) accumulation length =20.

shown in simulation results. Assuming that the modulation scheme of DQPSK and accumulation length of 50 symbols is used in DCR architecture, the proposed method was verified by using the system simulation.

Fig. 8 shows the performance characteristics of phase offset correction used the early-late phase compensator with accumulator in the presence of random phase offset. In Fig. 8, the phase offset means a random phase error that is occurred in some fixed range. Therefore, the phase error of 25° to 35° means the random phase offset that is generated in range of 25° to 35°. The phase error is compensated in the early-late phase compensator by the unit of data block. In the random phase offset of 45° to 55°, the performance degradation is occurred to 4 dB relative to an



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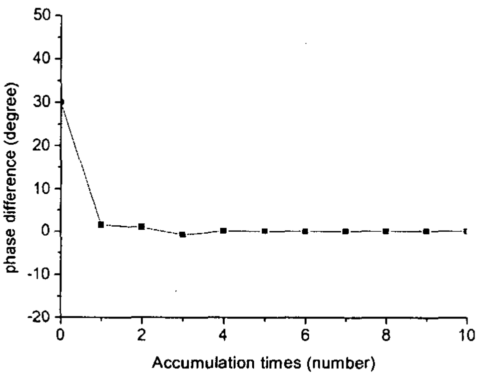

(b)

Fig 7. Phase difference performance dependent on accumulation times at SNR of 4 dB, (a) accumulation length =1 and (b) accumulation length =20.

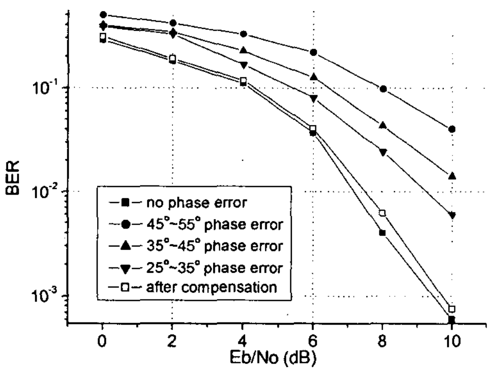

Fig 8. Performance of six-port DCR using the early-late phase compensator in the presence of random phase offset.

ideal case with no phase offset. However, it is shown from Fig. 8 that the proposed early-late phase compensator effectively corrects the phase offset, which approaches the ideal performance.

In case of the slowly-varying phase error, the proposed recursive phase offset compensation method corrects the phase error very well, which is shown in Fig. 9. It is clear from Fig. 9 that the performance for the slowly-varying phase error in range of 0° to 40° agrees with the ideal performance after phase offset compensation. However, the time delay is occurred in accumulator, if the accumulation length N in an accumulator is increased. In the viewpoint of implementation, the time delay corresponding to the delay is necessary in the RF input signal path. Therefore, it is necessary to be implemented as the proper accumulation length N

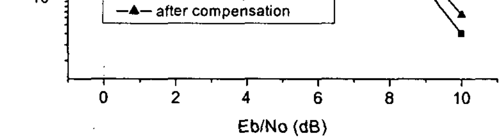

Fig 9. Performance of six-port DCR using the recursive early-late phase compensator in the presence of slowly varying phase offset.

according to transmission channel conditions. Fig. 10 shows a mean square error (MSE) curve that means the difference between the estimated phase error and the real phase error:

$$MSE=\frac{1}{N}\sum_{n=0}^{N-1}|\hat{e}(n)-e(n)|^2 \tag{18}$$

It is shown from Fig. 10 that the phase offset can be compensated very well under low accumulation length in case of high SNR signal.

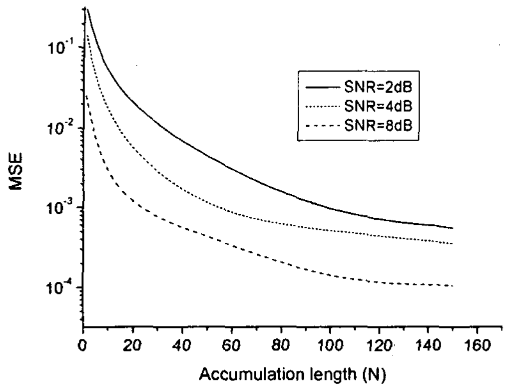

Fig 10. MSE performance of phase error dependent on accumulation lengths.

The proper accumulation length can be used according to the required channel environment.

V. Conclusions

The frequency and phase offset between the RF input signal and the local oscillator signal affect the transmission performance as a major impairment factor in direct conversion receiver, though the frequency and phase offsets may be covered by the same automatic frequency and phase tracking circuit with the conventional hetero-dyne receiver. Using the early-late phase compensator and accumulator in RF-front end signal stage, the frequency and phase offset compensation method between the RF input signal and the local oscillator signal was proposed in this paper.

The conventional I/Q imbalance compensation processor in baseband signal processing stage of a direct conversion receiver can be designed as a fine frequency and phase tacking function by an ingenious frequency and phase offset tracking in RF input stage. Also, the conventional I/Q imbalance compensation processor can be designed with a simple architecture. The proposed phase offset compensation corrects the varying phase offset besides the fixed large frequency and phase offset. Furthermore, the phase offset compensation corrects the wide phase error over the limited tracking range of conventional frequency and phase offset tracking method. It has been found that the compensated performance by using the proposed method approaches the ideal performance with no phase error. In the viewpoint of design, also, it is possible to implement the accumulator with a proper accumulation factor.

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