Adaptive IF selection and IQ mismatch compensation in a low-IF GSM receiver*

Zhang Cheng(张成), Wang Lifang(王丽芳), Tan Xi(谈熙)†, and Min Hao(闵昊)

State Key Laboratory of ASIC & System, Fudan University, Shanghai 201203, China

Abstract: This paper presents an algorithm that can adaptively select the intermediate frequency (IF) and compensate the IQ mismatch according to the power ratio of the adjacent channel interference to the desired signal in a low-IF GSM receiver. The IF can be adaptively selected between 100 and 130 kHz. Test result shows an improvement of phase error from 6.78° to 3.23°. Also a least mean squares (LMS) based IQ mismatch compensation algorithm is applied to improve image rejection ratio (IRR) for the desired signal along with strong adjacent channel interference. The IRR is improved from 29.1 to 44.3 dB in measurement. The design is verified in a low-IF GSM receiver fabricated in SMIC 0.13 μm RF CMOS process with a working voltage of 1.2 V.

Key words: low-IF; adaptive selection; phase error; IRR; LMS algorithm; power ratio

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1. Introduction

Nowadays, wireless transceivers require a high level of integration. For broadband systems, such as WCDMA and TD-SCDMA, zero-IF is the first choice. However, for narrow-band systems such as GSM, it is difficult to use zero-IF architecture: the 200 kHz GMSK-modulated GSM signal contains significant energy at a very low frequency; as a result, DC offset, $1/f$ noise and second order distortion will deteriorate the signal seriously.

Low-IF architecture is a good choice for GSM receivers. It can reduce the impact of DC offset and $1/f$ noise effectively, and the IIP2 requirement is reduced as compared with zero-IF architecture. The most serious problem is the image of adjacent channel interference caused by IQ mismatch. The image interference is superimposed at the location of the desired signal, and causes degradation of the SNR.

GSM limits the 1st adjacent channel to be 9dB larger than the desired signal, the 2nd and 3rd adjacent channel to be 41 dB and 49 dB larger[1], as shown in Fig. 1. The IF is always set to half of the channel bandwidth or a little higher.

The IF selected determines the image rejection ratio (IRR) requirement and influences EVM. If the IF is 100 kHz, the dominant image is the spectral tail of the 2nd adjacent channel, and the required IRR is 30 dB[2]. When the IF is moved to 130 kHz, the IRR requirement reaches 40 dB and the dominant image is also generated by the 2nd adjacent channel. A lower IF solution relieves the demand for IRR, but at the cost of EVM. In order to cancel the DC offset in an analog baseband circuit, a high pass filter is always used. The high pass filter has a significant variation of group delay at low frequency, so the phase error becomes serious when the IF moves from 130 to 100 kHz. Thus it is desirable to choose the IF according to the strength of the interference.

Normally, the IRR is below 30 dB without any compensation. In order to meet the IRR requirement, IQ mismatch compensation (IQMC) has to be applied. IQMC has two schemes: compensation using a training signal[3, 4] or compensation using an adaptive algorithm[5−8]. Compensation based on training requires a training signal generator. And the performance depends on the quality of the generated training signal. So it is not a good choice for on-line compensation. An adaptive algorithm is easy to implement digitally and is suitable for on-line compensation. The least mean squares (LMS) algorithm is always used to compensate IQ mismatch after sampling the ADC, but it is vulnerable to the impact of wireless fading: in the absence of strong adjacent channel interference, the image interference will not impact the desired signal, but a change of the desired signal due to wireless fading will cause fluctuations in the compensation coefficients, and the quality of the desired signal will be impacted. Consequently, in this work we

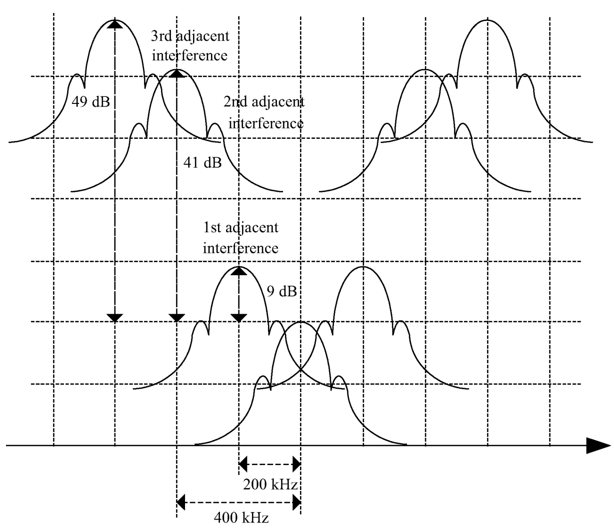

Fig. 1. Desired signal and adjacent channel interferences.

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† Corresponding author. Email: tanxi@fudan.edu.cn

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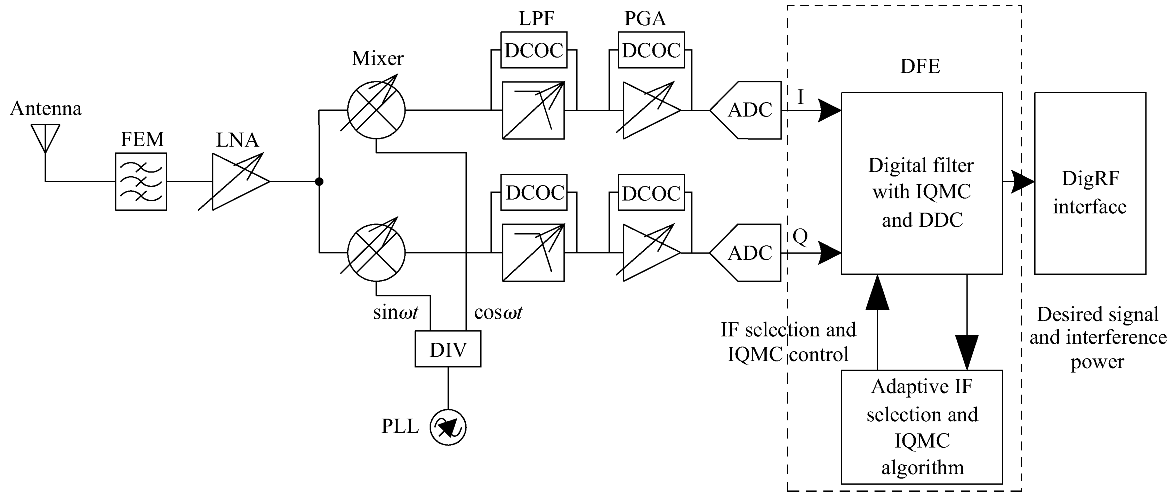


Fig. 2. Architecture of the receiver.

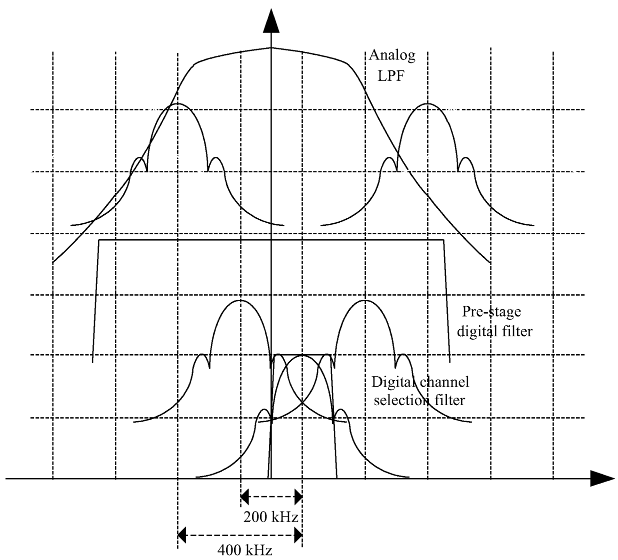


Fig. 3. Analog LPF and digital channel selection filter.

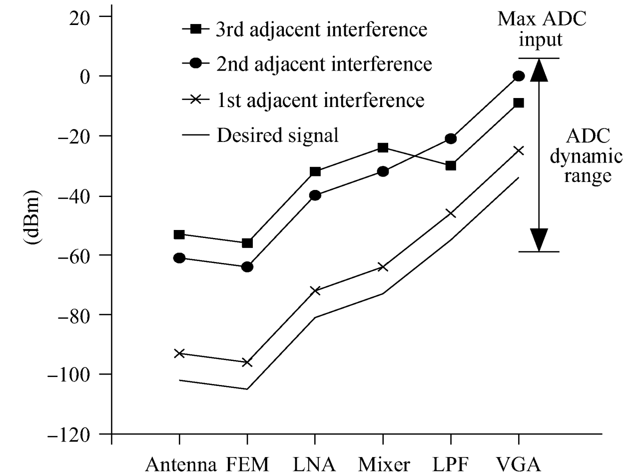


Fig. 4. Possible signal levels as they pass through the receiver channel.

apply an IQMC algorithm which can be adaptively turned on and off according to the strength of the interference to optimize the receiver performance.

In this paper, a low-IF GSM receiver with adaptive IF selection and an IQMC algorithm is implemented, as shown in Fig. 2. IF selection and the IQMC algorithm is implemented in the digital front end (DFE) after the ADC, and the down-converted data is transferred to the DigRF interface. Based on the power ratio of the adjacent channel interference to the desired signal, IF and IQMC can be adaptively selected and applied. When the interference is sufficiently small, the IRR requirement is very low. IF can be adaptively selected to 130 kHz, which can effectively reduce the impact of the high-pass pole induced by DCOC and the $1/f$ noise. Meanwhile, the compensation algorithm is shut down to avoid the error caused by wireless fading. When the interference becomes stronger, an IF of 100 kHz is selected to obtain a better IRR. When the 2nd adjacent channel interference is very large, the adaptive IQ mismatch compensation based on the LMS algorithm is applied to suppress the image generated by the interference.

2. Analysis

2.1. Interference

In the receiver channel, as shown in Fig. 2, the RF front-end can only attenuate blockers MHz away, such as a –23 dBm blocker at 3 MHz[1], and has almost no rejection on the adjacent channel interference. After down-conversion, the analog baseband LPF provides attenuation on the adjacent channel interference, but not much. The center frequency of the desired signal is $+100$ kHz, so the image interference at the negative adjacent channel is much more serious than the positive adjacent channel. The 3 dB low-pass pole of the LPF is set to 250 kHz, as shown in Fig. 3. It has no attenuation on the 1st adjacent channel, 7 dB attenuation on the 2nd adjacent channel, and 24 dB attenuation on the 3rd adjacent channel. Figure 4 illustrates the possible signal levels which include the desired signal and adjacent channel interferences as they pass through the receiver channel. When these interferences reach the ADC input, as compared with the desired signal, the 1st

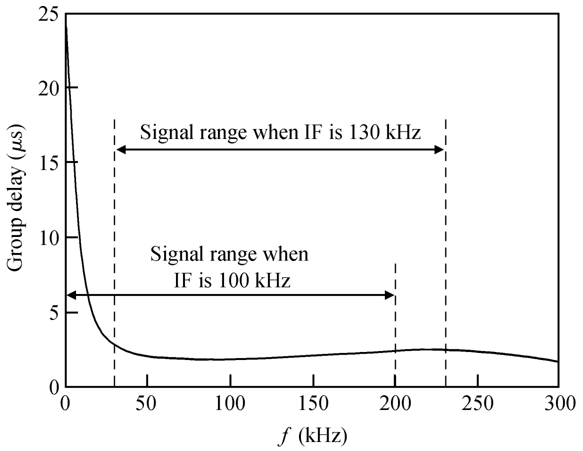


Fig. 5. Group delay of the RX front end.

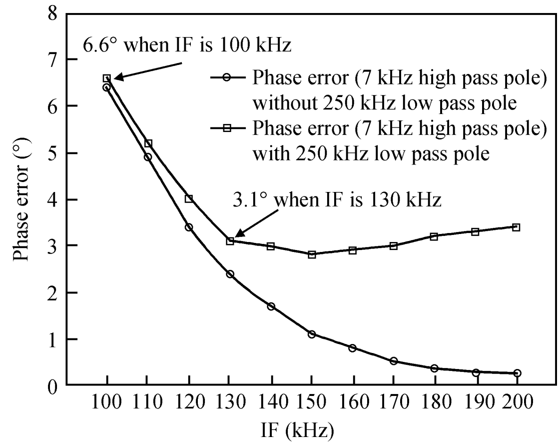


Fig. 6. Phase error due to the analog HPF and LPF.

adjacent channel interference is 9 dB larger, the 2nd adjacent channel interference is 34 dB larger, and the 3rd adjacent channel interference is 25 dB larger. In the extreme case, the desired signal along with the 34 dB larger 2nd adjacent channel interference reaches the ADC input, and the IRR requirement is the highest in all cases[2].

After ADC sampling, the data is processed by the DFE before transferring to the baseband processer. Digital filters and gain control are the most basic modules, and for a low-IF receiver, digital down-conversion (DDC) is also necessary. With the development of signal modulation, the channel characteristics have become increasingly demanding, The DFE makes more digital calibrations and compensations, such as digital domain DC offset cancellation (DCOC) and IQMC[9]. Most of the blockers are filtered by a pre-stage digital filter with a cut-off frequency of 541.7 kHz. After the adjacent channel selection filter, only the desired signal is retained, as shown in Fig. 3. So we can calculate the signal power before and after the channel selection filter, and get the power ratio of the interference to the desired signal.

2.2. Phase error versus IF frequency

Besides noise, non-linearity and image interference caused by imperfect image rejection, the receiver channel can be influenced by the channel filter, including the analog LPF, the HPF induced by analog DCOC and the digital channel selection filter. GSM signal is GMSK modulated and only phase modulation is applied, so the signal is immune to amplitude variations and sensitive to phase error. A digital channel selection filter is designed using an FIR filter and has little influence on the receiver channel.

The analog LPF and HPF are non-linear in phase response. In the receiver, the 3 dB low-pass pole of the LPF is set to 250 kHz according to the block filtering and phase response specification[1, 2]. In addition, the 3 dB high-pass pole of the HPF is set to 7 kHz according to the transmitter/receiver switching and the phase response specification[1, 2]. The LPF has a small group delay variation around the low-pass pole, and the HPF has a significant group delay variation at low frequency, as shown in Fig. 5. The best choice is to transfer the desired signal in the flat region of group delay. Obviously, 30–230 kHz has a smaller group delay variation than 0–200 kHz. In Fig. 6, the phase error of the desired signal transferred through the receiver channel is simulated in ADS. If there is only a 7 kHz high-pass pole in the channel, the phase error decreases with IF increasing. When the 250 kHz low-pass pole is added, the phase error reaches the minimum and then increases with IF increasing. This is because when the IF is larger than 150 kHz, the 250 kHz low-pass pole will attenuate the spectrum of the desired signal and some phase information will be lost. So an IF of 130 kHz offers a much lower phase error and it can be used when the adjacent channel interference is small.

2.3. IQ mismatch and compensation

IQ mismatch is mainly generated in the down-conversion mixer. The threshold voltage mismatch of the switching pairs in the mixer will cause gain and phase mismatch. The divider will also generate a quadrature error, which causes phase mismatch when it divides the PLL frequency into in-phase (I) and quadrature (Q). The amplification mismatch in analog baseband will cause gain mismatch as well. The IQ mismatch mentioned above varies with temperature, voltage, process, radio frequency, gain configuration and so on. So an on-line compensation for IQ mismatch is needed.

In an ideal quadrature receiver, the RF signal is multiplied by $\cos\omega_0 t$ and $\sin\omega_0 t$. It can be considered as multiplied by a complex number $\cos\omega_0 t + \mathrm{j}\sin\omega_0 t$, equivalent to a complex exponential $\mathrm{e}^{-\mathrm{j}w_0 t}$. When IQ mismatch is considered, the complex number is revised to $\cos\omega_0 t + \mathrm{j}(1+\alpha)\sin(\omega_0 t + \phi)$, equivalent to $\frac{1+(1+\alpha)\mathrm{e}^{\mathrm{j}\phi}}{2}\mathrm{e}^{\mathrm{j}\omega_0 t} + \frac{1-(1+\alpha)\mathrm{e}^{-\mathrm{j}\phi}}{2}\mathrm{e}^{-\mathrm{j}\omega_0 t}$. As shown in Figs. 7(a)–7(c), the input RF signal is multiplied by a mismatched LO in the time domain. In the frequency domain, the desired signal and the interference are added with the image of themselves. As a result the desired signal is polluted by the image of the interference. The compensation of IQ mismatch is equivalent in order to cancel the image.

In this paper we use the LMS algorithm to filter the image of the composite signal. The LMS algorithm is a class of adaptive filter used to mimic a desired filter by finding the filter coefficients that relate to producing the LMS of the error signal (difference between the desired and the actual sig-

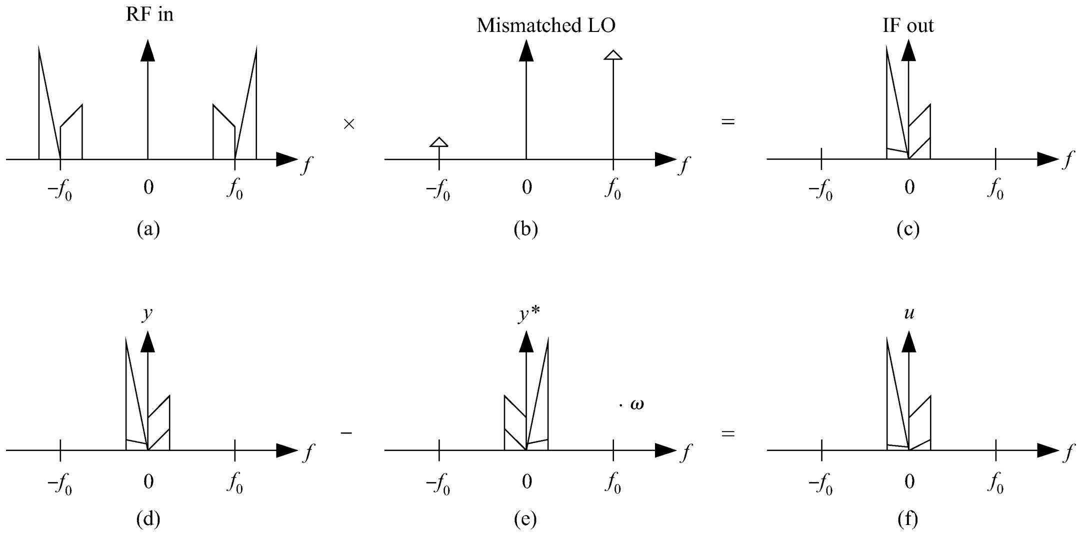


Fig. 7. Generation of image by IQ mismatch and cancellation of image by IQMC.

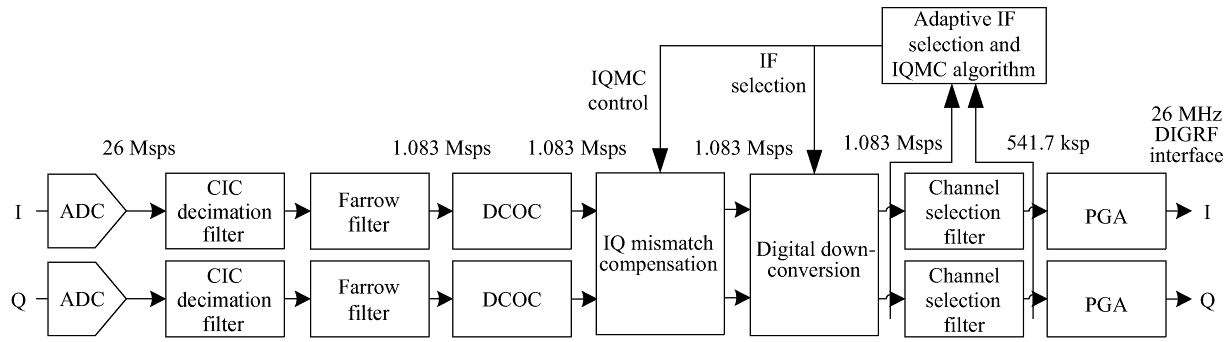


Fig. 8. Architecture of DFE.

nal)[10]. It was invented in 1960 by Bernard Widrow[10] and has been widely used in adaptive filters[5–8]. As shown in Figs. 7(d)–7(f), the output IF signal y is used as the reference of the algorithm. The complex conjugate y^* is the image of y in the frequency domain. ω is the filter coefficient of the algorithm. If a suitable coefficient ω can be found to weigh the image of the composite signal, $y^* \cdot \omega$ can be regarded as the approximation of the image and canceled from the IF output signal y. The final filtered signal is $u = y - y^* \cdot \omega$, as shown in Fig. 7(f). In a quadrature receiver is without IQ mismatch, the auto-correlation of I and Q channels should be equal and the cross-correlation between I and Q channels should be zero[5, 11]. In the algorithm, a feedback loop is used to find a suitable coefficient ω that can make the auto-correlation error and cross-correlation approach zero. The detail implementation will be presented in the next section.

3. Implementation

3.1. System architecture

Figure 8 illustrates the architecture of the DFE for GSM. The sampling rate of the ADC is 26 Msps, because it is part of a multi-mode receiver that needs to support TD-SCDMA signal as well. After the pre-stage digital filter, the input signal is down-sampled to 1.083 Msps, and the spectrum between –541.7 and 541.7 kHz is retained. So only the 1st, 2nd and 3rd adjacent channel are reserved and other blockers are totally filtered. Then DCOC, IQMC and DDC modules are used to process the signal with the same sampling rate. The signal is down-converted to zero-IF and then goes into the channel selection filter. Only the desired signal between –100 and 100 kHz is retained, and the sampling rate is converted to 541.7 kHz. The filtered signal is amplified by the digital PGA packaged in serials according to DigRF requirement and then transferred to the baseband processer. Therefore, we can calculate the power before and after the channel selection filter, and get the power ratio of the interference to the desired signal. It lays a foundation for the state control.

The flowchart of the state control is shown in Fig. 9. When the receiver is turned on, an IF of 100 kHz is selected by default and no IQ mismatch compensation is applied. The signals before and after the channel selection filter are collected to get the average power, and the power ratio of the interference to the desired signal is calculated. When the interference power is 30 dB larger than the desired signal, the 2nd adjacent channel interference is very large, so an IF of 100 kHz is selected and an IQMC is applied. When the power ratio is larger than 6 dB and smaller than 30 dB, the image of the adjacent channel is moderate, so an IF of 100 kHz is enough to suppress image and an IQMC is not applied. When the power ratio is smaller than 6 dB, an IRR of 20 dB is enough for this state, so an IF

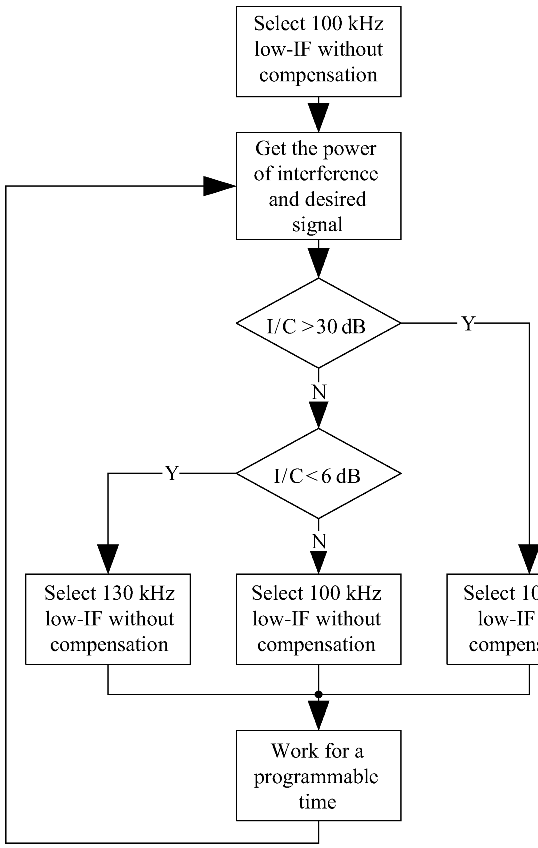


Fig. 9. Flowchart of state control.

of 130 kHz is selected and an IQMC is not applied. Shift and subtract operation can be used to finish the power comparison. The state can be recalculated for a programmable time and the time depends on the variation of the signal condition.

In Section 2, Figure 4 shows that when an IF of 100 kHz is selected, the 1st, 2nd and 3rd adjacent channel interferences are 9, 34 and 25 dB larger than the desired signal. Similarly when an IF of 130 kHz is selected, the 1st, 2nd and 3rd adjacent channel interferences are 9, 36 and 27 dB larger. So the threshold in the state control is suitable for both IF selections. DDC is realized using a complex multiplier and a numerically controlled oscillator (NCO). Because the sampling rate of the input signal is 1.083 Msps, the ratio of IF to the sampling rate is 6/65 and 3/25. The IF can be easily generated by using a look-up table with a sampling rate of 1.083 Msps. The frequency of the PLL is controlled by the baseband processer using a look-up table as well, so it is very easy to switch the PLL frequency according to the IF selection.

3.2. Image-rejecting LMS algorithm

As mentioned in Section 2, the LMS algorithm is used to filter the image. As shown in Fig. 10, $y$is the input signal with image, y^* is the complex conjugate of y, u is the compensated output signal, ω is the compensation coefficient, and μ is the compensation step. The aim is to find a suitable coefficient ω that can make the auto-correlation error and the cross-correlation approach zero. Mathematically the aim is shown as $E(u_\mathrm{I}u_\mathrm{I} - u_\mathrm{Q}u_\mathrm{Q}) \rightarrow 0$ and $E(u_\mathrm{I}u_\mathrm{Q}) \rightarrow 0$, and $E(\cdot)$ is the expectation operator here[5, 11]. So it is equal to

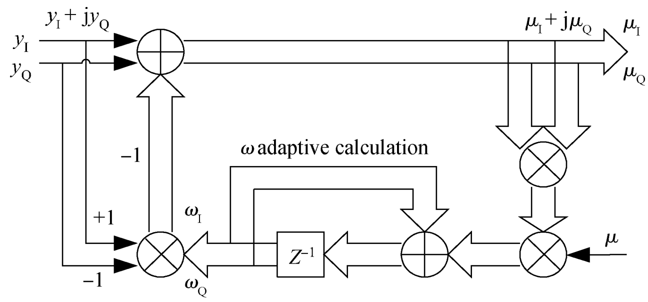


Fig. 10. Architecture of the IQMC algorithm.

$E(uu) = E(u_\mathrm{I}u_\mathrm{I} - u_\mathrm{Q}u_\mathrm{Q}) + \mathrm{j} \cdot 2E(u_\mathrm{I}u_\mathrm{Q}) \rightarrow 0.$

The coefficient ω is approached by $\omega(n+1) = \omega(n) + \mu u(n)u(n)$ and the final compensated output is calculated by $u = y - y^*\omega$. The feedback loop is shown in Fig. 10. After several iterations, $E(u{\cdot}u)$ will approach zero and the algorithm will converge. As a result, a suitable ω can be found to weight the image of the input signal and the image can be cancelled from the input signal.

μ is the compensation step and is inversely proportional to the power of the input signal. In the special state when IQMC is applied, the interference is 30 dB larger than the desired signal. For the effect use of the ADC input range, the interference is magnified to almost the maximum ADC input[1, 2]. So we can fix the value of μ in the realization. A single tone is used in simulation to find the proper value and 1/32 is adopted here. We can set the initial value of ω to make the convergence faster. The initial value ω_0 can be obtained by training the algorithm using a signal with a tested gain and phase mismatch[6]. We can also use a gradually reduced value of μ to get a quick approach of ω at first and then converge precisely[5].

The simulation result is shown in Fig. 11. Figure 11(a) shows a single tone located in 100 kHz without IQ mismatch. With 0.5 dB gain mismatch and 3° phase mismatch, the image of the single tone is generated in –100 kHz (983 kHz using FFT in Matlab) and the IRR is about 28 dB, as shown in Fig. 11(b). After IQMC, the image is suppressed and the IRR is almost 50 dB, as shown in Fig. 11(c). Figure 11(d) shows a desired signal located in 100 kHz along with a 2nd adjacent channel interference located in –300 kHz (783 kHz using FFT in Matlab) without IQ mismatch. With 1 dB gain mismatch and 5° phase mismatch, the image of the interference is generated in 300 kHz and the IRR is about 22 dB, as shown in Fig. 11(e). After IQMC, the image is suppressed and the IRR is almost 46 dB, as shown in Fig. 11(f).

4. Measurement

A multi-mode transceiver for GSM and TD-SCDMA is implemented in SMIC 0.13 μm RF CMOS process, and the microphotograph of the die is shown in Fig. 12. The RX channel can be configured as a low-IF GSM receiver with a voltage supply of 1.2 V. It includes the RX front end and the analog output, ADC, DFE and digital output for the baseband processer. The DFE contains the algorithm of adaptive IF selection and IQ mismatch compensation. The test results are as follows.

The switching of the states works normally with the change of the power ratio. The test bench is shown in Fig. 13. We can

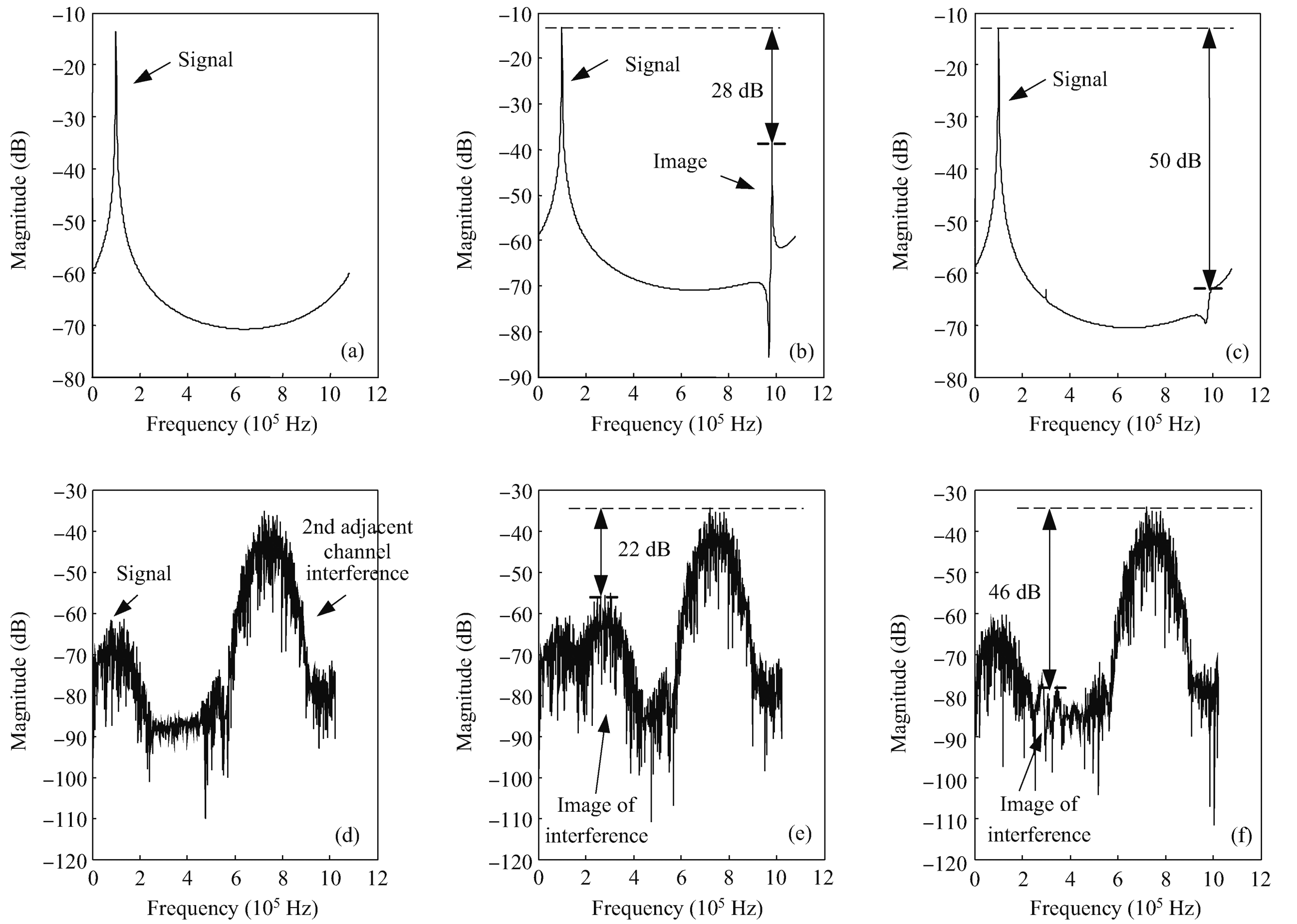


Fig. 11. Simulation result of the IQMC algorithm.

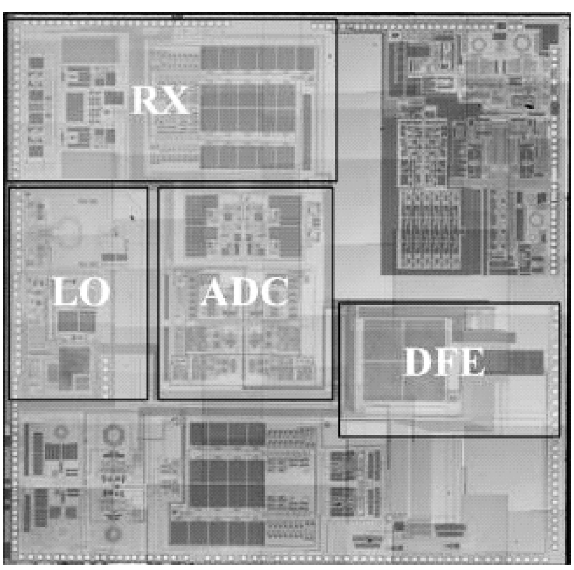


Fig. 12. Microphotograph of multimode transceiver.

collect the final filtered signal in the digital output and analyze the phase error of the desired signal with an IF of 100 and 130 kHz. In the DFE the desired signal is down-converted by a DDC and filtered by a channel selection filter, so we are unable to obtain image information in the final output. So we use the analog output of the RX frontend, an off-chip dual-channel ADC and a FPGA board with the DFE code to simulate the RX channel, and collect the signals before and after the IQMC module in the DFE. The data collected is analyzed using Agilent 89600 Vector Signal Analyzer software.

Figure 14 shows the phase error of the desired signal with an IF of 100 and 130 kHz. The phase error with an IF of 130 kHz is only 3.23° compared with 6.78° with an IF of 100 kHz. So when the interference is very small, the signal quality can be improved by the IF switching from 100 to 130 kHz.

Figures 15 and 16 illustrate the improvement of IRR using a single tone and a modulated signal. Tested using a single tone, IRR is improved from 29.4 to 45 dB as shown in Fig. 15. When a modulated signal is used, the IRR is improved from 29.1 to 44.3 dB as shown in Fig. 16.

The summary of measured performance and comparisons are shown in Table 1. The channel quality can be obviously improved by adaptive IF selection and IQMC. When compared with other low-IF GSM receivers, IF can be adaptively selected to get a lower phase error, and IQMC is applied on-line and adaptively shut down to avoid the impact of wireless fading. The algorithm is implemented in a digital circuit and no training signal generator is needed.

5. Conclusion

A low-IF GSM receiver with adaptive IF selection and IQ

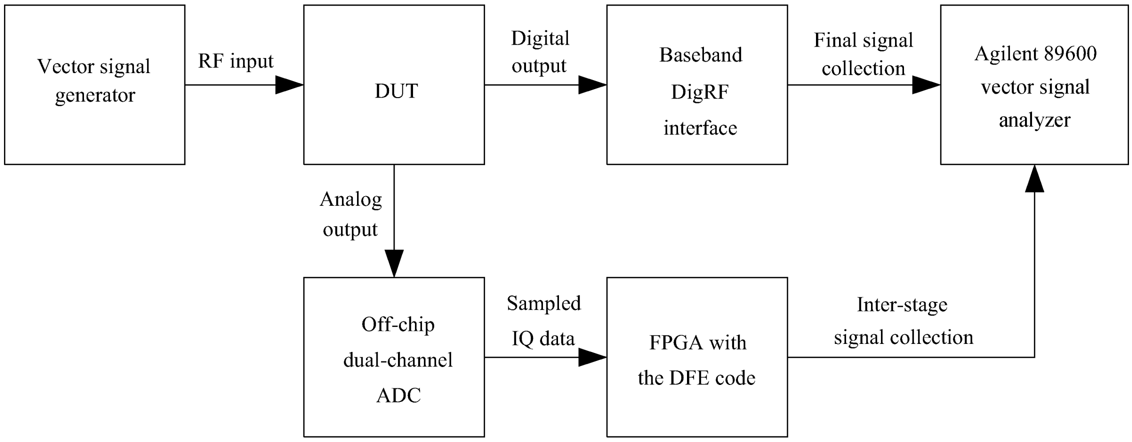
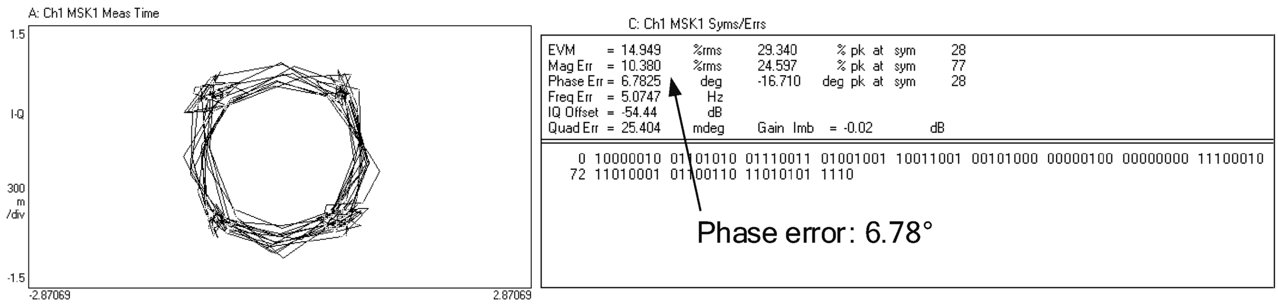
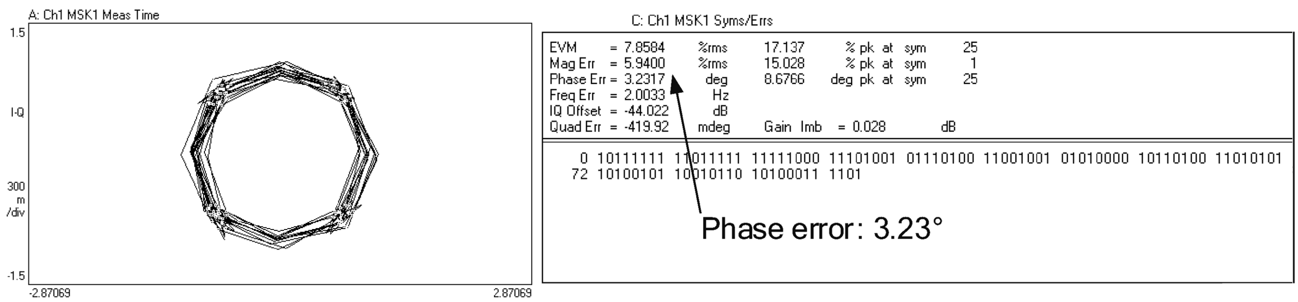


Fig. 13. Test bench.

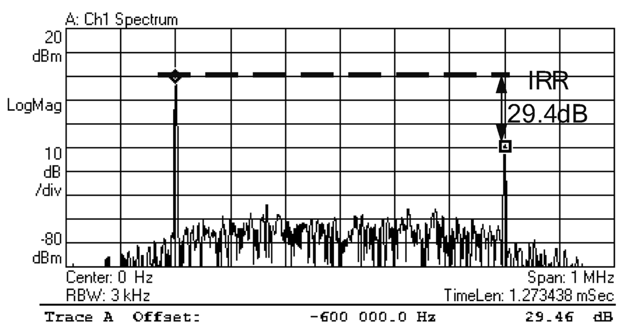


(a)

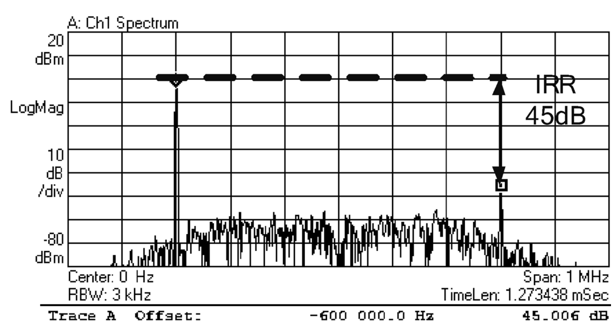


(b)

Fig. 14. Phase error of the desired signal with IF of 100 kHz and 130 kHz.



(a)



(b)

Fig. 15. IRR of single tone before and after the IQMC module.

mismatch compensation is fabricated in SMIC 0.13 μm RF CMOS process. The IF and IQMC module can be adaptively selected according to the power ratio of the adjacent channel interference to the desired signal. At 1.2 V supply voltage, the test result shows a phase error improvement from 6.78° to 3.23° and an IRR improvement from 29.1 to 44.3 dB. It can tolerate

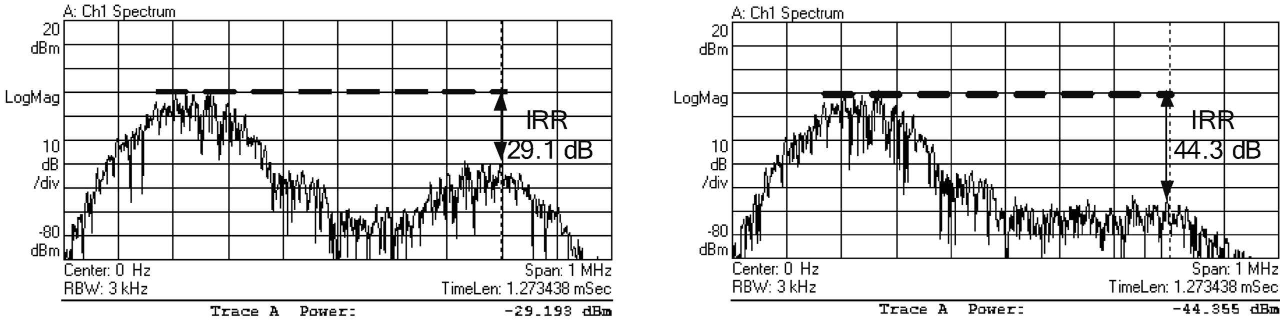


Fig. 16. IRR of modulated signal before and after the IQMC module.

Table 1. Summary of measured performance and comparisons.

	Compensation	IRR after compensation	IF selection	Phase error
This work	On-line compensation based on LMS, shut down when interference is small	44.3	Adaptive selection between 100 and 130 kHz according to interference	Improvement from 6.78° to 3.23°
Ref. [3]	Off-line compensation using a training signal	50	100 kHz	—
Ref. [4]	Off-line compensation using a training signal	50	200 kHz	—
Ref. [5]	On-line compensation based on LMS, impacted by wireless fading when interference is small	50	130 kHz	—

the adjacent channel interference in GSM system with sufficient margin.

References

[1] Rudell J C, Weldon J, Ou J J, et al. An integrated GSM/DECT receiver design specifications. UCB Electronics Research Laboratory Memorandum, 1998

[2] Gu Qizheng. System design of transceivers for wireless communications. Springer, 2005

[3] Glas J P F. Digital I/Q imbalance compensation in a low-IF receiver. IEEE Proceeding on Global Telecommunications Conference, Sydney, 1998, 3: 1461

[4] Maeda K, Hioe W, Kimura Y, et al. Wideband image-rejection circuit for low-IF receivers. IEEE International Solid-State Circuits Conference, 2006

[5] Elahi I, Muhammad K, Balsara P T. I/Q mismatch compensation using adaptive decorrelation in a low-IF receiver in 90-nm CMOS process. IEEE J Solid-State Circuits, 2006, 41(2): 395

[6] Elahi I, Muhammad K, Balsara P T. Parallel correction and adaptation engines for I/Q mismatch compensation. IEEE Trans Circuits Syst II: Express Briefs, 2009, 56(1): 86

[7] Valkama M, Renfors M. Advanced DSP for I/Q imbalance compensation in a low-IF receiver. IEEE International Conference on Communications, 2000, 2: 768

[8] Der L, Razavi B. A 2-GHz CMOS image-reject receiver with LMS calibration. IEEE J Solid-State Circuits, 2003, 38(2): 167

[9] Hueber G, Zou Y, Dufrene K, et al. Smart front-end signal processing for advanced wireless receivers. IEEE J Sel Topics in Signal Processing, 2009, 3(3): 471

[10] Widrow B, Glover J R Jr, McCool J M, et al. Adaptive noise cancelling principles and applications. Proc IEEE, 1975, 63(12): 1692

[11] Pun K P, Franca J E, Azeredo-Leme C. The correction of frequency dependent I/Q mismatches in quadrature receivers by adaptive signal separation. Proceedings 4th International Conference on ASIC, 2001: 424