System Level Design of CDMA RF Receivers Using the Receiver Noise Equation

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Abstract: In this paper a common design method for RF receivers of different CDMA standards is introduced. The method adopted a new equation, receiver noise equation, for the analysis of each standard. The test conditions for RF receivers in four different CDMA standards, CDMA cellular, PCS, WCDMA, and cdma2000 are analyzed based on the receiver noise equation. With the result of the analysis, the specifications for RF receivers of different CDMA standards are derived.

1. Introduction

System level design, the first phase in the design of a RF receiver, determines overall specifications of the receiver from the communication standards. For system level design of a RF receiver, the designer needs a thorough understanding of test conditions from the standard to identify SNR degrading factors and their effects on the system level performance specifications. And the designer must do several inevitable trade-offs between those SNR degrading factors. So a new method, which can simplify system level design of a RF receiver, is needed and we've introduced the receiver noise equation for that purpose. [1] Since its first commercial service in Korea, CDMA has been adopted in 2G and 2.5G standards and is now being implemented in 3G systems. Thus, it is valuable to introduce a common method of designing CDMA RF receivers for various CDMA standards such as CDMA cellular [2], PCS [3], WCDMA [4], and cdma2000 [5]. In this paper we've introduced a common system level design method for CDMA receivers, which utilizes the receiver noise equation as a tool for the analysis of the test conditions for RF receivers in each standard.

2. Back Ground

The receiver noise equation may be viewed as an extended added noise analysis, and it summarizes noise and other SNR degrading factors in the receiver. To use the receiver noise equation in the analysis of receiver test conditions, we will provide a brief background of it. [1]

2.1 Added noise in noisy system

When the system in Fig. 1, with gain G and noise factor F, has signal S_{in} and noise N_{in0}[1] as input, the system's output signal and noise will be

$$S_{out} = GS_{in}\,, \qquad (1)$$

$$N_{out} = GN_{in0} + N_a\,. \qquad (2)$$

Where N_a is the added noise by the system, which is independent of the input noise. From the definition of noise factor, the noise factor F can be stated as

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{S_{in}}{N_{in0}} \Big/ \frac{GS_{in}}{GN_{in0} + N_a} = 1 + \frac{N_a}{GN_{in0}}\,. \qquad (3)$$

For the added noise N_a we can rewrite the equation (3) as

$$N_a = GN_{in0}(F-1)\,. \qquad (4)$$

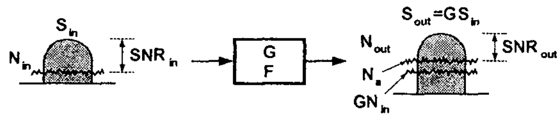

Fig.1 Signal in a noisy system with gain of G and the noise factor of F

2.2 Receiver noise equation

To make sure of a system's ability to receive weak signal, its noise characteristics are usually expressed by an equivalent input noise power as in Fig. 2.

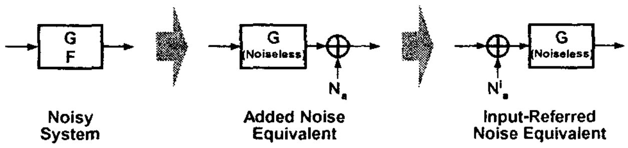

Fig. 2 Input referred nioise equivalent of a system

From equation (4), the input referred added noise N^i_a is

$$N^i_a = \frac{N_a}{G} = N_{in0}(F-1)\,. \qquad (5)$$

By dividing both side of equation (5) with N_{in0} and defining a new parameter, the normalized input referred added noise n^i_a, we can get the equation,

$$n^i_a = \frac{N^i_a}{N_{in0}} = F - 1\,. \qquad (6)$$

There are many SNR degrading factors in a receiver for wireless communication: receiver thermal noise, intermodulation product, reciprocal mixing product, Tx leakage noise and so on. The SNR degrading factors are independent of each other, and they can be treated as noises in the viewpoint of SNR. So a receiver can be modeled as a noisy system with multiple noise sources like Fig. 3.

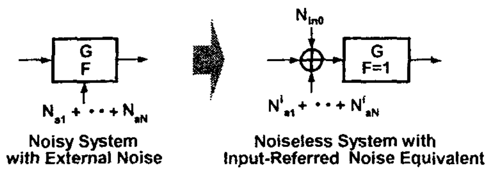

Fig. 3 Equivalent input referred noise when there are N noise sources

And, by extending equation (6), the SNR degradation by the receiver can be calculated by equation (7), named as ***the receiver noise equation***.

$$\frac{SNR_{in}}{SNR_{out}} = 1 + \sum_{K=1}^{N} n_{aK}^{i} \quad (7)$$

2.3 Noise factors in RF receiver

The major SNR degrading factors and their normalized input referred added noise are summarized in table 1.

TABLE 1. SNR degrading factors [1]

Category	Factors	Values	
Intrinsic noise source	Thermal noise (NF)	$N_{Th}^{i} = N_{in0}(F-1)$	(8)
Extrinsic noise sources	Tx noise leakage in Rx band	$N_{Tx}^{i} = \frac{P_{Tx\_noise}}{S_{dup1}}$	(9)
	Cross modulation product	$N_{XM}^{i} = \alpha \frac{P_{Tx}^{2}}{S_{dup2}^{2}} \frac{P_{int}}{IIP3_{LNA}^{2}}$	(10)
	Reciprocal mixing product	$N_{RM}^{i} = P_{int} \cdot PN \cdot B$	(11)
	Intermodulation product	$N_{IMDN}^{i} = \beta_N \frac{P_{int}^{N}}{(IIPN)^{N-1}}$	(12)
	Image	$N_{Image}^{i} = \frac{P_{Image}}{S_{Image}}$	(13)
	Quantization noise	$N_{q}^{i} = \frac{1}{G} \frac{P_{FSR}}{SNR_{ADC}}$	(14)
	Imperfectly filtered interferers	$N_{int}^{i} = \frac{P_{int}}{S_{int}}$	(15)

3. SYSTEM LEVEL DESIGN OF THE CDMA RF RECEIVERS

Using equation (7), now we can simplify the system level design of CDMA receivers. In CDMA standard, the documents states several test conditions which confirm receiver's minimum performance that is verified by the FER (or BER) in the worst communication environments. The performance is directly related to the *Eb/Nt* at the receiver back-end and the minimum SNR value for proper demodulation can be calculated using equation (16), the CDMA equation.

$$SNR = \frac{E_b}{N_t}\frac{B}{R} = \frac{E_b}{N_t}\frac{1}{G_p} . \quad (16)$$

So total SNR degradation in receiver must satisfy equation (17).

$$\frac{SNR_{in}}{SNR_{out}} = 1 + \sum_{K=1}^{N} n_{aK}^{i} \le \frac{SNR_{in}}{SNR_{req}} . \quad (17)$$

3.1 Receiver sensitivity

In sensitivity test condition, the signal power and noise power at the input of the receiver can be found as

$$S_{in} = Traffic\ E_c = (I_{or})\ \text{dBm} + \left(\frac{Traffic\ E_c}{I_{or}}\right)\text{dB} , \quad (18)$$

$$N_{in} = N_{in0} = -174\ \text{dBm} + (10\log B)\ \text{dB} . \quad (19)$$

In W-CDMA, $DPCH\_E_c$ is used instead of $Traffic\ E_c$.

And the SNR degradation by the system must be less than SNR_{in}/SNR_{req}, where

$$SNR_{in} = (S_{in} - N_{in0})\ \text{dB} , \quad (20)$$

$$SNR_{req} = \left(\frac{E_b}{N_t} - PG\right)\text{dB} . \quad (21)$$

In the sensitivity test condition, there is no interfering signal but the transmitter power. Looking into this test situation, we can find four noise sources; the input thermal noise, the receiver added thermal noise, transmitter noise leakage in Rx band, and the quantization noise. Thus the receiver noise equation, concerning the noise sources listed above, is

$$\frac{SNR_{in}}{SNR_{out}} = 1 + n_{Th}^{i} + n_{Tx}^{i} + n_{q}^{i} \le \frac{SNR_{in}}{SNR_{req}} . \quad (22)$$

When designing the RF receiver, we usually choose the ADC carefully not to degrade the receiver's performance. In typical CDMA receivers, the ADCs are often with 4 bit resolution and sampling speed of 4~8 times the data rate, so, from equation (14), n_q^i is about −13 dB. Compared with the input thermal noise N_{in0}, N_q^i is small enough to be ignored. So we can rewrite equation (22) as equation (23) where F=1+ n^i_{Th}. Hereafter we ignore quantization noise in other noise equations.

$$\frac{SNR_{in}}{SNR_{out}} = F + n_{Tx}^{i} \le \frac{SNR_{in}}{SNR_{req}} \qquad (23)$$

Since typical noise power of CDMA transmitter in Rx band is −135 dBm/Hz [6], $n_{Tx}^{i} \approx 1$ when duplexer's Tx-Rx isolation is greater than about 40 dB.

From equation (23) we can find the noise factor requirement of the receiver as

$$NF_{max} \cong 10\log\left(\frac{SNR_{in}}{SNR_{req}}\right) \text{ dB}. \qquad (24)$$

3.2 Single tone desensitization

In this test condition, the input signal power is increased by 3 dB from the sensitivity test condition and the FER(or BER) requirement become less strict. There are another noise sources besides the one considered in sensitivity test: the reciprocal mixing product, cross modulation product, and imperfectly filtered interferer. Thus we can state the noise equation as

$$\frac{SNR_{in}}{SNR_{out}} = F + n_{TX}^{i} + n_{RM}^{i} + n_{XM}^{i} + n_{int}^{i} \le \frac{SNR_{in}}{SNR_{req}}. \qquad (25)$$

Then with the assumption that the receiver just meets the requirements of the sensitivity test and the inteferer is sufficiently suppressed by channel filtering, the contribution of the reciprocal mixing product and cross modulation product to the receiver's input referred noise can be calculated as

$$n_{RM}^{i} + n_{XM}^{i} \le \frac{SNR_{in}}{SNR_{req}} - \left(F + n_{Tx}^{i}\right). \qquad (26)$$

If we assume that there is only small cross modulation product that can be ignored, and the phase noise is flat in the band of interest, the phase noise can be calculated from

$$PN \text{ [dBc/Hz] @ offset} \cong N_{RM}^{i} - P_{int} - 10\log(B). \qquad (27)$$

But in the situation the linearity of the LNA and the isolation of the duplexer is not so good that the cross modulation must be considered. So trade-offs between the phase noise of the receiver and the LNA's linearity must be considered. Fig. 3 represents trade-offs for three different CDMA receiver systems. In cdma2000 and CDMA PCS test conditions, soaking factor α is set to be −5.6 dB and in CDMA cellular −3dB [7]. In W-CDMA test condition the cross modulation product can be ignored because blocking tone is modulated and small.

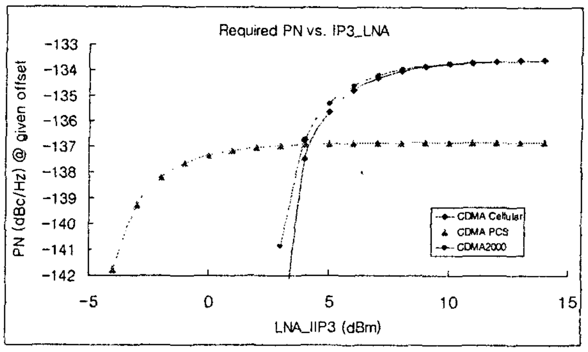

Fig. 4. Trade-offs between the phase noise of the receiver and the LNA's linearity with 55 dB duplexer's isolation at Tx band. The frequency offset for CDMA cellular is 900 kHz, and 1.25 MHz for others.

3.3 Intermodulation spurious response

In this test, we can write the receiver noise equation as

$$\frac{SNR_{in}}{SNR_{out}} = F + n_{Tx}^{i} + n_{RM1}^{i} + n_{RM2}^{i} + n_{IMD3}^{i} + n_{int1}^{i} + n_{int2}^{i}. \qquad (28)$$

However the reciprocal mixing products can be ignored in this test because of small interferer power and larger frequency offsets. And if we assume that inteferer is sufficiently suppressed by channel filtering, then we can state the noise equation as

$$\frac{SNR_{in}}{SNR_{out}} = F + n_{Tx}^{i} + n_{IMD3}^{i} \le \frac{SNR_{in}}{SNR_{req}}. \qquad (29)$$

After calculating n_{IMD3}^{i}, minimum IIP3 is found from

$$IIP3 = \frac{1}{2}\left(3 \times P_{int} - N_{IMD3}^{i}\right) \text{dB}. \qquad (30)$$

3.4 Adjacent-channel selectivity (cdma2000, WCDMA)

Adjacent-channel selectivity (ACS) is defined as the relative attenuation of the adjacent-channel power. From this test situation we can find some important requirements in cdma2000 and W-CDMA.

In cdma2000, ACS test is much similar to the single tone desensitization test, but we can ignore the cross modulation product since the cross modulation product does not overlap with our signal. Thus receiver noise equation can be written as

$$\frac{SNR_{in}}{SNR_{out}} = F + n_{Tx}^{i} + n_{RM}^{i} \le \frac{SNR_{in}}{SNR_{req}}. \qquad (31)$$

3.5 Receiver's blocking characteristics (cdma2000, W-CDMA)

From the out-of-band blocking test of the receiver we can figure out the image rejection requirement of the receiver.

Typically the IF frequency of the receiver is from several tens to a few hundreds of MHz. In this case the maximum interferer can be located at image band, and the receiver noise equation become

$$\frac{SNR_{in}}{SNR_{out}} = F + n^i_{Tx} + n^i_{Image} \leq \frac{SNR_{in}}{SNR_{req}}. \qquad (32)$$

From above equation we can determine the minimum required image rejection performance in cdma2000 and W-CDMA.

3.6 The results of system level design

For a given receiver architecture, we can get the values of required NF, PN (phase noise), IIP3 and image rejection ratio using table 1, the receiver noise equations derived above and equation (17). Table 2 summarized the specifications for heterodyne receivers.

TABLE 3. Summary of system requirements for CDMA receivers.

Calculated values	cdma2000	W-CDMA	CDMA PCS	CDMA Cellular
NF_{max} (dB)	9.5	7.3	5.8	9.5
PN (dBc/Hz)	-134 @1.25MHz	-113 @5 MHz	-137 @1.25MHz	-134 @900kHz
$IIP3_{LNA}$ (dBm)	7		2	8
$IIP3_{min}$ (dBm)	-21	-17.5	-11.5	-13.5
Image rejection (dB)	89	88		

4. CONCLUSION

In this paper we reviewed the receiver noise equation and summarized some important SNR degrading factors in a RF receiver. And we analyzed test conditions in various CDMA standards using the receiver noise equation and derived the allowable SNR degradation in each test condition. Then we have done the system level design of RF receivers of different CDMA standards. Consequently, the receiver noise equation simplifies the system level design of a RF receiver and may be used as a common tool for the analysis of RF test conditions in communication standards.

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