RF Receiver Requirements for 3G W-CDMA Mobile Equipment

The first standardization phase for upcoming third-generation (3G) wireless communications is coming to an end. As is typical for standardization work, sufficient analog performance has been assumed and predominant emphasis has been placed on modulation and coding. However, recent revisions to the standardization document for the European wideband CDMA (W-CDMA) proposal,[1] known as UTRA/FDD, enable a prediction of required performance for the RF front end. Such requirements are important when preparing commercial products for the new market. In this article, receiver requirements for the mobile unit are derived in terms recognizable by the RF designer.

For RF designers who are experienced with 2G TDMA/FDMA wireless systems, the introduction of W-CDMA requires some change of mind. First, rather than being separated in frequency or time, users are now separated by orthogonal codes. As the use of codes implies a spectral spreading, the treatment of overall signal-to-noise ratio requires considerations that are different from those required for TDMA systems. Second, a single radio channel behaves more like band-limited noise than a single sinusoid. Statistical terms like peak-to-average power ratio are therefore necessary to reflect this new constellation of signals.

General characteristics of the UTRA/FDD system are listed in ***Table 1***.[1] The nominal frequency spacing between adjacent channels is 5 MHz and the signal bandwidth is 3.84 MHz (corresponding to the chip rate). The downlink employs quadrature phase-shift keying (QPSK) modulation. Root-raised-cosine filtering is applied to shape the spectrum. Using orthogonal spreading and gold-code scrambling, several CDMA channels are multiplexed onto the same frequency channel.[2] Hence, the received signal consists of many simultaneously transmitted channels that use the same carrier frequency. As a result, large amplitude variations occur over time. The uplink is similar but uses a more complicated hybrid-QPSK modulation scheme. Although a combination of code allocation and complex scrambling is used to minimize the number of

TABLE I

UTRA/FDD W-CDMA SYSTEM CHARACTERISTICS

Parameter	Specification
Uplink frequency band (Tx) (MHz)	1920 to 1980
Downlink frequency band (Rx) (MHz)	2110 to 2170
Tx-to-Rx frequency separation (MHz)	134.8 to 245.2
Nominal channel spacing (MHz)	5
Chip rate (Mcps)	3.84

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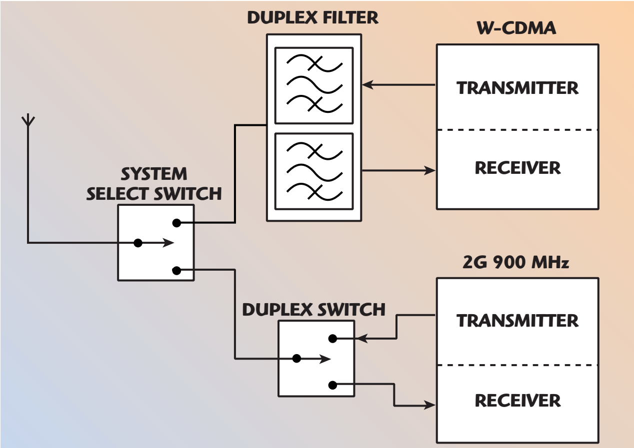


▲ *Fig. 1 Example of a duplex arrangement of a mobile receiver unit including 3G W-CDMA and 2G TDMA systems.*

signal nulls,[2] the envelope of the transmitted signal continues to display large amplitude variations. These variations place high linearity requirements on the power amplifier, which is believed to be a major RF design challenge.

Until the new 3G system delivers the coverage and services offered by the well-established 2G systems, multimode terminals with both 2G and 3G capabilities are required. Such a transceiver system configured for two wireless systems is shown in ***Figure 1***. In the transceiver system, a system select switch is used for selection between a 2G 900 MHz system (E-GSM) and a 3G W-CDMA system. The 2G system applies time division duplex (TDD) as well as frequency division duplex (FDD), and a duplex switch is used to select transmit or receive modes. Since the considered W-CDMA system only applies FDD and thus employs simultaneous transmission and reception, a duplex filter is required to provide isolation between the transmitter and the receiver. The continuous presence of the high power transmitter signal causes problems with spurious leakage from the transmit band located at a 134.8 to 245.2 MHz offset. Unless sufficient selectivity is available between the Tx and Rx bands, this spurious transmitter signal will cause severe dynamic range and intermodulation problems in the receiver chain.

From the previous comments, it should be clear that a high performance duplex circuit with good Tx-Rx isolation is needed. Based on data for switches and ceramic duplex filters available commercially today, an estimate of duplex circuit performance is listed in ***Table 2***. The 4 dB loss in the receive path has severe implications for the overall noise figure, however, since a small physical size is mandatory, it appears inevitable. The power level of the transmitter leakage signal at the receiver input is determined by taking the transmitter power class, adding the specified tolerance (+1/–3 or +2/–2 dB), adding the transmit path loss (2.5 dB) and subtracting the expected duplex filter isolation. The result is between –23.5 and –34.5 dBm and, since it is still being debated which maximum power levels will apply to hand-held units, a spurious transmitter level around –30 dBm is expected to be typical. The receiver must be able to handle this signal without significant performance degradation.

In the next section, the test cases specified in the standardization document[1] are studied in detail and issues of noise, second-order distortion, third-order intermodulation, selectivity and oscillator phase noise are treated. From this treatment, performance requirements for the W-CDMA receiver are derived. Note that all derived expressions assume insertion in decibel/decibel relative to 1 mW (dB/dBm) numbers and that signal powers are specified over a channel bandwidth (3.84 MHz) as in the UTRA/FDD standard.[1] A complete list of symbols and conventions used in this paper can be found in the sidebar on the following page. (Receiver requirements are only approximate since they do not relate to a specific receiver architecture.) Given a detailed architecture, more accurate requirements can be derived by studying the test cases specified by the standard.[1] However, for the purpose of assessing challenges faced by RF designers of 3G wireless equipment, the treatment is adequate. This article concludes with a direct-conversion receiver example, which illustrates a possible implementation that complies with derived requirements.

TABLE II

ANTICIPATED PERFORMANCE FOR W-CDMA DUPLEX ARRANGEMENT

Duplexer Parameter	*Anticipated Performance*
Duplex filter Tx loss (dB)	< 1.5
Duplex filter Rx loss (dB)	< 3.0
Loss of system select switch and antenna feed (dB)	< 1.0
Combined Tx loss (dB)	< 2.5
Combined Rx loss (dB)	2.0 to 4.0
Duplex filter Tx-Rx isolation in Tx band (dB)	> 60
Transmitter power classes (hand-held and fixed-mounted units) (dBm)	33/27/24/21
Typical transmitter leakage signal at receiver input (dBm)	–30

TEST CASES

The UTRA/FDD standard[1] describes a number of test scenarios in which the user bit rate is fixed at 12.2 kbps and the bit error rate (BER) must be below 10^{-3}. The desired downlink channel signal includes two or more orthogonal CDMA channels, which comprise the dedicated physical channel (DPCH) carrying the user data, a synchronization channel and, in some cases, other users' data channels. The standard specifies total power levels within the channel bandwidth and the relative level of the DPCH. For simplicity, the desired channel power is specified as the DPCH channel power throughout this article.

In the baseband receiver, the despreading process concentrates the desired signal energy in a bandwidth that corresponds to the channel symbol rate. Since noise and interference are uncorrelated with the despreading code, noise is not concentrated in a smaller bandwidth. Further, signal decoding results in a coding gain, and the total resulting improvement in signal-to-noise ratio is defined as the user data processing gain given by[3]

$$G_P = 10\log_{10}\left(\frac{3.84\,\text{Mcps}}{12.2\,\text{kbps}}\right) = 25\,\text{dB}$$

Note that this notation differs from the standard CDMA processing gain definition, which relates correlation time to chip time.[6] However, the chosen definition facilitates a more general comparison of different systems. The required minimum E_b/N_t for a BER of 10^{-3} is determined from simulations to be 5.2 dB.[3] The term E_b/N_t is used here instead of the traditional notation E_b/N_0 since most tests include interference in addition to noise. It is also suggested that an implementation margin be added to account for various baseband imperfections.[3] The required effective E_b/N_t is then expressed as

$$\left(\frac{E_b}{N_t}\right)_{eff} \approx 7\,\mathrm{dB}$$

which complies with the chosen definition of processing gain.

NOISE FIGURE

The noise figure (NF) of the UTRA receiver is calculated from the standard's reference sensitivity test. The desired channel power is $P_{R,DPHC} = -117$ dBm. Using the previously determined $(E_b/N_t)_{eff}$ requirement and including the user data processing gain, the maximum allowable noise power within the channel bandwidth is calculated to be

$$\begin{aligned} P_N(\text{acceptable}) &= P_{R,DPHC} - \left(\frac{E_b}{N_t}\right)_{eff} + G_p \\ &= -117\,\mathrm{dBm} - 7\,\mathrm{dB} + 25\,\mathrm{dB} \\ &= -99\,\mathrm{dBm} \end{aligned}$$

When the NF of the receiver and the bandwidth (BW) are known, the actual noise power is determined using

$$\begin{aligned} P_N(\text{actual}) &= NF + 10\log_{10}(k \bullet T_0 \bullet BW) \\ &= NF - 138\,\mathrm{dBW} \\ &= NF - 108\,\mathrm{dBm} \end{aligned}$$

where

k = Boltzmann's constant
T_0 = standard noise temperature

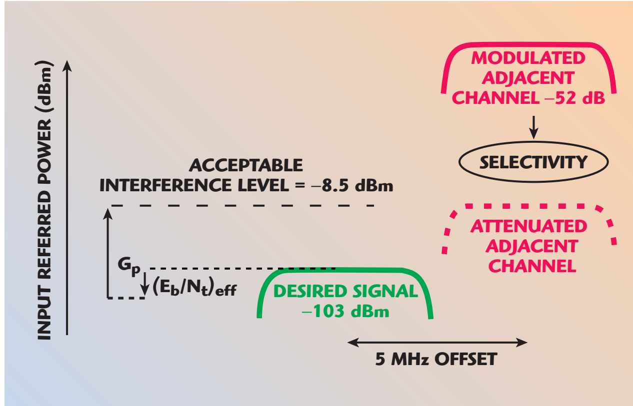
Since the actual noise power must be lower than or equal to the acceptable noise power, the NF requirement is

$$\begin{aligned} NF &\le P_N(\text{acceptable}) + 108\,\mathrm{dBm} \\ &= -99\,\mathrm{dBm} + 108\,\mathrm{dBm} \\ &= 9\,\mathrm{dB} \end{aligned}$$

This NF requirement is for the entire receiver. Subtracting the loss of 4 dB in the duplex circuit, the NF requirement for the rest of the receiver is 5 dB. This level appears to be within reach for low cost integrated receivers. It should be noted that the NF must be met in the presence of the transmitter leakage signal.

ADJACENT-CHANNEL SELECTIVITY

Adjacent-channel selectivity is defined as the relative attenuation of the adjacent-channel power. Selectivity includes filtering at the IF, analog baseband and digital baseband, and the frequency sensitivity of the demodulator. A test setting requirement for the first adjacent-channel selectivity is shown in



▲ *Fig. 2 Test for adjacent-channel selectivity.*

Figure 2. In this test, the desired signal power is $P_{R,DPHC} = -103$ dBm. Since this level is 14 dB above the sensitivity limit, noise is of minor importance. The first adjacent channel has a power of $P_{AC1} = -52$ dBm centered around a 5 MHz offset.

Treating the adjacent-channel signal as noise, the required first adjacent-channel selectivity can be derived. The acceptable interference level, P_I, is determined in the same

NOTATION, SYMBOLS AND ABBREVIATIONS USED IN THIS ARTICLE

Note that all power levels and intercept points are given in decibels relative to 1 mW (dBm), power levels of modulated signals are measured within a channel bandwidth (3.84 MHz) and all gain loss values are given in decibels (dB).

BER:	bit error rate
BW:	channel bandwidth (3.84 MHz)
DPCH:	dedicated physical channel
E_b/N_t:	ratio of average bit energy to noise and interference power spectral density
$(E_b/N_t)_{eff}$:	effective E_b/N_t including an implementation margin
G_P:	user data processing gain
IIP_2:	second-order intercept point referred to the input
IIP_3:	third-order intercept point referred to the input
k:	Boltzmann's constant of 1.38×10^{-23} J/K
NF:	noise figure
P_{AC1}:	power of the first adjacent channel
P_{BLOCK}:	power of blocker signal
P_{BLeak}:	power of blocking signal leaking to the demodulator
P_I:	power of intermodulation product
P_{I3}:	power of third-order intermodulation products
P_{INT}:	interfering signal power
P_N:	noise power
P_{N+I}:	noise and interference power
$P_{R,DPCH}$:	received DPCH channel power
P_{TxLeak}:	power of transmitter leakage signal
P_{2DIS}:	power of second-order distortion products
$P_{2DISeff}$:	effective power of second-order distortion products (after removal of DC and components above the signal bandwidth)
T_0:	standard noise temperature of 290 K

manner as was used during the NF calculation:

$$P_I = P_{R,DPCH} - \left(\frac{E_b}{N_t}\right)_{eff} + G_P = -103\,dBm - 7\,dB + 25\,dB = -85\,dBm$$

and the adjacent-channel selectivity requirement at 5 MHz is

$$\text{Selectivity}(5\,MHz) \geq P_{AC1} - P_I = -52\,dBm - 85\,dBm = 33\,dB$$

SECOND-ORDER INTERCEPT POINTS

Low even-order distortion, especially second-order distortion, is crucial to the receiver's performance because of the presence of strong modulated signals with time-varying envelopes. When a second-order nonlinearity is exposed to such a signal, a spurious baseband signal proportional to the squared envelope is generated at baseband, which disturbs the reception of the desired signal. Two such groups of disturbing signals are present: unwanted channels in the receive band (downlink) and the transmitter leakage signal. (The problem of unwanted channels in the receive band is addressed in the in-band blocker test.[1])

The spectral shape of these signals is the same as for the wanted signal (root-raised-cosine) but the spectral shape of the second-order product is different, as shown in ***Figure 3***. A significant DC component is present and the spectrum is broader than the desired baseband signal. Typically, the DC component represents 50 percent of the power while 50 percent of the remaining power lies above the desired signal bandwidth. Consequently, a combination of highpass and lowpass filtering can improve E_b/N_t by approximately 6 dB. Highpass filtering of the W-CDMA signal can be accomplished with negligible degradation of performance due to the large-signal bandwidth.[4] However, the actual improvement in E_b/N_t depends on the present signal configuration and is different for uplink and downlink signals. According to simulations, the possible suppression of the spurious second-order product ranges from 4 to 13 dB.

IIP_2 is determined by the in-band blocker test. The desired signal has a power of $P_{R,DPCH}$ = –114 dBm. The modulated blocker has a power of P_{BLOCK} = –44 dBm and is offset in frequency by a minimum of 15 MHz. In this scenario, the demodulator experiences three sources of interference: noise with power P_N, highpass and lowpass filtered second-order products of the blocker signal with power $P_{2DISeff}$ and blocker leakage around 15 MHz at baseband with power P_{BLeak}. Since the power of the desired signal in this test is 3 dB higher than for the sensitivity test, it is assumed that noise constitutes 50 percent of the total disturbing power. For simplicity, the remaining power is divided equally (25 percent 6 dB) between the second-order products and the blocker leakage. The acceptable noise plus interference level measured at the antenna input is expressed as

$$P_{N+I} = P_{R,DPCH} - \left(\frac{E_b}{N_t}\right)_{eff} + G_P = -114\,dBm - 7\,dB + 25\,dB = -96\,dBm$$

and the acceptable levels are

$$P_N = P_{N+I} - 3\,dB = -99\,dBm$$

and

$$P_{BLeak} = P_{2DISeff} = P_{N+I} - 6\,dB = -102\,dBm$$

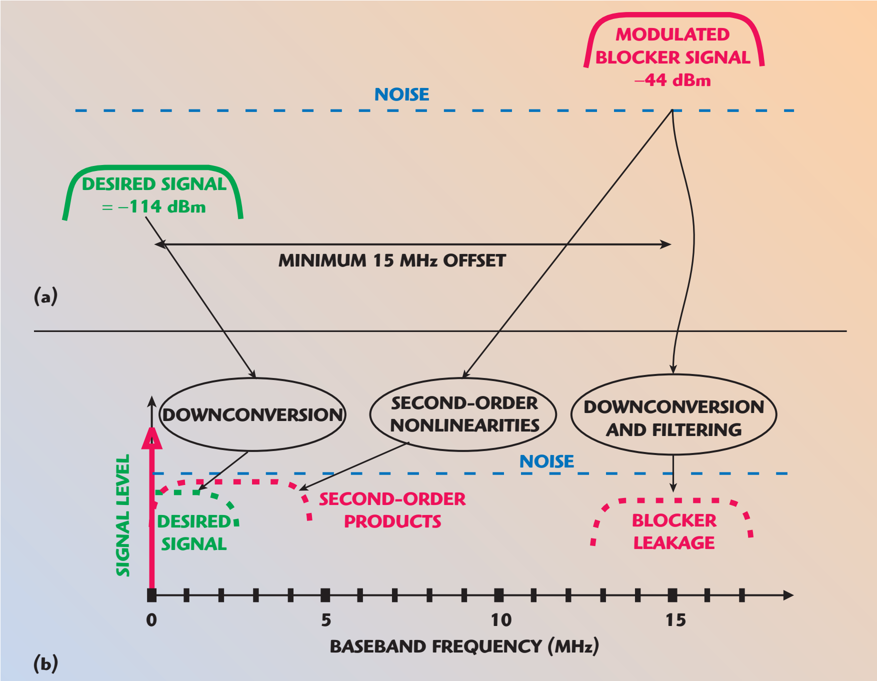
Note that $P_{2DISeff}$ is the effective level of second-order distortion that can be tolerated. However, as a 6 dB improvement due to baseband filtering is assumed, an additional 6 dB of second-order distortion actually can be accepted. Hence, in the calculation of the required IIP_2, the value of $P_{2DISeff}$ is corrected to $P_{2DIS} = P_{2DISeff} + 6$ dB. Consequently, the requirement to the second-order input intercept point is obtained using

$$IIP_2(15\,MHz) \geq 2P_{BLOCK} - P_{2DIS} = 2(-44)\,dBm - (-102+6)\,dBm = 8\,dBm$$

The necessary selectivity for a channel at 15 MHz offset is found to be

$$\text{Selectivity}(15\,MHz) \geq P_{BLOCK} - P_{BLeak} = -44\,dBm - (-102)\,dBm = 58\,dBm$$

In the specification document, an additional blocker test is specified with



▲ *Fig. 3 In-band modulated blocker test; (a) RF spectrum with desired signal and offset modulated blocker, and (b) baseband spectrum with desired and disturbing signals.*

a blocker power of –56 dBm and a 10 to 15 MHz frequency offset. Corresponding to previous calculations, the IIP_2 requirement is derived using

$$\begin{aligned} IIP_2(10\,\mathrm{MHz}) &\\ &\geq 2P_{BLOCK} - P_{2DIS} \\ &= 2(-56)\,\mathrm{dBm} - (-102+6)\,\mathrm{dBm} \\ &= -16\,\mathrm{dBm} \end{aligned}$$

Finally, the required out-of-band IP_2 is determined by the transmitter leakage level at the receiver input. The disturbance mechanisms are the same as those shown previously but the blocker signal is replaced by the transmitter leakage signal. Since the duplex distance is a minimum 134.8 MHz, the direct transmitter leakage through the receiver to the demodulator is insignificant.

Since the transmitter signal is always present, the second-order products should be sufficiently suppressed (for example, 10 dB below the noise level). A rough estimate of IIP_2 is then determined using

$$\begin{aligned} IIP_2(Tx) &\geq 2P_{TxLeak} - (P_N + 6\,\mathrm{dB} \\ &\quad -10\,\mathrm{dB}) \\ &= 2(-30)\,\mathrm{dBm} - \\ &\quad (-99-4+6-10)\,\mathrm{dBm} \\ &= 47\,\mathrm{dBm} \end{aligned}$$

The noise level has been corrected for the 4 dB duplexer loss, thus $IIP_2(Tx)$ refers to the circuit after the duplexer. Again, a 6 dB improvement due to highpass and lowpass filtering has been assumed.

THIRD-ORDER INTERCEPT POINTS

The third-order intercept point of the UTRA receiver is determined using the intermodulation test described in the UTRA standard. The intermodulation test scenario is shown in ***Figure 4***. The desired signal is at $P_{R,DPCH}$ = –114 dBm, 3 dB above the minimum sensitivity. Two interfering signals are offset 10 and 20 MHz from the desired signal. The first interferer is a CW signal at P_{INT} = –46 dBm; the second interferer is a modulated signal with a power of P_{INT} = –46 dBm. As the desired signal is close to the minimum sensitivity level, both noise and interference

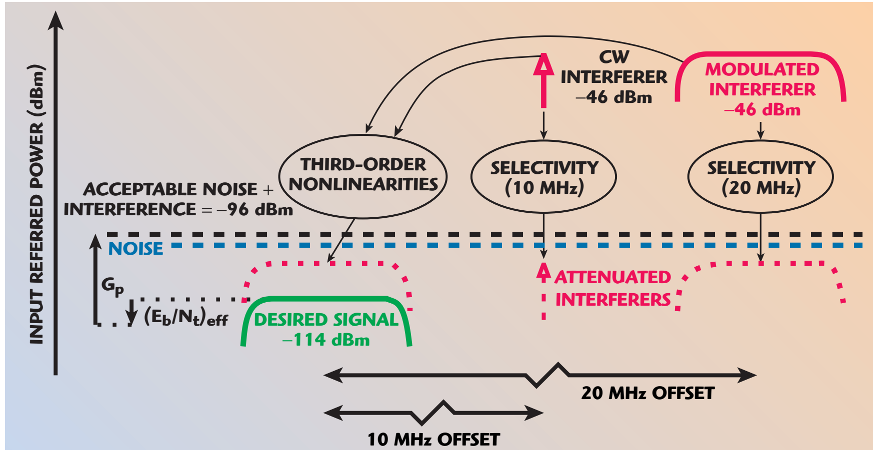
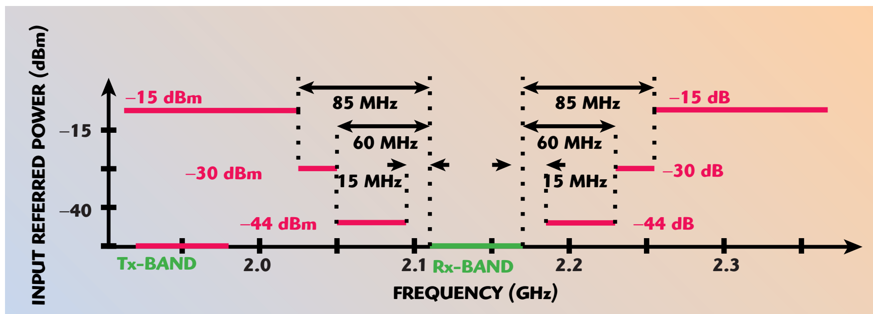


Fig. 4 Intermodulation test.

Fig. 5 Out-of-band CW blocker test.



must be taken into account. Assuming that the third-order intermodulation product of the two interferers may be treated as noise, the maximum level of noise and interference is found to be

$$\begin{aligned} P_{N+I} &= P_{R,DPCH} - \left(\frac{E_b}{N_t}\right)_{eff} + G_P \\ &= -114\,\mathrm{dBm} - 7\,\mathrm{dB} + 25\,\mathrm{dB} \\ &= -96\,\mathrm{dBm} \end{aligned}$$

where P_{N+I} is referred to the antenna input.

In this test case, several interfering products are created, thus the allowable noise and interference power (P_{N+I}) must be distributed. The assumed power distribution is: noise, 50 percent of power (–3 dB); intermodulation, 15 percent of power (–8 dB); CW interferer's blocking effect, 15 percent of power (–8 dB); modulated interferer's blocking effect, 15 percent of power (–8 dB); and oscillator noise, five percent of power (–13 dB). Second-order distortion products are neglected. The power level corresponding to each of the interfering or blocking products is then P_{N+I} – 8 dB = –104 dBm. This power level, along with the relationship between intermodulation power level and input intercept point, gives the minimum receiver IIP_3:

$$\begin{aligned} IIP_3&(10/20\,\mathrm{MHz}) \\ &\geq P_{INT} + \frac{1}{2}\left(P_{INT} - (P_{N+I} - 8\,\mathrm{dB})\right) \\ &= -46\,\mathrm{dBm} + \frac{1}{2}\left(-46 - (-104)\right)\mathrm{dBm} \\ &= -17\,\mathrm{dBm} \end{aligned}$$

In addition, the test results in two selectivity requirements are

$$\begin{aligned} \mathrm{Selectivity}&(10\,\mathrm{MHz, CW}) \\ &\geq P_{INT} - (P_{N+I} - 8\,\mathrm{dB}) \\ &= -46\,\mathrm{dBm} - (-104)\,\mathrm{dBm} \\ &= 58\,\mathrm{dB} \end{aligned}$$

and

$$\begin{aligned} \mathrm{Selectivity}&(20\,\mathrm{MHz}) \\ &\geq P_{INT} - (P_{N+I} - 8\,\mathrm{dB}) \\ &= -46\,\mathrm{dBm} - (-104)\,\mathrm{dBm} \\ &= 58\,\mathrm{dB} \end{aligned}$$

The out-of-band CW blocker test, shown in ***Figure 5***, indirectly sets an IP_3 requirement for the receiver. If a CW blocker is present at some frequency distance (for example, 67.4

MHz) from the receive band and the transmitter leakage signal is located at the double frequency distance (134.8 MHz), then a third-order intermodulation product is created at the receive frequency in the same way as the intermodulation test described previously.

The level of the CW blocker and the attenuation in the duplex filter depend on the frequency band. For typical duplex filters, the CW blocker level after the duplex filter is below –45 dBm. For calculation of the IIP_3, the transmitter leakage signal of –30 dBm and the CW blocker of –45 dBm are replaced with two signals of equal level such that

$$P_{INT} = \frac{1}{3}(-30\,\text{dBm}) + \frac{2}{3}(-45\,\text{dBm}) = -40\,\text{dBm}$$

since the interferer closest to the desired signal has the highest weight in third-order intermodulation. Because of the large frequency offset, blocking effects are negligible and the allowable interference level is $P_{N+I} - 3$ dB since noise contributes 50 percent of the power. Correcting this level with the duplexer loss of 4 dB, an IIP_3 is found to be

$$IIP_3(67.4 / 134.8\,\text{MHz}) \geq P_{INT} + \frac{1}{2}\left(P_{INT} - \left(P_{N+I} - 3\,\text{dB} - 4\,\text{dB}\right)\right)$$
$$= -40\,\text{dBm} + \frac{1}{2}\left(-40\,\text{dBm} - \left(-96\,\text{dBm} - 3\,\text{dB} - 4\,\text{dB}\right)\right) \approx -8\,\text{dBm}$$

This number is for the receiver part after the duplexer and is highly dependent on the actual duplexer characteristics.

IMAGE REJECTION

The required image rejection also can be determined from the out-of-band blocker test. If the image frequency is distanced at more than 85 MHz from the receive band, the necessary rejection is

$$\text{Image rejection } (> 85\,\text{MHz}) \geq P_{BLOCK} - \left(P_{N+I} - 3\,\text{dB}\right)$$
$$-15\,\text{dBm} - \left(-96\,\text{dBm} - 3\,\text{dB}\right) = 84\,\text{dB}$$

In the calculation it has been noted that noise constitutes 50 percent of the disturbing power P_{N+I}.

OSCILLATOR PHASE NOISE

The presence of blocking signals sets requirements for the LO noise sidebands. The worst-case scenario is probably set by the intermodulation test where a –46 dBm CW blocker is present at a 10 MHz offset. Allowing five percent of the disturbing power in this test to come from the oscillator noise, the LO noise power must be below P_{N+I} – 13 dB = –109 dBm. This level corresponds to –63 dBc measured over a 3.84 MHz bandwidth when taken relative to the CW-blocker carrier. This number can be transferred to the LO since it represents a cross-modulation phenomenon. The spectral shape of the LO noise sidebands is unknown, however, taking the case of a flat spectrum seems reasonable because of the large frequency offset. With this assumption, the –63 dBc over 3.84 MHz corresponds to a power spectral density of –129 dBc/Hz. This specification must be met for an offset from the LO carrier of more than 10 MHz – BW/2 ≈ 8 MHz.

REQUIREMENT SUMMARY

A summary of receiver requirements for the entire receiver and the part of the receiver that follows the duplex circuits is listed in ***Table 3***.

RECEIVER EXAMPLE

Because of its high noise and selectivity performance, the heterodyne receiver architecture has been the preferred architecture for the 2G market. However, as issues of power consumption, cost and size become more critical than ever, other architecture candidates are being explored. Recently, homodyne (or direct-conversion) receivers have emerged for the GSM market and many consider this architecture the proper choice for 3G systems. A particular nicety is the fact that the large signal bandwidth makes W-CDMA systems less susceptible to the 1/f noise and DC off-set problems inherent in homodyne receivers.

An example of an UTRA/FDD direct-conversion receiver is shown in ***Figure 6***. An interstage bandpass filter is used to provide sufficient attenuation of the transmitter leakage signal. Sufficient selectivity with low insertion loss is possible with commercial ceramic or surface

TABLE III

SUMMARY OF REQUIREMENTS

Requirement	Entire Receiver	After Duplex
Noise figure (dB)	≤ 9	≤ 5
In-band selectivity (dB)		
first adjacent channel (5 MHz)	≥ 33	≥ 33
CW interferer (10 MHz)	≥ 58	≥ 58
third adjacent channel (15 MHz)	≥ 58	≥ 58
modulation blocker (> 15 MHz)	≥ 58	≥ 58
Intercept points (dBm)		
IIP_2 (10 MHz)	≥ –16	≥ –18
IIP_2 (15 MHz)	≥ 8	≥ 6
IIP_2 (Tx)		≥ 47
IIP_3 (10/20 MHz)	≥ –17	≥ –19
IIP_3 (67.4/134.8 MHz)		≥ –8
Image rejection (> 85 MHz) (dB)	≥ 84	n/a
Oscillator noise sidebands at > 8 MHz offset (dBc/Hz)	≤ –129	

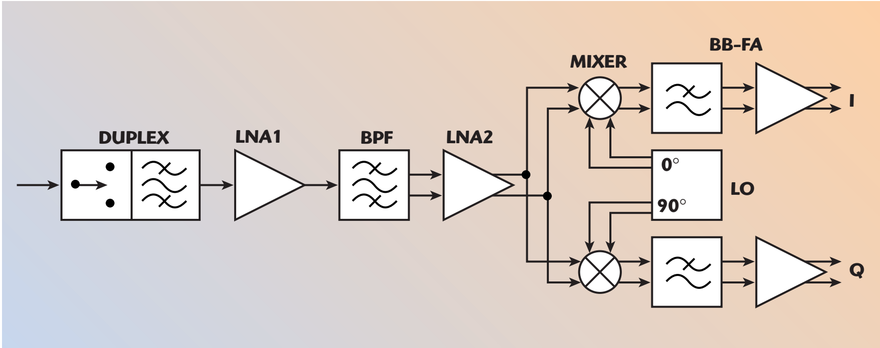


Fig. 6 Direct-conversion receiver including filter.

TABLE IV

BLOCK SPECIFICATIONS FOR A DIRECT-CONVERSION RECEIVER

Block	Duplexer	LNA1	BPF	LNA2	Mixer	BB-FA	Combined	Required
Gain in Rx band (dB)	–3 ±1	15 ±1	–2 ±1	8 ±1	10 ±1			
Rx/Tx selectivity (dB)	≥ 60	≥ 0	≥ 21	≥ 0	≥ 0	≥ 0		
Noise figure (dB)	≤ 4	≤ 2.5	≤ 3	≤ 3	≤ 15	≤ 25	≤ 8.8	≤ 9
IIP_2 (15 MHz) (dBm)					≥ 37	≥ 47	≥ 8.5	≥ 8
IIP_2 (Tx) (dBm)					≥ 37	≥ 47	≥ 48.5	≥ 47
IIP_3 (67.4/134.8 MHz) (dBm)		≥ –3					≥ –3	≥ –8
IIP_3 (10/20 MHz) (dBm)		≥ –3		≥ 3	≥ 10	≥ 20	≥ –16.8	≥ –17

Note: The numbers for IIP_2 (Tx) and IIP_3 (67/135 MHz) are for the receiver part after the duplexer. Other numbers are combined values for the entire receiver, including duplex filter and system select switch.

acoustic wave (SAW) filters. The filter may have a single-ended or balanced output, however, the second low noise amplifier (LNA) stage should have a balanced output to facilitate good even-order distortion performance of the mixers.

Overall block requirements are listed in ***Table 4***. Due to the interstage bandpass filter, the overall out-of-band IIP_3 performance is dominated by the first LNA and this block must comply with the overall requirement of –8 dBm. Note that the IIP_3 has been set slightly higher at –3 dBm to relieve the performance requirement to the mixer and BB-FA blocks. For the direct-conversion receiver, the mixer and baseband unit are critical components for the overall linearity and noise while most gain is placed with the baseband unit. IIP_2 and IIP_3 requirements to the mixer and baseband units are difficult but certainly realistic. With respect to noise, the baseband unit constitutes a major challenge if low cost technologies such as CMOS are to be used. However, recent work has shown much progress in this area.[5] In the example, 1 dB of gain tolerance of the first receiver blocks is assumed. A higher tolerance makes it difficult to meet any worst-case specification.

Most of the Tx signal suppression is obtained in the duplex and interstage bandpass filters. The interstage bandpass filter also attenuates out-of-band blockers but, since the filter characteristics are typically less steep in the upper stop band, only limited selectivity toward these disturbing signals can be assumed. Hence, the BB-FA unit must implement most of the required selectivity derived in this article. In-band disturbances can be suppressed only at baseband. In this sense, one of the most fundamental decisions is the distribution of filtering requirements between analog and digital hardware. With the high chip rate employed in 3G W-CDMA systems, constraints of low power limit the available analog-to-digital converter (ADC) resolution.

Assuming a sampling frequency of 15.36 MHz (corresponding to four samples per chip), it is not possible to use digital filtering with the third adjacent channel and the first modulated blocker (> 15 MHz) due to aliasing. Hence, these interferers must be suppressed in analog hardware prior to sampling. With the first and second adjacent channels each additional bit enables 6 dB of digital selectivity. Preliminary analyses[7] indicate that four to five bits are required as minimum ADC resolution (no digital selectivity), and 8 to 10 dB bits immediately appears to be a necessary choice. This selectivity may be combined with a fourth-order Butterworth analog filter (2.5 MHz cutoff frequency) to achieve the listed selectivity requirements.

Issues other than those considered here are critical to the implementation of the direct-conversion receiver. Such issues include DC offsets, in-phase and quadrature gain/phase imbalance problems, LO-to-antenna leakage and susceptibility to 1/f noise. Baseband highpass filtering should be combined with adaptive correction for sufficient performance of this architecture.[4]

CONCLUSION

Detailed specifications for a W-CDMA receiver were derived from the tests presented in the standardization documents. It was shown that a direct-conversion receiver architecture with reasonable block requirements is capable of meeting derived specifications. The problems caused by the continuous presence of the transmitter leakage signal emphasize the need for a high performance duplex filter. There are still implementation challenges left for RF designers, but the specifications seem reasonable enough to facilitate the design of the low power, low cost, hand-held multimedia products that the world is awaiting.

ACKNOWLEDGMENT

The RISC Group would like to acknowledge the helpful discussions with local industry partners, including Bosch Telecom Denmark, Maxon Cellular Systems (Denmark), RTX Telecom, Telital and Texas Instruments Denmark. ■

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