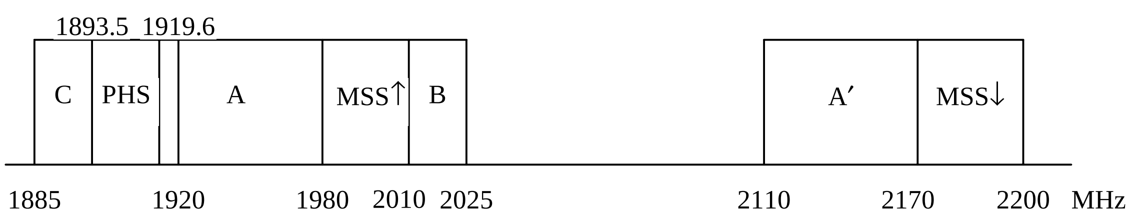
2 System Overview

This chapter gives an overview of W-CDMA systems that is relevant to the radio design.

2.1 Operating Band Structure

The W-CDMA radio of this work operates in the 1920-1980MHz band for the uplink (from mobiles to base stations) and 2110-2170MHz band for the downlink (from base stations to mobiles). These are the main bands for IMT-2000 and are designated as Band A for the uplink and Band A′ for the downlink [2]. These two bands are in the 230MHz global spectrum identified by the ITU World Administrative Radio Conference (WARC-92) [5] for a worldwide standard called the Future Public Land Mobile Telephone System (FPLMTS) – renamed International Mobile Telecommunication 2000 (IMT-2000) in mid-1995. The FPLMTS is a 3rd generation globally compatible digital mobile radio system that would unify the diverse systems such as paging, cordless, and cellular systems, as well as low earth orbit (LEO) satellites, into a common flexible radio infrastructure. Figure 1 shows the frequency plan of the 230MHz global spectrum in Japan [2].



MSS: Mobile satellite service

PHS: Personal Handyphone System – a standard supports indoor and local loop applications in Japan

(1) A (1920-1980 MHz), A′ (2110-2170 MHz) – the radio operating band

(2) B (2010-2025 MHz) – Time-division-duplex (TDD) system

(3) C (1885-1895 MHz, 1918.1-1920 MHz) – PHS use

Figure 1. The frequency plan of the 230MHz global spectrum for IMT-20000 in Japan.

The W-CDMA is a frequency division duplex (FDD) system. FDD allows a simultaneous two-way communication by employing two separate frequency channels. The frequency separation between the transmit and receive channels is 190MHz. The lower band (A) carries information from the mobile terminals to the base stations. On the other hand, the upper band (A‘) carries information from the base stations to the mobile terminals. The traffic from the mobile terminals to the base stations is called the uplink, while the traffic from the base stations to the mobile terminals is called the downlink.

Both the A and the A‘ bands are 60MHz wide. Both of them are divided into twelve frequency channels. Each frequency channel is 5MHz wide. Two channels, which are 190MHz apart, are called a duplex pair. A duplex pair provides simultaneous two-way communication. Figure 2 shows the operating band structure for the mobile terminals.

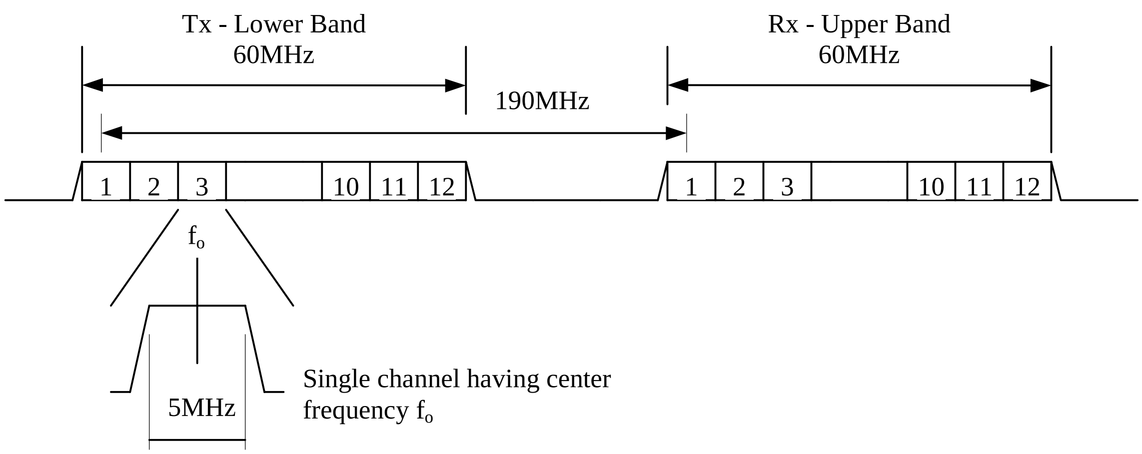


Figure 2. Operating band structure to mobile terminals.

The twelve duplex pairs permit frequency division multiple access (FDMA). FDMA means that a number of two-way communications can be conducted simultaneously by assigning each communication to a different duplex pair. This operating band structure provides for twelve channels in terms of FDMA. This is very low. However, the multiplexing power in W-CDMA is not from the FDMA. It is from the code division multiple access (CDMA). Fukasawa [6] showed that the 5MHz channel capacity of the W-CDMA is 82. It is 3.4 times the capacity of current analog cellular systems (AMPS).

2.2 Code Division Multiple Access (CDMA)

W-CDMA is a direct sequence spread spectrum (DSSS) system. Code division multiple access (CDMA) is a unique trait of spread spectrum systems. The terminologies of CDMA and spread spectrum basically refer to the same type of systems. In cellular applications, CDMA is generally used to emphasize the multiple access nature of the systems.

The direct sequence spreading process multiplies an information stream with a high chip rate pseudo-noise (PN) code. Since the information stream is relatively low data rate as compared to the chip rate, the spectrum of the spread output is considerably wider than the original information stream. The PN code is the signature of the spread signal. This embedded signature allows despreading with a synchronized replica of the PN code at the receiving end.

W-CDMA systems spread the bandwidth of an information stream to a much wider bandwidth and lower the power spectral density (PSD) accordingly. As a result of PN codes, a spread signal has a noise-like quality. The transmit spread signal from an additional user causes a slight rise in the noise floor to the current users in the channel. The degradation of the performance of the receivers due to this additional power from the transmitter ultimately limits the system capacity. This is the most important characteristic of the W-CDMA system. Power becomes the common shared resource for users [7]. The interference power is shared between the mobile terminals in the cell and each terminal contributes to the interference. Radio resource management is to allocate power to each user such that the maximum interference is not exceeded. The system can easily add a user on the spectrum until the interference becomes intolerable. This is the real advantage of the W-CDMA. In cellular terms, frequency reuse is one. Everyone shares all the frequencies and the interference is uniformly spread over all the users. On the other hand, FDMA and TDMA systems have a well-defined number of users based on the available spectrum and time slots respectively. Therefore, the W-CDMA gives more flexibility on cell capacity management.

Power management provisions and tolerance of co-channel interference in W-CDMA systems allow the use of the same frequency in adjacent cells. A frequency assignment plan is no longer needed. In FDMA and TDMA cellular systems, each cell only uses a part of the whole operating band in order to avoid adjacent channel interference. The number of available channels of a cell is inversely proportional to the cluster size. A cluster in cellular systems is a group of cells that collectively use the whole operating band. A typical cluster size is 7. Thus, the available channels of a cell are only a seventh of the total. On the other hand, all the cells can use the whole operating band in the W-CDMA. W-CDMA can boost the system capacity dramatically.

2.3 Data and Chip Rate

The radio of this work is specified for 128Kbps data rate and 4.096Mcps chip rate. The full W-CDMA specification allows variable data rates and chip rates at 1.024/4.096/8.192/16.385Mcps [3]. Spreading involves the data and chip sequences. The data sequence is the information stream and the chip sequence is the spreading code. The information stream is a relatively low bit rate sequence, while the spreading code is a relatively high chip rate sequence. The ratio of the chip rate to the data rate defines the processing gain (PG) of the system.

$$PG = 10 \cdot \log\left(\frac{R_{chip}}{R_{data}}\right) \quad \text{dB} \qquad (2.1)$$

The PG for the specified chip rate and data rate of the radio is 15dB.

2.4 Channel Bandwidth

As mentioned in Section 2.1, the channel bandwidth is 5MHz. The full W-CDMA specification allows the channel bandwidths of 1.25/5/10/20MHz [3]. The 5MHz bandwidth is the direct result of the choice of the chip rate and the pulse shaping filter. W-CDMA specifies a square root raised cosine pulse shaping filter with roll off factor of

0.22. The use of a pulse shaping filter is to conserve the channel bandwidth. The square root raised cosine filter satisfies the Nyquist criterion such that the introduction of the pulse shaping does not cause intersymbol interference. Rectangular pulses without shaping requires the channel bandwidth to be double of the pulse rate. However, if rectangular pulses are shaped with the filter, the channel bandwidth is give by

$$BW_{ss} = (1+\alpha)\cdot R_{chip} \tag{2.2}$$

where

$\alpha = 0.22$: is the roll-off factor of the square-root raised cosine filter.

The channel bandwidth is found to be 4.997MHz≈5MHz.

The choice of a wide channel bandwidth can achieve high data rate. For instance, the 5MHz bandwidth can support a data rate up to 384Kbps. The use of a wide channel bandwidth enables RAKE receivers to resolve more multipaths. This improves the receiver sensitivity or lowers the transmit power requirement for mobile terminals. Adachi and Sawahashi [8] demonstrated the decrease of the transmit power with increasing the spreading bandwidth on a field experiment in Tokyo. Thus the W-CDMA can accommodate more users on a frequency channel.

2.5 Spreading and Modulation

W-CDMA specifies a two-layered spreading structure. The 1st spreading code is a short code for channelization purposes. The code is derived from a Walsh/Hadamard function. The spreading code for the 2nd layer spreading is a long Gold code for randomization. The spreading process is not included in this work. It is performed in the baseband processor. A detail discussion can be found on [9]. The baseband processor sends the direct (I) and quadrature (Q) spread sequences in digital format to the radio. The radio uses quadrature phase shift keying (QPSK) technique to modulate the sequences on the carrier.

2.6 Transmit, Adjacent Channel and Spurious Power

The transmitter is specified to have the maximum output power in the range from 29dBm to 33dBm. The output power is controllable over 70dB range - the minimum output power is from –41dBm to –37dBm. The power control step size is 1dB.

Transmitter power control (TPC) is essential to direct sequence spreading spectrum (DSSS) systems. It is required to combat the near-far problem. The near-far problem refers to a neighboring transmitter that can overpower a desired signal from a far transmitter. Without power control, interference will not be spread uniformly over all users. The near-far problem can degrade the system capacity tremendously.

W-CDMA provides TPC on both the uplink and the downlink. There are two types of the TPC: open-loop TPC and closed-loop TPC [10].

Open loop TPC is used when closed-loop TPC cannot be applied. For instance, a mobile terminal wants to access the system. Since the mobile terminal is not talking with the base station, it has to estimate the path loss of the channel by measuring the received power level of the perch channel from the base station. The perch channel provides the transmission level of the base station. The perch is a uni-directional channel from base stations to mobile terminals. Based on the measured result and the given transmission level, the mobile station can calculate the path loss and determine the transmit power.

Once the connection is established between the mobile station and base station, the closed-loop TPC is used. The closed-loop TPC is based on the signal-to-interference ratio (SIR). Figure 3 show an example of the TPC process configuration.

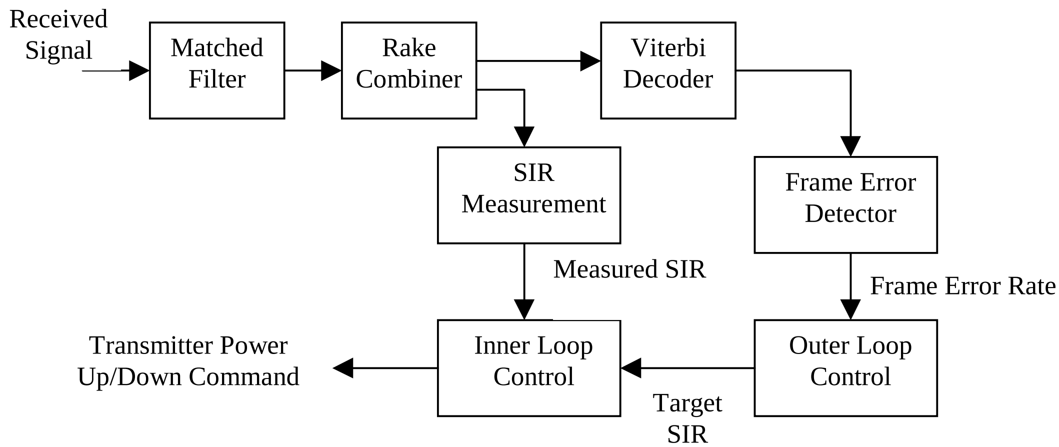


Figure 3. An example of TPC process configuration.

The closed-loop TPC involves two sub-loops: the inner loop and the outer loop. The outer loop adjusts the target SIR based on the quality of the received signal. The inner loop measures the SIR of the received signal. If the measured SIR is higher than the target SIR, a bit called the TPC is set to “0”. This TPC bit commands the transmitter to lower the transmit power by 1dB. Whereas, the TPC is “1”, the transmitter has to increase the transmit power by 1dB.

W-CDMA specifies the power control cycle to be 0.625ms. The fast control cycle makes possible tracking rapid multipath fading. The fast TPC can always minimize the transmit power according to the traffic load. Thus, the mutual interference between users is minimized or the channel capacity is maximized. Moreover, keeping the transmit power low helps to conserve the battery power. The battery life is prolonged.

W-CDMA specifies 5MHz channel bandwidth and 4.997MHz spread signal bandwidth. There are almost zero guard bands between adjacent channels. This imposes a stringent requirement on the adjacent channel power. Table 1 lists spectral leakage specifications of the radio. Figure 4 shows the specification pictorially.

Table 1. The spectral leakage specification of the radio.

Adjacent Channel Leakage	-40dBc in 5MHz band	5MHz from the center
	-60dBc in 5MHz band	10MHz from the center
Spurious Emission	-60dBc or less	All spurs other than adjacent channel leakage
Transmitter Intermodulation	-60dBc or less	External CW interferer

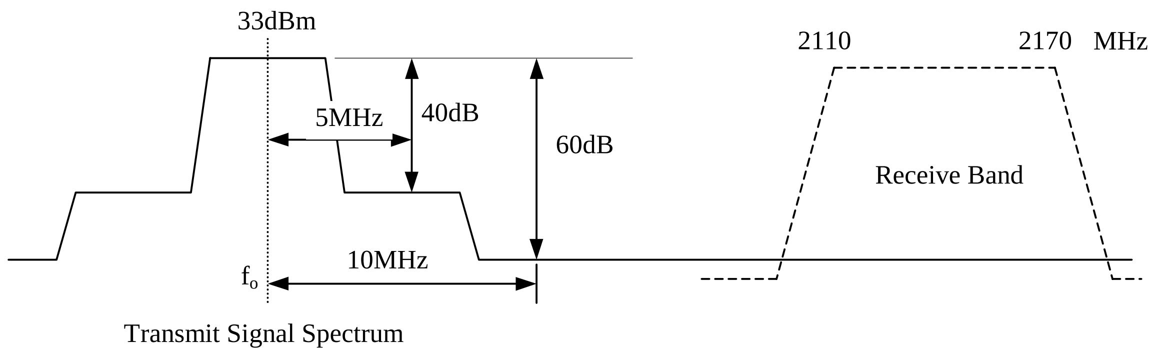


Figure 4. The spectral leakage diagram.

The use of QPSK linear modulation raises a design conflict with the adjacent power requirement. QPSK signals are passed through the square root raised cosine filter to limit the signal bandwidth in 5MHz. The QPSK signals lose their constant envelope property after this filter operation. The peak-to-average factor of the filtered envelope of a QPSK signal is around 4.6dB on average.

Non-constant envelope signals must be amplified by linear amplifiers to prevent spectral regrowth. Because of the large peak-to-average factor of the QPSK modulated signal, the back off from the 1dB output compression point of the amplifier is large. The large back off causes inefficient power amplification or less battery life. The power handling capability of the amplifier has to be considerably greater than the required average power output.

2.7 Receiver Sensitivity

W-CDMA employs pilot symbol-aided coherent detection to optimize receiver sensitivity. The pilot symbols associates in the both uplink and downlink as shown in Figure 5 [10].

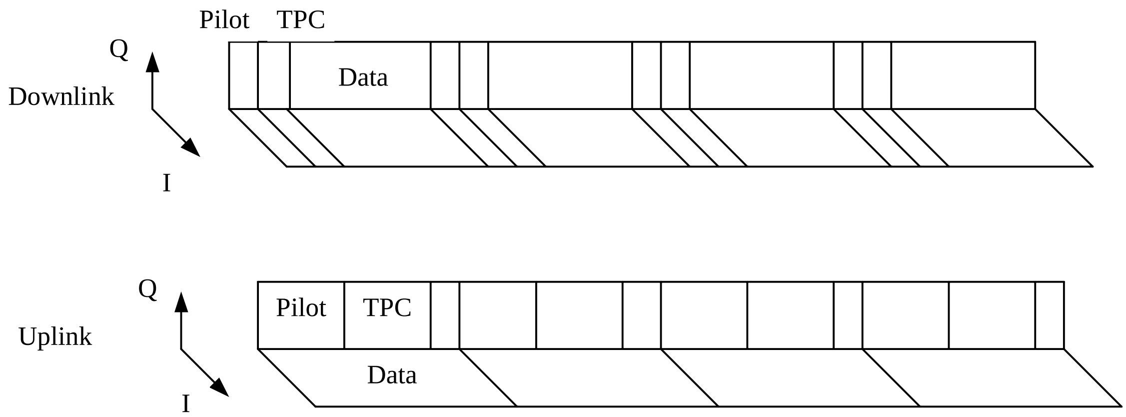


Figure 5. Multiplexing of pilot symbols.

The pilot symbols on the downlink are time multiplexed with the TPC command and the data; while the pilot symbols on the uplink are IQ multiplexed. The pilot symbols are used for channel estimation at the receivers. The estimation allows the coherent detection and automatic frequency control. Detection can achieve 10^{-3} BER at 6dB or less E_b/N_o on the traffic channel. The specified minimum input power is –113dBm at the receiver.

2.8 Automatic Gain Control (AGC)

1st-generation analog cellular systems used frequency modulation (FM). FM receivers use very high gain IF amplifiers with a limiter. The output to the detection circuits is fairly constant regardless the received signal strength. AGC is generally not found in analog cellular mobile units. However, this hard-limited non-linear amplification is not acceptable for quadrature phase shift keying (QPSK) modulated signals. In this case, an

AGC circuit is essential to maintain a constant input to analog-to-digital converters (ADC). The AGC dynamic range is specified to be 80dB.

2.9 Automatic Frequency Control (AFC)

The channel estimation with pilot symbols gives a frequency estimation. The frequency estimation gives an input to the AFC so that the received signal can be converted to baseband precisely [11].

Let's assume the received signal to be

$$r(t-\tau_0) = A(t-\tau_0)\cdot\cos[(\omega_c+\Delta\omega)(t-\tau_0)+\Phi(t-\tau_0)+\theta_0] \tag{2.3}$$

where

$\Phi(t)$: is the instantaneous phase.

τ_0, $\Delta\omega$, θ_0 : are the unknown time delay, frequency error and phase offset respectively. They need to be estimated by the receiver.

The radio gets the estimated frequency error from the processor to drive the AFC so that the signal can be converted to baseband precisely. (2.3) can be resolved to the in-phase and quadrature components as

$$I_r(t) = A(t-\tau_0)\cdot\cos[\Delta\omega\cdot t-(\omega_c+\Delta\omega)\cdot\tau_0+\Phi(t-\tau_0)+\theta_0] \tag{2.4}$$

$$Q_r(t) = A(t-\tau_0)\cdot\sin[\Delta\omega\cdot t-(\omega_c+\Delta\omega)\cdot\tau_0+\Phi(t-\tau_0)+\theta_0] \tag{2.5}$$

Figure 6 shows the rotating phasor of (2.4) and (2.5).

$$\begin{aligned} R(t) &= I_r(t)+j\cdot Q_r(t) \\ &= A(t-\tau_0)\cdot\exp\{j\cdot[\Delta\omega\cdot t-(\omega_c+\Delta\omega)\cdot\tau_0+\Phi(t-\tau_0)+\theta_0]\} \end{aligned} \tag{2.6}$$

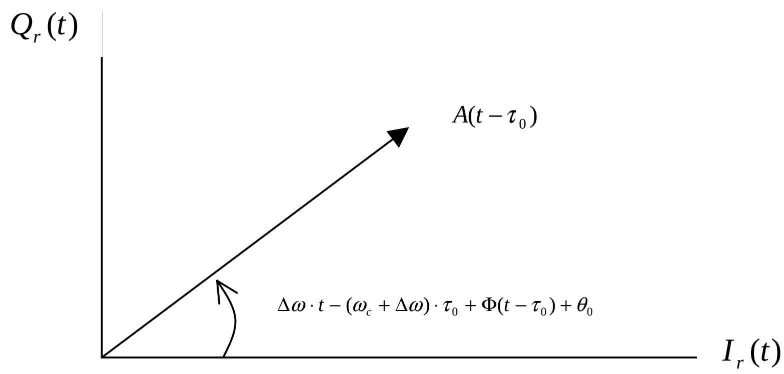


Figure 6. Phasor of the received signal.

If the carrier can be tracked by the AFC such that $\Delta\omega = 0$, the received signal will be a delayed version of the transmitted signal with a phase shift of $-\omega_c \cdot \tau_0 + \theta_0$. The received signal can be detected as the delay and phase estimations are found from the signal processing. However, if the AFC can't track the signal for a zero frequency error, a constant-rate phase rotation of $\Delta\omega \cdot t$ keeps continuous moving of the signal constellation and detection is impossible. To accomplish the precise tracking, the AFC is specified to have very high frequency resolution at 0.03125ppm per step. The full tracking range is ±2ppm.

2.10 Receiver Selectivity and Spurious Response

To achieve the objective of maximizing the radio link performance, W-CDMA specifies the receiver selectivity and the spurious response. Table 2 lists the selectivity and spurious response to the radio. Figure 7 depicts the adjacent channel selectivity specification, while Figure 8 depicts the spurious response specification.

Table 2. The selectivity and spurious response specification of the radio.

Adjacent Channel Selectivity	33dB or more	@ 5MHz from the center
Intermodulation Response	60dB or more	@ 10 and 20MHz from the center
Spurious Response	60dB or more	@ 10MHz from the center

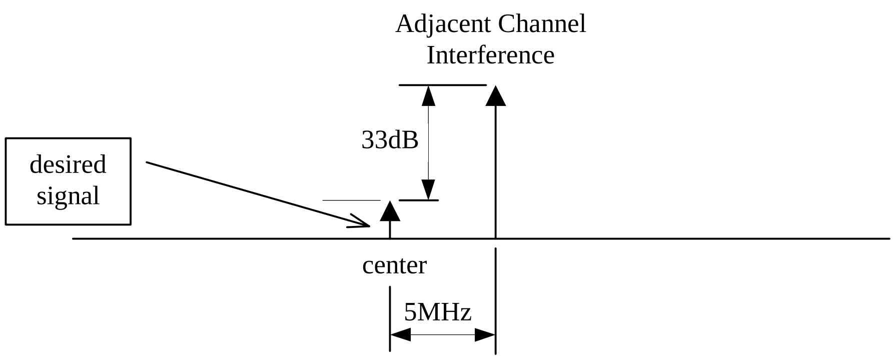


Figure 7. The adjacent channel selectivity.

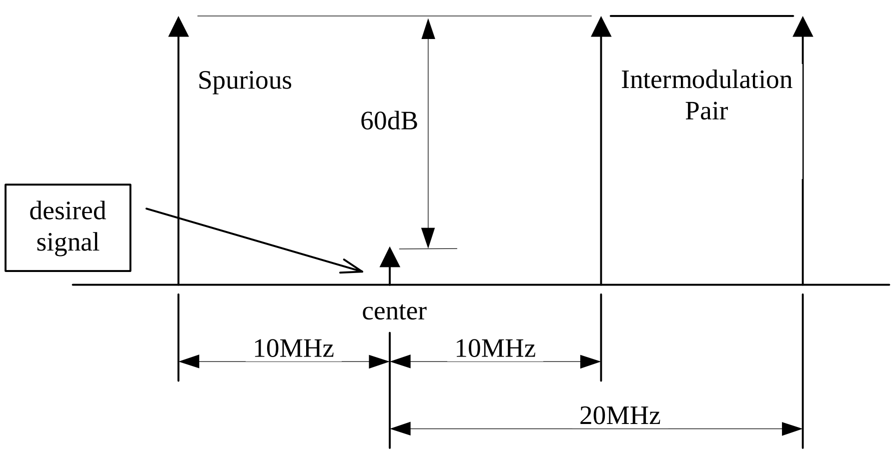


Figure 8. The spurious response.

2.11 Diversity Receiver

W-CDMA employs two receivers in the radio. One is the main receiver and the other is the diversity receiver. Providing 2-branch antenna diversity can significantly reduce the target E_o/N_o for a specific BER. Adachi and Sawahashi [8] have shown 3dB diversity gain for 10^{-3} BER on a field experiment in Tokyo.

The diversity receiver also facilitates the inter-frequency handover operation. W-CDMA employs hierarchical cell structures (HCSs) that overlay macrocells on top of smaller micro- or picocells. The HCSs boost system capacity and offer full coverage in urban environments. However, cells of different cell layers will operate on different frequencies as shown in Figure 9 [6]. This requires inter-frequency handover ability in the mobile terminals.

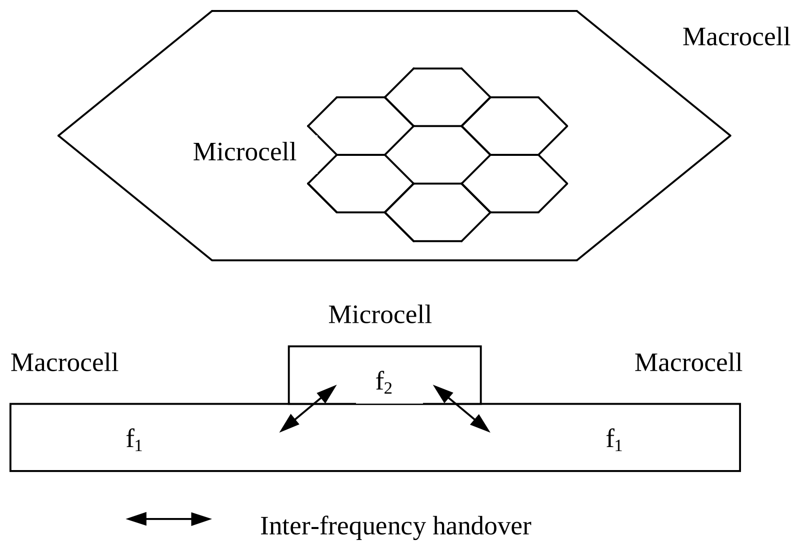


Figure 9. Inter-frequency handover in HCS scenario.

In order to perform the seamless inter-frequency handover, the mobile terminal has to carry out a cell search on frequency channels different from the current frequency channel with no interruption to the current data flow. One of the receivers temporarily branches from diversity reception to perform cell search until the handover is completed.