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ADJACENT CHANNEL INTERFERENCE

Adjacent channel interference and/or cochannel interference affect a cellular mobile radio system in two ways. Unacceptable adjacent channel or cochannel interference causes call quality degradation such as dropped calls and crosstalk. Also, the presence of adjacent channel interference or cochannel interference reduces the overall system capacity. In a cellular system, radio channels can be assigned to different users in the frequency domain. Adjacent channel interference limits the number of radio channels that can be assigned within the available spectrum. On the other hand, frequency can be reused in the space domain. Cochannel interference determines the frequency reuse efficiency that can be achieved for a given geographic area. For both analog and digital cellular systems, proper frequency or power planning is necessary to maintain the overall interference level within the acceptable adjacent channel and cochannel interference limits so that good call quality and high system capacity can be realized.

In this article, we discuss the cause of adjacent channel interference, present a few formulas for calculating it, and suggest remedies for mitigating it. Also, in the last section we give some guidelines for designing adjacent channels in a cellular mobile radio system. The discussion of the related topic of cochannel interference can be found in Refs. 1 and 2.

Adjacent Channel Interference in a Mobile Radio Environment

Adjacent channel interference occurs in a radio channel when unwanted energy from channels adjacent to it falls into its desired bandwidth. In a mobile radio environment, the desired signal and the interference signal usually experience path loss and fading when they travel from the transmitter to the receiver (3,4). The fading discussed in this article includes fast fading and slow fading (1,5,6,7). Fast fading and slow fading are also known as multipath fading and shadow fading respectively.

Adjacent channel interference at the mobile receiver may come from the serving base station and/or from a different base station. If the desired signal and the adjacent channel signal are transmitted by the same base station, without power control their amplitudes received at the mobile station are typically comparable. Also, their fading is often correlated, since signals of the desired channel and the adjacent channels engage the same propagation process. When the desired signal and the adjacent channel interference come from different base stations, their amplitudes and fading are more likely to be uncorrelated due to the different propagation paths involved.

On the other hand, adjacent channel interference at the base-station receiver may come from mobiles in its own cell or mobiles in the adjacent cells. The signals transmitted by different mobile stations propagate through different radio paths before reaching the base-station receiver. As a result, their fadings are generally independent. In contrast to the mobile-receiving case, without power control the average signal strength received at the base station can be significantly different from mobile to mobile. The received signal strength depends on the relative distance between base station and mobile station.

When the fading of the desired signal and the adjacent channel signal is uncorrelated, the desired signal may experience deep fading when the adjacent channel signal reaches its peak. The uncorrelated fading and uneven received power in a mobile radio environment post a significant challenge for cellular-system engineering and result in stringent interference requirements for land cellular mobile systems.

For cellular-system design, adjacent channel interference and cochannel interference requirements are often specified in terms of the carrier-to-adjacent-channel interference ratio *C/A*, and the carrier-to-cochannel interference ratio *C/I* respectively, in the radio-frequency (*RF*) band (1,2). Alternatively, the signal level relative to interference can be measured by using the signal-to-noise ratio (*SNR*) at the baseband (1,2). Through subjective tests such as the mean opinion score (*MOS*) test and/or objective tests such as the bit error rate (*BER*) test, a relationship can be established between the baseband SNR and the *RF*-band *C/A* or *C/I* for a specific voice quality at a specific vehicular speed (8). As discussed later in this article, such a relationship is important for cellular-system design.

In this article, adjacent channel interference is classified into two categories: *in-band* and *out-of-band*. The power spectral center of in-band adjacent channel interference falls within the bandwidth of the desired signal. In contrast, the power spectral center of out-of-band interference generally falls outside the bandwidth of the desired signal.

In-Band Adjacent Channel Interference

In-band adjacent channel interference is generated by spurious emissions resulting from unwanted transmitter effects such as harmonic emission, parasitic emission, intermodulation products (*IMP*s), and frequency conversion products (9). Nonlinearity at the receiver also causes in-band *IMP* interference. In-band adjacent channel interference may be created by unwanted emissions at frequencies far away from the frequency of the desired radio channel. For example, two signals at frequency f_1 and f_2 produce third-order *IMP* interference at frequencies $2f_2-f_1$ and $2f_1-f_2$.

Figure 1 shows the in-band adjacent channel interference in a desired channel with bandwidth W_c at carrier frequency f_c. This interference is caused by transmission of an adjacent channel with bandwidth W_a at frequency f_a in the *RF* band [Fig. 1(a)]. The in-band adjacent channel interference observed in the baseband is shown in Fig. 1(b), where W'_c and W'_a are the baseband bandwidths for the desired and interfering signals respectively.

Following is an example of the in-band adjacent channel interference involving frequency modulation (*FM*) (1,5,10). *FM* is the modulation employed by the existing analog cellular radio transmission technologies, including Advanced Mobile Phone Systems (*AMPS*) (10) and its derivatives such as Total Access Communication Systems (*TACS*) (11). Both *AMPS* and *TACS* are frequency-division multiple-access (*FDMA*) systems. The channel bandwidths of *AMPS* and *TACS* are 30 kHz and 25 kHz respectively. Since the power spectral center of the in-band adjacent interference is generally centered in the desired signal frequency band, the calculations of that interference are similar to those of cochannel interference as discussed in Refs. 1 and 5. When the amplitude of the interference signal is less than that of the desired signal, which is the case most frequently encountered, the minimum baseband SNR in a nonfading environment is found by Lee (5) to be

$$\mathrm{SNR} = \frac{\Phi^2}{2WS_\delta} \qquad (1)$$

where Φ is the mean square modulation index, W is the channel bandwidth, and S_δ is the spectral density of baseband adjacent channel interference measured at the center frequency of the desired channel. In a Rayleigh fading environment, the interference signal and the desired signal may undergo independent Rayleigh fading. The calculation of baseband SNR therefore involves correlation between the received amplitudes of the

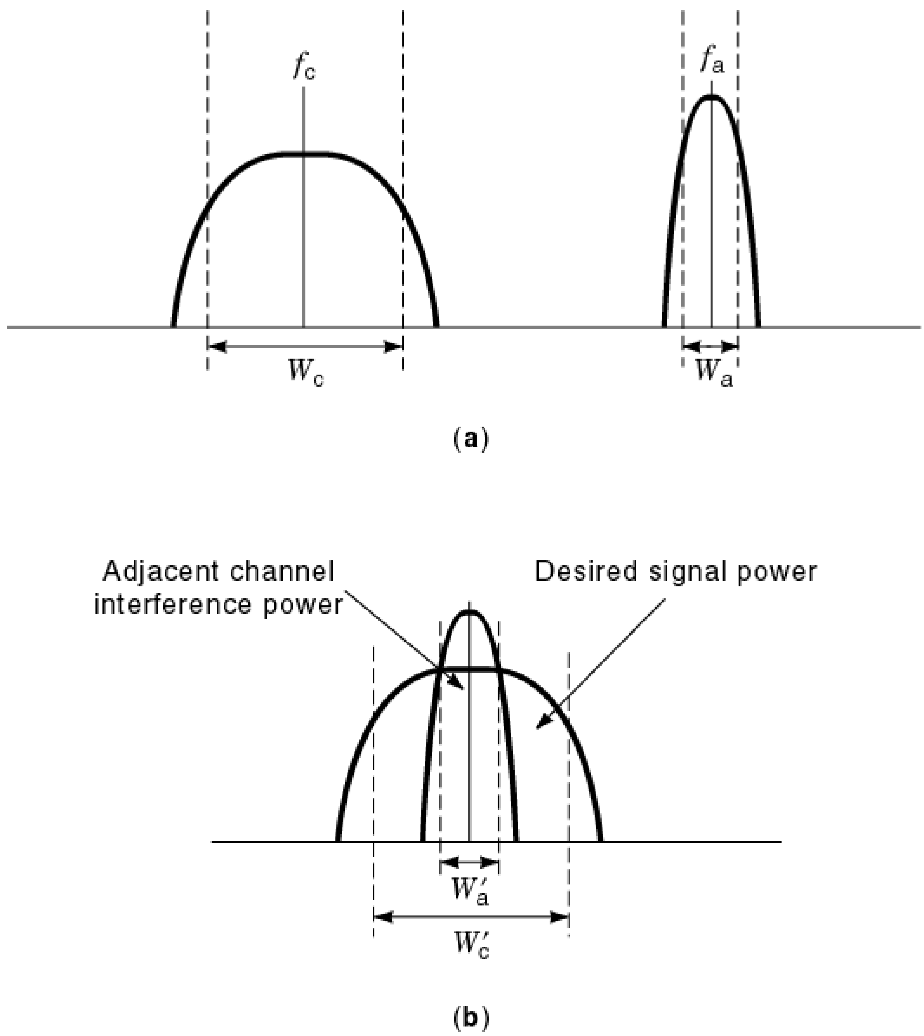

Fig. 1. In-band adjacent channel interference (a) in the *RF* band and (b) in the baseband.

interference signal and the desired signal. In this case, the baseband SNR can only be evaluated numerically. For detailed discussion regarding the adjacent channel SNR in a Rayleigh-fading environment, readers are referred to Refs. 1 and 5.

Out-of-Band Adjacent Channel Interference

Out-of-band adjacent channel interference is caused by unwanted emissions immediately outside the desired bandwidth of a radio channel. These unwanted emissions typically result from imperfections of filtering and modulation. Figure 2 shows the out-of-band adjacent channel interference in a desired channel at carrier frequency f_C in the *RF* band. This interference is caused by transmission of two channels immediately adjacent to the desired channel at frequencies f_{a+1} and f_{a-1}.

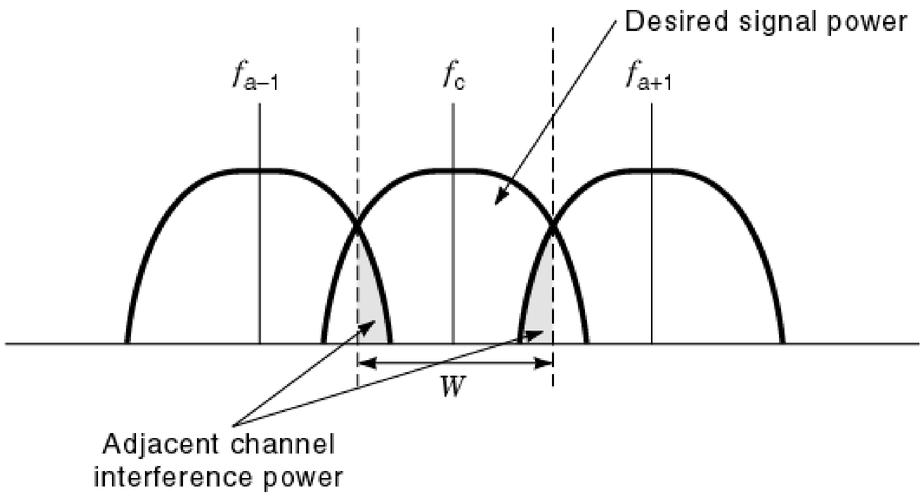

Fig. 2. Out-of-band adjacent channel interference in the *RF* band.

For the out-of-band adjacent channel interference, one definition of *C/A* can be found in Ref. 12. It is expressed as a function of the power spectral density (*PSD*) $G(f)$ of the modulated signal and the transfer function $H(f)$ of the receiver bandpass filter (*BPF*):

$$\frac{C}{A} = \frac{\int_{-\infty}^{\infty} G(f)|H(f)|^2\,df}{\int_{-\infty}^{\infty} (f)|H(f-\Delta f)|^2\,df} \qquad (2)$$

where Δf is the channel center-to-center frequency spacing. If the channel bandwidth W of the interfering signals is the same as that of the desired signal as depicted in Fig. 2, we have $\Delta f = W$.

Remedy for Adjacent Channel Interference

Frequency Planning. Out-of-band adjacent channel interference generally can be prevented by proper frequency planning or channel assignment. Immediately adjacent channels must not be assigned to the same base station in most cellular systems. Under certain propagation conditions, adjacent channels may not even be assigned to adjacent cells.

For the analog systems such as *AMPS* (10) and *TACS* (11), a separation of 7 to 21 radio channels between adjacent channels is typically required for each base station. Similar requirements can be found for narrow-band digital systems such as the IS-136 time-division multiple access (*TDMA*) system (13). IS-136 *TDMA* is one of the digital cellular systems designed for digital migration of *AMPS*. Each IS-136 *TDMA* channel occupies a bandwidth of 30 kHz, the same as *AMPS*, and has six time slots. Three full-rate voice users can be supported by each *TDMA* channel. Since each *AMPS* and IS-136 *TDMA* channel occupies a bandwidth of 30 kHz, the above requirement implies a frequency separation of 210 kHz to 630 kHz. Slightly different channel separation requirements are specified for another digital system, Global System for Mobile Communications (*GSM*) (14,15,16). *GSM* is also a *TDMA* system. Each *GSM* channel occupies a bandwidth of 200 kHz and has eight time slots. Eight full-rate voice users can be supported by each *GSM* channel. For a *GSM* system, the active radio channels in a single base station are normally separated 4 channels, or 800 kHz, apart.

Also, the poor adjacent channel performance associated with analog systems such as *AMPS* and *TACS* often prohibits the use of adjacent channels in adjacent cells. For digital *FDMA* systems such as *GSM* and IS-136 *TDMA*, adjacent channels can be assigned to the adjacent cells under most conditions except when the serving cell is significantly larger than the neighboring cells.

For CDMA systems such as IS-95 cdmaOne (17,18), carrier channels can be placed to be adjacent to each other in all cells or sectors. IS-95 cdmaOne is another digital cellular system designed for digital migration of *AMPS*. Each IS-95 cdmaOne channel occupies a bandwidth of 1.25 MHz. The universal frequency reuse capability of CDMA significantly increases system spectrum efficiency. However, in general the efficiency associated with universal frequency reuse cannot be fully realized, due to other cells' adjacent and cochannel interference (18,19).

In-band adjacent channel interference can also be prevented by proper frequency planning if its occurrence is predictable. Otherwise, one has to resort to adaptive interference avoidance schemes.

Filtering. The use of a *BPF* in a mobile radio system is also effective in removing out-of-band adjacent channel interference. However, unlike the out-of-band adjacent channel interference represented by Eq. (2), the in-band adjacent channel interference is generally not an explicit function of the frequency separation between the desired and adjacent channels. For example, as shown in Eq. (1), the baseband SNR due to adjacent channel interference in a nonfading environment is independent of the frequency separation. Obviously, the energy of interference falling into the bandwidth of the desired signal cannot be filtered by the *BPF*. Moreover, the occurrence such interference is often difficult to predict.

However, if the desired signal and the adjacent channel interference signal are decorrelated during the propagation process, more sophisticated filtering can reduce the in-band as well as the out-of-band adjacent channel interference. For instance, after propagation, the desired signal and the adjacent channel signal transmitted from the same base station to a mobile station often have different time delays. The time-delay spread tends to decorrelate the received amplitudes of the two signals. If the frequency separation between the desired signal and the adjacent channel signal is large enough, the Rayleigh fading of the two signals becomes essentially independent. As a result, the adjacent channel interference can be reduced by demodulation. The correlation of received amplitudes of two signals transmitted from the same base station was represented as a function of their frequency separation by Gans and Yeh in Ref. 1.

For the signaling tones, analog systems such as *AMPS* and *TACS* employ fast frequency-shift keying (*FFSK*) (9) waveforms with high deviation. The modulated waveforms therefore have significant adjacent channel sideband components. On the other hand, even though the digital modulation commonly used for some existing digital cellular system, such as QPSK (20) and GMSK (14,15), has an FSK-like waveform, the adjacent channel sidebands in most digital systems are significantly reduced by filtering (digital signal processing) (21). As a result, digital systems such as *GSM* and IS-136 are more robust to adjacent channel interference than analog systems such as *AMPS* and *TACS*.

Guard Band. For roaming purposes, digital cellular systems are overlaid on the analog *AMPS* systems in North America. As a result, digital networks, including IS-136 *TDMA* and IS-95 cdmaOne, always coexist with *AMPS* in the same system in the cellular bands. More often, throughout the world, radio transmission technologies are operated in adjacent frequency bands in the same market. A guard band is therefore required between systems employing different radio transmission technologies to prevent mutual interference.

A frequency separation of 270 kHz (or 9 *AMPS* channels) is typically set aside between *AMPS* and IS-95 cdmaOne to ensure no harmful interference between them. No guard band is required between IS-136 *TDMA* and *AMPS*. A guard band of 200 kHz (or 1 *GSM* channel) is often required between *GSM* and a system employing a different radio transmission technology.

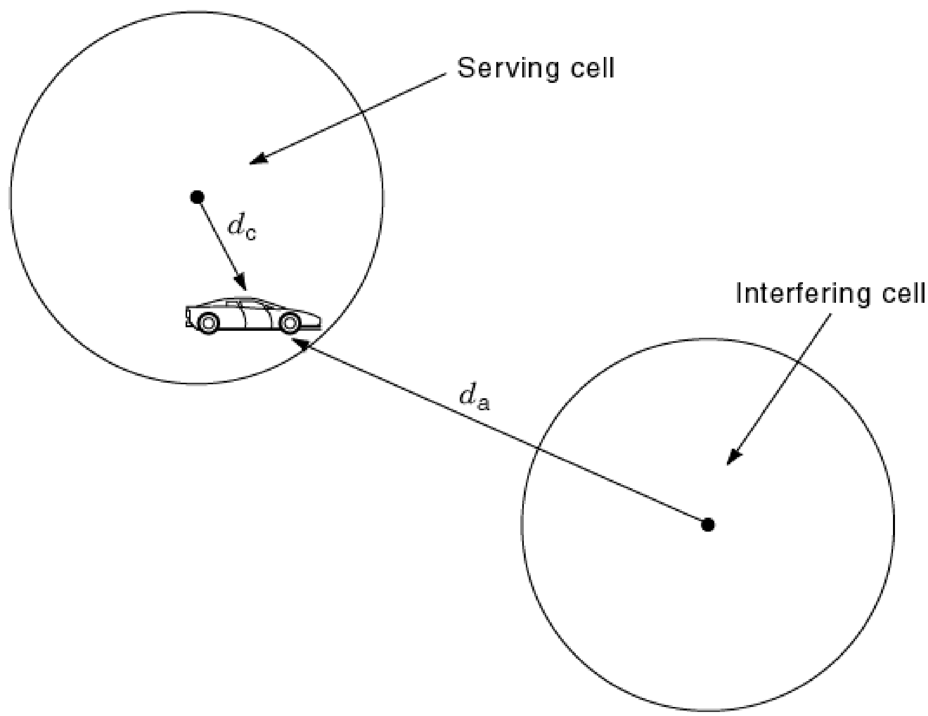

Fig. 3. Adjacent channel interference at mobile station served by a base station at a distance d_c from an interfering base station at a distance d_a.

System Design Guideline

Adjacent channel interference can be significantly reduced by the application of good engineering practice and proper system design. In this section, we use *AMPS* and IS-136 *TDMA* as examples to present some system design guidelines based on the TIA/EIA specifications (10,13).

For *AMPS* and IS-136 *TDMA*, the TIA/EIA specifications require that, within the 30 kHz channel bandwidth, the power of the adjacent channel interference shall be 26 dB below that of the desired carrier signal. That is

$$C/A > 26 \text{ dB} \tag{3}$$

Also, the adjacent channel interference A is typically required to be 10 dB below the cochannel interference I. If we represent the total interference, including both cochannel and adjacent channel interference, by I_{tol}, then we have

$$\frac{C}{I_{tol}} = \frac{C}{I + A} \tag{4}$$

and the above requirement implies that adjacent channel interference A contributes 1 dB to the total interference I_{tol}. For example, if C/I due to cochannel interference is 16 dB, adjacent channel interference with $C/A =$ 26 dB causes 1 dB degradation in C/I_{tol}. As a result, $C/I_{tol} = 15$ dB.

In a land mobile environment, received signal at a distance d from the transmitter can be described by an inverse power law, $1/d^{\gamma}$, where γ is the path loss decay index. The path loss decay index typically ranges from 2 to 4, depending on the propagation environment (3). The *C/A* ratio can then be estimated by the following formula:

$$\frac{C}{A} = 10\log\frac{d_{\rm c}^{\gamma_{\rm c}}}{d_{\rm a}^{\gamma_{\rm a}}} + \text{radio attenuation factor} \tag{5}$$

where $d_{\rm c}$ is the distance between the serving base station and the mobile station, $d_{\rm a}$ is the distance between the interfering base station and the mobile station, and $\gamma_{\rm a}$ and $\gamma_{\rm c}$ are the path loss decay indexes associated with the serving cell and the interfering cell respectively. The radio attenuation factor is a function of frequency separation, filter, and modulation characteristics as described by Eq. (2). Figure 3 shows an example of adjacent channel interference at a mobile station served by a base station at a distance $d_{\rm c}$. The interference signal comes from an interfering base station at a distance $d_{\rm a}$.

As seen from Eq. (5), *C/A* is a function of the path loss decay indexes $\gamma_{\rm a}$ and $\gamma_{\rm c}$ and of the ratio of distances from the mobile station to the serving and interfering base stations, $d_{\rm c}/d_{\rm a}$. If the desired signal and the adjacent channel signal come from the same base station, *C/A* is solely determined by the radio attenuation factor. When the serving cell is significantly larger than the interfering cell (i.e., $d_{\rm c} > d_{\rm a}$), the adjacent channel interference is worse than when the desired signal and the adjacent channel signal come from the same base station. Similarly, when the path loss decay index for the serving cell is less than that for the interfering cell (i.e., $\gamma_{\rm a} < \gamma_{\rm c}$), the *C/A* ratio is smaller than when the desired signal and the adjacent channel signal come from the same base station so that $\gamma_{\rm a} = \gamma_{\rm c}$. This occurs, for example, when the interfering signal propagates over water but the desired signal travels past many buildings.

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HOWARD H. XIA
Vodafone AirTouch Plc