COCHANNEL INTERFERENCE

Over the past decade, the demand for wireless voice, data, and facsimile services has exploded. To keep pace with this explosive demand, the wireless industry is currently launching an aggressive campaign to deploy and operate an ever-increasing number of wireless systems in a comparatively small and modestly increasing sliver of spectrum. As an example, consider the broadband Personal Communications Services (PCS) industry. As many as 2042 licenses are available for potential PCS service providers, and all these providers must operate their respective systems in only 120 MHz of spectrum. Moreover, each provider is free to choose any technology. Currently, as many as eight technologies are standardized for use in broadband PCS. Traditionally, wireless system engineers focus on designing systems that provide a large subscriber base with an acceptably high Quality of Service (QOS) and Grade of Service (GOS) and operate in a fixed spectrum allocation. To meet these spectrally constrained requirements, wireless engineers use combinations of multiple access techniques and frequency reuse. Wireless engineers use multiple access techniques to support parallel transmission by subscribers over a fixed spectrum allocation. Some common techniques include Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA).

Regrettably, the number of transmissions supported by any multiple access technique is not only finite but also a function of available bandwidth (spectrum). Therefore, to further increase their system's spectral efficiency or available capacity, wireless engineers reuse frequencies in different regions over the given service area. This technique, frequency reuse, provides a tradeoff between spectrum efficiency (or capacity) and interference. If a wireless engineer designs a system with a high frequency reuse, the system will be spectrally efficient, thereby having a high GOS. However, the same service will also be encumbered by excessive cochannel interference, which will contribute to a low QOS. On the other hand, if the same engineer reduces the frequency reuse, the system's spectral efficiency will decrease, thus reducing the GOS. However, the system's cochannel interference will decrease, thereby increasing the system's QOS. In any event, wireless engineers can manage this particular form of self-interference via a prudent system design (i.e., selection of multiple access technique, cell layout design, and frequency plan). In the section entitled "Intrasystem Interference," we discuss self-interference and its relationship to various system design parameters such as the frequency reuse factor and the frequency reuse distance.

On the other hand, the proliferation of so many PCS licenses in such a small spectral allocation imposes some unique challenges to wireless system engineers regarding interference management and mitigation. In the PCS industry, up to six operators will provide service to the same service area via adjacent frequency bands. Each operator may use any of eight standardized technologies, each with different emission characteristics and performance requirements. Furthermore, no coordination procedures exist between any operators that provide service to the same area. This potentially dangerous situation increases the likelihood of a unique type of interference called PCS-to-PCS Interference (PPI). PPI occurs when the in-band or out-of-band emissions of one (offending) PCS system, with a given technology and system layout, interferes with receivers (usually mobile subscriber receivers) of another (victim) PCS system with a different technology and different system layout. The next section provides a detailed discussion of the two major PPI interference mechanisms. PPI is disconcerting to wireless engineers for two reasons. First, unlike self-interference (brought about by frequency reuse), which usually occurs along the cell boundary, PPI can occur anywhere in the victim PCS system's service area. Second, wireless engineers cannot easily predict or mitigate PPI because the wireless engineer for one PCS system has no control over the design of the other PCS system. Therefore, most mitigation techniques that involve wireless system design and layout require some form of cooperation between competing PCS operators. The section entitled "Interference Mitigation Techniques" presents a number of these techniques as well as equipment design approaches that should mitigate PPI. Recall that PPI is a consequence of the different PCS systems and their varying emission limits and performance requirements. In the section entitled "IS-95," we discuss the performance requirements and emission specifications of one PCS technology, IS-95. We also discuss relevant regulations that apply to the PPI issue. The subsection entitled "Interference Estimation Methodology" presents an interference analysis methodology that shows how emissions from one base station transmitter can cause excessive interference to nearby mobiles that subscribe to a competing service. Conclusions are presented in the last section.

INTERFERENCE SOURCES IN WIRELESS COMMUNICATIONS

In the design and analysis of any wireless system, engineers must consider a vast number of interference sources and mechanisms. These include various intrasystem interference sources such as cochannel interference resulting from frequency reuse, adjacent-channel interference and alternate channel interference caused by the specific frequency plan used in the system design, interference from spurious emissions and other transceiver nonlinearities, and intermodulation interference from multicarrier transmission systems in base station transceivers. Also included are a number of intersystem interference sources, which are currently unique to the PCS industry. These sources include cochannel interference, adjacent channel interference resulting from the near-far phenomenon, and intermodulation interference.

To discuss all the interference mechanisms in wireless communications is beyond the scope of this paper. Rather, this section discusses the major interference sources. In particular, we discuss how these interference mechanisms are generated, how they are related to relevant system design parameters, and what overall effect they have on system performance. With that in mind, we limit our discussion in the next section to cochannel interference resulting from frequency reuse. In particular, we show the relationship between frequency reuse (or the frequency reuse factor) and the system Carrier to Interference Ratio (CIR) requirement for acceptable QOS. Then we limit our discussion to two PPI mechanisms—adjacent channel interference (due to the near-far phenomenon) and intermodulation interference—which may occur when two or more PCS service providers colocate their respective base station transceivers.

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Intrasystem Interference

Any wireless communication system that employs a frequency reuse scheme is subject to cochannel interference. Indeed, cochannel interference is the primary interference mechanism and is the major factor that limits the capacity of any wireless system that employs frequency reuse. Cells that reuse the same frequency are commonly referred to as cochannel cells. Wireless engineers place cochannels at a sufficiently large distance from one another so that the emissions from one cell do not cause excessive interference into any subscriber in another cochannel cell. We call this distance the reuse distance. One can clearly see the tradeoff between reuse distance, capacity, and interference. If the reuse distance increases, then the capacity decreases and the cochannel interference decreases, thereby increasing QOS. Conversely, decreasing the reuse distance increases capacity at the expense of increased interference, thereby degrading QOS.

Other factors that affect signal quality include the location and velocity of the mobile station. Generally, mobile stations that are located at the edge of a given cell receive a nominal carrier signal. Furthermore, these mobile stations also have a higher probability that the carrier signal is shadowed by some obstruction in the transmission path. Note that line of sight transmission is unlikely in such conditions. Therefore, mobile stations that reside at the fringe of a given cell have a higher probability of receiving excessive cochannel interference than mobile stations residing in the cell's interior. If the mobile is moving at high speeds, the received carrier signal suffers from fast fading. Therefore, even though the CIR is under static conditions, it is large enough to maintain reliable communications. Under fading conditions, the CIR periodically drops below the threshold required to maintain reliable communication. Thus, wireless engineers generally add a fade margin in the link budget to account for signal variations resulting from fading and shadowing.

To illustrate the basic relationships between frequency reuse, capacity, and the system CIR requirement for acceptable QOS, consider the following example. Suppose a wireless service provider (cellular, PCS, or otherwise) with an allocation of M channels deploys a system over the given service area using the canonical, single sector, hexagon grid model (Fig. 1). Furthermore, suppose that the provider implements a frequency reuse scheme in the standard method by partitioning the M channels into N channel sets where each set contains one set of frequencies. The provider then assigns these channel sets to a contiguous group of hexagons called a cluster, where N is the cluster size. For a standard hexagon cell pattern, the cluster will tessellate if N takes on values of 1, 3, 7, 9, 12, etc. Finally, the provider achieves frequency reuse by repeating the preceding channel assignment for each cluster in the service area. Because each channel is assigned to only one cell in every N cell cluster, we say that the frequency reuse factor is $1/N$. Also, for the canonical hexagon cell pattern, the relationship between reuse distance and cluster size is

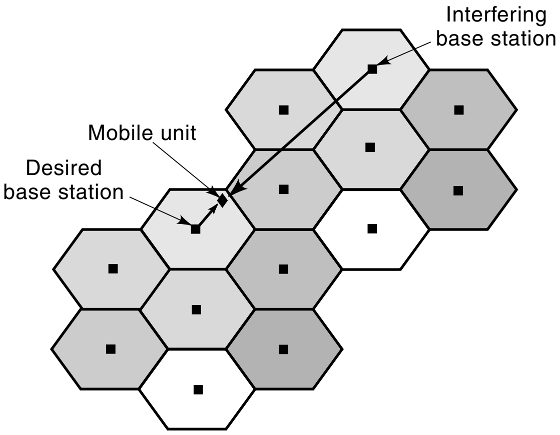


Figure 1. Cochannel problem in a typical cellular environment. Here the reuse factor is seven.

$$D = R\sqrt{3N} \tag{1}$$

where D is the reuse distance, N is the reuse factor, and R is the radius of the cell. Assuming a path-loss exponent to be 4, an approximate value for CIR is given by

$$\mathrm{CIR} = \frac{C}{\sum_{i=1}^{6} I_i} \tag{2}$$

$$\approx \frac{R^{-4}}{6D^{-4}} \tag{3}$$

$$= 1.5N^2 \tag{4}$$

Now consider the Advanced Mobile Phone System (AMPS) wherein traffic modulation is based on analog Frequency Modulation (FM). For a standard AMPS receiver (i.e., a standard Phased Lock Loop FM receiver) to reliably demodulate a FM signal, thus providing toll-quality speech, the CIR must not fall below 63.09 (or 18 dB). Then a cluster size of seven will provide sufficient protection from cochannel interference so that a CIR of 18 dB is maintained. This results in a frequency reuse factor of $\frac{1}{7}$. Furthermore, suppose that a cellular service provider designs an AMPS-based system in such a manner that it consists of 42 cells and has sufficient spectrum to accommodate 21 duplex channels. Then with a frequency reuse of $\frac{1}{7}$, the provider can assign the same channel to every seventh cell. Thus, the provider assigns three channels to each cell. If we assume that no channels are used for signaling or control purposes, this wireless system can support a capacity of 126.

Suppose however, that by using some interference mitigation techniques (e.g., interference cancellation), a manufacturer designs an interference-resistant AMPS-compliant receiver that reliably demodulates the FM signal when the CIR = 8 (or 9.03 dB). Then a cluster size of three will provide sufficient protection from cochannel interference. This results in an increased frequency reuse factor of $\frac{1}{3}$ and an increase in capacity that exceeds a factor of 2. Indeed, in this example, with an increased frequency reuse of $\frac{1}{3}$, the provider can assign each cell seven channels rather than three. Hence, the available capacity increases from 126 to 294. Note that if one designed an interference-resistant receiver that operated with a CIR of 1.5 (or 1.76 dB), wireless systems with a frequency reuse of 1 would then be possible. A CDMA system such as IS-95 with its Rake receiver design is an example of such a system.

Intersystem Interference

The advent of Personal Communication Services to the wireless industry has developed a number of new opportunities, including higher-quality, less-expensive service; increased opportunities for competition among service providers; and plenty of capacity to support the ever-increasing demand for wireless communication services. PCS has also provided a number of issues and challenges to the wireless system engineers given the task to design and roll out such systems. Of all the challenges and issues facing PCS system engineers, perhaps none is as perplexing as the PCS-to-PCS Interference issue. PPI occurs when the radio frequency emissions of one PCS network, which uses a given technology, interfere with the receiving equipment of another PCS network, which uses a different technology. PPI is a direct consequence of the large number of PCS systems being deployed across America, the fixed spectrum within which these systems must operate, and the different technologies available to potential PCS service providers. The proliferation of these technologies is a major contributor to PPI simply because different technologies possess different emission characteristics, channel configurations, occupied bandwidths, and receiver performance requirements.

Two or more PCS systems can interfere with one another in three different manners depending on their relative deployment. If two PCS systems operate in the same frequency block but are deployed in adjacent service areas, they may be subject to coblock PPI. Coblock PPI is generally limited to regions around the service area boundaries. PCS providers can minimize the impact of coblock PPI via frequency coordination, power control, and careful design of the antenna coverage pattern.

This section focuses on the remaining two PPI mechanisms: adjacent channel interference and intermodulation interference. Both interference mechanisms occur whenever two or more networks, each with different technologies, operate in the same service area and use nearby frequency allocations. This is indeed the case for the PCS industry. In each service area, six PCS operators provide their respective service within the same 120 MHz allocation. It is likely that each of these operators will provide service using different technologies. The Telecommunications Industries Association (TIA) has currently standardized eight technologies for use in licensed PCS. Furthermore, no PCS operator has any control over the choice of technology, system layout, or frequency plan of any other PCS operator that provides service in the same area. This leads to a potentially dangerous interference environment where adjacent channel interference and intermodulation interference could be prevalent.

The next section describes adjacent channel PPI in some detail. It also shows how adjacent channel PPI is a consequence of the near-far phenomenon. This phenomenon, which primarily affects mobile stations, occurs when a mobile station is far from its serving base station but very near a base station that serves another network in the same service area. After that we examine intermodulation PPI and see how this form of interference occurs when two or more providers operate base stations in the same area.

Adjacent Channel Interference. Adjacent channel interference generally affects the mobile receiver. Moreover, this form of interference is a consequence of the near-far phenomenon. The near-far phenomenon arises when a mobile station is far from its serving base station (e.g., on the fringe of the serving cell) but is very near a base station belonging to another PCS network. In such cases, the mobile station must attempt to receive a weak signal from its serving base station while receiving a strong signal from the other (or interfering) base station. It is important to note that even though the interfering base station is transmitting a relatively weak out-of-band signal, the propagation loss from that base station to the mobile station is so small that the signal is relatively strong when it arrives at the mobile station. On the other hand, the propagation loss from the serving base station to the mobile station is very large. Therefore, the relatively strong signal transmitted from this base station becomes relatively weak when it arrives at the receiver. In this classic near-far situation, the out-of-band interference will overwhelm the mobile station, thus creating a hole in the network.

The consequence of the near-far phenomenon implies that a coverage hole will reside around every PCS base station that is not colocated or located near all other providers operating in the same service area. This consequence is rather disconcerting. It implies that as other PCS providers begin to turn up their systems in a given service area, subscribers, who may have enjoyed high-quality service from another PCS provider currently operating in that service area, will now experience abrupt interruptions of service (in the form of dropped calls) whenever they pass by a base station that belongs to the new, competing service (of course, the converse is also true). It also implies that these coverage holes can occur throughout the service area. Furthermore, these coverage holes are more likely to occur in high-capacity regions, such as urban centers, where PCS providers deploy numerous base stations to support the expectedly high subscriber demand.

The impact to network performance may be illustrated by the following example. Consider a customer based in Saratoga Springs, New York, which is just north of Albany, New York, on I-87. This customer regularly commutes from his home in Saratoga Springs to work in Albany and frequently uses his PCS service during these times. In fact, the customer has always enjoyed reliable and clear communications from his service for the past year. However, a week ago, this customer experienced a dropped call as soon as he entered Albany on I-87. On the way home that day, the customer again experienced a dropped call at the same location. In fact, every day that week, when the customer crossed the Albany city limits, his ongoing call was lost (i.e., dropped). Of course, the loss of calls was the result of a coverage hole caused by a base station that was recently placed into operation by another PCS provider that serves the same area. Nevertheless, the customer did not care about that. What was once a good, reliable service became a poor service. So, the customer stopped the current service and switched to the service offered by the new provider.

It is important to note that this customer is not the only individual who experienced lost calls in this example. Indeed, each customer who commutes into Albany from the north will experience the same problem and become dissatisfied with the existing service. The example shows that adjacent channel interference from other service providers' base stations will create coverage holes in a given network. These coverage holes, depending on their location, will result in customer dissatisfaction, loss of customers, loss of revenue, and loss of profitability. Therefore, the existence, location, and size of these coverage holes can have a direct and adverse impact on the financial performance of the given network.

Intermodulation Interference. Intermodulation interference is a common problem in situations where many transceivers operate at the same location (e.g., on a radio tower). This form of interference is a consequence of the nonlinear behavior of the transmitters on the tower and the interaction between the various transmitted signals and various imperfections on the tower. A common example of the former case is a transmitted signal from one transceiver leaking into the power amplifier of another transceiver. The presence of the leaked signal will cause the power amplifier (a nonlinear device) to produce intermodulation interference into the corresponding receive channels of some of the transceivers on the tower. A common example of the latter case is the interaction of two or more transmitted signals and a rusty bolt on a tower. Such an interaction will produce intermodulation interference into the corresponding receive channels of some of the transceivers on that tower.

Intermodulation interference is not unique to the PCS industry. Indeed, the cellular industry also had to cope with intermodulation interference whenever two cellular service providers shared the same tower with one another or with a Specialized Mobile Radio (SMR) provider. However, because cellular and SMR providers implemented common, narrow band technologies, they could easily resolve interference cases by moving one or more of the frequency assignments by one or two channels.

The effect of intermodulation interference is illustrated in the following example. Suppose a customer in Blacksburg, Virginia, has enjoyed a high quality of service from his PCS service for the past 12 months. This particular customer travels only in and around Blacksburg. Therefore, he rarely leaves the coverage area of the three sectors operating on the one tower in Blacksburg. However, last week he noticed that his calls were being interrupted, and the interruption in service was becoming more consistent. What particularly bothered the customer was that the voice quality of the other party was exceptional (indicating that there was no interference in the downlink). Nevertheless, frustrated with the consistent interruptions in service, the customer cancelled his PCS service and subscribed to a competing PCS service, which went into operation about a week ago. Coincidentally, the competing PCS service provider operates its service in that area on the same tower.

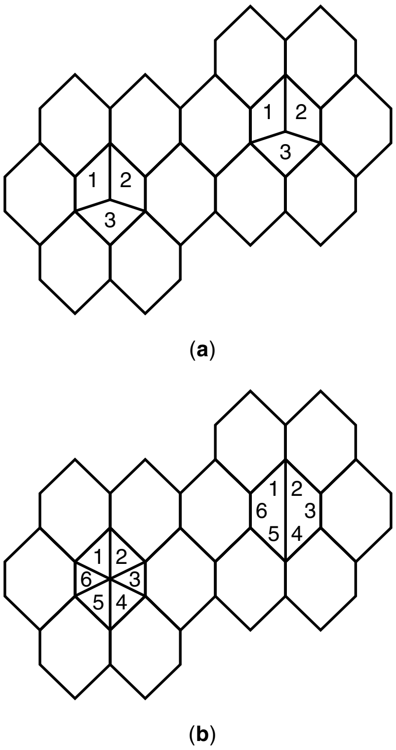
The customer in question was a victim of intermodulation interference. This particular form of interference affects only the uplink. Therefore, the sector serving the customer could not clearly receive the signal from the customers mobile station, even though the customer could receive the signal from the sector. Because the sector in question was unable to receive the signal after as many as 64 attempts, the PCS system dropped the call. Such interference events will affect the network by causing large holes in the uplink coverage. These holes will adversely affect call quality and grade of service. This has a direct and deleterious impact on system capacity, subscriber satisfaction, and network revenue.

INTERFERENCE MITIGATION TECHNIQUES

In the initial phase of a cellular network deployment, capacity is not an issue, and hence a cellular service provider designs the network to maximize coverage. Base stations are sited to maximize the range of operation, which depends on the propagation characteristics of the particular location. Hence, cluster sizes are large. As the network matures, capacity becomes an important issue. The service provider reduces the cluster size to increase capacity by providing more channels per area. The penalty is a reduction in carrier to interference ratio (CIR). In the first- and second-generation cellular systems (AMPS and GSM), omnidirectional antennas are replaced by directional antennas to increase the CIR. Interference can be minimized by carefully designing the system (e.g., sectorization, channel allocation, etc.) or by implementing interference mitigation techniques based on signal processing at the receiver.

Sectorization

Cochannel interference may be decreased by replacing a single omnidirectional antenna at the base station with several directional antennas, each radiating within a specified sector. By using directional antennas, a given cell receives interference from and transmits to only a fraction of cochannel cells. The reduction in cochannel interference depends on the number of sectors or on the beamwidth of the directional antenna. A cell is usually partitioned into three 120° or six 60° sectors. When sectoring is employed, the channels are separated into sectored groups and are used only within a particular sector, as illustrated in Fig. 2. In a typical seven-cell reuse pattern,



(a)

(b)

Figure 2. Sectorization in a typical cellular system: (a) 120° sectorization and (b) 60° sectorization.

the number of interferers in the first tier is six, but when 120° sectorization is employed, the number of interferers is reduced to two.

When the mobile is at the edge of the cell, a reuse factor of 12 is required to maintain a CIR of 18 dB. However, with 120° sectorization, a CIR of 18 dB can be achieved with a reuse factor of 7. Thus, sectorization reduces interference, which can be translated into an increase in capacity by approximately $\frac{12}{7}$. In practice, the reduction in interference offered by sectoring enables cell planners to reduce the cluster size and provides additional degrees of freedom in assigning channels. The penalty for improved CIR and the resulting improved capacity is an increase in the number of antennas and a decrease in trunking efficiency as a result of channel sectoring at the base station.

Channel Allocation

For effective use of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing the capacity and minimizing the interference is required. When a user is on a particular channel at the edge of the cell, the user may suffer from cochannel interference. In this scenario, the user can be moved to a new channel, and the probability of cochannel interference can be reduced. If the old channel is allocated to a user close to the base station, this user may not suffer from interference. Various channel assignment strategies have developed and are classified as fixed or dynamic.

In a fixed-channel allocation scheme, each cell is allocated a predetermined set of channels. All the calls are serviced using the allocated channels. If all the channels are used, the call is blocked. There are several variants to this approach. In one approach, a cell can borrow channels from the neighboring cells. The mobile switching center (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not interfere with any of the calls in progress in the donor cell.

In a dynamic channel allocation scheme, channels are not allocated in a predetermined fashion. Every time a call is initiated, the servicing base station requests a channel from the MSC. The switch then allocates a channel to the requested cell following an algorithm that takes into account the likelihood of future blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel, and other parameters.

Signal Processing Techniques

Interference rejection is important for several reasons. Cellular capacity is inherently interference limited, particularly by cochannel interference (CCI) and adjacent channel interference (ACI). One solution to combat CCI and ACI is to split cells and decrease power, but cell splitting is expensive. Interference rejection techniques often represent a less-expensive alternative to cell splitting.

In addition, as newer communication technologies supersede older technologies, interference rejection techniques are important in helping to facilitate compatibility during transitions between the old and new technologies. Several examples illustrate the need for compatibility: coutilization of the existing cellular band with new narrow band CDMA and TDMA digital cellular signals, design of broadband CDMA overlaying AMPS signals in the cellular bands, coutilization of the new personal communication system band (1.8 GHz to 2.2 GHz) with existing microwave systems, the addition of a vast number of new low-earth-orbiting (LEO) satellites with overlapping footprints with older satellites, and accommodation of high definition television (HDTV) transmissions within the current TV band.

Adaptive Interference Rejection. Interference rejection techniques often need to be adaptive because of the dynamic nature of interference and the channel. Methods of interference rejection can be viewed as adaptive filtering techniques. The term *filter* is often used to describe a device (software or hardware) that is applied to a set of corrupted data to extract information about a prescribed quantity of interest. The design of an optimum filter requires a priori information about the statistics of the data to be processed. Where complete knowledge of the relevant signal characteristics is not available, an adaptive filter is needed. This filter is a self-designing device that relies on a recursive algorithm to converge to the optimum solution in some statistical sense. A useful approach to the filter-optimization problem is to minimize the mean-square value of the error signal, defined as the difference between some desired response and the actual filter output (1).

Single-Channel versus Multichannel. Single-channel adaptive filtering techniques are interference rejection techniques employing one antenna as opposed to multichannel techniques, which employ multiple antennas, such as arrays or cross-polarized antennas. Multiple antennas allow multichannel reception (i.e., each channel carries a different version of the transmitted signal). The differences in the received versions of the signal at each antenna can be used to enhance and detect the desired signal. With single-channel reception, only one version of the transmitted signal is received, usually by only one antenna. A classification of single-channel interference rejection techniques is shown in Fig. 3.

Multichannel interference rejection techniques, specifically array signal processing, has attracted a lot of interest in recent times. Array signal processing was previously restricted to military purposes, and recently commercial wireless systems have adopted this technique to improve signal quality and increase system capacity. Space Division Multiple Access (SDMA) has attracted considerable attention as a means of increasing the capacity in cellular communications. SDMA allows users within a cell to use the same frequency by employing a spatial filter at the base station. SDMA exploits spatial diversity, and it increases the signal to interference ratio by spatially isolating the desired user from the interference. In the past, capacity enhancement using adaptive arrays for land mobile radio systems have been investigated (2,3). Adaptive arrays have been investigated for CDMA (4,5), TDMA (6,7), and FDMA (8,9) systems to mitigate cochannel interference and multipath components. Capacity increase provided by adaptive arrays for CDMA systems have been investigated in the past (10–12).

Spread Spectrum versus Nonspread Spectrum. Spread spectrum (SS) is by nature an interference tolerant modulation. However, there are situations where the processing gain is inadequate, and interference rejection techniques must be employed. This is especially true for direct sequence spread spectrum (DS-SS), which suffers from the near-far problem.

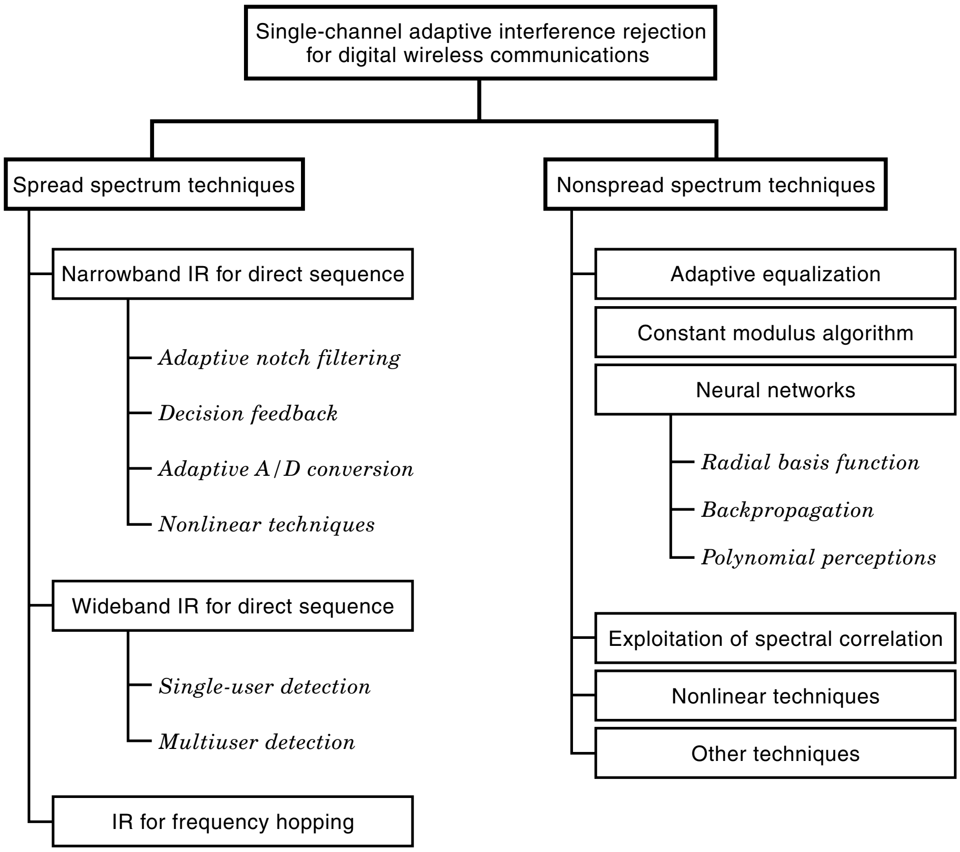


Figure 3. Classification of single-channel interference rejection techniques.

SS categories include direct sequence (DS), CDMA, and frequency hopping (FH).

Several tutorial papers have been published on interference rejection in SS, and Milstein's paper (13) is of particular interest. Milstein discusses in depth two classes of rejection schemes (both of which implement an adaptive notch filter): (1) those based upon least mean square (LMS) estimation techniques and (2) those based upon transform domain processing structures. The improvement achieved by these techniques is subject to the constraint that the interference be relatively narrow band with respect to the DS waveform. Poor and Rusch (14,15) give an overview of narrowband interference suppression in SS CDMA. They categorize CDMA interference suppression by linear techniques, nonlinear estimation techniques, and multiuser detection techniques. A more detailed survey of different signal-processing techniques can be found in Ref. 16.

A classification of wideband interference rejection techniques for direct sequence CDMA is shown in Fig. 4. The current generation of CDMA systems employs single-stage correlation receivers that correlate the received signal with a synchronized copy of the desired signal's spreading code. Conventional receivers treat multiple access interference (MAI), which is inherent to CDMA, as additive noise. In the downlink, the orthogonality of the codes helps mitigate mutual interference. But in the uplink, the users are operating in asynchronous mode, and hence the orthogonality of the codes is no longer beneficial. Therefore multiuser rejection techniques have been developed to use the knowledge of all the users' codes at the base station to reject interference.

INTERFERENCE ISSUES

This section focuses on transceiver issues and FCC regulations to reduce interference in the licensed PCS bands. The interference problem is enhanced by coexisting multiple standards, which can interfere with each other and make the interference analysis much more complicated. The receiver issues can be classified as

- Transmitter output,
- Channel planning,
- Transmit/receive duty cycle,
- Transmitter intermodulation, and
- Receiver interference performance.

In the following study, the IS-95 CDMA standard is used as a representative signal standard. However, the analysis is applicable for different standards such as IS-136, PACS, and PCS1900.

FCC Regulations

The FCC Rules (17) and the FCC Memorandum (18) state that the base stations are limited to 1640 W peak equivalent isotropically radiated power (EIRP) with an antenna height of 300 m. Base station heights may exceed 300 m but with a corresponding decrease in the radiated power. These requirements are listed in Table 1.

Mobile or portable stations are limited to 2 W EIRP peak power, and the equipment must employ means to limit the

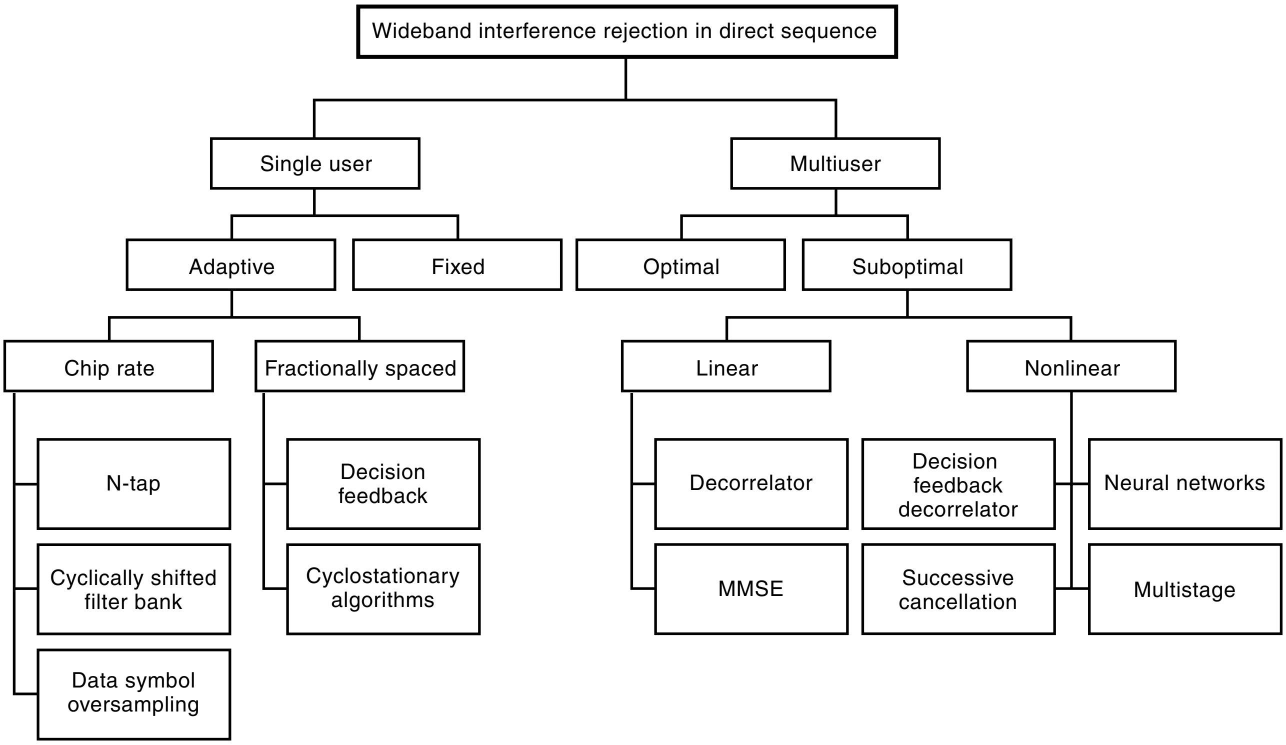


Figure 4. Classification of wideband interference rejection techniques for direct sequence CDMA systems.

power to the minimum necessary for successful communications. On any frequency outside the licensee's frequency block, the power of any emission shall be attenuated below the transmitter power P by at least $43 + 10 \log P$ dB. The antenna height at the base station dictates the coverage of the base station. Therefore, the taller the antennas, the less power they are allowed to transmit. There is a tradeoff between the coverage of and the amount of interference emitted by a certain base station. The antenna height must be designed to reduce the amount of interference to the neighboring base stations.

Table 1. Reduction in Power for Antenna Heights over 300 m

Height (m)	Maximum EIRP (W)
<=300	1,640
<=500	1,070
<=1,000	490
<=1,500	270
<=2,000	160

IS-95

This subsection deals with the receiver issues for IS-95 systems. The following FCC requirements are extracted from Refs. 19–21).

Power Characteristics for Base Station and the Mobile. The FCC also regulates spurious emissions outside the band of interest to minimize adjacent channel interference. When transmitting on any valid band, the spurious emissions shall not exceed −13 dBm outside the band of interest. The resolution bandwidth for measuring these emissions shall be 1 MHz, except within the 1 MHz bandwidth immediately outside and adjacent to the frequency block, where the resolution bandwidth of at least 1% of the emission bandwidth of the fundamental emission of the transmitter shall be employed.

The transmitter output power of the base station in any 1.25 MHz band of the base station's transmit band between 1930 and 1990 MHz and in any direction shall not exceed 100 W. For all the frequencies within the band 1930 MHz to 1990 MHz, the total conducted spurious emissions in any 30 kHz band greater than 885 kHz from the CDMA center channel frequency shall not exceed a level of −45 dBc.

The mobile unit also has a set of transmitter power constraints; a mobile unit should not transmit more than 3 dBW EIRP. The amount of spurious emissions allowed is summarized in Table 2.

Channel Spacing. The channel assignments for the mobile and the base station are specified in Table 3. The channel spacing and the filter mask decide the adjacent channel interference. Certain channel assignments are valid, and others are conditionally valid. Transmission on conditionally valid channels is permissible if the adjacent block is allocated to

Table 2. Spurious Emissions Limits

Center Frequency Offset	Spurious Emissions <
>1.265 MHz for 30 kHz bandwidth	−60 dBm/30 kHz
>1.75 MHz for 1 MHz bandwidth	−55 dBm/MHz

Table 3. Channel Assignments

Transmitter	CDMA Channel Number	Center Frequency of CDMA Channel (MHz)
Mobile	$0 \leq N \leq 1199$	$1850.00 + 0.050N$
Base	$0 \leq N \leq 1199$	$1930.00 + 0.050N$

the licensee or if other valid authorization has been obtained. Also the base station transmit carrier frequency shall be maintained within $\pm 5 \times 10^{-8}$ of the CDMA frequency assignment. The mobile transmit carrier frequency shall be below the base station transmit frequency, as measured at the mobile, by 80 MHz ± 150 Hz.

Transmit/Receive Duty Cycle. The transmit and the receive duty cycle decide the amount of cochannel interference contributed by any user. In a IS-95 system, when operating in a variable data rate transmission mode, the mobile transmits at nominal controlled power levels only during gated-on periods, each defined as a power control group. The time response of the ensemble average of power control groups, all with the same mean output power, shall be within the limits in Fig. 5. During the gated-off periods, between the transmissions of power control groups, the mobile shall reduce its mean output power by at least 20 dB either with respect to the mean output power of the most recent power control group or to the transmitter noise floor, whichever is greatest.

Transmitter Intermodulation. Spurious intermodulation products are produced whenever frequency signals mix in nonlinear RF stages. In particular, transmitter final stages tend to be quite nonlinear, with the presence of at least one strong signal guaranteed. Other signals may be picked up by the antenna and transferred to these stages with subsequent retransmission of the resulting spurious intermodulation products. The main concern is usually the third-order intermodulation products because resulting intermodulation products can fall on nearby frequencies of interest. In-band transmitter intermodulation generation will generally be of greater concern than in-band sideband noise, as the latter is of much less power compared to the former. These problems get complicated if different standards coexist, for example, AMPS and CDMA.

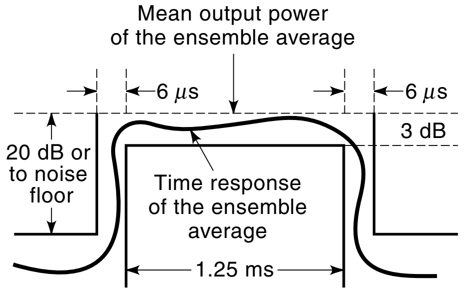


Figure 5. Transmission envelope mask (average gated-on power control group).

Interference Estimation Methodology

The methodology used here is adopted from References 22 and 23. Here the T-R separation, for which the spurious emissions from the transmitter (at maximum power because the mobile is assumed to be at the cell edge) of one technology would impact the receiver of the other technology, is estimated using simple path-loss calculations. Interference between four transmitter/receiver pairs are analyzed:

- Technology A mobile transmitter impacting a Technology B base,
- Technology A base transmitter impacting a Technology B mobile,
- Technology B mobile transmitter impacting a Technology A base, and
- Technology B base transmitter impacting a Technology A mobile.

Here the analysis includes only the effects of transmit power, antenna height, and feeder losses. Third-order intermod products, multiple interferers, coherent interference, and antenna radiation pattern are not included.

To analyze the amount of interference, the metric used is the *degradation in receiver sensitivity* also called *receiver desensitization* and the threshold for impact when the interference power plus the existing thermal noise plus the in-system interference power is 3 dB above the original interference plus thermal noise power. For example, a 3 dB receiver desensitization reduces the effective system range and reduces the cell size by 15% to 30%. The propagation environment is modeled using a two-slope path loss model (24) as

$$r_t = \frac{4h_b h_m}{\lambda}$$

$$\text{Path loss} = \left(\frac{4\pi r}{\lambda}\right)^2, r \leq r_t \tag{5}$$

$$\text{Path loss} = \left(\frac{4\pi r^2}{\lambda r_t}\right)^2, r > r_t \tag{6}$$

where h_m and h_b are the heights of the mobile and the base antennas, respectively. The quantity λ is the wavelength of the carrier frequency and r is the T-R separation.

The channel frequencies can be determined from the standards specifications. The frequency bands of different technologies are chosen so that the frequency separation is minimal.

Calculation of Interference Distance versus Receiver Desensitization

The following calculation is extracted from Ref. 25. The procedure to calculate the interference distance as a function of receiver desensitization follows.

In Ref. 25, the following parameters are defined:

- N_i, n_i—original interference density (dBm/Hz) (n_i in mW/Hz),
- NF—receiver noise figure (dB),
- (N_o, n_o—thermal noise density (dBm/Hz) (n_o in mW/Hz),
- (N_e, n_e—out-of-band emission density (dBm/Hz) (n_e in mW/Hz).

All the summations in the following discussion are done in milliwatts per hertz, not in decibel-watts per hertz.

Desensitization (*D*) for TDMA Systems (PCS1900, IS-136) and CDMA Systems (IS-95). Desensitization for TDMA systems is defined as

$$D = 10 \times \log_{10}\left[\frac{(n_\mathrm{e} + n_\mathrm{i} + n_\mathrm{o})}{(n_\mathrm{i} + n_\mathrm{o})}\right] \mathrm{dB} \qquad (7)$$

Here we need to know $(n_\mathrm{e} + n_\mathrm{i} + n_\mathrm{o})/(n_\mathrm{i} + n_\mathrm{o})$.

For CDMA systems, D is defined in a different way because power control is employed in these systems. In IS-95 if there is extra interference, all the mobiles in the cell/sector will raise their power to maintain the required $E_\mathrm{o}/N_\mathrm{t}$ where $N_\mathrm{t} = n_\mathrm{i} + n_\mathrm{o} + n_\mathrm{e}$. Thus D will also depend on the number of active mobile units. For ten mobiles, the desensitization is close to

$$D = 10 \times \log_{10}\left[\frac{n_\mathrm{e} + n_\mathrm{o}}{n_\mathrm{o}}\right] \mathrm{dB} \qquad (8)$$

Procedure.

1. Given D in decibels, the corresponding N_e is calculated using Eq. (7) or (8).
2. Find the path loss (PL) for the calculated N_e using the following expression. The emission power spectral density (received at the receiver antennas port of the receiver module) can be expressed as

   $$\begin{aligned}\mathrm{PL} = {} & P_\mathrm{tx} - L_\mathrm{tx} + G_\mathrm{tx} + E_\mathrm{msk}(\Delta f) - 10 \times \log_{10}(\mathrm{RBW}) \\ & - N_\mathrm{e} + G_\mathrm{rx} - L_\mathrm{rx}\, \mathrm{dBm/Hz}\end{aligned}$$

   where

   P_tx is the Tx power at the antenna port of the Tx module (dBm),

   L_tx is the Tx cable loss (dB),

   G_tx is the Tx antenna gain (dB),

   Δf is the offset frequency of the emission relative to the carrier frequency,

   E_msk is the Emission mask specification at Δf,

   RBW is the resolution bandwidth (Hz),

   PL is the required path loss (dB),

   G_rx is the Rx antenna gain (dB),

   L_rx is the Rx cable loss (dB).
3. Calculate the cell radius r using Step 2 and using the propagation formula in Eqs. (5) and (6).

This methodology can be used to design systems with minimal interference. Therefore, the separation between base stations can be determined using this approach. The distance between the base stations is dependent on the path loss model being used. The two-slope path loss model may not be the appropriate model for many environments. Hence site-specific propagation tools can be used to determine path loss in any given geographical region.

CONCLUSIONS

In this article we addressed interference issues in wireless communications systems. Interference issues are an increasingly complex problem with the current systems. PCS systems face more interference related challenges than any other existing wireless systems because of the coexistence of different signal standards. Systems with measures to counteract interference are deployed to increase the signal-to-interference plus noise ratio and to improve capacity. Most of the future wireless systems will have some type of signal-processing-based interference mitigation technique.

In practice, other issues determine the capacity of a system. The margin in the link budget given for fading can reduce the system capacity. If an adaptive signal-processing technique is employed at the receiver to combat interference as well as fading, the system performance will improve. For example, if there are multiple antennas at the base station, signals at different antennas can be combined, fading effects can be mitigated, and interference rejection can be used.

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CODE, ASSEMBLY LANGUAGE. See PROGRAM ASSEMBLERS.