NTIA Report TR-10-467

A Co-Channel Interference Model for Spread Spectrum Technologies

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U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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ABBREVIATIONS/ACRONYMS

BPSK	binary phase shift keying
CDMA	code division multiple access
CMRS	commercial mobile radio services
CN	core network
COQPSK	complex offset quadrature phase shift keying (HPSK)
DPCCH	dedicated public control channel
DPDCH	dedicated public data channel
DS/SS	direct sequence/spread spectrum
ECC	error correction coding
FDD	frequency division duplex
FDMA	frequency division multiple access
GSM	global system for mobile communications
HPSK	hybrid phase shift keying (COQPSK)
I	in-phase
ITS	Institute for Telecommunication Sciences
ICIM	ITS CMRS interference model
LOS	line of sight
LTE	long term evolution
MAI	multiple access interference
MI	multipath interference
NTIA	National Telecommunications and Information Administration
OFDM	orthogonal frequency division multiplex
OQPSK	offset quadrature phase shift keying
OVSF	orthogonal variable spreading factor
PCPICH	primary common pilot channel
PCS	personnel communication system
PN	pseudo-noise
Q	quadrature-phase
QPSK	quadrature phase shift keying
QoS	quality of service
SIR	signal-to-interference ratio

TDMA	time division multiple access
WCDMA	wideband code division multiple access
UMTS	universal mobile telecommunications system
UTRAN	UMTS terrestrial radio access network
UE	user equipment

A CO-CHANNEL INTERFERENCE MODEL FOR SPREAD SPECTRUM TECHNOLOGIES

Teresa Rusyn and Timothy Riley[1]

Even under ideal circumstances, insufficient spectrum is available for assigning a unique band of frequencies to each communication system. In less ideal circumstances, when a communication system experiences outages due to equipment failure or natural or man-made disasters, the demands on the existing spectrum become even greater. More efficient use of the available spectrum requires sharing between multiple systems. To allow similar and dissimilar systems to co-inhabit a frequency band, the interactions between the systems need to be better understood. The Institute for Telecommunication Sciences (ITS) has developed the ITS CMRS Interference Model (ICIM) tool for generating and evaluating the interference between similar and dissimilar communication systems either co-located or located in adjacent areas. This tool generates system-specific interference signals to determine the level of co-channel interference from both immediate and adjacent cells. It produces a representation of an instantaneous air-interface signal, which can contain outputs of multiple base stations with variable numbers of logical channels for each base station and can assign relative power levels for each individual logical channel. Both forward and reverse link processes are included.

Keywords: mobile communications; digital modulation; CDMA; WCDMA; 3G; QPSK; OQPSK; HPSK; interference; modeling; spectrum sharing

1 INTRODUCTION

Recent natural disasters demonstrate how important Commercial Mobile Radio Services (CMRS) have become in establishing emergency communications. In emergencies, usage rates of communication services increase significantly. When emergency responders are unable to establish inter-agency communication links, especially with responders from outside the affected area, they must rely on commercial systems as a last (or only) resort. This sudden influx of traffic overloads the system, decreases signal quality, and further disrupts service in the affected area. Beyond the physical damage, additional factors contribute to diminished wireless network channel capacity, such as co-channel and adjacent-channel interference as well as multiple, independent, non-interoperable systems operating in and servicing the same geographical area, which often use the same frequency bands and infrastructure (base station sites and towers).

One way of coping with damaged or destroyed infrastructure is to deploy temporary equipment to supplement or replace the surviving system. In these cases, responders must know what equipment needs to be deployed in which locations to make efficient use of limited resources.

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Understanding the interference issues, dynamics, and load patterns of the original system is key to effective, post-disaster support by national security/emergency preparedness (NS/EP) planners and network operators in overloaded environments.

In addition to emergency situations, the lack of available spectrum becomes an issue as next- and future-generation commercial communication systems are developed. Spectrum dedicated to systems supporting emergency responders must be allocated from frequencies already in use. As a result, spectrum sharing by multiple users is necessary if all proposed systems are implemented.

Increased demand for mobile communications capacity requires the most efficient use of limited spectrum resources possible. Code division multiple access (CDMA) is a technology used in current cellular systems and is even more prominent in next-generation systems. Code division schemes are beneficial because they make efficient use of allotted spectrum and are relatively unaffected by noise. However, the capacity of technologies using CDMA is limited by the number of other CDMA users occupying the same frequency band. These legitimate users appear to each other as an increase in the noise floor and are referred to as *co-channel interferers*.

In cellular systems, most power control schemes automatically increase power levels when the level of interference is unacceptable. This increases the interference level for all users of a frequency band and can cause a cumulative effect where all users are operating at maximum power levels while still experiencing a diminished quality of service (QoS). As dependence on code division technology increases, the spectrum must be used more efficiently, making a clear understanding of the effects of interference essential.

Work in detecting, identifying, and mitigating co-channel interference requires tools to characterize the interference experienced by air-interface signals. One tool would be a set of interference models that can be used to predict levels of interference and identify sources of interference. Several standard propagation models are accepted by industry members (e.g., Okumura-Hata, COST 231, Walfish-Ikegami) but no interference model has been developed or accepted. ITS has developed an interference model capable of implementing any cellular technology, including such CDMA-based systems as the TIA/EIA-95B standard and WCDMA (wideband CDMA). The model generates system-specific interference signals to determine the level of co-channel interference from both immediate and adjacent cells. It produces a representation of an instantaneous air-interface signal, which can contain outputs of multiple base stations with variable numbers of logical channels for each base station and can assign relative power levels for each individual logical channel. Both forward and reverse link processes are included in the model.

This report describes the ITS CMRS interference model (ICIM) tool. Additional detailed information on the technical aspects of the technologies is included in the appendices and a list of literature and websites is included at the end of this report for further information.

2 THE ITS CMRS INTERFERENCE MODEL (ICIM) TOOL

2.1 History

In 1997, ITS developed a Personnel Communication System (PCS) interference model [1]. The initial development covered system-specific interference models to determine co-channel interference from the immediate and adjacent cells for two licensed PCS technologies: PCS 1900 (a narrowband time division multiple access (TDMA) system based on Global System for Mobile (GSM)) and code division multiple access based on the IS-95 standard. The model accounted for system considerations and management functions (such as power control in IS-95) affected by the dynamic nature of the interference.

The new ICIM tool builds on the previous work [2], [3]. This effort began when literature searches showed that no existing CMRS models met requirements for the study of large-scale networks and the effects of partial infrastructure collapse. The ICIM consists of a set of individual technology models that can be used in a common physical framework. Presently, ITS has developed models for two CMRS technologies. The first technology is an advanced version of the IS-95 system mentioned above; that system is now the TIA/EIA-95B standard, which was incorporated into the CDMA2000 standard. This system is referred as CDMA95B in this report. The second technology is wideband code division multiple access (WCDMA). The framework of the ICIM is described in Section 2.2.2, CDMA95B is described in Section 2.2.3.2, and WCDMA is described in Section 2.2.3.3.

2.2 ICIM Description

The basic idea behind the ICIM tool is to design a number of CMRS technology models to study the interference effects of a network system. This simulation effort studies the co-channel interference caused by a sum of undesired signals on a desired traffic signal. The undesired signals are co-channel, interfering signals in the same system over a multi-cell, multi-mobile station (multi-user) network. The desired signal is a traffic channel between the primary base station and one designated target mobile station in the primary cell. In CDMA95B and WCMDA systems, the base station to mobile station (forward) links have a different frequency carrier than the mobile station to base station (reverse) links, so the desired and undesired signals in any one simulation are either all forward links or all reverse links.

The ICIM considers interference effects in the forward and reverse links. Interference in the forward link degrades the signal received by the target mobile station. The interfering signals are the pilot or control channel of the primary base station, the traffic channels transmitted from the primary base station to the other mobile stations in the primary cell, and the composite air-interface signals transmitted from other base stations defined in a scenario. Interference in the reverse link degrades the signal received by the primary base station. In this case, the interfering signals are the air-interface signals of any mobile station defined in a scenario other than the target mobile station. Since WCDMA mobile stations transmit control channels as well as traffic or data channels, the control channel transmitted from the target mobile station is another interfering signal.

At the start of the design process, the effort was divided into two components. One component is a model of an extensive CMRS network that is the physical framework common to the entire simulation process (the framework model). The second component is the set of models for the different CMRS technologies (the technology models).

The framework model builds a comprehensive cellular network starting with a high-level cell configuration. Next, the framework model defines the size, shape, and orientation of each cell with its base station. Finally, the framework model defines the number and position of the mobile stations within each cell. Power loss and propagation delay for each composite air-interface signal in each cell are calculated. All of these elements can be saved and used for multiple simulation runs of any technology model, or for runs of multiple technology models allowing comparisons on the same defined framework.

Each technology model constructs a representation of a sampled air-interface signal of the defined technology. The output of a technology model is a sampled signal representing the coded and modulated signals of one or more data channels and, in some situations, one or more control channels.

2.2.1 Scope and Limitations

The ICIM tool uses the individual technology models to study the interference effects of a sizable cellular network, in a variety of situations, on a specified communication link. The purpose of this tool is not to produce a realizable, practical network, but to study interference issues with a much larger set of interferers than is presently available from other sources.

The output is a ‘snapshot’ of a composite air-interface signal for the defined network composed of all the traffic channels present for either forward or reverse links plus any control channels necessary for synchronization (i.e., pilot channels). This snapshot represents a static view of a network. There is no option for dynamically changing network configurations, although changes to the network are possible by manually changing certain parameters and running the simulation additional times to study how changes to the network (i.e. a base station failure) affect the interference of the system. In fact, the tool has a provision to define the parameters for a new simulation run starting with the parameters of a previous run.

This set of technology models is geared towards studying the effects of different network configurations and technologies on interference levels affecting a particular target link. The target link is always between the base station and a designated mobile station. The position of the mobile station can be anywhere in the primary cell, but must be linked to the primary base station. The initial shape of the cells in the network is circular and they are fitted together in a hexagonal pattern. Initially, all the cells are the same size; the size and shape of a cell can change in supplemental simulation runs as described in Section 2.2.2.2.

The topology of the network is considered smooth earth over distances of, at most, several miles. There are no obstructions to cause diffraction or multipath situations and all antennas on all stations are considered isotropic. The framework model calculates propagation delay based on the distance between the transmitting station and the receiving station, but does not calculate any delay spread. Delay is rounded to the nearest multiple of chip periods to make combining signals easier (see Appendix A). The framework also calculates power loss over the distance using a modified basic transmission loss formula. For the forward link in each cell, all traffic channel amplitudes are set equal before considering power loss. In the reverse channel, all logical channels from mobile stations are calculated to reach the base station they are linked to at the same power level (after power loss considerations).

The input to a technology model is a set of random binary sequences. The input does not need to be random, but there is no mechanism in the ICIM to recover any type of information or structure in the signal except for synchronization purposes. Due to the constraints of working on small-scale computers, the input sequence length is necessarily limited and not appropriate for containing information. Each binary sequence contains either a pilot channel, a control channel with synchronization ability, or a traffic channel assigned to a defined mobile station in the network. A technology model contains only those pieces of the process that directly affect the transmission properties of the air-interface signal. These pieces include channelization coding, scrambling coding, and the modulation schemes for the different technologies. As such, there is no error correction coding included.

A further limitation to the scope of this report is that it presents only two technology models, CDMA95B and WCDMA. Both are based on code division methodologies and are direct-sequence (DS) type CDMA systems.

In some cases, the limitations of the technology models used in this report are due to limitations in processing equipment or because the modeling effort has not yet added more capability. Section 3 discusses some possible future work on the modeling effort.

2.2.2 Framework Model

The heart of the ICIM tool is the physical framework model. The framework model consists of a network of cells and a model of the propagation channel through which the air-interface signals travel. The framework model consists of an idealized network of multiple cells, one base station per cell, with multiple mobile stations available for each cell. The propagation channel model for the composite air-interface signal includes power loss based on a modified free space power loss where the user defines the power loss exponent for the distance. Also, the signal includes delay based on propagation time from the interfering station to the target station.

Figure 1 shows the framework model consisting of a network of one to 19 cells. All the defined cells are circular with the same radius (R_{cell}), fitted together in a hexagonal pattern for any original simulation run and are designated numerically starting with $Cell_1$. The cell under study is $Cell_1$and is referred to as the primary cell; it is located in the center surrounded by up to three rings of six cells. Since the circular cells are fitted into a hexagonal pattern, there is some overlap between adjacent cells.

Each cell can contain either a random or a user-specified number of mobile stations. The primary cell must contain at least one mobile station for the desired or target link and each defined cell must have one base station with one pilot or control channel. There are no other restrictions to the number of mobile stations or logical channels in the network configuration. The target mobile station can be in the overlap region between the primary cell and another cell, but the target mobile station must always be linked to the primary base station. Most runs of the ICIM require a defined target link, although there is an option to define only the pilot channel of the primary base station if there is only one defined base station in the run. The target link is restricted to the traffic channel (forward or reverse link) between the primary base station and the target mobile station in the primary cell. The user can define which cells are present in the simulation.

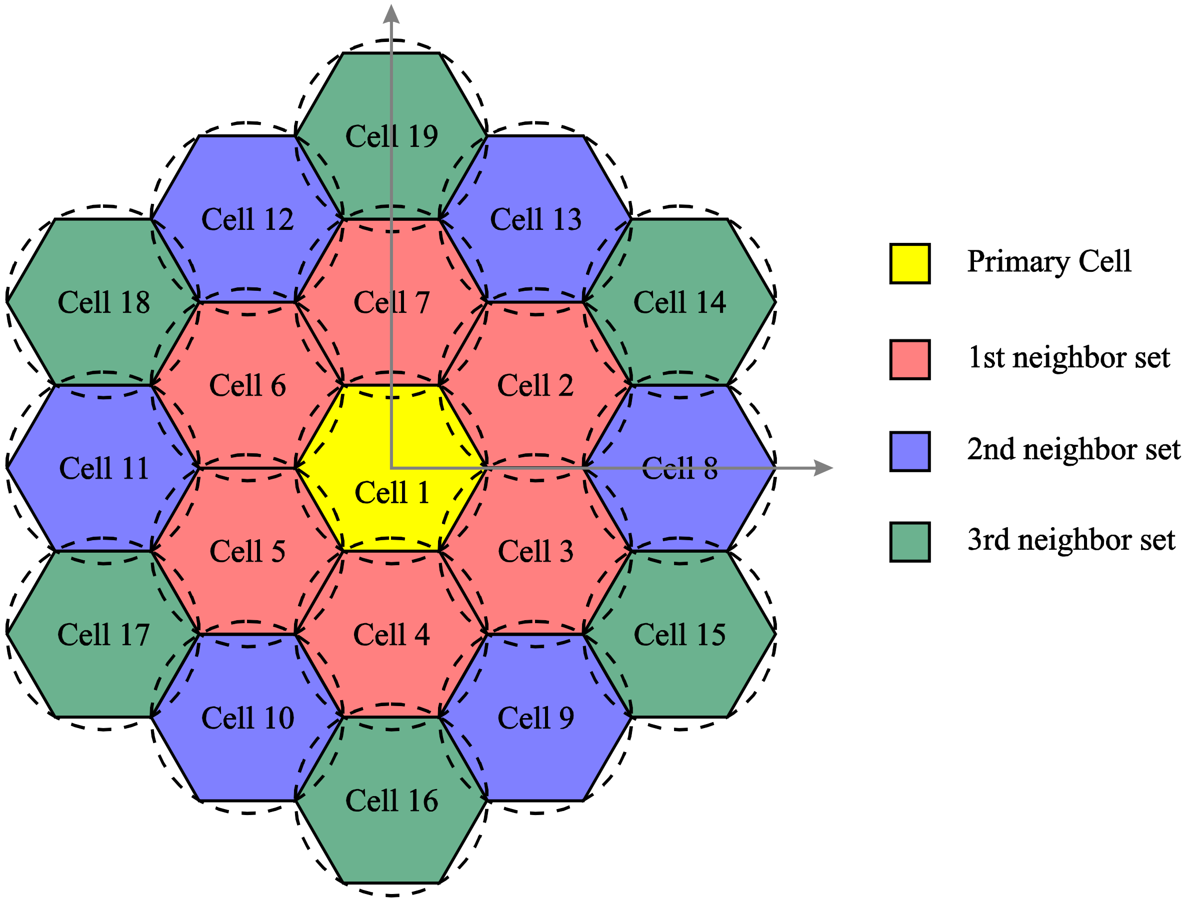

Figure 1. Framework model geometry.

Positioning in the framework model uses the Cartesian coordinate system where the position of the primary base station (BS_1) is always at position (0, 0). The framework is designed so that the target base station, which acts as the reverse link receiver, is the primary base station and the target mobile station, which is the forward link receiver, is positioned in the primary cell. This can be done without a loss of generality since all the positioning for the cells is referenced to the primary base station.

The number of cells and the number of mobile stations in each cell is defined by the simulation parameters. For each cell, the position for each mobile station in that cell is determined randomly within the circular boundaries of the cell. Any mobile station in the overlap area between cells might actually be linked to the base station that is slightly more distant than the other base station. Once the positions of all the mobile stations are defined, the position values are adjusted using the primary base station reference. There is an option to manually position the target mobile station, allowing the user to calculate the level of interference on a mobile station either close to the base station or at the edge of the primary cell.

The framework model calculates the distances of the base stations to the target mobile station, or mobile stations to the primary base station, depending on whether the simulation run is analyzing a forward link or a reverse link, respectively. Distances are calculated in multiples of the cell radius (R_{cell}). R_{cell} has a default value of 1 km, but the user can define the radius as a multiple of 1km. These distances are important for power loss and signal propagation delay calculations.

2.2.2.1 Propagation Channel Model

The ICIM compares a desired signal against an undesired signal, which may be an aggregate of multiple signals. The ICIM does not take into account distortion of the signal so the channel is considered distortionless. Since the ICIM only considers a static network configuration in any one simulation run, the propagation channel model does not calculate any type of dynamic fading. Therefore, the propagation channel model consists of a power loss mechanism and a delay mechanism that are both tied directly to the path lengths of the defined links.

The power loss used is a modified free space transmission loss for isotropic antennas described in [4] and [6]:

$$L(dB) = -32.44 - 20\log_{10} f_{MHz} - a \cdot 10\log_{10} d_{km}. \tag{1}$$

Here, the default for the exponent *a* is -2.55 which is in the range of typical values for a CMRS [7], but the user can change this value in the program. The propagation channel model can support other power loss schemes through an additional module to the framework but, at present, the modified free space loss model is the only one available in the ICIM.

There are delays and power losses due to the propagation distance. These values are calculated for the target signal and each interfering signal included in the aggregate air-interface signal. The outputs of the ICIM are the signal to interference (SIR) levels of the system and a representation of the sampled composite interference and target signals. Equation (2) defines the SIR used in this report, where *ds* refers to the desired signal and *is* refers to the aggregate interference signal.

$$SIR = \frac{P_{ds}}{P_{is}} \tag{2}$$

Delay due to propagation distances significantly affects any CMRS and needs to be accurately modeled. Signals that are synchronized when they are transmitted will be asynchronous when they arrive at a receiver if they travel different distances. Orthogonal codes used in CDMA systems can lose some of their orthogonality by this asynchronous reception [5]. The framework calculates the propagation delay in increments of chip times to maintain the sampling of the air-interface signals.

Any special delays or power considerations need to be addressed by the user when defining the simulation parameters.

2.2.2.2 Dynamic Situations

The ‘snapshot’ character of this tool does not lend itself to handling dynamic situations automatically. However, a user can save all the parameters from an initial simulation run and modify them for subsequent simulation runs to analyze a changing situation. After the initial simulation run, the existing network can be modified to add, delete or move any mobile stations (even the target mobile station, as long as it stays in the primary cell). The target mobile station can change position incrementally to show linear movement or by larger distances within the cell to demonstrate the changes in the interference depending on its relative position to the primary base station or other base stations. Other modifications include adding or deleting base stations, resulting in the loss of a mobile station’s link to its original base station. The mobile stations then can link to the nearest existing base station and effectively become part of its new base station’s cell. In these scenarios, a cell’s size and shape change. Scenarios 3 and 5 in Section 2.4 show the effects of failing base stations.

2.2.3 Technology Models

The technology models are, by definition, different. However, the technology models start with the same basic considerations as much as possible. The input is a set of random, binary sequences (although the sequences do not need to be random). The technology models do not include any forward error correction to help preserve information in the sequences. In actuality, the only ‘information’ used in these technology models is the pilot or control channels that keep synchronization of the various traffic channels in the overall aggregate signal.

When combining signals that have been transmitted at different times and that have propagated different distances, producing different delays, care must be taken to consider the relative phases of the signals. In other words, the signals must add vectorally.

2.2.3.1 Common Aspects

One of the more confusing aspects of CDMA descriptions in the literature is the frequent use of the word channel. The channels used in this report are defined as follows:

Frequency:	the allotted range of frequencies for multiple access transmission
Logical:	the coded and modulated channel of one user
Pilot or Control:	the logical channel defined for synchronization
Traffic:	the logical channel that carries data or voice information
Desired:	the logical channel of the target link
Interference:	the aggregate of all defined channels except the desired channel
Data:	the input data stream
I (in-phase):	the component following spreading of the in-phase track
Q (quadrature):	the component following spreading of the quadrature track
Propagation:	the physical channel that the air-interface signal propagates through

2.2.3.1.1 CDMA Methodology

There are several techniques to allow multiple users to occupy a particular frequency range and/or time period. A system can divide up a frequency range into frequency slots (frequency division) or time slots (time division) or a combination of the two. Another technique is to use orthogonal coding (code division) with or without frequency or time division techniques. As a spread spectrum technique, CDMA has proven to be an efficient use of the limited frequency spectrum for communications. Channel separation comes from coding the data stream of the data channel with orthogonal or quasi-orthogonal codes. Coding also spreads the data stream over a wider bandwidth, reducing the modulated signal's susceptibility to noise and increasing the frequency range's capacity. Multiple users can share the same frequency range during the same time period, eliminating the need for planning frequency reuse and time division allocations. The CDMA signal is interference limited primarily due to multiple access interference (MAI). The signal spreading makes the signal relatively immune to noise degradation, but it is still subject to interference from co-channel signals and other similar signals [7], [8].

The trade-offs for this increased efficiency include the added complexity in the transmission and reception systems and the interference limitation on the air-interface signal. Because of this increase in efficiency, CDMA dominates the 2.5G and 3G wireless schemes. Although interference limited, the power level for a CDMA air-interface signal for one logical channel can actually be lower than the power level for the combined interference channels.

Figure 2 shows the top-level flow of a CDMA transmission system. For this work, the technology models do not include any error-correction coding (ECC) since it does not directly affect the air-interface signal and because the purpose of the error-correction coding is to recover the information going into the system. As mentioned in Section 2.2.1, the technology model only includes operations that directly affect the air-interface signal and data necessary for synchronization, so the input to the ECC block in Figure 2 is the same as the input to the rest of the system in this report.

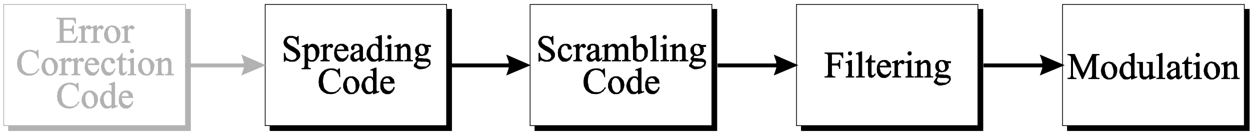

Figure 2. CDMA flow diagram.

2.2.3.1.2 Coding

The most important topic for CDMA systems is coding. Codes in direct sequence spread spectrum CDMA (DS-CDMA) perform many functions including spreading the bandwidth of the input data streams, combining data streams with different data rates into a signal with a single chip rate, providing signatures to different logical channels to keep them separate, and providing signatures to composite logical channels in one cell to distinguish them from composite logical channels in other cells if they have the same carrier frequency [7], [8].

Two types of coding are used in both CDMA95B and WCDMA, which are both DS-CDMA type systems. The first type uses matrices of orthogonal codes built using matrix algorithms. These codes perform the spreading function for the data streams and, for some of the links, provide intra-cell channelization. While the spreading codes do increase the bandwidth of the signal, they do not eliminate the inherent spectral structure within the signal and, in fact, add a frequency component to the spectral structure of the signal related to the relatively short code word length.

The second type of coding uses pseudo-noise (PN) sequences. Depending on the link, these codes provide intra-cell channelization, inter-cell channelization, scrambling, I and Q channel separation within the logical channel, or a combination of these functions. These codes scramble the signal, making it look 'noise-like' and eliminating the structure within the spread bandwidth of the signal.

In considering a set of spreading codes ($S_m = s_{m,n}$ where $s_{m,n} \in \{-1, +1\}$) of length N, the codes are orthogonal if [8]:

$$\sum_{n=0}^{N-1} s_{i,n} s_{j,n} = \begin{cases} 0 & if \quad i \neq j \\ N & if \quad i = j \end{cases} \tag{3}$$

These codes have the following properties [4]:

1. The autocorrelation should approximately equal the length of the code at the peak and close to zero everywhere else.
2. The cross-correlation should be zero or very small.
3. The number of +1's in each should not differ from the number of -1's by more than one (in polar notation).
4. The scaled dot product of each sequence should be equal to 1 where the scaling factor is equal to the codeword length (N from(2)).

Here we introduce the ± 1 polar form where binary 0's are mapped into +1's and binary 1's are mapped into -1's. In polar form, we can use simple chip-by-chip multiplication to encode signals instead of using modulo-2 arithmetic (XOR). Also, this mapping imitates a physical ± 1 peak analog signal that could represent voltage, current or power. In the ICIM the polar form represents an instantaneous normalized peak power level.

The code's orthogonality requires that the cross-correlation of the code words be close to or equal to zero so that logical channels encoded with different code words are separable. The autocorrelation function should have a peak at time shifts that equal integer multiples of length N and be approximately zero everywhere else to help in synchronizing the received signal. An example of orthogonal coding is in Appendix B.

As technologies move from second-generation (2G) to third-generation (3G), the designs have started introducing quasi-orthogonal codes (such as the Gold codes used in WCDMA [6], [10]). Quasi-orthogonal codes separate logical channels or sets of logical channels (such as channels within one cell) and can scramble signals. These codes are not strictly orthogonal, but are close enough to orthogonal to separate logical channels in a practical system.

Orthogonality is CDMA's strength, but it is also its weakness. The codes for CDMA are designed to produce clear separation between individual mobile station traffic channels and between different base station composite signals. However, the transmitted orthogonality can and does degrade during transmission. The propagation channel characteristics distort signals moving through it, which affects the orthogonality of the signal. While the ICIM does not include distortion in the propagation channel, signals, also, take a finite amount of time to propagate through the propagation channel. The amount of time depends on the distance between the transmitter and the receiver. Even in a static system, the transmission delays are going to be different since the distances for the target link and the interfering links are different. These different delays can cause a shift in the signal codes, which can affect the orthogonality between two codewords and, therefore, affect the ability to completely separate the two logical channels.

The primary technique to avoid shifting codes from affecting the system's orthogonality is to use codes that are dissimilar enough that they will stay orthogonal for the time delays in the system. This is the technique used in the ICIM.

2.2.3.1.3 Spreading and Despreading Operations

For a constant signal power, as the spreading code acts on the data sequence the bandwidth expands and the peak spectral power level of the signal decreases. This property of spreading allows the signal from one data channel to appear as a lower power interference source to the other data channel signals in the system. In fact, the spread signal can have a negative SIR compared to the total composite air-interface signal of the system.

The chip rate of the data channel after the spreading operation is the final chip rate of the system for both CDMA95B and WCDMA. Both CDMA95B and WCDMA can accept data channels with a set of different data rates defined for the technology. The different input data rates have to differ from the base data rate by a factor of 2^{-m} where m is an integer. The base data rate is the rate of the data sequence that is the input for the spreading operation using the lowest spreading rate defined for the system. For CDMA95b the base data is 19.2 kb/s for the forward link and 28.8 kb/2 for the reverse link. The base data rate for WCDMA has a spreading factor of 4. For both forward and reverse links the base rate is 960 kb/s. However, the final chip rates do not change for different input data rates. The two technologies adjust the data rates using different algorithms, which will be discussed in more detail in Sections 2.2.3.2 for CDMA95B and 2.2.3.3 for WCDMA.

A very important aspect of spreading codes is the processing gain. The processing gain for a direct sequence system is the ratio of the RF bandwidth of the direct sequence/spread spectrum (DS/SS) signal to the bandwidth of the original data signal. The practical approximation for the processing gain is:

$$PG_{DS} \cong \frac{T_b}{T_c} \tag{4}$$

where T_b is the period of one bit of information from the data sequence input and T_c is the period of one chip from the spreading code [7], [8]. In WCDMA the value of the processing gain will equal the spreading factor, which is the number of chips in the spreading code per bit in the data sequence [6].

In all cases, a CDMA system splits the signal into in-phase (I) and quadrature (Q) channels. At times this is done with two copies of the same data channel and at other times the signal goes through a serial to parallel converter. The details of how CDMA95B and WCDMA accomplish these tasks are given in their respective sections.

In the receiver, the composite air-interface signal is multiplied by the spreading code that corresponds to the desired signal. In the case of the desired component of the composite signal, the sequence is despread. The bandwidth decreases to that of the original data sequence and, since the power remains the same, the amplitude increases by a factor roughly equal to the system's processing gain. The other data channels remain spread out over the bandwidth of the spread signal and the amplitudes do not change. After a low pass filter, the desired signal has a positive signal to interference ratio (SIR) and can be extracted. In practical CDMA systems, after dispreading and demodulation, the signal is integrated over the period of one data bit (T_b). The integration step performs the function of a low pass filter and the integrated signal is passed onto a decision device to extract the data of the transmitted signal corresponding to the spreading code used in the receiver [4]-[11].

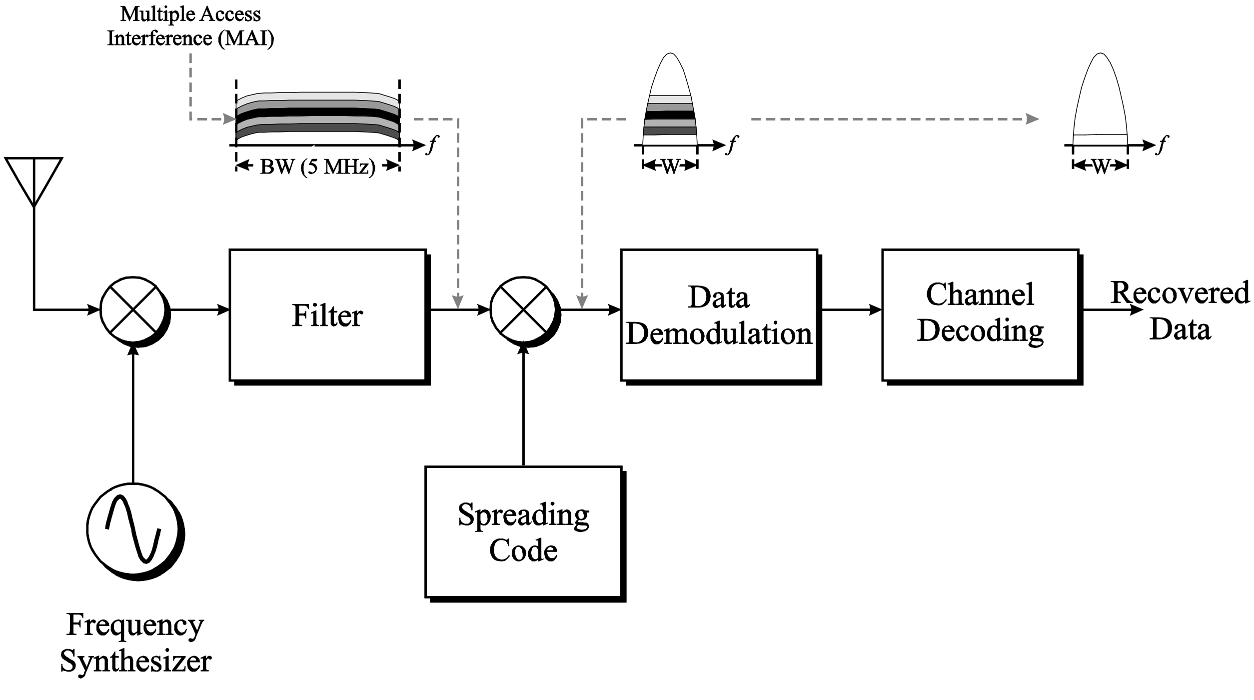

Figure 3. Despread figure.

The SIR of the despread signal to the spread version of the same signal is approximately equal to the processing gain (i.e., the processing gain for a CDMA95B forward link signal is ~18dB, which corresponds to a spreading factor of 64). The SIR of the despread signal to the rest of the composite signal is dependent on the number of other logical channels, the relative processing gains of each logical channel in the composite signal, and the effects of the propagation channel.

2.2.3.1.4 Baseband Filtering

Any system that changes a digital sequence into an analog signal needs to filter the digital sequence at the baseband level to restrict the bandwidth of the unmodulated signal. Standards for the CDMA technologies [6], [7] do not dictate the filter design. They only specify the baseband signal requirements.

For both CDMA95b and WCDMA technology models in the ICIM, the baseband filter is a raised cosine filter with parameters specific to the inputs for any one simulation run [6]. The defining equation for the filter is:

$$h(t) = \frac{\sin\left[(1-\alpha) + 4\alpha\left(\frac{t}{T}\cos\left[(1+\alpha)\pi\frac{t}{T}\right]\right)\right]}{\left(\pi\frac{t}{T}\right)\left[1-\left(4\alpha\frac{t}{T}\right)^2\right]} \tag{5}$$

The value T is the chip period. The parameter α determines the trade-off between how flat the filter response is and how sharply the edges of the filter fall off. To a great extent, the filter defines the spectral shape of the air-interface signal of the CDMA system (both CDMA95B and WCDMA). The value of α for both technology models is 0.22 and cannot be changed.

2.2.3.1.5 Quadrature Phase Shift Keying (QPSK)

In QPSK, the phase of a constant amplitude signal shifts among four phases depending on the value of a set of two chips in the input data sequence. The quadrature nature of the modulation requires that the four phase values be 90 degrees apart. For both CDMA95B and WCDMA the phase values are π/4, 3π/4, 5π/4, and 7π/4.

All of the links in CDMA95B and WCDMA use some form of QPSK modulation. The traffic and pilot or control channels consist of two components, the in-phase (I) component and the quadrature (Q) component [7]. The I component gets multiplied by $\cos(2\pi ft + \varphi/4)$ where f is the carrier frequency of the system and the Q component is handled similarly except that it is multiplied by $\sin(2\pi ft + \varphi/4)$. The I and Q components are added together to produce a QPSK modulated air-interface signal [4], [6], [9]-[11].

The forward links of the CDMA95B and the WCDMA systems use a straight QPSK modulation. The changes to QPSK for the reverse links in this report are found in their respective sections (2.2.3.2.2 and 2.2.3.3.2).

2.2.3.1.6 Reverse vs. Forward Link

Most CMRS systems are asymmetrical in that the forward link is different from the reverse link. Generally systems are asymmetrical due to the differences between the amplifiers in the base and mobile stations. These differences take into consideration the relative limitations of the components on mobile stations versus base stations including power capabilities and amplifier configurations [7]. In addition, the reverse link of the CDMA95B system is not coherent in that there are no pilot or control channels to synchronize the transmissions. The CDMA95B reverse link uses a type of modulation using Walsh codes to overcome this limitation as described in Section 2.2.3.2.2.

2.2.3.1.7 Inputs and Outputs

The input of the technology model is a set of binary sequences, with one sequence per mobile station. Due to the memory restrictions on a standard PC, the sequence lengths are generally too short to include any type of information, except for synchronization on pilot channels. Pilot channels are different for different links and different technologies; detailed descriptions are in Sections 2.2.3.2 and 2.2.3.3.

The data output of the technology model is in the form of a sampled analog air-interface signal and a sampled analog target signal. The air-interface signal is a composite of all the interfering signals in the defined system. Analysis is based on comparing these two signals. The most common analysis metric is the signal-to-interference ratio (SIR) between the desired target signal and the interfering composite signal.

2.2.3.1.8 Near-Far Effects

CDMA has an intrinsic problem in a cellular network layout. As RF signals propagate their power decreases by an exponential factor. (That factor is -2 in free space, but is typically around -2.5 to -3.5 for practical CDMA systems [7], [12].) Thus, two signals with the same transmitted power but emanating from different sources will not necessarily have the same power levels at a common receiver. For CDMA signals, which appear as interference to each other, one signal will generally have a higher SIR than the other. A significant difference in the SIRs can result in the signal with the lower power being adversely affected. Proper power management and dynamic control can overcome this problem [4], [6].

In the reverse link, the ideal situation has all the received signals reaching the base station at roughly the same power level so that the SIR for each logical channel is approximately the same. This ensures that each logical channel has a reasonable margin in its SIR and the system has the best capacity.

For the forward link, overcoming the problem requires the opposite strategy. The base station must transmit all the logical channels at close to the same power level so that the SIR of the closer mobile stations is nearly the same as that of the mobile stations further out in the cell.

2.2.3.1.9 Interference

This study considers the two interference processes involved in spread-spectrum communication. The first is associated with the forward link where the target mobile station has to separate the desired signal from the aggregate interference signal. The other is associated with the reverse link where the base station has to separate the desired signal from the aggregate interference signal.

The interference associated with the forward link is directed at the target mobile station and comes from base stations other than the primary base station and the signal from the primary base station, not including the logical channel to the target mobile station. The level of interference from any one base station will depend on the number of mobile stations in the corresponding cell, but every base station will be transmitting a minimum of one channel (pilot or control channel).

In the reverse link, the base station receives interference from all mobile stations in all cells. The power levels and time delays are calculated directly from the distance between the mobile stations and the primary base station. Determining power levels is not as straightforward as with the forward link interference. The original power level for each mobile station is based on the distance from the mobile station to its corresponding base station, so, for each mobile station, both the distance from the mobile station to its base station and the distance from the mobile station to the primary base station have to be calculated.

The distance (r_m) from the interfering mobile station to its corresponding base station in relation to all the other distances for the mobile stations in that cell determines the transmitted level of power from that mobile station. The power loss and time delay of that signal, however, are calculated from the distance between the interfering mobile station and the primary base station.

The ITS tool can characterize one-on-one, one-on-many, and many-on-one interference. As a result, potential solutions to congestion can be proposed to solve existing problems or to anticipate and avoid potential problems. These two types of interference are considered separately since, in general, the forward and reverse links in CDMA95B and WCDMA use different frequencies to separate them.

2.2.3.2 CDMA95B

This technology model is based on the CDMA95B standard [9], [11] and produces a representation of an instantaneous CDMA95B air-interface signal. CDMA95B has a transmission chip rate of 1.2288 Mcps and it uses a 1.25 MHz-wide frequency channel. The signal can contain outputs of multiple base stations with variable numbers of logical channels for each base station and can assign relative power levels for each individual logical channel. Both forward and reverse link processes are included. All base stations contain a pilot channel as well as the traffic channels defined for the cell. Pilot channels are all 0’s (or +1’s in polar form).

Both the forward link and the reverse link in CDMA95B use the same two short pn sequences for scrambling. One code is for the I channel and the other is for the Q channel. The recursive equations for the pn sequences are [11]:

$$\begin{aligned} x(14+1) &= x(13)+x(9)+x(8)+x(7)+x(5)+x(0) && \text{for I channel} \\ x(14+1) &= x(12)+x(11)+x(10)+x(6)+x(5)+x(4)+x(3)+x(0) && \text{for Q channel} \end{aligned} \tag{6}$$

The least significant bit of the shift register ($x_0(n)$) defines the pn sequence bit at time n.

2.2.3.2.1 Forward Link

For forward link signals (Figure 4), a 64-chip length Walsh code spreads the data input channel. After the spread sequence is split into an I channel and a Q channel, the orthogonal I and Q short PN codes scramble the respective sequences and provide separation for the composite base station air-interface signal. The resulting I and Q channels pass through a baseband filter. After the filtering, the system modulates the channels using QPSK as described in Section 2.2.3.1.5.

The power level for a single logical channel is an arbitrary gain factor of the baseband filter, which is set separately for each logical channel. In the ICIM the power loss for each logical channel is included in the gain factor for the baseband filter. All the Walsh and PN code definitions come from requirements in the CDMA95B standard [4], [5], [9], [11]. Figure 4 shows example waveforms at different stages of the spreading and modulating processes. The waveforms are essentially the same for forward and reverse, CDMA95B and WCDMA processes, and so are not repeated in Figures 5, 8 and 10.

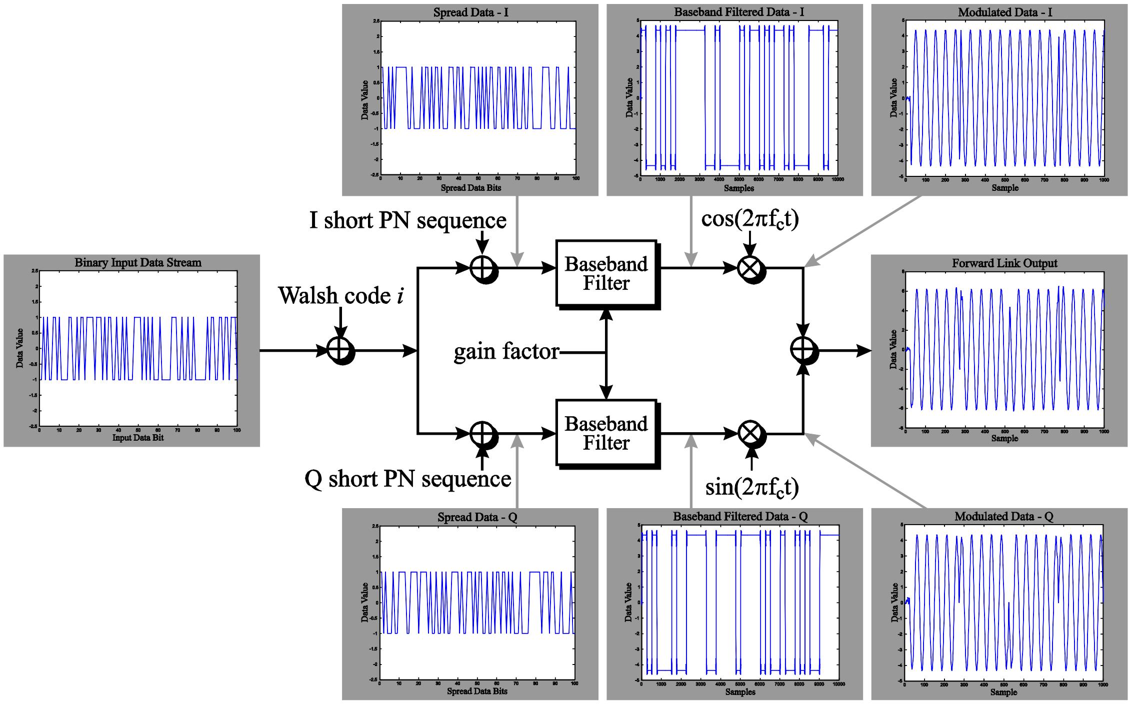

Figure 4. CDMA95 forward channel block diagram with example waveforms.

2.2.3.2.2 Reverse Link

For reverse link signals (Figure 5), the input sequence is modulated with the 64-chip length Walsh codes. In the modulation process, the input data stream is divided into 6-bit binary sections and then the Walsh code that matches the equivalent decimal number replaces the 6-bit section (e.g., 001010 is binary for the decimal 10 and that binary segment is replaced by the 10th 64-bit Walsh code). The resulting data sequence is more robust to decode the original six bits since reverse channels do not have pilot channels to help synchronize the logical channel at the base station receiver. A long pn code based on a channel specific identifier spreads the data sequence to the 1.2288 Mcps rate for the CDMA95B system. Then the data sequence divides into I and Q channels. The recursive equation for the long pn code is [11]:

$$\begin{aligned} x(42+1) = \; & x(42)+x(35)+x(33)+x(31)+x(27)+x(26)+x(25)+x(22)+ \\ & x(21)+x(19)+x(18)+x(17)+x(16)+x(17)+x(16)+x(10)+ \\ & x(7)+x(6)+x(5)+x(3)+x(2)+x(1)+x(0) \end{aligned} \tag{7}$$

The same short PN codes used in the forward channel scramble the I and Q channels. The reverse link process then delays the Q data stream by a half chip. The CDMA95B system then uses the QPSK scheme defined in Section 2.2.3.1.5. The resulting modulation is called offset quadrature phase shift keying (OQPSK).

There is no error correction added to the input sequence; only spreading codes and modulation processes are used. The technology models do not check for recovery information contained in the input. The only goal is to determine how well the system can transmit the bits of the input binary sequence.

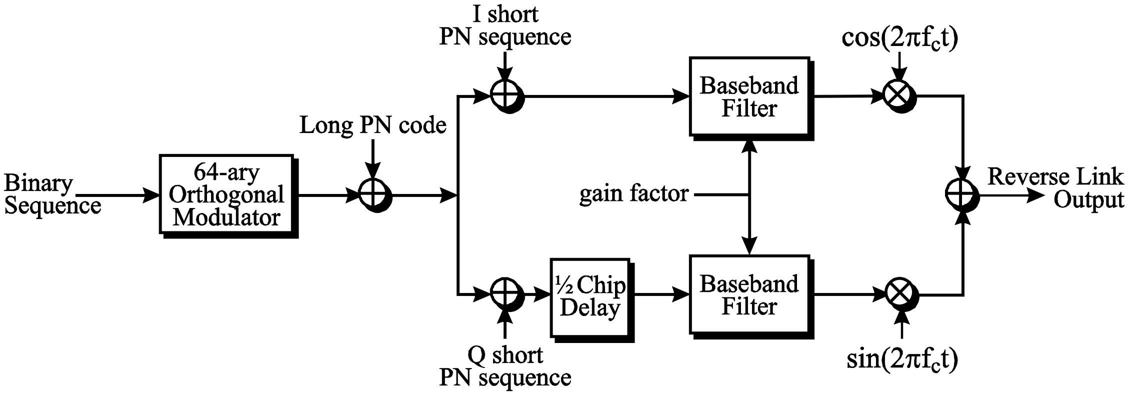

Figure 5. CDMA95 reverse channel block diagram.

2.2.3.2.3 Output Signal

Figure 6 shows the output of the technology model for one logical channel consisting of a vector of numerical values representing a sampled QPSK or OQPSK signal. In this figure, a chip has 250 samples and phase changes in between the chips are evident at 270 samples, 520 samples, and 770 samples.

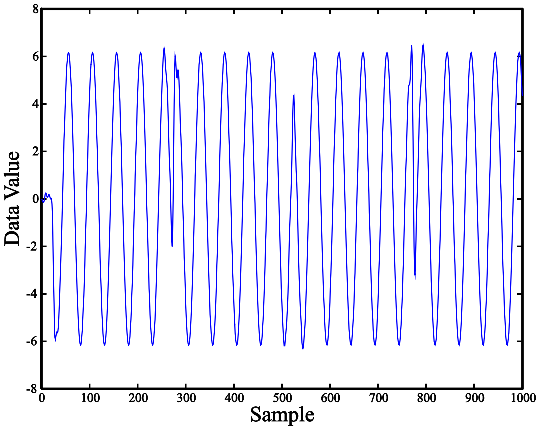

Figure 6. Typical output signal of a single logical channel.

The ICIM calculates each logical channel's sampled QPSK or OQPSK signal contribution separately, then sums all signals identified in a scenario to form a composite output signal. The power level for a single logical channel is the gain factor of the baseband filter and is set separately for each one. Figure 7 shows the composite of the signals transmitted from all sources identified in a specified scenario. The top plot shows the overall structure of the signal, while the bottom plot shows the signal's fine detail.

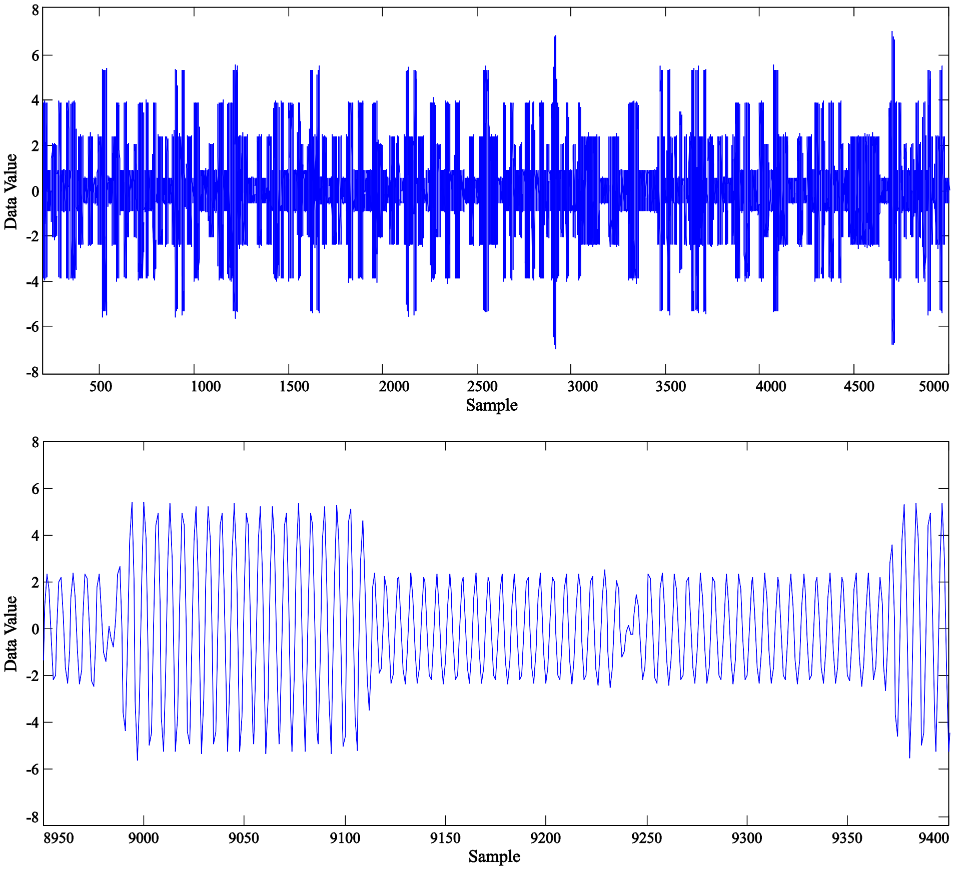

Figure 7. Aggregate output signal (top: coarse structure; bottom: fine structure).

2.2.3.3 WCDMA

WCDMA was developed for the International Mobile Telecommunications 2000 (IMT-2000) global standard through the Third-Generation Partnership Project (3GPP). The purpose of advancing a third-generation telecommunications system was to develop a global high-speed system capable of multimedia services.

Unlike CDMA95B, WCDMA is merely the radio interface piece of the physical layer of a larger network architecture called the Universal Mobile Telecommunications System (UMTS). The highest level of abstraction for the UMTS divides the system into the core network (CN), the UMTS terrestrial radio access network (UTRAN) and the user equipment (UE). WCDMA comprises the physical layer of the UTRAN frequency division duplex (Ultra FDD) version of UMTS [7].

The "lowest" layer, the Physical Layer, is the level that comprises the physical and electrical characteristics of the air-interface. This layer modulates the signal for transmission, adds a scrambling code to differentiate between cells for downlink and UEs for uplink, and channelizes the signal for channel separation and data rate control. The layer also combines possible multiple inputs into a single input sequence for each radio link (RL) which is coded and modulated for transmission.

The transmission chip rate for WCDMA is 3.84 Mcps. WCDMA is designed to use a 5.0 MHz frequency channel. Data rate changes for WCDMA are accomplished as part of the spreading code. This process is discussed in Appendix C.

In reality, the data stream goes through error correction and multiplexing circuits before spreading. The ICIM does not include any of these processes, so they are not discussed here.

As in the CDMA95B system, the WCDMA technology model includes only traffic channels and any pilot channels necessary for the air-interface signal. Traffic channels are referred to as dedicated physical data channels (DPDCH) for both forward and reverse channels. Channels supplying the pilot function are referred to as dedicated physical control channels (DPCCH). A major difference between CDMA95B and WCDMA systems is that the reverse channels of WCDMA systems all have DPCCHs associated with them. This is a change that is indicative of the difference between 2G, 2.5G and 3G systems. For the forward channel in WCDMA, the DPCCHs are combined with the DPDCHs and include a separate control channel called the primary common pilot channel (PCPICH). The processes for forward and reverse links are very different from each other and are presented in different sections below [7], [10].

2.2.3.3.1 Forward Link

The circuit that generates the air-interface signal of the forward link of one WCDMA logical channel is shown in Figure 8. The composite forward channel for a WCDMA system consists of one PCPICH and a number of DPDCHs.

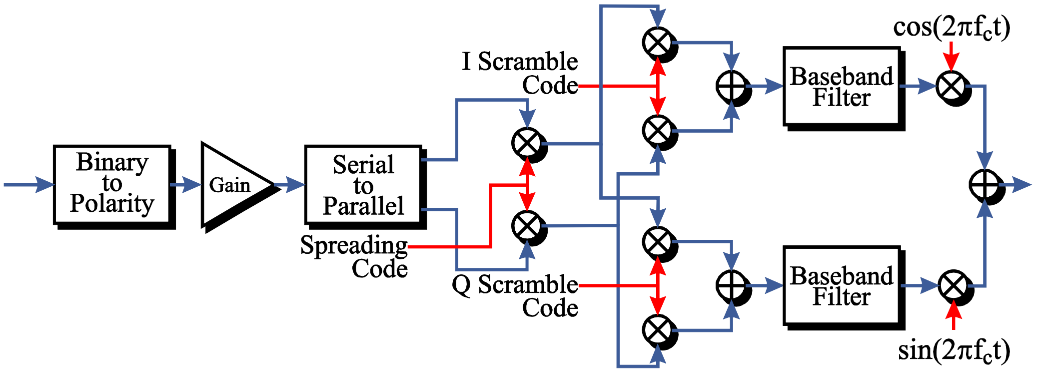

Figure 8. WCDMA forward channel block diagram.

The algorithm for spreading a data stream in the forward channel is more complicated than for the CDMA95B system. The spreading codes are determined by the orthogonal variable spreading factor (OVSF) using the following algorithm:

$$
\begin{gathered}
C_{ch,1,0} = 1 \\
\begin{bmatrix} C_{ch,2,0} \\ C_{ch,2,1} \end{bmatrix} = \begin{bmatrix} C_{ch,1,0} & C_{ch,1,0} \\ C_{ch,1,0} & -C_{ch,2,0} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \\
\begin{bmatrix} C_{ch,2^{(n+1)},0} \\ C_{ch,2^{(n+1)},1} \\ C_{ch,2^{(n+1)},2} \\ C_{ch,2^{(n+1)},3} \\ \vdots \\ C_{ch,2^{(n+1)},2^{(n+1)}-2} \\ C_{ch,2^{(n+1)},2^{(n+1)}-1} \end{bmatrix} = \begin{bmatrix} C_{ch,2^n,0} & C_{ch,2^n,0} \\ C_{ch,2^n,0} & -C_{ch,2^n,0} \\ C_{ch,2^n,1} & C_{ch,2^n,1} \\ C_{ch,2^n,1} & -C_{ch,2^n,1} \\ \vdots & \vdots \\ C_{ch,2^n,2^n-1} & C_{ch,2^n,2^n-1} \\ C_{ch,2^n,2^n-1} & -C_{ch,2^n,2^n-1} \end{bmatrix}
\end{gathered}
\qquad (8)
$$

Each intra-cell forward channel is multiplied by a unique code as described in Appendix C. The PCPICH always uses the OVSF channelization code 0, with the spreading factor (*sf*) of 256. This technology model only defines one data channel per mobile station so the forward traffic channels contain one DPDCH (DPCCH is considered to be embedded in the DPDCH). DPDCHs use codes that have other channelization numbers and different spreading factors according to their data rates. When a DPDCH uses an OVSF codeword with a spreading factor of less than 256, care needs to be taken because more than one 256 code word is affected (see Appendix C). None of the other defined control channels in the physical layer of WCDMA are included at this time. Adding a set of the additional control channels is part of the future work consideration, but they do not affect the structure of the air-interface and so were not included here.

The data sequence chip rate is 3.84 Mcps. The sequence runs through a serial to parallel converter so that every other chip feeds into the in-phase (I) branch and the other chips feed into the quadrature (Q) branch. The signal is also multiplied by a gain factor at this point; the gain factor includes a multiplier for power loss based on distance.

At this point, the in-phase branches of all the logical channels defined at the base station are added together and all the quadrature branches of the logical channels are added together. The combined I and Q branches are multiplied by a scrambling code built by a Gold code generator (Appendix D) that is unique to that base station. The scrambling step is a complex operation that includes the I and Q branches of the combined input sequences and the I and Q branches of the scrambling code. The complex scrambling circuit is shown in Figure 9.

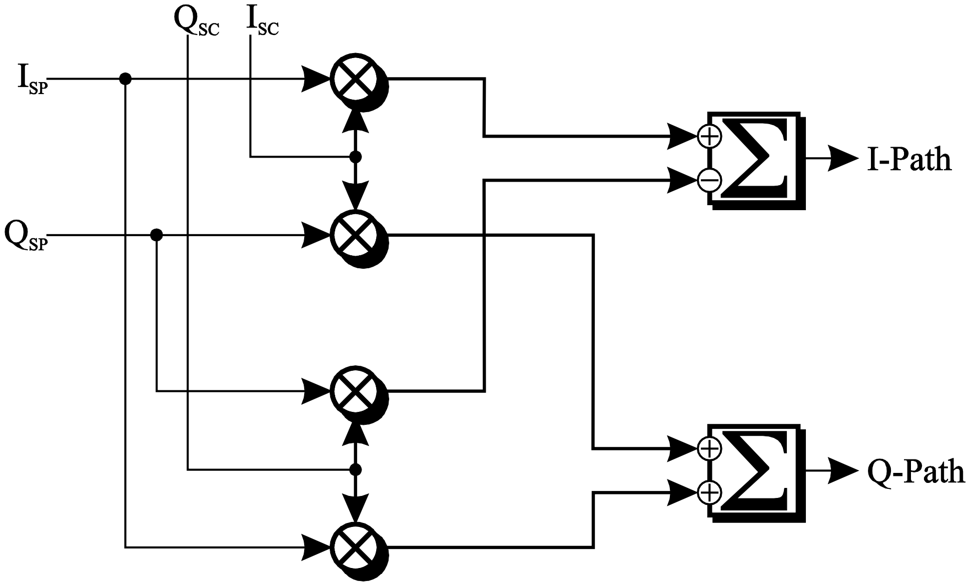

Figure 9. Complex scrambling.

The resulting I and Q phase branches are:

$$\left(I_{sp}I_{sc} - Q_{sp}Q_{sc}\right) + j\left(I_{sp}Q_{sc} + Q_{sp}I_{sc}\right) \tag{9}$$

where I_{sp} and Q_{sp} are the complex branches of the combined spread sequence and I_{sc} and Q_{sc} are the complex branches of the scrambling code. The equivalent complex mathematical equation for this operation is:

$$A_{sp}A_{sc}\exp\left(j\phi_{sp}\right)\exp\left(j\phi_{sc}\right) = A_{sp}A_{sc}I_{sc}\exp\left(j\phi_{sp} + j\phi_{sc}\right) \tag{10}$$

Both sequences are filtered with a raised cosine filter. This filtering shapes the sequences, limiting the occupied bandwidth of the signals they now represent. After filtering, the I and Q channels are modulated using the QPSK scheme from Section 2.2.3.1.5.

2.2.3.3.2 Reverse Link

As in the CDMA95B system, the reverse link needs to be more robust to account for the power restrictions on the mobile stations. The composite logical channels for the reverse link of each mobile station in WCDMA, however, have a separate control channel (DPCCH) that performs pilot functions, so the reverse channels are no longer added into one composite channel.

For the reverse channel, the DPCCH is always in the Q channel. When there is only one DPDCH, it is in the I channel of the system. Additional DPDCHs within any one mobile station are split between the I and Q channels. Each logical channel is spread and is multiplied by a gain factor before the channels are added together coherently into separate I and Q channels. When there are multiple simultaneous data channels transmitted from a mobile station, the data channels must have a spreading factor of 4. As was stated in the forward link section, only one data channel is defined for any one mobile station, so there is one DPDCH in the I channel and the DPCCH is in the Q channel.

Figure 10 shows the simplified process to build the air-interface signal for one WCDMA reverse link channel. The spreading factor for the input data sequence ranges from 4 to 256 in increments of 2^n. The β values in Figure 10 are gain factors that reflect a defined ratio between the DPCCH and the DPDCH. The ratios of β_c to β_d (control to data) range from 1/1 to 1/15 [9]. In the WCDMA technology model, the ratios for each mobile station are chosen randomly.

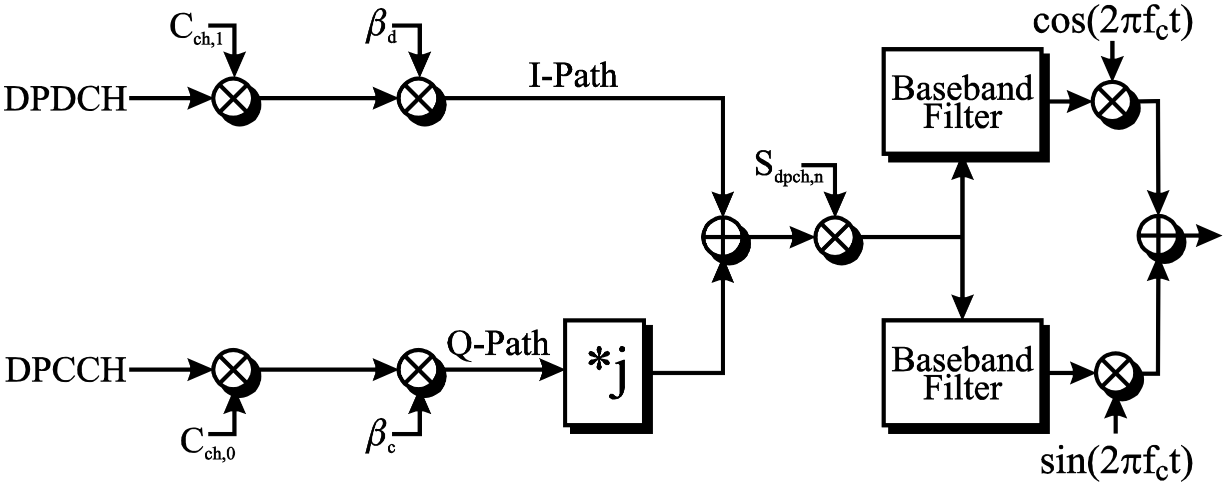

Figure 10. WCDMA simple reverse channel block diagram.

The reverse link of WCDMA uses the same OVSF code tree as the forward link, but only uses the upper half of the codes. These code words produce sequences that have two consecutive chips equal to each other. This restriction is the first step in the hybrid phase shift keying (HPSK) technique. There are two types of scrambling codes used in the reverse link, a long code and a short code. The details for the codes are discussed in Appendix D; Figures D-2 and D-3 show the circuits for the codes. The long code ($C_{long,n}$) is the one used in normal operations so it is the only scrambling code used in this technology model.

The two outputs of Figure D-2 combine as in (7) to form a complex scrambling code to scramble the I and Q channels of the WCDMA reverse link. The scrambling code and the complex spread code multiply using the same technique shown in Figure 9.

$$C_{long,n} = C_{long,1,n}\left(i\right)\left(1 + j\left(-1\right)^{i} C_{long,2,n}\left(2\left\lfloor {}^{i}\!/_{2}\right\rfloor\right)\right) \tag{11}$$

After filtering, the I and Q channels are modulated using the QPSK scheme from Section 2.2.3.1.5. The overall modulation scheme which includes the type of OVSF codes used, the scrambling code, and the QPSK end is called complex offset quadrature phase shift keying (COQPSK) or hybrid phase shift keying (HPSK). Appendix D.1 describes HPSK in greater detail. The reverse channels of the different mobile stations then add incoherently.

2.3 A Typical ICIM Scenario

Once a scenario is defined and the interference signal is generated, various scenario parameters can be altered to observe the effects on the interference levels at various base and mobile station locations. Base and mobile stations can be added or removed, mobile stations can be moved, and power levels can be adjusted. It is up to the user to decide which changes best reflect the conditions he or she wishes to study. One such scenario and sequence of changes is presented here as an example. This scenario uses the CDMA 95B technology model, but WCDMA is equally suited for the scenario.

Figure 11 displays a typical scenario showing the effects of system failure on the co-channel interference experienced by mobile stations in a cellular system. All cells in the system are populated by a centrally located base station and a variable number of mobile stations, which are randomly positioned within the cell. The main (center) cell contains eight mobile stations, which are numbered as shown. Cell 6 contains eight mobile stations, while cell 5 contains a single mobile station.

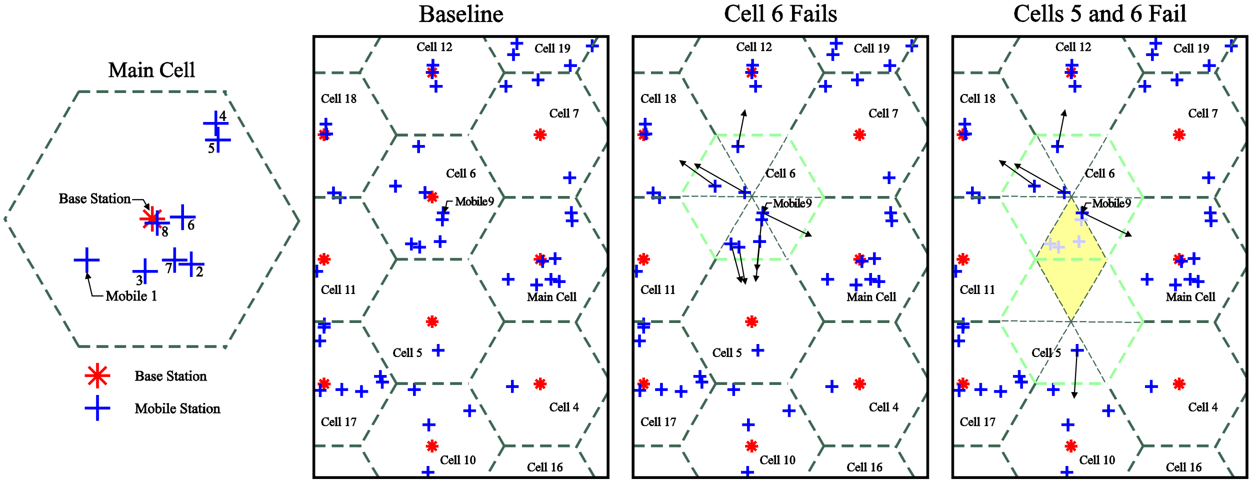

Figure 11. Steps of a typical scenario.

In the initial state, all base stations are operating and are servicing their respective mobile stations. When the base station of cell 6 is removed, the mobile stations of cell 6 are picked up by their nearest base station. In this situation, the main cell's base station picks up a single mobile station (designated as mobile station 9), cell 5's base station picks up four mobile stations, while the remainder are picked up by other surrounding cells. Figure 12 shows the increase in co-channel interference experienced by the eight mobile stations in the main cell, as well as the ninth mobile station whose service is transferred to the main cell. In this scenario any of the mobile stations in Figure 11 could be the target mobile station.

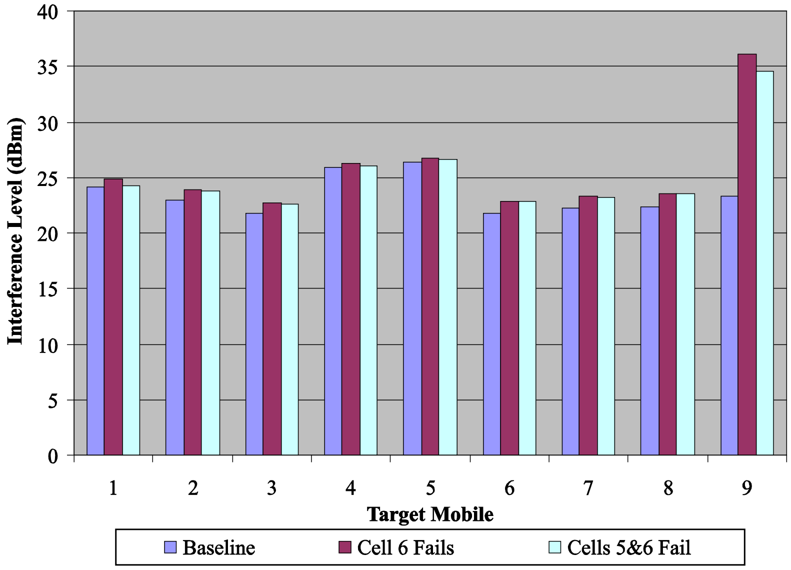

Figure 12. Interference experienced by target mobile stations.

When the base station of cell 5 is removed, an assumption is made that the four mobile stations cell 5 picked up from cell 6 (those located in the yellow, diamond-shaped area) are no longer in position to receive service from any adjacent cell's base station. They are removed from service and no longer affect the interference levels of nearby mobile stations. Cell 5's single mobile station is picked up by its adjacent cell, and the interference levels for the nine mobile stations being observed are recalculated. Figure 12 shows the resultant change in interference. In most cases, the interference is reduced due to the loss of the four mobile stations that lost their service. Mobile station 6 and mobile station 8 show almost no change in experienced interference due to their proximity to the main cell's base station.

2.4 Output Analysis

For CDMA systems, all logical channels have a processing gain applied through the spreading factor. In CDMA95B, forward channels have a processing gain of 18dB due to the Walsh 64 codes used to spread the signal. The reverse link is a little more complicated than that, coming out to (64/6)*4 = 42.7 or approximately 16dB. In WCDMA, the spreading is done with the OVSF tree and is dependent on a spreading factor that is related to the data rate of the input sequence. Higher data rates also can have lower power levels, which can, in turn, provide less interference to desired channels with lower data rates. The spreading factor does provide a straightforward processing gain similar to the CDMA95B forward link, but with varying levels (i.e. 4 to 256 in powers of 2 or their dB equivalents). This must be taken into account when comparing the interference levels of CDMA95B and WCDMA.

Seven example scenarios (four for CDMA95B and three for WCDMA) are presented to demonstrate the possible ways the ICIM's output can be interpreted and analyzed. The following list gives the initial conditions for each scenario. All cell numbers refer back to Figure 1.

1. CDMA95B forward link with the target mobile station located close to the primary base station (19 cells involved).
2. CDMA95B forward link with the target mobile station located near the edge of the primary cell where it borders on cell 2 (19 cells involved).
3. The same as in scenario 2 except that the base station of cell 2 is not available (18 cells involved)
4. WCDMA forward link with the same initial conditions as for scenario 2 where the target mobile station is near the edge of the primary cell (19 cells involved).
5. WCDMA forward link with the same initial conditions as for scenario 3 (18 cells involved).
6. CDMA95B reverse link with target mobile station located at a random position in the primary cell (19 cells involved).
7. WCDMA reverse link with target mobile station located at a random position in the primary cell (19 cells involved).

The figures in this section show the SIR levels of specific scenarios where the desired signal is the logical channel between the primary base station and the target mobile station and the interference signal is the cumulative power level of the other logical channels. Each figure shows how the SIR changes as the cumulative power level of each cell is added to the total interference level. The first point in each figure (i.e., the value of "Cell Number 1") compares the desired channel with the combined power of the interference channels in the primary cell along with any pilot channels defined by the scenario characteristics.

Figure 13 compares scenarios 1 and 2 where the only change is the relative location of the target mobile station relative to the primary base station. The target mobile station in scenario 1 is close to the primary base station, while in scenario 2 it is within the overlap region between the primary cell and cell 2. For situations like scenario 2, the mobile station may actually have a stronger signal from a base station other than the base station it is communicating with. The strength of the link between base station and mobile station is the major consideration for establishing a link, but other factors such as traffic patterns or handoffs when the mobile station is moving from one cell to another could result in the mobile station connecting to a base station with slightly lower signal strength.

The dominant interferer for scenario 1 is, as expected, the composite forward link signal from the primary base station. The other base station signals do not increase the interference level significantly since the primary base station acts almost as a jamming source to the interfering channels from the other cells.

Where the target mobile station is located near the edge of the primary cell as in scenario 2, the initial SIR value is roughly the same as scenario 1. This is due to the process for overcoming the CDMA near-far problem (see Section 2.2.3.1.8). The composite forward link signal from the primary base station is still a dominant interferer, but composite signals from other base stations, especially from cells located close to the target mobile station add significant levels of interference. The signal from the base station in cell 2, which is the next closest cell in this scenario, doubles the interference power level for the SIR.

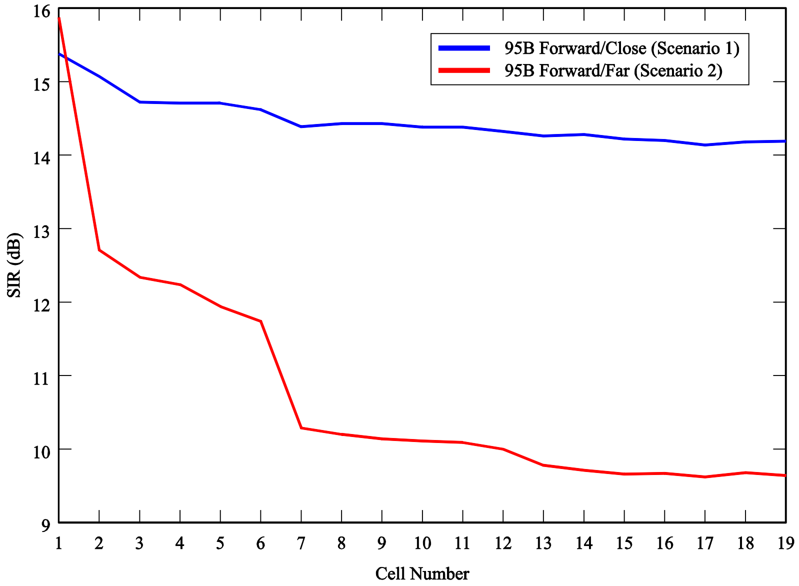

Figure 13. Signal-to-Interference Ratios (SIR) experienced by the base station under test for scenarios 1 and 2.

With the increased effect from the immediate surrounding cells, the outermost ring of cells does not decrease the SIR noticeably and, except for cell 7 which is closest to the target mobile station, neither does the second ring of cells. This trend is consistent for all the scenarios presented here.

Scenarios 2 and 3 have the same physical network except that, for scenario 3, the base station in cell 2 is disabled. All the mobile stations in cell two are reassigned to the next closest base station. Cell 2 goes offline for some reason, such as some natural disaster. When a cell in the ICIM goes offline, all the cells with numbers greater than that cell (> 2 in this case) are renumbered to their original designation minus 1. Comparing scenarios 2 and 3 (Figure 14), we see that the final SIR value of the two scenarios is roughly the same. The outer cells and other cells not physically close to the target mobile station still do not make noticeable contributions to the interference levels. However, the effects of the cells close to the target mobile station do change. The primary base station, which picks up one mobile station, has a greater interference level as do the base stations in new cells 2 and 6. But now the greatest change in interference level, other than that of the primary cell, comes from new cell 6 (formerly cell 7) where the interference level roughly doubles compared to the interference level of the new cells 1 through 5 combined.

The SIR levels for the WCDMA scenarios are very different from the scenarios for the same networks CDMA95B, although the pattern for how the interference levels change is very similar. The dominant interferers are the same. They are the base stations in cells 1, 2, and 7 in the scenarios with 19 cells and base stations in cells 1, 2, and 6 in the scenarios with 18 cells. Changes in the SIR levels between CDMA95B and WCDMA systems, even when looking at the same physical networks, is expected due to the variable data rate capability of WCDMA. Higher data rates will have lower spreading factors and, therefore, lower processing gains. Some of the difference in processing gain can be offset if the power levels of the individual logical channels change with data rate as well as the spreading factor, but that influence is not reflected in this study.

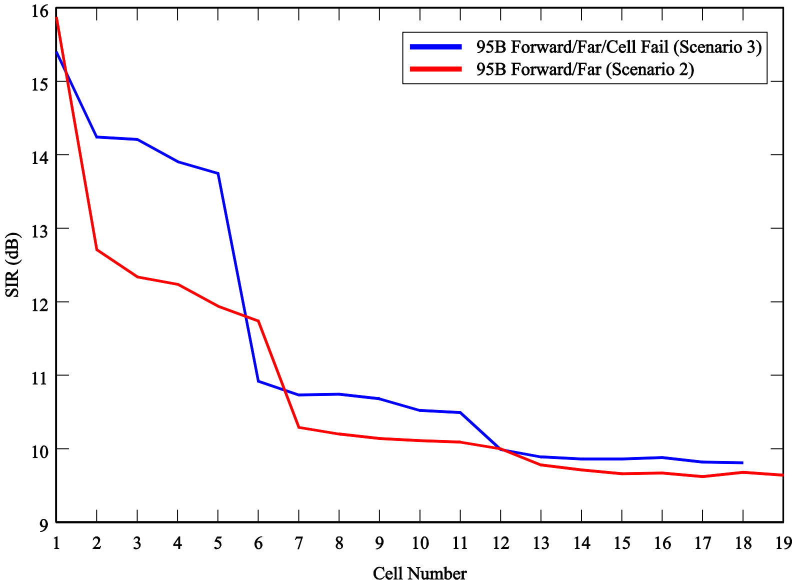

Figure 14. Signal-to-Interference Ratios (SIR) experienced by the base station under test for scenarios 2 and 3.

An additional issue with the differences in the SIR levels between CDMA 95B and WCDMA is the complex scrambling method of WCDMA (see Appendix D). The output of the complex scrambling portion of WCDMA coding ranges between ± 2 instead of ± 1 s in CDMA95B. This reduces the signal to co-channel interference ratio by 6 dB (*20 log10(2)*).

As in all the forward link scenarios, the dominant interferer in both scenarios 4 and 5 (Figure 15) is the primary base station. The effects of the other cells, even the ones closest to the target mobile station are very similar to the effects from scenarios 2 and 3 respectively. At least for this study, the effect of the varying spreading factor is not as significant a factor when considering the interference level from base stations with which the mobile station is not directly communicating.

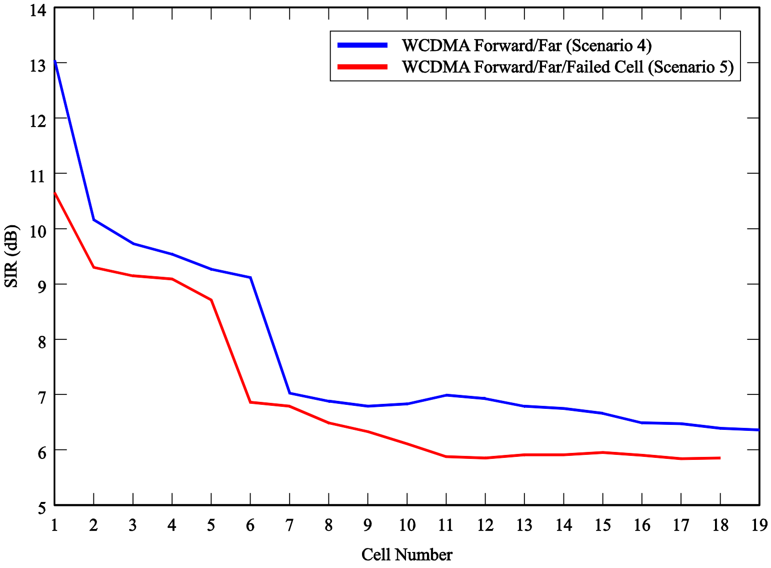

Figure 15. Signal-to-Interference Ratios (SIR) experienced by the base station under test for scenarios 4 and 5.

Comparing forward and reverse links shows the same differences in both cases. The forward links in the previous five scenarios show different levels of contributions that directly correspond to the distance between the base station and the target mobile station. In the reverse link scenarios (Figure 16), the SIR values decrease at a relatively constant rate as the SIR values for the cells in the first ring are added to the interference level, and shows an asymptotic decrease as the cells in the two outer rings are added. The decrease is likely due to the fact that the average distance from the mobile stations in any one cell (other than the primary cell) to the primary base station is roughly equal to the average distance of the mobile stations in any other cell that is in the same neighbor set in the network. (see Figure 1).

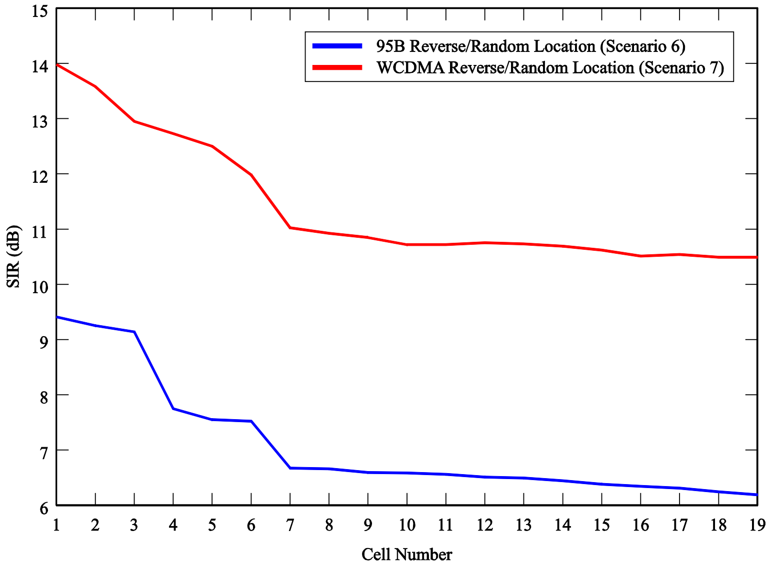

Figure 16. Signal-to-Interference Ratios (SIR) experienced by the base station under test for scenarios 6 and 7.

3 FUTURE WORK

At this point, the simulation effort can proceed in several possible directions. These directions include adding new technology modules, improving the propagation channel model, increasing the ICIM's capabilities (the ability to easily modify scenario parameters), and adding more comparison methods.

In considering new technologies, the easiest one to add is CDMA2000. It is the other major third-generation technology and is an advancement of CDMA95B. Another new technology to model would be orthogonal frequency division multiplexing (OFDM). OFDM is the primary technology for the two candidate technologies for IMT-Advanced (the follow-up of IMT-2000): long term evolution (LTE), a project of 3GPP's technology development, and IEEE's 802.16 (WiMAX). The WCDMA technology model can, also, be expanded to include a control channel made up of a composite of defined control channels with all of their specific modulation and spreading parameters to produce a closer representation of the interference levels inherent in a WCDMA system.

The propagation channel model included in the ICIM tool is presently fairly simple when one considers that the air-interface signals travel through a complex and very dynamic medium. Some of the effects on the signals include fading, delay, delay spread, and distortion. The propagation channel model consists of a modifiable free space transmission loss where the user can define the exponent of the range and delays for line of sight (LOS) paths. Due to its modular configuration, more complicated power-loss models, such as Rayleigh and Rician fading can be introduced as options to be selected by the user. Including terrain profiles also could increase the effectiveness of the ICIM.

This work is necessarily limited in scope as described in Section 2.2.1. However, the work has reached a point where some of the limitations can be changed or even eliminated. The foremost limitations that should be changed are the carrier frequency-chip rate ratio and the length of the input sequence. These limits initially were imposed due to the PC's inability to filter and modulate long sampled sequences. Easing these limits would allow simulation runs at carrier frequencies close to the actual transmission frequencies. Adding a batching ability would give the effort a slightly more dynamic ability. Currently, each simulation has to be run separately. Batching would allow a user to follow a moving target mobile station, a series of infrastructure collapses (such as in a major disaster), or increasing or decreasing numbers of mobile stations. Lastly, the ability to vary the transmission power levels would more closely simulate a voice transmission where quiet times could be transmitted at a lower power level than during a time when speech is present.

One comparison method that could be added would allow two or more different technology systems to be present in the same network area or even be co-located at the same physical antenna structure. If the carrier frequency-chip rate ratio limit is relaxed, another method could use bit error rate comparisons for studying interference levels.

The ICIM is currently implemented in MATLAB™. To speed up the computation times, it could be re-coded to run on a parallel processing system, or be re-coded in C or FORTRAN.

While analyses within the ICIM (such as calculating the fading effects using a series of simulation runs designed to mimic a moving system) are valuable, the raw output of the ICIM can be used as input to other analysis and simulation systems. The output can be formatted to be compatible with an arbitrary waveform generator (AWG), which can then be used as an interference input to a physical propagation environment simulator for use in testing other types of communication systems (such as those used by emergency service personnel and first responders) that may be operating in or near the frequencies used by cellular systems. The output can also be used in software-based simulation systems as well. In most cases, simulators (both hardware- and software-based) use a Gaussian noise source to simulate environmental noise and interference. The ICIM can supply a more realistic interference signal that potentially can uncover problems that may arise from interaction between the system-under-test's signal and the interference signal.

4 SUMMARY

Software- and hardware-based simulations can use the sampled signal from the ICIM to evaluate system designs. These simulations can characterize one-on-one, one-on-many, and many-on-one interference. As a result, potential solutions to congestion can be proposed to solve existing problems or to anticipate and avoid potential problems.

The ITS interference modeling work has developed a tool that can provide a more realistic representation of the effects of interference in an extensive network for at least two mobile communication technologies, namely CDMA95B and WCDMA. The ICIM can show interference in a static network, as well as in a network that loses part of its infrastructure due to man-made or natural disasters. Although the ICIM produces a 'snapshot' of a single network configuration, it can depict a quasi-dynamic environment through additional simulation runs with modifications of the original parameters. The scenarios from Section 2.4 show how the interference changes for a particular link when the common physical network changes.

5 FURTHER INFORMATION

This section provides additional resources to investigate the topics discussed here in more depth than presented in this report.

Websites

The third-generation standard of the WCDMA technology we used for the technology model was based on a 1999 release. This release and the current release, which includes details about long-term evolution (LTE), are available through the 3GPP website:

http://www.3gpp.org/

CDMA95B is now incorporated into CDMA2000. The current release of that standard is available through the 3GPP2 website:

http://www.3gpp2.org/

The Alliance for Telecommunication Industry Solutions (ATIS) is a good source for general information on wireless technologies. Their Wireless Technologies and Systems Committee (WTSC) website is:

http://www.atis.org/0160/index.asp

The International Telecommunications Union – Radiocommunication Sector (ITU-R) is an international standards body and is a rich source of information. Their website for IMT-2000 is:

http://www.itu.int/osg/spu/imt-2000/technology.html

The website for IMT-Advanced is:

http://www.itu.int/ITU-R/index.asp?category=information&rlink=imt-advanced&lang=en

The ITU recommendation containing more information on propagation channel models is ITU-R Rec. M.2135 and is available at:

http://www.itu.int/rec/R-REC-M/en

Books

Any of the books in the Reference section are excellent sources for more information, especially reference [8] (*The Next Generation CDMA Technologies*).

One of the best technical books on CDMA was written by one of its developers and the inventor of the algorithm used for decoding convolutionally encoded data:

> Andrew J. Viterbi, *CDMA Principles of Spread Spectrum Communication*, Reading, MA, Addison-Wesley, 1995.

6 REFERENCES

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[8] Hsiao-Hwa Chen, *The Next Generation CDMA Technologies*, Chichester, UK: John Wiley & Sons Ltd., 2007.

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[10] 3GPP^{TM} 3G TS 25.201 V3.1.0, "Technical Specification Group Radio Access Network; Physical Layer-General Description," 3rd Generation Partnership Project, Release 1999.

[11] 3GPP2^{TM} C.S0002 V.3.0, "Physical Layer Standard for CDMA2000 Spread Spectrum Systems," 3rd Generation Partnership Project 2, Release 0, June 15, 2001.

[12] Keiji Tachikawa (editor), *W-CDMA Mobile Communications System*, UK, John Wiley & Sons, Ltd., 2002.

Appendix A: Adding Modulated Signals to Produce Composite Air-Interface Signals in the CDMA95B Technology Model

This appendix discusses the summing of I and Q components of the composite CDMA95B air-interface signals [5]. CDMA95B signals are quadrature phase shift key (QPSK) modulated. The complex equation for a QPSK signal is

$$s(t) = A_c e^{j(2\pi ft+\theta(t))} \tag{A-1}$$

where $A_c = \sqrt{m_I^2 + m_Q^2}$ and $\theta = \tan^{-1}(m_Q / m_I)$. The values m_I and m_Q are the magnitudes of the I and Q data streams respectively for any time, t [1].

The physical representation of the signal is

$$s(t) = \mathrm{Re}\left\{ A_c e^{j(2\pi ft+\theta(t))} \right\} \tag{A-2}$$

which can be rewritten as:

$$\begin{aligned} s(t) &= A_c\left[\cos\left(2\pi ft \ +\theta(t)\right)\right] \\ &= A_c\left[\cos\left(2\pi ft\right)\cos\left(\theta(t)\right) \ - \ \sin\left(2\pi ft\right)\sin\left(\theta(t)\right)\right]. \end{aligned} \tag{A-3}$$

Changing from an analog representation to a digital representation results in:

$$s(n) = A_c\left[\cos\left(2\pi fn\right)\cos\left(\theta(n)\right) \ - \ \sin\left(2\pi fn\right)\sin\left(\theta(n)\right)\right] \tag{A-4}$$

where n is shorthand for $t=nT$ with T being the sample rate. This is the beginning equation for deriving the different types of signal addition.

A.1 Single Channel

In a single logical channel, all values in the I- and Q-data streams are ±1 times some gain value a, which is equal for both I and Q. Thus, the magnitudes of I and Q at any and all values of n are equal to $\pm a$. This makes all $\theta(n)$ values odd multiples of $\pi/4$.

$$mag\left[\cos\left(\frac{k\pi}{4}\right)\right] = mag\left[\sin\left(\frac{k\pi}{4}\right)\right] = \frac{\sqrt{2}}{2} \tag{A-5}$$

where $k = 1, 3, 5, 7$. The value of k reflects the signs of the cosine and sine terms of (A-4). The values for CDMA95B states are shown in Table 1 [2].

Table 1. Cosine and Sine Values for (A-4) Based on the *k* Value

k value	State	Normalized m_I, and m_Q	Normalized m_Q	Normalized cos and sin values related to kπ/4
1	0	+ 1,+1	-1	cos() - [-sin()]
3	1	-1,+1	-1	-cos() - [-sin()]
5	2	-1,-1	+1	-cos() - [+sin()]
7	3	+1,-1	+1	cos() - [+sin()]

One can change the form of (A-4) to fit this convention:

$$\begin{aligned} s(n) &= A_c\left[\left(\frac{m_I(n)}{a}\frac{\sqrt{2}}{2}\right)\cos(2\pi fn)-\left(\frac{(-m_Q(n))}{a}\frac{\sqrt{2}}{2}\right)\sin(2\pi fn)\right] \\ &= \left(A_c\frac{\sqrt{2}}{2a}\right)\left[m_I(n)\cos(2\pi fn)\ +\ m_Q(n)\sin(2\pi fn)\right]. \end{aligned} \tag{A-6}$$

Using $A_c = \sqrt{m_I^2 + m_Q^2}$, (A-6) becomes:

$$\begin{aligned} s(n) &= \left(\sqrt{m_I^2+m_Q^2}\,\frac{\sqrt{2}}{2a}\right)\left[m_I(n)\cos(2\pi fn)+m_Q(n)\sin(2\pi fn)\right] \\ &= \left(\sqrt{a^2+a^2}\,\frac{\sqrt{2}}{2a}\right)\left[m_I(n)\cos(2\pi fn)+m_Q(n)\sin(2\pi fn)\right] \\ &= \left(\sqrt{2a^2}\,\frac{\sqrt{2}}{2a}\right)\left[m_I(n)\cos(2\pi fn)+m_Q(n)\sin(2\pi fn)\right] \\ &= \left[m_I(n)\cos(2\pi fn)+m_Q(n)\sin(2\pi fn)\right]. \end{aligned} \tag{A-7}$$

This is the algorithm that is used to modulate a single logical channel in the CDMA95B technology model.

A.2 Multiple Channels, Single Base Station (Forward Link)

In the case of multiple forward channels that are all contained in a single cell, the data streams of each data channel are added together while still in digital form, but after spreading. The I and Q data streams from this composite signal, as in the single logical channel case, contain values that are ± 1 times some gain factor that is the same value for both the I and the Q value. Unlike the single logical channel case, the gain factor is not constant for the length of the data streams. Instead, the gain factor becomes a function, *a(n)*, which is the same for both I and Q. Therefore, across any chip, the magnitudes of I and Q are still equal and (A-7) becomes:

$$s(n)=\left[\sum m_I(n)\cos(2\pi fn)+\sum m_Q(n)\sin(2\pi fn)\right] \qquad \text{(A-8)}$$

for all I and Q channels.

A.3 Multiple Channels, Multiple Base Stations (Forward Link)

This scenario is affected by the delay calculated by the framework model.

For no delay or delay in chip intervals only, the base station composite signals will still have phase changes of $k\pi/4$. Therefore, (A-8) is valid.

For a scenario in which there is a delay for at least one base station composite signal such that the signal will add to the other composite signal(s) at a point that is not at a chip boundary, (A-8) no longer holds. The $\cos(2\pi fn)$ term becomes $\cos(2\pi fn+\phi)$ and the phase differences between the signals can no longer be considered a multiple of $\pi/4$. In these cases the signals must be added vectorally. (A-4) becomes:

$$s(n)=A_c\left[\cos(2\pi fn+\varphi)\cos(\theta(n))-\sin(2\pi fn+\varphi)\sin(\theta(n))\right] \qquad \text{(A-9)}$$

where $\theta(n)$ is still a multiple of $\pi/4$, but ϕ can be any angle between [0, 2π).

A.4 Multiple Channels, Single or Multiple Base Station (Reverse Link)

In CDMA95B, the reverse channels are not synchronized even when they are in the same cell. As a result, the characteristics of a composite reverse link signal are similar to the characteristics of a multiple base station forward link signal. In the technology model, the two types of signals are handled in the same way.

A.5 Conclusion

This appendix has shown that as long as composite signals add at chip intervals, the signal components can be added algebraically. However, when composite signals add at points internal to the chips, the signal components must be added vectorally. Although the example used here is specifically a CDMA95B system, the same process holds true for a WCDMA system.

Appendix B: Orthogonal Coding

Below is an example of how orthogonal coding keeps different data channels separate when they are combined prior to being modulated and transmitted [4].

The following sequences are user input data sequences (u_x) and spreading codes (w_x).

$$
\begin{aligned}
u_1(n) &= [-1,-1,+1,+1,+1,-1] \\
u_2(n) &= [+1,+1,-1,+1,-1,-1] \\
u_3(n) &= [-1,-1,+1] \\
w_1(n) &= [+1,-1,+1,-1] \\
w_2(n) &= [+1,+1,-1,-1] \\
w_3(n) &= [+1,+1,+1,+1,-1,-1,-1,-1]
\end{aligned}
\tag{B-1}
$$

The sequences u_3 and w_3 will show how to use coding to deal with variable rates. The input sequences all represent the inputs for the same time period, T_1. The bit rate for u_3 is $3/T_1$ as opposed to $6/T_1$ for the other inputs. To keep the chip rate the same for all the inputs, the spreading code (w_3) has to be twice as long as the other codes.

B.1 Spreading

The representation of the spreading starts with changing the binary sequences to signals sampled at the chip rate. For these signals, $t=nT_{chip}$.

$$
\begin{aligned}
u_1(t) &= (-1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1) \\
u_2(t) &= (+1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; -1) \\
u_3(t) &= (-1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; -1\; -1 -1\; -1\; -1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1) \\
w_1(t) &= (+1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1 -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1) \\
w_2(t) &= (+1\; +1\; -1\; -1\; +1\; +1\; -1\; -1\; +1\; +1\; -1\; -1\; +1 +1\; -1\; -1\; +1\; +1\; -1\; -1\; +1\; +1\; -1\; -1) \\
w_3(t) &= (+1\; +1\; +1\; +1\; -1\; -1\; -1\; -1\; +1\; +1\; +1\; +1\; -1 -1\; -1\; -1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1)
\end{aligned}
\tag{B-2}
$$

These signals after spreading are:

$$
\begin{aligned}
u_1(t)w_1(t) &= (-1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; +1\; -1\; -1\; +1\; -1\; +1) \\
u_2(t)w_2(t) &= (+1\; +1\; -1\; -1\; +1\; +1\; -1\; -1\; -1\; -1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1\; +1\; +1\; -1\; -1\; +1\; +1) \\
u_3(t)w_3(t) &= (-1\; -1\; -1\; -1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; +1\; -1\; -1\; -1\; -1)
\end{aligned}
\tag{B-3}
$$

Finally the composite signal is the chip-by-chip sum of the three spread signals:

$$
\begin{aligned}
C(t) &= u_1(t)w_1(t) + u_2(t)w_2(t) + u_3(t)w_3(t) \\
&= (-1\; +1\; -3\; -1\; +1\; +3\; -1\; +1\; -1\; -3\; +1\; -1\; +3\; +1\; +1\; -1\; +1\; -1\; +3\; +1\; -3\; -1\; -1\; +1)
\end{aligned}
\tag{B-4}
$$

B.2 Despreading

To despread the signal, multiply the composite signal by the appropriate spreading code, then integrate the new signal across the symbol period and map it to + or – 1. The data rate comes into play here since the symbol period for user 3 is twice as long as for users 1 and 2.

$$C(t)w_1(t) = (-1\ -1\ -3\ +1\ +1\ -3\ -1\ -1\ -1\ +3\ +1\ +1\ +3\ -1\ +1\ +1\ +1\ +1\ +3\ -1\ -3\ +1\ -1\ -1) \tag{B-5}$$

After integration over the symbol period (4 chip periods), the sequence becomes:

$$\begin{aligned} &(-4,-4,+4,+4,+4,-4) \rightarrow [-1,-1,+1,+1,+1,-1] = u_1(n) \\ &C(t)w_2(t) = (-1\ +1\ +3\ +1\ +1\ +3\ +1\ -1\ -1\ -3\ -1\ +1\ +3\ +1\ -1\ +1\ +1\ -1\ -3\ -1\ -3\ -1\ +1\ -1) \end{aligned} \tag{B-6}$$

After integration over the symbol period (4 chip periods), the sequence becomes:

$$\begin{aligned} &(+4,+4,-4,+4,-4,-4) \rightarrow [+1,+1,-1,+1,-1,-1] = u_2(n) \\ &C(t)w_3(t) = (-1\ +1\ -3\ -1\ -1\ -3\ +1\ -1\ -1\ -3\ +1\ -1\ -3\ -1\ -1\ +1\ +1\ -1\ +3\ +1\ +3\ +1\ +1\ -1) \end{aligned} \tag{B-7}$$

After integration over the symbol period (8 chip periods), the sequence becomes:

$$(-8,-8,+8) \rightarrow [-1,-1,+1] = u_3(n) \tag{B-8}$$

Appendix C: OVSF Coding

Both the forward and reverse links in WCDMA use orthogonal variable spreading factor (OVSF) codes for spreading. OVSFs are built starting with a seed $C_{ch,1,0}$=1. The algorithm for subsequent levels is $C_{ch,2sf,2n}$=$C_{ch,sf,n}$ $C_{ch,sf,n}$ and $C_{ch,2sf,2n+1}$=$C_{ch,sf,n}$ - $C_{ch,sf,n}$. The OVSF code words are the same as the Walsh code words used in CDMA95B, but are organized differently. Figure C-1 [4] shows the OVSF tree up to code words 16 digits long using binary code words. The defined code words for WCDMA are up to 512 digits long [7], [8], [10].

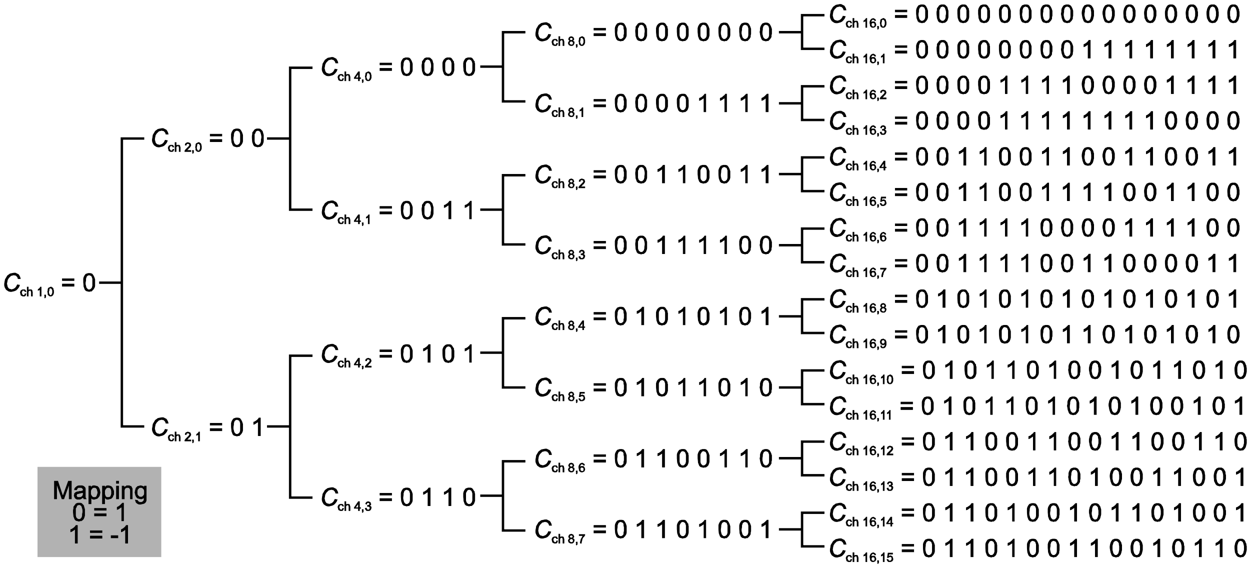

Figure C-1. OVSF coding tree.

OVSF codes allow data rate matching. The spreading factor (*sf*) of the code ranges from 4 to 512 in increments of 2^n. This allows the WCDMA system to accept input data rates from 7.5 kbps to 960 kbps.

The code word $C_{ch,256,0}$ is dedicated for the DPCCH in the reverse link and the PCPICH in the forward link. These channels are control channels for the links and contain the pilot information for the links for synchronization.

Each code word assigned to a traffic or control channel has to be unique whether in whole or in part. Therefore, the system needs to monitor not only the assigned code word, but all the code words with larger spreading factors that contain that word. Figure C-2 shows the restrictions caused by some code word choices; some code words are not available (crossed out sections) when the system uses code words $C_{ch,4,3}$ and $C_{ch,8,1}$.

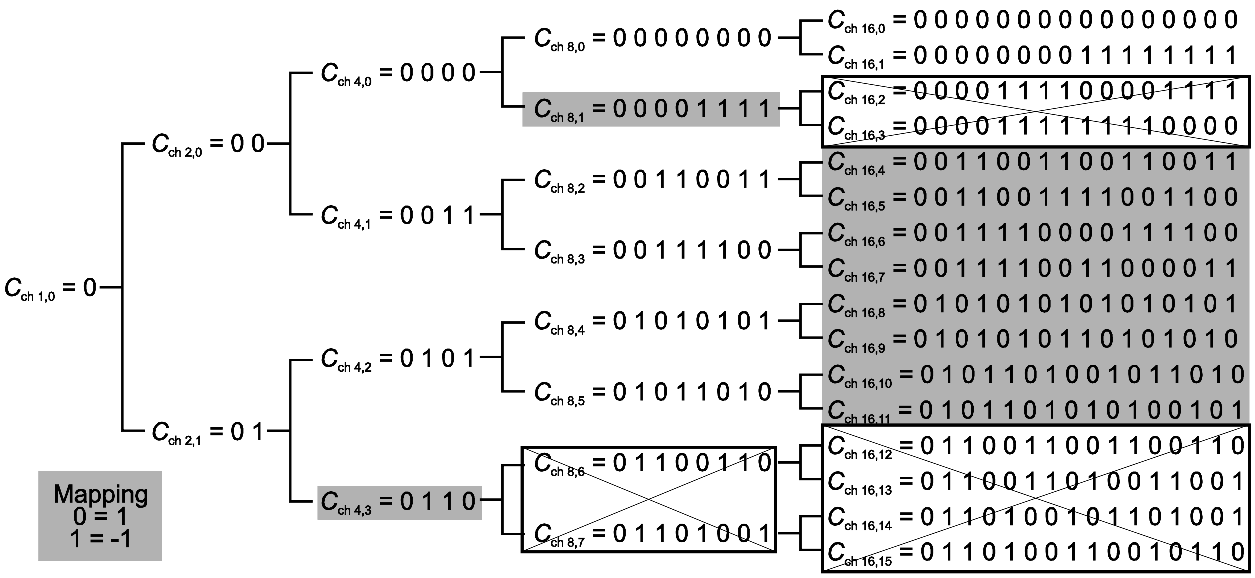

Figure C-2. Restrictions caused by code word choices.

Appendix D: WCDMA Scrambling Codes

Unlike the spreading function, WCDMA forward and reverse links have different scrambling codes. The scrambling codes for both links provide interference mitigation, but the scrambling code also provides channelization of the different mobile stations in the cell in the reverse link [7], [8].

The WCDMA scrambling codes are designed for high autocorrelation when the sequences have a *2N* time shift when the sequence has length *N* and low for all other time shifts and have a low cross-correlation value everywhere. Gold codes used in WCDMA for scrambling are not perfectly orthogonal in that they have more than one autocorrelation peak and non-zero offset autocorrelation and a non-zero cross correlation value.

Gold codes are made from two equal length *m* sequences. *M* sequences (maximum length sequences) are PN sequences that have very good autocorrelation properties, but poorer cross correlation properties. To increase the cross correlation properties, Gold codes combine *2m* sequences with modulo-2 addition (XOR operation). While not orthogonal, the Gold codes have only three cross correlation values (-1, -*t(n), t(n)-2*) where *t(n)* is [8]:

$$\begin{aligned} t(n) &= 2^{(n+1)/2} + 1 \quad n\ odd \\ t(n) &= 2^{(n+2)/2} + 1 \quad n\ even \end{aligned} \tag{D-1}$$

(D-2) and (D-3) are the recursive equations to calculate the next value into the shift register for the *m* sequences of the forward scrambling code. The superscript values for (D-2) to (D-5) refer to a position in the shift register of the pn sequence generator corresponding to the recursive equation.

$$x(17+1) = x(7) + x(0) \tag{D-2}$$

$$x(17+1) = x(10) + x(7) + x(5) + x(0) \tag{D-3}$$

Figure D-1 shows the logical circuit for the Gold code.

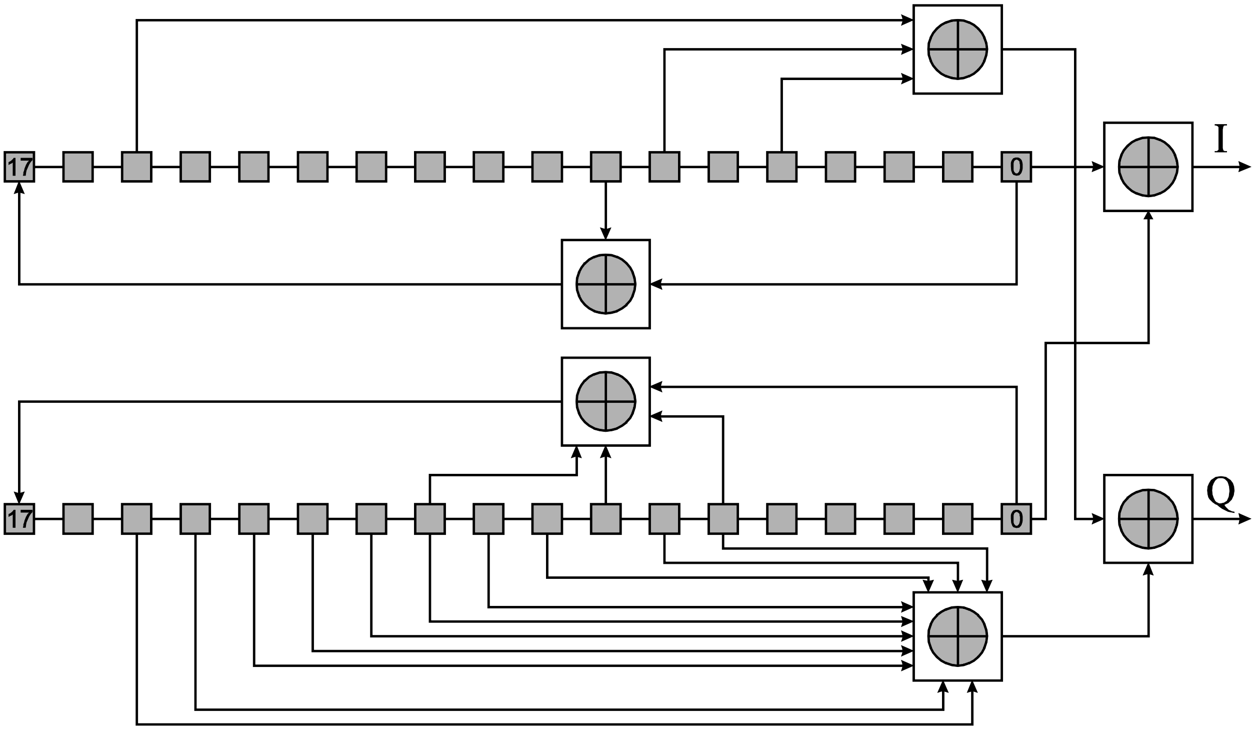

Figure D-1. Scrambling code generator for the forward link.

The initial state for the first sequence is determined by a chosen scrambling sequence of 25 binary bits (the most significant bit is always 1). However, the initial state of the second sequence is all 1's.

The recursive equations for the reverse link are (D-4) and (D-5) with the related circuit shown in Figure D-2.

$$x(24+1) = x(3) + x(0) \tag{D-4}$$

$$x(24+1) = x(3) + x(2) + x(1) + x(0) \tag{D-5}$$

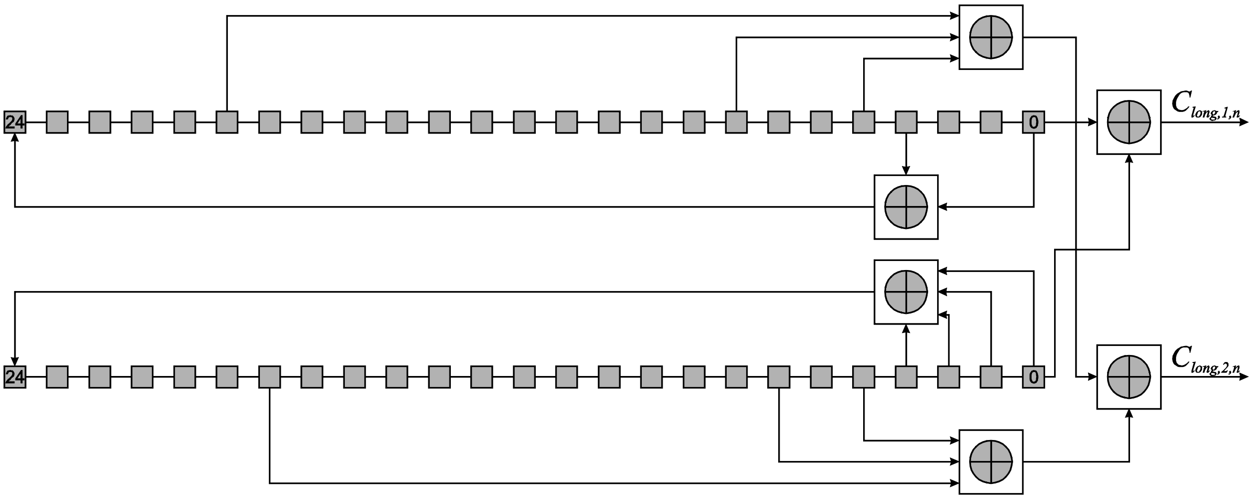

Figure D-2. Long scrambling code generator for the reverse link.

Figure D-3 is the circuit that produces the short scrambling code for the WCDMA reverse link; it is not included in the technology model since the long scrambling code is used for normal operation [7], [10].

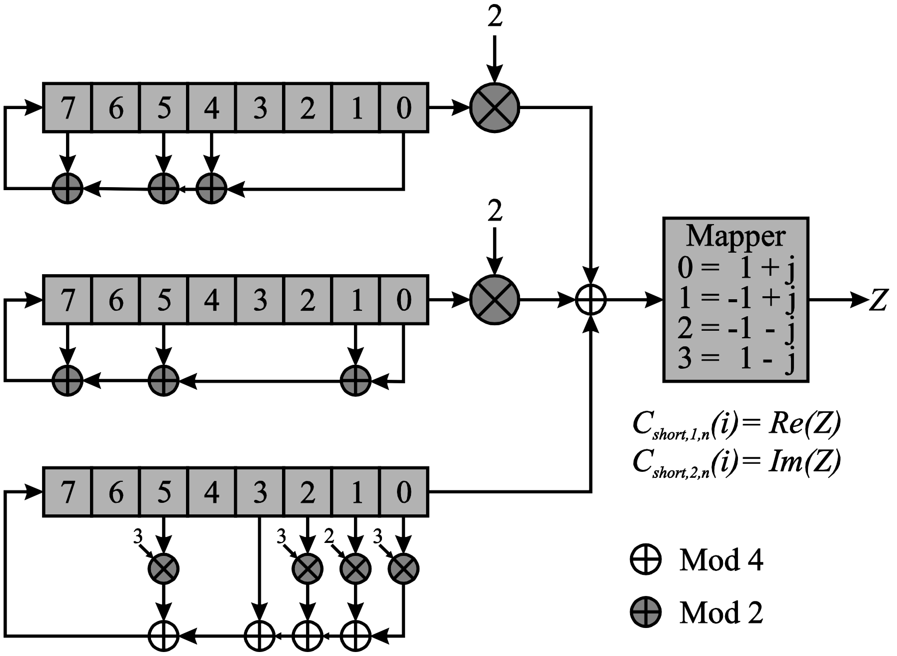

Figure D-3. Short scrambling code generator for the reverse link.

The scrambling codes for both links are complex as are the spread data sequences of the system. The logical circuit for multiplying the two sets of complex sequences in either link is shown in Figure 9 described by (D-6). The resulting signal is described by (D-7).

$$\left(I_{sp}I_{sc} - Q_{sp}Q_{sc}\right) + j\left(I_{sp}Q_{sc} + Q_{sp}I_{sc}\right) \tag{D-6}$$

$$A_{sp}A_{sc}\exp\left(j\phi_{sp}\right)\exp\left(j\phi_{sc}\right)=A_{sp}A_{sc}I_{sc}\exp\left(j\phi_{sp}+j\phi_{sc}\right) \qquad \text{(D-7)}$$

From (D-7) we see that the magnitude of the signal is the product of the magnitudes of the two complex sequences.

D.1 HPSK

WCDMA’s reverse link suffers from the same limitations as CDMA95B’s. Namely, the mobile stations have limited resources. In particular, designers of WCDMA wanted to limit the required dynamic range of the power amplifiers in the mobile stations. Phase changes of 180° strain that range since they require a zero phase crossing and produce larger overshoots than other phase changes. So, in the reverse link, the scrambling code is part of a process called hybrid phase shift keying (HPSK) or sometimes called orthogonal complex QPSK (OCQPSK) [7].

HPSK limits the types of transitions between pairs of adjacent chips in a sequence, but does not limit the transitions from one pair to another.

The first step occurs on the channelization process. The channelization codes for the traffic channels in the reverse link are always taken from the upper half of the OVSF tree where at least two consecutive chips do not change state. For mobile stations that transmit only one data channel, the channelization code word is determined by $k = SF/4$ which forces it to be in the upper half of the code tree.

For normal operation (the only type of operation modeled here), the scrambling code for the reverse link is a Gold code built by the two *m* sequences defined in (D-4) and (D-5). The second equation is decimated by 2 and then replicated so that every even placed chip is equal to the odd placed chip in front of it. The combination of the two sequences including the decimation is shown in (D-8):

$$C_{long,n}=C_{long,1,n}\left(i\right)\left(1+j\left(-1\right)^{i}C_{long,2,n}\left(2\left\lfloor {i}/{2}\right\rfloor\right)\right) \qquad \text{(D-8)}$$

where C_{long1} is from the first *m* sequence and C_{long2} is from the second sequence.

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Even under ideal circumstances, insufficient spectrum is available for assigning a unique band of frequencies to each communication system. In less ideal circumstances, when a communication system experiences outages due to equipment failure or natural or man-made disasters, the demands on the existing spectrum become even greater. More efficient use of the available spectrum requires sharing between multiple systems. To allow similar and dissimilar systems to co-inhabit a frequency band, the interactions between the systems need to be better understood. The Institute for Telecommunication Sciences (ITS) has developed the ITS CMRS Interference Model (ICIM) tool for generating and evaluating the interference between similar and dissimilar communication systems either co-located or located in adjacent areas. This tool generates system-specific interference signals to determine the level of co-channel interference from both immediate and adjacent cells. It produces a representation of an instantaneous air-interface signal, which can contain outputs of multiple base stations with variable numbers of logical channels for each base station and can assign relative power levels for each individual logical channel. Both forward and reverse link processes are included.

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