cdma2000 Physical Layer: An Overview

Serge Willenegger

Abstract: **cdma2000 offers several enhancements as compared to TIA/EIA-95, although it remains fully compatible with TIA/EIA-95 systems and allows for a smooth migration from one to the other. Major new capability include: 1) connectivity to GSM-MAP in addition to IP and IS-41 networks; 2) new layering with new LAC and MAC architectures for improved service multiplexing and QoS management and efficient use of radio resource; 3) new bands and bandwidths of operation in support of various operator needs and constraints, as well as desire for a smooth and progressive migration to cdma2000; and 4) flexible channel structure in support of multiple services with various QoS and variable transmission rates at up to 1 Mbps per channel and 2 Mbps per user.**

Given the phenomenal success of wireless services and desire for higher rate wireless services, improved spectrum efficiency was a major design goal in the elaboration of cdma2000. Major capacity enhancing features include: 1) turbo coding for data transmission; 2) fast forward link power control; 3) forward link transmit diversity; 4) support of directive antenna transmission techniques; 5) coherent reverse link structure; and 6) enhanced access channel operation.

As users increasingly rely on their cell phone at work and at home for voice and data exchange, the stand-by time and operation-time are essential parameters that can influence customer's satisfaction and service utilization. Another major goal of cdma2000 was therefore to enable manufacturers to further optimize power utilization in the terminal. Major battery life enhancing features include: 1) improved reverse link performance (i.e., reduced transmit power per information bit); 2) new common channel structure and operation; 3) quick paging channel operation; 4) reverse link gated transmission; and 5) new MAC states for efficient and ubiquitous idle time operation.

This article provides additional details on those enhancements. The intent is not to duplicate the detailed cdma2000 radio access network specification, but rather to provide some background on the new features of cdma2000 and on the qualitative improvements as compared to the TIA/EIA-95 based systems. The article is focused on the physical layer structure and associated procedures. It therefore does not cover the MAC, LAC, radio resource management [1], or any other signaling protocols in any detail. We assume some familiarity with the basic CDMA concepts used in TIA/EIA-95.

Index Terms: **3G, IMT-2000, radio interface, CDMA, CDMA-MC, cdma2000, IS-95.**

I. INTRODUCTION

cdma2000 represents an evolution from cdmaOne, which is based on the TIA/EIA-95 family of standards. While cdma2000 is fully backward compatible with the cdmaOne systems and terminals, its development took into account the extensive experience acquired through the operation of cdmaOne systems, as well as the requirements of next generation wireless data systems. As we will show, the result is an extremely efficient and versatile multi-service radio access system.

One major addition to the cdma2000 specification is the support of IS-41 and GSM-MAP connectivity. It is indeed possible for a cdma2000 cell to support both IS-41 and GSM-MAP enabled terminals. The radio related aspects are handled according to cdma2000 specification, while the Call Control, Mobility Management, and Supplementary Services aspects are managed according to the respective network protocols. With the introduction of a User Identification Module (UIM) specification, cdma2000 is therefore well suited for global roaming.

Originally under TIA TR45.5, the responsibility of the cdma2000 work has been moved to a newly formed organization called "The third Generation Partnership Project 2," or 3GPP2, thereby benefiting from the expertise of specialists from Chinese, Japanese, Korean, and North American standards bodies. The ITU approved the cdma2000 radio access system as the CDMA Multi-Carrier (MC) member of the IMT-2000 family of standards.

cdma2000 release 0 was published in the summer of 1999, release A in early 2000, and release B will be published by the end of 2000. Release 0 of cdma2000 provides functionality at the physical layer for Spreading Rate 1 and Spreading Rate 3 (SR3). Release 0 provides the signaling support for Spreading Rate 1 using the TIA/EIA-95 common channels. Release A primarily provides signaling support for Spreading Rate 3 and for a new set of common channels.

The cdma2000 standard includes a large number of specifications. The most important air interface specifications are shown in Table 1. These are shown with the designators used by 3GPP2 as well as the designators used by TIA. For the most part, the TIA designators correspond to the equivalent TIA/EIA-95 family document as the TIA/EIA-95 family documents were enhanced to provide support for third generation capabilities and services.

Although cdma2000 is backward compatible with TIA/EIA-95 and supports most of TIA/EIA-95 structure and procedures, we will focus on the procedures typically used by a terminal and base station supporting its advanced features. After a general introduction of the physical layer modes and channel structure, we will present a typical sequence of mobile station operations, from system acquisition to inter-system handover, and introduce the associated channels and procedures as we walk through this sequence of events.

Manuscript received February 23, 2000.

Serge Willenegger is with QUALCOMM International, Switzerland, e-mail: sergew@qualcomm.com.

Table 1. Major cdma2000 air interface specifications.

3GPP2	TIA Number	Descriptive Title
C.S0001	TIA/EIA/IS-2000-1	cdma2000 - Introduction
C.S0002	TIA/EIA/IS-2000-2	cdma2000 - Physical Layer
C.S0003	TIA/EIA/IS-2000-3	cdma2000 - MAC
C.S0004	TIA/EIA/IS-2000-4	cdma2000 - Layer 2 LAC
C.S0005	TIA/EIA/IS-2000-5	cdma2000 - Layer 3
C.S0006	TIA/EIA/IS-2000-6	cdma2000 - Analog
C.S0010	TIA/EIA-97	Base Station Minimum Performance
C.S0011	TIA/EIA-98	Mobile Station Minimum Performance
C.S0014	TIA/EIA/IS-127	Enhanced Variable Rate Codec (EVRC)
C.S0015	TIA/EIA-637	Short Message Service
C.S0016	TIA/EIA/IS-683	Over the air service provisioning
C.S0017	TIA/EIA/IS-707	Data services for Spread Spectrum Systems
C.S0020	TIA/EIA/IS-733	High Rate (13 kbps) Speech SO
C.S0022	IS-801	Location Services (Position Determination Service)
C.S0023	IS-820	Removable User Identity Module

II. PHYSICAL LAYER MODES

The cdma2000 physical layer includes several modes of operation. This enables the operators to deploy and configure their network based on their own needs, environment, and local regulations. Several options exist for the band of operation, system bandwidth, and mode of transmission.

Starting with the operating band, cdma2000 has been specified for operation in the 800 MHz cellular bands (normal and Japanese), the 1.7 GHz Korean and 1.9 GHz PCS bands, the NMT-450 band, and the IMT-2000 bands. Nevertheless nothing fundamentally precludes the deployment of cdma2000 in other duplex bands, such as the ones under consideration for the upcoming WARC'2000, or the 700 MHz TV band under consideration by the United States' Federal Communications Commission.

Within a given band, cdma2000 can be deployed using different bandwidths. Both a 1.25 MHz full duplex bandwidth—referred to as "Spreading Rate 1" (SR1), or "1x"—and a 3.75 MHz full duplex bandwidth—referred to as "Spreading Rate 3" (SR3), or "3x"—have been specified. The 1.25 MHz configuration is similar to and compatible with the TIA/EIA-95 direct sequence, direct spread bandwidth. The 3.75 MHz configuration uses a multi-carrier forward link (FL) and direct spread reverse link (RL); the forward link multi-carrier signal is obtained by aggregating three consecutive 1x carriers. An important aspect of Spreading Rate 3 is that it can overlay Spreading Rate 1 carriers as is shown in the fourth configuration of Fig. 1. Finally, a hybrid SR3 forward link / SR1 reverse link configuration has been incorporated in the release A of cdma2000 in order to better match data traffic patterns and speed up the introduction of peak download rates offered by the 3x bandwidth. This is shown in the third configuration of Fig. 1. This flexible 1x, 3x approach enables existing cdmaOne operators to have a smooth migration to the cdma2000 features. As an example, a cdmaOne operator could first migrate one 1.25 MHz cdmaOne carrier to cdma2000 SR1 mode. As wireless data services become more popular it could then overlay a multi-carrier system on top of three 1.25 MHz carriers and progressively migrate all users to the multi-carrier SR3 mode while still supporting legacy SR1 and cdmaOne terminals.

In a given band and bandwidth configuration, an operator may then choose among various forward link transmission schemes. The first available option is to use direct transmission, which consists in transmitting the up-banded 1x or 3x signal(s) from a single antenna. A second option is to use diversity transmission. For SR1 this consists in demultiplexing and modulating the data into two orthogonal signals, each of them transmitted from a different antenna at the same frequency. The two orthogonal signals are generated using either Orthogonal Transmit Diversity (OTD) or Space-Time Spreading (STS). The IQ mapping and scrambling for STS is shown in Fig. 3. For SR3, diversity transmission consists in demultiplexing the signal into three streams corresponding to the three carriers which can be transmitted from the same or from different antennas. The receiver reconstructs the original signal using the diversity signals, thus taking advantage of the additional space and/or frequency diversity. The final transmission option offered by both SR1 and SR3 systems consists in directive transmission. Using antenna processing techniques the base station directs a beam towards a single user, a group of users, or a specific location, thus improving link margin and providing space separation in addition to code separation.

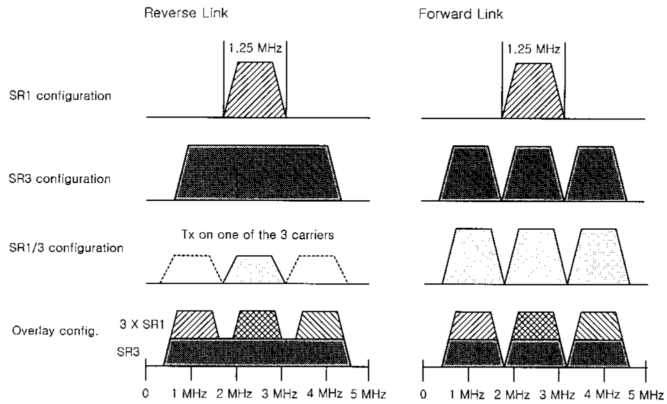


Fig. 1. cdma2000 bandwidths of operation.

The various modes of transmission are illustrated in Fig. 2. Depending on the radio environment transmit diversity techniques may improve the link performance by up to 5 dB.

In the following sections, we describe the various physical layer channels in a generic manner, not referring to any specific band, bandwidth, or transmission mode.

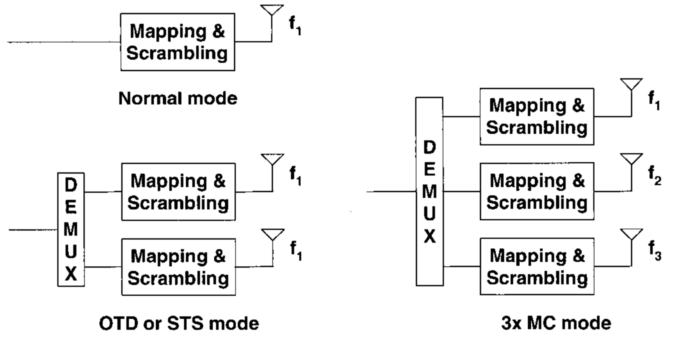


Fig. 2. cdma2000 modes of transmission.

III. TIMING AND NUMEROLOGY

For compatibility reasons, cdma2000 timing is the same as TIA/EIA-95 timing and can be easily related to the Universal Coordinated Time (UTC). The forward link transmission timing of all cdmaOne and cdma2000 base stations in the world is thus synchronized within a few microseconds. The base station synchronization can be achieved through several techniques, including self-synchronization, radio beep, or through satellite based systems such as GPS, Galileo, or GLONASS. The reverse link timing is based on the received timing derived from the first multi-path component used by the terminal.

There are multiple benefits to base station synchronization which fully justify the incremental cost and effort associated with the support of synchronization. The common time reference allows for improved acquisition and handoff procedures since there is no time ambiguity (besides propagation delay) when looking for and adding a new cell in the active set. It also enables the system to operate some of the common channels in soft-handoff [2], which leads to a highly improved common channel operation efficiency. Finally, the common network time reference allows to implement highly efficient position localization techniques, thereby allowing carriers to offer their customers advanced value added services and fast relief to distress calls.

cdma2000 numerology is fully in line with TIA/EIA-95 for the same compatibility reason. The fundamental spreading rate is 1.2288 Mcps for SR1 and each SR3 forward link carriers and 3.6864 Mcps for SR3 RL direction. The basic frame length is 20 ms divided in 16 equal power control groups. In addition, cdma2000 defines a 5 ms frame structure, essentially in support of signaling bursts, as well as 40 and 80 ms frames which offer additional interleaving depth and diversity gains for non real time services.

IV. FORWARD LINK

On the forward link, the base station transmits multiple common channels as well as multiple dedicated channels to the terminals located in its coverage area. In general, all the channels are mutually orthogonal as the bits they carry are spread with mutually orthogonal variable length Walsh functions, or mapped to different frequencies (SR3 configuration). As opposed to TIA/EIA-95, cdma2000 does not limit the Walsh code selection to a Walsh space of dimension of 64. Instead, the orthogonal spreading code is chosen from a Walsh tree growing from dimension 4 to dimension 256. This structure allows for more flexibility in the transmission rate range of any channel. Note that when operating a multi-carrier (SR3) forward link the Walsh code used to spread a given channel is the same on all three carriers.

One notable exception to the mutual orthogonality of channels, is when the system becomes code limited (all the codes available in the Walsh tree are used) rather than interference limited. In order to overcome code limited situations, cdma2000 defines a set of Quasi-Orthogonal Functions (QOF) as an extension to the orthogonal code set. QOFs are another orthogonal code set that minimizes the maximum correlation with the original orthogonal code set. The usage of QOFs is particularly useful for the Dedicated Control Channel in a spot beam, or in a beam directed to a single mobile station. In the latter case, the antenna beams provide some orthogonality between users.

While TIA/EIA-95 forward link modulation is BPSK followed by QPSK scrambling, cdma2000 forward link modulation is QPSK followed by QPSK scrambling. Switching to QPSK adds one dimension to the signal and effectively expands the orthogonal space. The number of modulation symbols necessary to transmit a given number of bits is halved, and the Walsh code length can be doubled; this effectively doubles the number of available orthogonal Walsh codes for a given data rate. After spreading, the chips are mapped (DEMUX) to an I and a Q branch in the case of SR1, or 3I and 3Q branches in the case of SR3. The IQ streams are then scrambled (complex multiply) with a time offset short complex PN sequence of length 2^{15} chips, or 26.6666 ms. The short PN sequence is the same system wide and the offset (PN offset) identifies the base station in its neighborhood. The scrambled QPSK stream is then fed to the base-band filter and fed into the RF section.

Fig. 3 represents the mapping, spreading, and scrambling when using the SR1-STS mode. Two consecutive complex coded bits are fed into two spreading and scrambling streams corresponding to the two transmit antennas. Complementary STS spreading is applied to both streams, followed by Walsh or QOF spreading and PN scrambling. Base band filtering is the final operation before the RF section.

V. REVERSE LINK

cdma2000 reverse link differs significantly from the TIA/EIA-95 M-ary orthogonal signaling structure, and is somewhat similar to the forward link structure. The cdma2000 reverse link includes several channels, one of which is a pilot channel, thus permitting coherent demodulation. Although the signals transmitted by different terminals within a cell are not orthogonal, the different channels transmitted by a given terminal are mutually orthogonal by design. The various channels are first spread using a Walsh code, which provides for channelisation and for resistance to phase errors in the receiver. The resulting BPSK modulated chips are then mapped to either the I or Q branches, and scrambled with a cell specific or user specific complex long code.

A technique called HPSK (Hybrid Phase Shift Keying) provides a one chip delay and decimation by 2 in the Q branch,

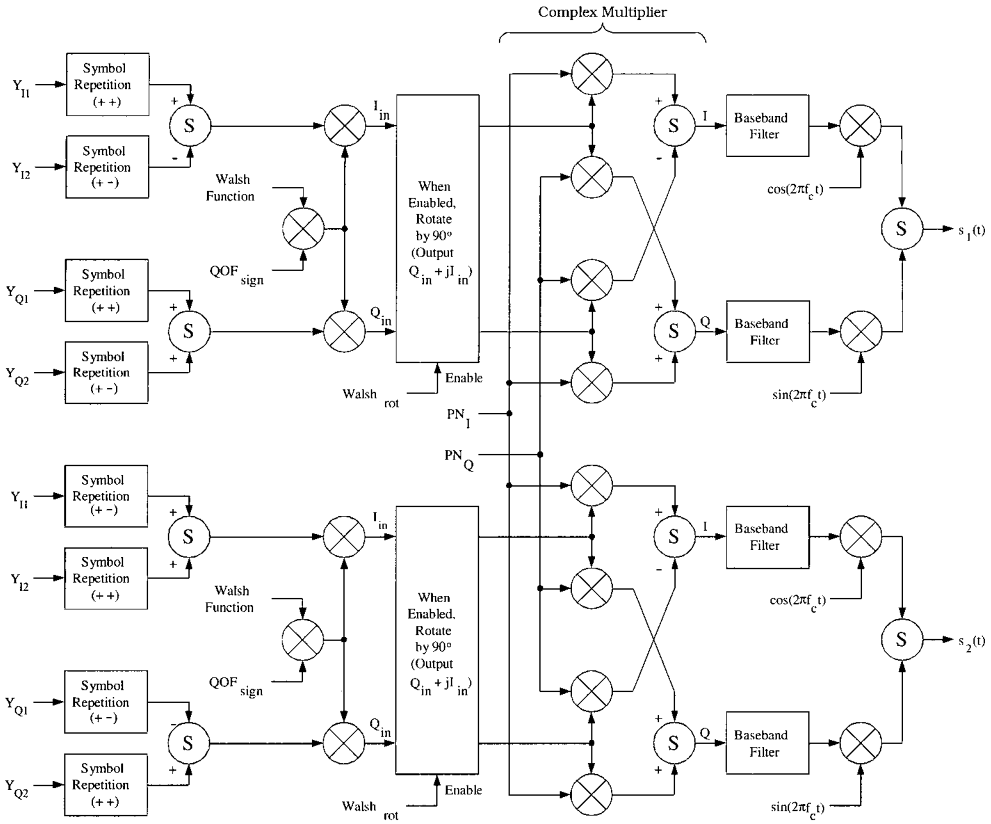


Fig. 3. DL mapping and scrambling in SR1-STS mode.

thus leading to a reduction in peak-to-average statistic of the RL signal in the order of 1 dB. The reduction of the signal dynamic decreases the required Power Amplifier (PA) headroom. This results in a more efficient utilization of the PA and allows for smaller designs. The HPSK scrambling is illustrated in Fig. 4 for SR3.

VI. ACQUISITION OF FL OVERHEAD CHANNELS

When powered on, the IS-2000 compatible terminal directs its hardware (search engine) to look for a **Forward Common Pilot Channel (F-PICH)**, or "Pilot channel." The F-PICH is a channel continuously transmitted by all cdma2000 compliant base stations, consisting of a constant value of 1, scrambled by the short complex PN sequence previously described. The pilot channel is used for acquisition, for various tracking loops, and as a reference for coherently demodulating the other forward link channels. Each base station transmitter scrambles all the forward link channels with a different offset relative to the Universal Coordinated Time (UTC). This offset is referred to as the PN offset, and represents the base station identity amongst neighbor base stations or sectors. The number of different PN offsets in the system is limited to 512, hence PN offsets may have to be reused within a given network. When using SR1 transmit diversity mode, a transmit diversity pilot channel (F-TDPICH) is transmitted from the diversity antenna and enables the terminal to estimate the channel and recover information transmitted from the diversity antenna.

Once at least one pilot is successfully acquired, the terminal is locked to the strongest available F-PICH. At that time, it does not have a time reference, and since the F-PICH signal is always the same, it cannot identify the base station it has just found. In addition, it doesn't know the system parameters, nor does it know whether it is allowed to operate with the associated network. In order to acquire all the information the terminal attempts to decode the **Forward Synchronization Channel (F-SYNC)**, or "Sync channel." The F-SYNC channel rolls over every 2^{15} chips, or 26.666 ms, and is synchronized with the F-PICH. Since the F-SYNC is scrambled with the same sequence as the pilot signal, it can be coherently demodulated and decoded. The Sync channel carries the Sync message, which contains system information such as protocol revision, system identities, code offset, system time, diversity mode, or broadcast channel and paging channel information. The Sync channel is based on an 80 ms superframe structure, which spans exactly three pilot signal periods. Since the transmission of the Sync message always starts at a superframe boundary, the terminal acquires the 20 ms timing at the same time as it decodes the Sync message. The F-SYNC radio frames each contain 32 information bits which are protected using a $R = 1/2$ convolutional code, 2 symbol repetitions, and block interleaving.

Once the terminal has acquired the F-SYNC channel, it is aware of its environment and can acquire additional information about the system, register, keep in touch (idle more operation), and eventually wait for or initiate a voice call and/or a data session. These operations usually happen through common channel signaling exchanges and are illustrated in the following sections.

The Sync message contains only minimal information about

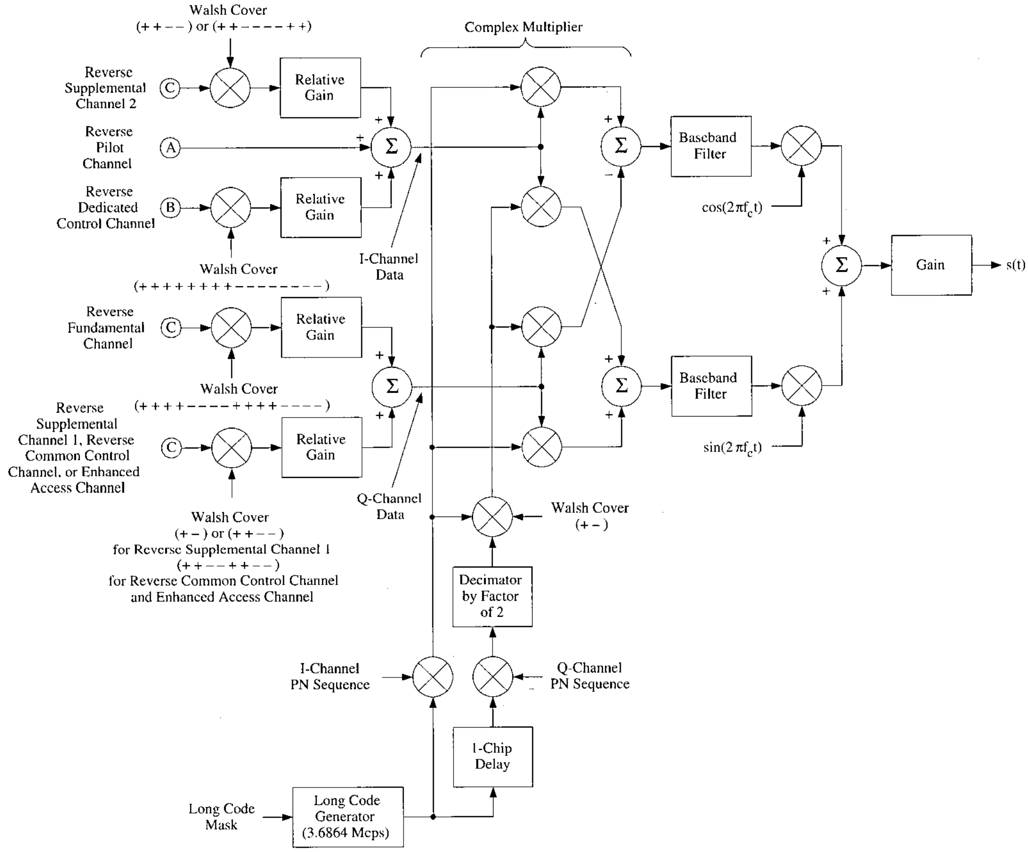


Fig. 4. RL channel mapping and scrambling for SR3.

the system. This information enables the terminal to check whether it has the hardware capability, the necessary authorizations, and the desire to operate within a specific network. Assuming this is the case, the terminal has to acquire additional and more detailed configuration parameters, which will enable it to operate with the system. In TIA/EIA-95, those parameters are sent over the paging channel through overhead messages. In cdma2000 1x the paging channel has been kept for compatibility reason with 95 systems. However, if compatibility with 95 systems is not required, the system parameters and other control information are transmitted over the **Broadcast Channel (F-BCCH)**. The broadcast channel frame always contains 744 bits and is transmitted at 19.2, 9.6, or 4.8 kbps using convolutional coding, sequence repetition, and block interleaving. For the highest transmission rate, the 744 bits in the frame are transmitted once; for the lower two rates, the 744 bits in the frame are transmitted either twice or four times. At the lower rates, this permits a terminal that is able to successfully receive the first copy of the broadcast frame to stop monitoring the channel after it has successfully received the frame, thus reducing battery consumption. In the remaining part of this article, most references to network configurable parameters will relate to parameters which are transmitted over the F-BCCH.

In parallel to the system acquisition procedure, and as long as the terminal is powered on (i.e., even after the acquisition phase is over), the terminal gets information from its search engine about new cells which may appear as it moves across the network. At some point a new cell could become stronger than the one the terminal currently listens to, and the terminal should then switch its receiver and listen to the best available cell (the procedure includes some hysteresis to limit the Ping Pong effect). This procedure is called **Idle Handoff**. According to cdma2000 specification, the terminal continuously maintains various lists of pilots or cells, depending on their status and properties. The pilot or cell that the terminal monitors in idle mode is included in the **Active Set**. In the overhead messages, the base station provides the terminal with a **Neighbor Set**, a list containing all the neighboring cells and associated parameters. The other cells are denominated as **Remaining Set** (cdma2000 also supports Private system operation but we will not discuss this option here). The Neighbor set helps the terminal prioritize its search effort, but does not restrict searching for other cells. Members of the neighbor set may also be located on different frequencies. After an idle-handoff and if the mobile has already registered with the network, the network overhead parameters determine the terminal's behavior and determine whether it should register. Although the terminal constructs its active set based on forward link measurement, the active set also applies to the reverse link.

VII. REVERSE CHANNEL STRUCTURE

Once the terminal has acquired all the system parameters as specified in IS-2000.5, it may proceed with registration, meaning it indicates its presence and seek authorization to operate with the system it has just acquired. The registration message is

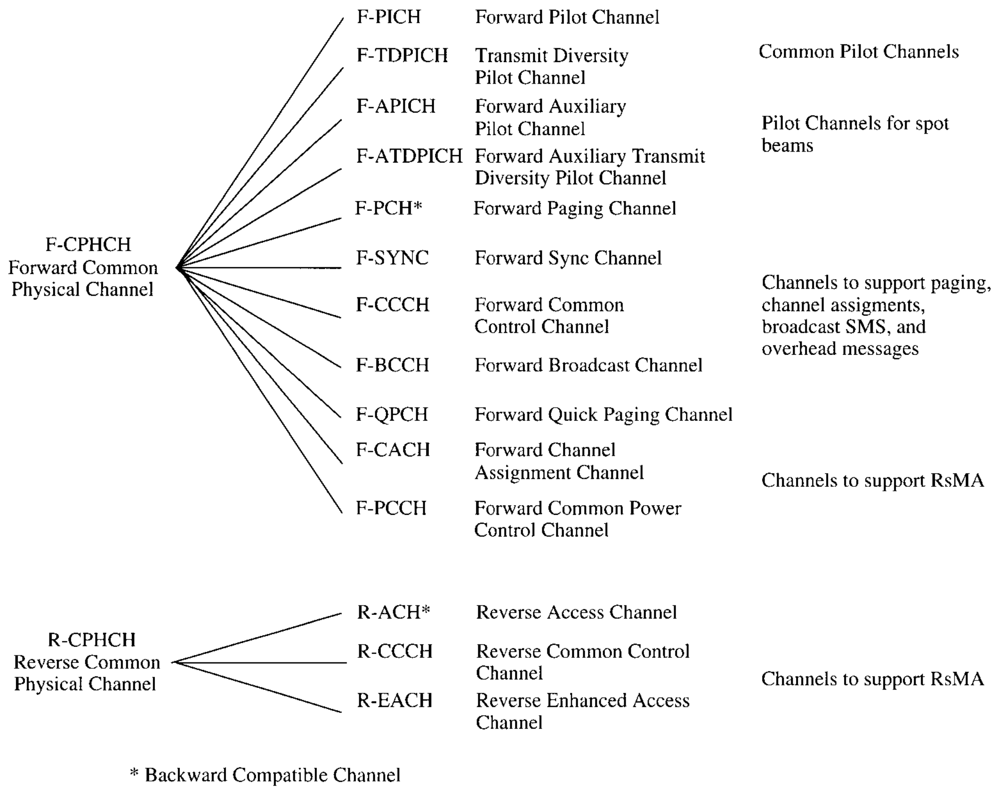


Fig. 5. cdma2000 common channels.

sent over the access channel. The access channel is a Reverse Link (RL) channel and we will now introduce some generic features of the cdma2000 reverse link.

The structure of RL channels is illustrated in Fig. 4. In addition to data or control channels, the cdma2000 signal transmitted by the terminal on the reverse link always includes a reference signal denominated as **Reverse Pilot Channel (R-PICH)**. The pilot channel consists in a continuous DC signal (before scrambling) used as the reference signal for searching, tracking, measurement and coherent demodulation at the base station. The pilot channel is transmitted on the I branch without any channelisation (or with a Walsh 0 channelisation). Additional reverse link channels are sent on the Q and/or I branch. Their mutual orthogonality is ensured by appropriate Walsh channelisation as described earlier. Although the R-PICH is a pure overhead channel (it does not carry any user information) it allows the transmission of data or control channels with much better modulation efficiency than M-ary modulation. Consequently, the addition of R-PICH results in improved link performance for most data rates.

When applicable, a **Reverse Power Control Sub-channel** is associated with the R-PICH. The forward link power control information is punctured at the end of each R-PICH power control group and takes 25% of the R-PICH slot. In gated mode, the power control rate is reduced proportionally to the gating factor.

VIII. COMMON CHANNELS

Common channels are used for brief (e.g., less than a second) exchange of information between a terminal and a base station. This type of exchange is supported on the reverse link by the enhanced access channel and reverse common control channel and on the forward link by the forward common control channel. The cdma2000 common channel structure is shown in Fig. 5.

Due to the new capabilities and flexibility as well as higher capacity introduced by cdma2000, common channel messages grow in size and numbers. Originally, TIA/EIA-95 common channel structure and operation was not designed with those requirements in mind. Consequently, using the TIA/EIA-95 common channel structure for cdma2000 common channel exchange might result in some level of system performance degradation. For example, the likelihood of successfully decoding an access message rapidly decreases as its length increases when the message is not power controlled. This forces the terminal to transmit the message multiple times or with higher power thus increasing the access delay or generating significant reverse link interference. On the forward link, the mobile battery life will be significantly reduced if the terminal has to decode more and longer paging messages. Those considerations led to the introduction of a new set of common channels and associated procedures in support of flexible and efficient common channel operation.

IX. MOBILE ORIGINATED COMMON CHANNEL EXCHANGE

cdma2000 defines five access modes. The first access mode consists in the TIA/EIA-95 access procedure and access channel. Again, this mode is only used in bands and on carriers for which support of legacy terminals is desired. cdma2000 terminals shall also support this mode if they have to operate with a TIA/EIA-95 system. The three other modes are supported by the **Enhanced Access Channel (R-EACH)** and **Common Control Channel (R-CCCH)** and are defined as basic access mode, reservation access mode and designated access mode. The reverse link access channels are scrambled with a cell and channel specific long code (the long code mask includes cell ID and channel number).

The enhanced access probe, which is the signal sent over the R-EACH, includes up to three parts: the preamble, the header, and the data part. The preamble part consists of the pilot channel, optionally transmitted for a configurable duration and with a configurable periodic on/off pattern. The initial preamble power is derived through an open loop power estimation, and is corrected with a configurable set of power offsets. The preamble is used by the base station to detect and prepare for the reception of the header and data parts. The header part is 5 ms long and contains 32 information bits. It is protected using 12 or 16 bit quality indicator, $R = 1/4$ convolutional code, quadruple symbol repetition, and block interleaving. The header part contains an access type indication, a hash ID and a rate indication or request. Finally, the data part consists in one or multiple frames of 5, 10, or 20 ms, and is transmitted at 38.4, 19.2, or 9.6 kbps. Protection is ensured by 8 bit frame quality indicator, $R = 1/4$ convolutional coding and block interleaving. Both the header and data parts are transmitted together with the pilot channel and are mapped on the Q channel with W2,8 channelisation.

When operating in the **basic access mode**, the terminal repeatedly transmits (using some configurable back-off procedures) the preamble followed by data part with increasing power until it receives an acknowledgement from the base station or until the maximum number for attempts is reached. This mode is well suited for the transmission of very short access messages. The overhead and additional delay associated with the more elaborated access modes would not be justified by the small gains obtained with such short transmissions.

Using the basic access mode for longer access messages or messages transmitted at higher rates would result in either significantly higher message error rates and access delays or additional interference to the base station receiver. Moreover, a cell might not always be able to accommodate higher rates access attempts. In order to efficiently support longer messages or higher rates on the access channel, cdma2000 therefore defines the **reservation access mode**. When a terminal decides (based on the message size, transmission rate, and network parameters) to access the system using the reservation access mode, it first has to seek authorization form the network, that is request some reverse link access capacity. Once the request is accepted, the terminal transmits the data part on a designated channel and adjusts the transmission power based on power control commands it receives from the base station. This procedure is illustrated in Fig. 6 and detailed in the following sections.

The reservation request is transmitted to the base station using the basic access mode where the data part is replaced with the header part. The terminal then monitors the **Common Assignment Channel (F-CACH)** and looks for an acknowledgement of the access attempt. The F-CACH is a forward link common channel designed to provide a fast response to reverse link access attempts. It allows for fast acknowledgment of access attempts and quick resolution of access collisions by identifying one terminal as the only one allowed to proceed with the transmission of the data part. Since the data part is power controlled, this collision resolution is necessary to avoid the situation that other terminals follow power control commands unrelated to their transmission. Such false capture could potentially result in catastrophic interference at the base station. F-CACH frames consist in 5 ms frames containing 32 information bits. Those frames are similar to the header part of the access message and include similar information, in particular the hash ID that uniquely identifies the captured terminal. In case a terminal does not detect a valid access acknowledgement on the F-CACH within a configurable time out period it stops its transmission and initiates another access probe after application of the back-off procedure.

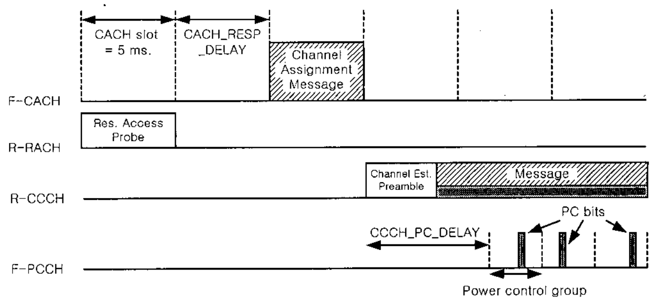


Fig. 6. Reservation access mode message sequence.

Once it has received the allocation message on the F-CACH, the terminal transmits the data part, optionally preceded by a preamble part, on the **Reverse Common Control Channel (R-CCCH)** as directed by the base station in the allocation message. The R-CCCH has the same structure and frame format as the R-EACH. The main difference with R-EACH operation is that the base station controls the R-CCCH utilization (versus random access). The terminal adjusts its output power as directed by the power control commands decoded from the associated **Common Power Control Channel (F-CPCCH)** subchannel. The F-CPCCH is a forward common channel which supports the transmission of multiple power control bits associated with various R-CCCH. The PC bits are not coded and each F-CPCCH can support from 24 power control subchannels at 800 bps to 96 subchannels at 200 bps. Each subchannel is uniquely associated with an R-CCCH and the PC bit position is randomized based on the decimation of a subchannel specific long code. Application of fast power control to the data part transmission significantly reduces the interference generated by access attempts and reduces the message error rate for long messages.

The **designated access mode** consists in a power controlled R-CCCH transmission in response to and as directed by a request contained in a forward link common channel message. This allows for a reduction in overhead when the base station expects an access attempt in response to a request (e.g., mobile terminated call origination).

The F-CACH can also be used to quickly transmit congestion control messages. The accessing terminals creating the congestion will quickly decode such message and adapt their access attempt parameters or delay the access in order to resolve the congestion.

Once it has successfully transmitted the access probe according to one of the three access modes, the terminal monitors the **Forward Common Control Channel (F-CCCH)** until it receives an acknowledgement or a time out period expires. In the latest case, the terminal then applies the access back-off procedure and accesses the system again until the message is acknowledged or a counter expires in which case it declares an access failure. The F-CCCH frames span 5, 10, or 20 ms and operates at 9.6, 19.2, or 38.4 kbps. The F-CCCH is also used to transmit page, signaling or data messages to one or a set of terminal as explained in subsequent sections.

If the radio conditions from a particular cell degrade during the access procedure, the terminal may perform an **Access handoff** or an **Access probe handoff** if allowed by the network and specific access parameters. In access handoff, the terminal may listen to a F-CCCH from a different cell after receiving the acknowledgement for its access. In access probe handoff, the terminal may monitor a different cell and transmit the access attempt again (using the long code mask of the new cell). Access handoffs and access probe handoffs improve the overall reliability of the access procedure.

Coming back to the registration phase, the terminal selects one of the allowed access modes to transmit the registration message. Upon successful registration, the terminal receives a confirmation of its registration over the F-CCCH together with a number of associated parameters (e.g., TMSI). The terminal is then in idle mode state. While in this mode, the terminal performs the usual idle mode operations. In addition to searching for new cells, performing idle-handoff and re-registering when required, the terminal must also check on a regular basis whether the network is trying to initiate a data exchange. This procedure and associated channels are described next.

X. MOBILE TERMINATED COMMON CHANNEL EXCHANGE

While in idle mode, the terminal processing units should ideally be powered down in order to save power and maximize battery life. However, the terminal also has to regularly monitor its environment and the network has to be able to contact the terminal at any time in case it has a call or data for that terminal. To best meet these opposite requirements, cdma2000 breaks the paging procedure into a page indication phase and a message transmission phase [3]. The page indication is very short and the mobile can process it very quickly, therefore minimizing its wake up time when the indicator is not detected, meaning there is no message to decode. The message length can be a few milliseconds long but the terminal only attempts to decode it (and uses the processing power to do so) when it has an indication that the base station might have sent a message. The **Quick Paging Channel (F-QPCH)** is a new channel that carries the page indicators.

The F-QPCH is structured in successive 80 ms quick paging slots each supporting 384 or 768 paging indicators. The system can therefore support up to 16 quick paging slots every 1.28 second, which corresponds to the minimum paging slot cycle. At registration, the terminal indicates a preferred slot cycle, ranging from 1.28 second to 2.43 minutes and derives its quick paging slot indicator index through an hash function. The hash function distributes the terminals across all slot indices and minimizes the number of terminals per indicator therefore reducing the probability of unnecessary wake-ups. In order to improve reliability of quick paging procedure, the terminal actually uses two paging indicators per assigned quick paging slot. In case the quality of the first indicator is insufficient, it uses the additional energy of the second indicator to improve the quality of the decision benefiting from some extra time diversity.

The base station has access to the same hash function and knows exactly when to transmit the page indicator for a given terminal. The indicator itself, consists of a simple on/off bit (OOK modulation) informing the terminal whether it should go back to sleep immediately (when the bit is not present) or whether it should expect and try to decode a message on the F-CCCH (when the bit is present). Breaking up the paging procedure into a page indicator and a message part leads to a significant reduction in wake-up time when no message is transmitted to the terminal [3]. Since the frequency of mobile terminated calls is much lower than the slot cycle, nearly 100% of the page indicators are off and the net result of QPCH operation is a significant increase in the overall stand-by time. Note that while monitoring the F-QPCH, the terminal may also perform measurements in support of cell selection and other idle mode procedures.

When receiving multiple cells from the same paging area and thanks to the tight synchronization of neighboring cells, the terminal can combine the QPCH indicators and F-CCCH messages from multiple cells as if it were in soft handoff [5]. This obviously improves the efficiency of the paging procedure.

One special F-QPCH indicator repeats every 40 ms and contains a **Configuration Change Indicator**. This indicator enables terminals which recently visited a cell (e.g., Ping-Pong effect when travelling along a cell boundary) to quickly verify whether the system parameters have changed; if they haven't, the terminal can resume the QPCH monitoring procedure without decoding the overhead messages, thereby saving more battery life.

Up to now we have described overhead and common channel operations as defined in cdma2000. The terminal is able to operate within a network relying only on the common channel structure and associated procedures. However, the services offered through common channel operation are limited to short or bursty data exchange and do not include sustained data transmission such as long file transfer, email downloads, voice or video sessions. In order to operate efficiently such services, the system should establish a dedicated communication channel with the terminal, or in TIA/EIA-95 terminology a "traffic channel." The following sections describe the traffic channel structure and operation in more details.

XI. DEDICATED CHANNELS

Set-up of a dedicated channel is triggered either by the terminal upper layers or by the network through paging. Upon such event, the terminal initiates the traffic channel set-up by transmitting a request to the network using one of the access modes

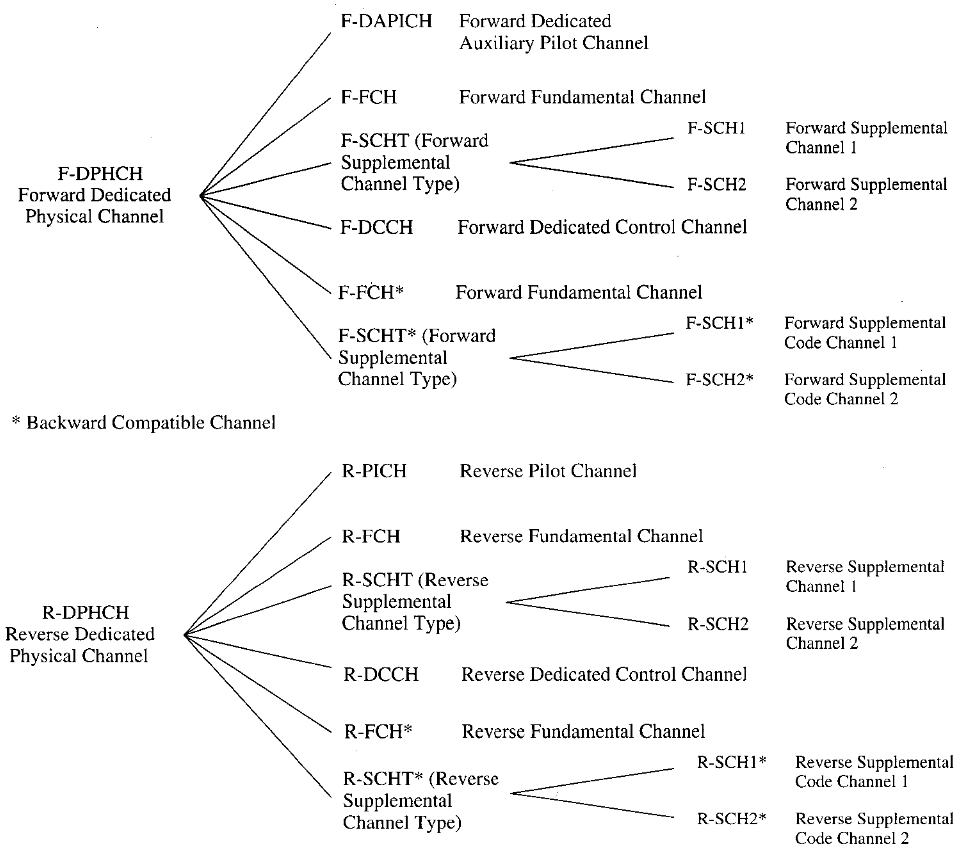


Fig. 7. cdma2000 dedicated channels.

described earlier. After the negotiation of various parameters—including service configuration (or service option, which refers to some pre-defined service configuration) through common channel signaling exchange—the network allocates one or several dedicated channels to the terminal (described together as forward traffic channel), and the terminal initiates the transmission of one or several reverse link channels (described together as reverse traffic channel). The structure of the dedicated channels is described in Fig. 7.

As we will show, the traffic channel structure and frame format is extremely flexible, and the number of possible combinations is almost infinite. In order to limit the signaling load that would be associated with a full frame format parameter negotiation, cdma2000 specifies a set of channel configurations which define a spreading rate and an associated set of frame formats for each configuration. The various channel configurations for both forward and reverse links are listed in Table 2 and Table 3 respectively. Fig. 8 shows the various coding parameters associated with FL radio configuration 9.

The cdma2000 forward traffic channel structure may include several physical channels as shown in Fig. 7. The **Fundamental Channel (F-FCH)** is equivalent in functionality to the TIA/EIA-95 Traffic Channel (TCH) and may transport medium rate data, voice or signaling multiplexed with one another at any rate from 750 bps to 14.4 kbps. The **Supplemental Channel(s) (F-SCH)** support high rate data services and may be allocated on a frame by frame basis, meaning the network may schedule transmission on the F-SCH on a frame by frame basis if desired. The F-SCH has the same functionality as the TIA/EIA-95-B supplemental code channel(s). The main difference lies in the offered peak rate (1 kbps to 1 Mbps) and rate granularity (any rate in the range allowed by the radio configuration). cdma2000 forward traffic channel may also include a **Dedicated Control Channel (F-DCCH)** in support of bursty user data or signaling. Finally the system may direct the terminal to use a **Forward Common or Dedicated Auxiliary Pilot Channel (F-CAPICH or F-DAPICH)** for channel estimation and power control if spot beam or directive antenna techniques are used in the base station. Note that the forward traffic channel always includes either a fundamental channel or a dedicated control channel. The reverse link power control information should be punctured on the F-FCH or F-DCCH when present and on the F-FCH when no F-DCCH is present. FL PC puncturing is described in the section on power control.

The main benefit of this multi-channel forward traffic structure is the flexibility to independently set-up and tear down new services without any complicated multiplexing reconfiguration or code channel juggling. The addition of a dedicated control channel allows for sending the signaling information without any impact on the parallel data stream. This avoids dim and burst or blank and burst which depending on the signaling activity might not be acceptable for some services. The structure also allows different handoff configurations for different channels. For example, the F-DCCH, which carries critical signaling information, may be in soft-handoff while the associated F-SCH operation could be based on a best cell strategy.

Table 2. Radio configuration characteristics for the forward traffic channel.

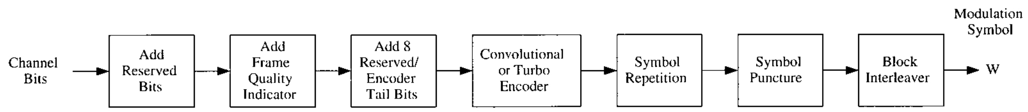
Radio Configuration	Associated Spreading Rate	Data Rates, Forward Error Correction, and General Characteristics
1	1	1200, 2400, 4800, and 9600 bps data rates with $R = 1/2$, BPSK pre-spreading symbols
2	1	1800, 3600, 7200, and 14400 bps data rates with $R = 1/2$, BPSK pre-spreading symbols
3	1	1500, 2700, 4800, 9600, 19200, 38400, 76800, and 153600 bps data rates with R = 1/4, QPSK pre-spreading symbols, TD allowed
4	1	1500, 2700, 4800, 9600, 19200, 38400, 76800, 153600, and 307200 bps data rates with $R = 1/2$, QPSK pre-spreading symbols, TD allowed
5	1	1800, 3600, 7200, 14400, 28800, 57600, 115200, and 230400 bps data rates with $R = 1/4$, QPSK pre-spreading symbols, TD allowed
6	3	1500, 2700, 4800, 9600, 19200, 38400, 76800, 153600, and 307200 bps data rates with $R = 1/6$, QPSK pre-spreading symbols.
7	3	1500, 2700, 4800, 9600, 19200, 38400, 76800, 153600, 307200, and 614400 bps data rates with $R = 1/3$, QPSK pre-spreading symbols.
8	3	1800, 3600, 7200, 14400, 28800, 57600, 115200, 230400, and 460800 data rates with $R = 1/4$ (20 ms) or $1/3$ (5 ms), QPSK pre-spreading symbols.
9	3	1800, 3600, 7200, 14400, 28800, 57600, 115200, 230400, 460800, and 1036800 bps data rates with $R = 1/2$ (20 ms) or $1/3$ (5 ms), QPSK pre-spreading symbols.

Note: For radio configurations 3 through 9, the forward dedicated control channel and forward fundamental channel also allow a 9600 bps, 5 ms format.

Table 3. Radio Configuration characteristics for the reverse CDMA channel.

Radio Configuration	Associated Spreading Rate	Data Rates, Forward Error Correction, and General Characteristics
1	1	1200, 2400, 4800, and 9600 bps data rates with $R = 1/3$, 64-ary orthogonal modulation
2	1	1800, 3600, 7200, and 14400 bps data rates with $R = 1/2$, 64-ary orthogonal modulation
3	1	1200, 1350, 1500, 2400, 2700, 4800, 9600, 19200, 38400, 76800, and 153600 bps data rates with $R = 1/4$, 307200 bps data rate with $R = 1/2$, BPSK modulation with a pilot
4	1	1800, 3600, 7200, 14400, 28800, 57600, 115200, and 230400 bps data rates with $R = 1/4$, BPSK modulation with a pilot
5	3	1200, 1350, 1500, 2400, 2700, 4800, 9600, 19200, 38400, 76800, and 153600 bps data rates with R = 1/4, 307200 and 614400 bps data rate with $R = 1/3$, BPSK modulation with a pilot
6	3	1800, 3600, 7200, 14400, 28800, 57600, 115200, 230400, and 460800 bps data rates with $R = 1/4$, 1036800 bps data rate with $R = 1/2$, BPSK modulation with a pilot

Note: For radio configurations 3 through 6, the reverse dedicated control channel and reverse fundamental channel also allow a 9600 bps, 5 ms format.



Bits/Frame	Bits	Bits	Data Rate (kbps)	R	Factor	Deletion	Symbols	Rate (ksps)
24 Bits/5 ms	0	16	9.6	1/3	1x	None	144	28.8
21 Bits/20 ms	1	6	1.8	1/2	8x	None	576	28.8
55 Bits/20n ms	1	8	3.6/n	1/2	4x	None	576	28.8/n
125 Bits/20n ms	1	10	7.2/n	1/2	2x	None	576	28.8/n
267 Bits/20n ms	1	12	14.4/n	1/2	1x	None	576	28.8/n
552 Bits/20n ms	0	16	28.8/n	1/2	1x	None	1,152	57.6/n
1,128 Bits/20n ms	0	16	57.6/n	1/2	1x	None	2,304	115.2/n
2,280 Bits/20n ms	0	16	115.2/n	1/2	1x	None	4,608	230.4/n
4,584 Bits/20n ms	0	16	230.4/n	1/2	1x	None	9,216	460.8/n
9,192 Bits/20n ms	0	16	460.8/n	1/2	1x	None	18,432	921.6/n
20.712 Bits/20n ms	0	16	1,036.8/n	1/2	1x	2 of 18	36,864	1,843.2/n
1 to 20.711 Bits/20n ms	0							

Fig. 8. Channel structure for FL RC9.

Besides peak rate increase and improved rate granularity, the major improvement to the traffic channel coding (both forward and reverse) is the additional support of turbo coding at rate 1/2, 1/3, or 1/4. The turbo code is based on an eight-state parallel structure and can only be used for supplemental channels and frames including more than 360 bits. Turbo coding provides a very efficient scheme for data transmission and leads to significant link performance and system capacity improvements.

Fig. 8 illustrates the channel structure for FL RC9. In this example, the frame size can be 20, 40, or 80 ms ($n = 1, 2, 4$) for F-SCH and only 20 ms ($n = 1$) for F-FCH. Turbo coding can be applied when the number of bits per frame is higher than 552.

When the number of bits per frame does not correspond to one of the predefined frame formats, cdma2000 defines a set of simple rules to derive an appropriate frame format based on the closest pre-defined format.

The reverse traffic channel structure is similar to the forward traffic channel and is illustrated in Fig. 7 and Fig. 4. In addition to the R-PICH the reverse link also includes a **Fundamental Channel (R-FCH)** and/or as a **Dedicated Control Channel (R-DCCH)** as well as one or several **Supplemental Channel(s)**

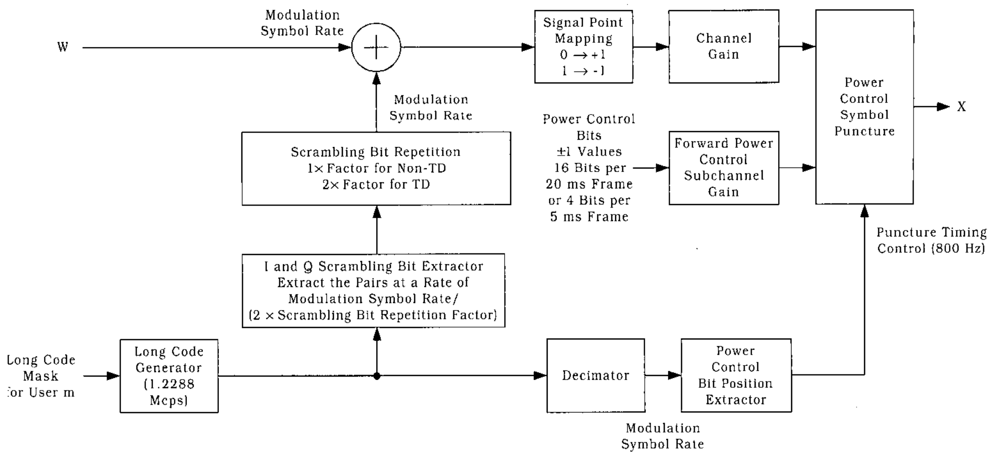


Fig. 9. Long code scrambling and PC puncturing for SR1 FL.

(R-SCH). Their functionality and encoding structure is the same as for the forward link with data rates ranging from 1 kbps to 1 Mbps. As already mentioned, this is a major departure from the TIA/EIA-95 structure that was based on a non-coherent Walsh modulation, which could not be directly processed coherently. Although the overhead introduced by the R-PICH decreases the benefit for low rate services, it is certainly a much better solution when considering higher bit rates, where the R-PICH overhead becomes very low compared to the gain of true coherent demodulation. The relative power allocated to R-PICH and data channels is a trade-off between the quality of the channel estimate and power control decision and the R-PICH overhead [6]. cdma2000 therefore specifies the optimum power offset relative to R-PICH power for each possible combination of transmission rate, interleaving length, and coding scheme.

In order to enhance battery life and channel capacity there are two gating modes supported by cdma2000 [7]. The first is typically used for voice operation and allows gating when operating in the 1/8th rate or lower rate mode. This mode is used when the terminal user is not speaking and has the mobile station transmit at a 50% duty cycle using 2.5 ms on and 2.5 ms off periods. A second gating mode is typically used with data operation when the R-DCCH is used and neither the terminal nor the access network has data to send. In this case, when the R-DCCH is not being used, the R-PICH is transmitted with 50% or 25% duty cycle. Although these techniques result in a less accurate channel estimation at the base station and poorer power control, the overall system capacity and battery life is improved when using these techniques.

XII. DEDICATED CHANNEL POWER CONTROL

Unlike TIA/EIA-95 where **Fast Closed Loop Power Control** was applied only to the reverse link, both cdma2000 channels can be power controlled at up to 800 Hz in both reverse and forward directions. The reverse link power control commands are punctured into the F-FCH or the F-DCCH depending on the service configuration. The forward link power control commands are punctured in the last quarter of the R-PICH power control slot. When gated transmission is used in the reverse link, the power control rate is reduced to 400 or 200 Hz on both links. The reverse link power control subchannel may also be divided into two independent power control streams, either both at 400 bps, or one at 200 bps and the other at 600 bps. This allows for independent power control of forward channels which are in different handoff configurations (as described earlier), essentially the channels in soft-handoff and those not in soft-handoff.

The introduction of fast forward link power control improves the link performance by several dBs depending on channel conditions. If the statistical multiplexing of the FL channels is sufficient, the gain in the link margin translates directly into an equivalent system capacity gain. However, if statistical averaging is not sufficient—for example when the base station only transmits to one user with very high data rate—the high dynamic range of the FL signal may result in PA inefficiencies and system instabilities due to the coupling with neighboring cells. In order to avoid any catastrophic instability the network may then limit the power dynamic range of the high rate channels. Alternatively it may also use the EIB (Erasure Indicator Bit) and QIB (Quality Indicator Bit) slow (50 Hz) quality control loop schemes. The EIB method is based on the quality indicator field of the F-FCH; the terminal sends back one bit per frame to the network indicating whether the CRC checked or not. The QIB method is similar but considers both the frame quality indicator field and power level estimation; moreover the QIB method can also be based on the F-DCCH when no F-FCH is transmitted.

The PC bit puncturing on the RL was described earlier. Fig. 9 illustrates the long code scrambling (similar to TIA/EIA-95) and PC bit puncturing for SR1 FL. W represents the coded bit input and X is the input to IQ mapping and spreading. The PC bit position is randomized based on the decimated long code value and punctured into either the F-FCH or F-DCCH.

In addition to the closed loop power control, the power on the reverse link of cdma2000 is also controlled through an **Open Loop Power Control** mechanism. This mechanism, which exists also in TIA/EIA-95, inverses the slow fading effect (path loss, shadowing) and acts as a safety fuse when the fast power control fails. When the forward link is lost, the closed loop reverse link power control is freewheeling and the terminal disruptively interferes with neighboring cells (e.g., turn a corner, loose the FL, and blast a new cell). In such case, the open loop reduces the terminal output power as it gets closer to any cell (i.e., sees additional power or reduced path loss) and therefore limits the impact to the system.

Finally the **Outer Loop Power Control** is driven by QoS requirements and drives the closed loop power control to the desired set point based on error statistics it collects from the supervised link (forward or reverse). It is worth noting that due to the expanded data rate range and various QoS requirements, different users will have a different outer loop thresholds, i.e., different users will be received with different power at the base station. This is different from TIA/EIA-95 where all users used one of the two rate sets and would be received with similar powers at the base station. One difficulty associated with such broad rate range appears in variable configurations when switching between rates. The required SIR value is not necessarily proportional to the data rate ratio and changing rates may imply changing the QoS if the channel gain is not adapted accordingly. In the forward link, this issue is left for the manufacturer to solve. In the reverse link, cdma2000 defines some nominal gain offsets based on various channel frame format and coding schemes. The remaining differences (depending on radio environment) will be corrected by the outer loop itself.

XIII. HANDOVER

In parallel to dedicated channel operation, the terminal keeps searching for new cells as it moves across the network. In addition to the active set, neighbor set and remaining set already introduced earlier when describing the idle mode operation, the terminal also maintains a **Candidate Set**. The procedure for adding and removing cells from the active set is also different from idle mode operation since the active set may include several cells. In the following we will focus on the dynamic threshold handover criteria noting that cdma2000 also supports the TIA/EIA-95A handover procedure.

Fig. 10 provides an example of handover sequence. At time 1, the neighbor pilot (P2) strength gets above the minimum threshold T_ADD for addition in the active set. However, its relative contribution to the total received signal strength is not sufficient and the terminal simply moves P2 to the candidate set. The actual decision threshold for adding a new pilot to the active set is defined by a linear function of signal strength of the total active, in dB. The network defines the slope and cross point of the function. At time 2, the strength of P2 is detected to be above the dynamic threshold and the terminal signals this event to the network. At time 3, the terminal receives a handoff direction message from the network requesting the addition of P2 in the active set. The terminal now operates in soft-handoff. At time 4, the strength of P1 drops below the active set threshold (meaning P1 contribution to the total received signal strength is not worth the cost of transmitting P1) and the terminal starts a handoff drop timer. At time 5, the timer expires and the terminal notifies the network that P1 dropped below the threshold. At time 6, the terminal receives a handoff message form the network moving P1 from the active set to the candidate set. At

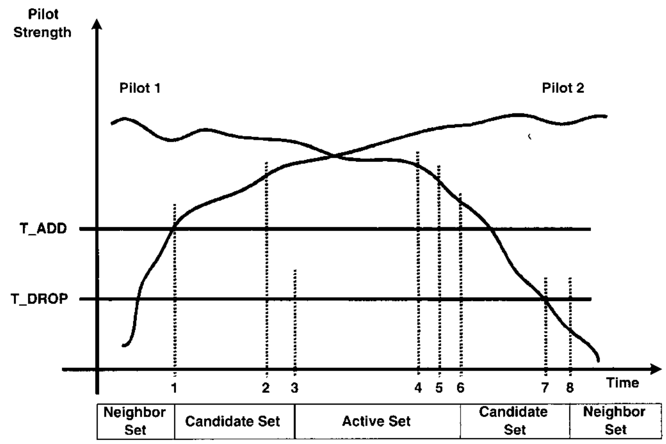


Fig. 10. Example of handover sequence.

time 7 P1 strength drops below T_DROP and the terminal starts a handoff drop timer, which expires at time 8. P1 is then moved from candidate set to neighbor set. This step by step procedure with multiple thresholds and timers ensures that the pilots are not constantly added and removed from the various lists and therefore, limits the associated signaling. It also ensures that system resource is only used when beneficial to the link.

In addition to intra-system, intra-frequency monitoring, the network may direct the terminal to look for base stations on a different frequency or even on a different system [8], [9]. A very special case of such handover measurement is when moving from a cdma2000 to a TIA/EIA-95 only coverage area or the opposite. The handover can then be either intra frequency if cdma2000 SR1 is used or inter-frequency. As described in cdma2000, the network provides a framework to the terminal in support of the inter frequency handover measurements. This consists in identity and parameters of the system to be measured and frequency of reporting. Within this framework, the terminal is free to perform the required measurements as allowed by its hardware capability. In case of a terminal with dual receiver structure, the measurement can be done in parallel. In case of a terminal with single receiver, the channel reception will be interrupted when performing the measurement. During the measurement, a certain portion of a frame will therefore be lost. The terminal may or may not be able to decode the damaged frame based on the remaining information. In order to improve the chance of successful decoding, the terminal is allowed to bias the FL power control loop and boost the RL transmit power before performing the measurement, therefore increasing the energy per information bits and reducing the risk of loosing the link in the interval. The network does not fully control the behavior of the terminal. This liberal approach to inter-frequency measurement allows terminal manufacturers to immediately (i.e., without any standard update) benefit from technological advances that allow them to reduce the measurement periods. This technique is illustrated in Fig. 11 for the forward link direction.

Based on measurement reports provided by the terminal, the network then decides whether to handoff a given terminal to a different system of frequency. It does not necessarily (network dependent) release the resource until it receives confirmation

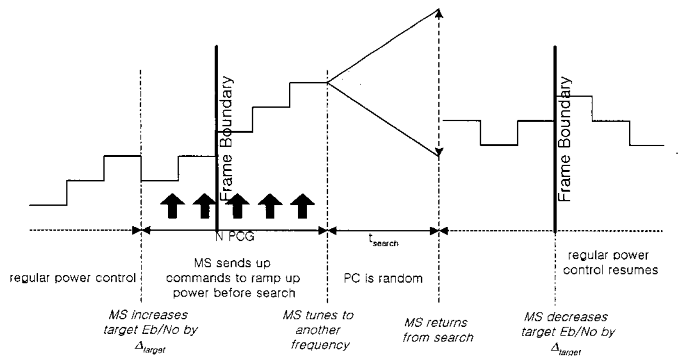


Fig. 11. Forward Link Tx power during HHO measurement.

that handoff was successful or a timer expires. This enables the terminal to come back in case it could not acquire the new frequency or the new system. This handoff failure recovery mechanism is already part of TIA/EIA-95-B specification.

XIV. PERFORMANCE

Performance evaluation of TIA/EIA-95 systems has been very controversial. With the addition of multiple additional modes, channels and frame structures as well as the variety of services and related QoS supported by its architecture, proper evaluation of cdma2000 performance will probably constitute an endless source of discussion in the future. Although the intent of this article is not to provide quantitative estimations of the performance of cdma2000, it is worth noting that based on the different improvements made to the channel structure, cdma2000 is expected be twice as efficient as TIA/EIA-95 for the same voice service, not taking into account gains offered by transmit diversity techniques. The performance for higher rate data services will further benefit from the improved coding scheme and longer interleaving spans offered by cdma2000.

XV. CONCLUDING REMARKS

We have described the cdma2000 physical layer structure and associated procedure and pointed out some of the improvements as compared to the TIA/EIA-95 systems. We can characterize cdma2000 as offering:

- additional connectivity (IP, IS-41, GSM-MAP);
- additional capability (new bands, higher rates, support of multiple services);
- more flexibility (multiple deployment options, new channel structure);
- improved performance due to
  - increased capacity (improved coding, coherent reverse link, fast forward power control, transmit diversity, enhanced access),
  - increased terminal battery life (quick paging, gated transmission).

cdma2000 offers an efficient third generation multi-purpose platform that can be the basis or the common denominator on top of which operators could consider more focused extensions. One example of such extension is the HDR (High Data Rate) concept recently introduced by QUALCOMM, which improves the radio efficiency of cdma2000 by specifically optimizing the access technology and procedures for IP services [10].

ACKNOWLEDGMENT

The author would like to thank Jack Holtzman, Stein Lundby, Joe Odenwalder and Edward Tiedemann for their help and comments on the article.

ACCESS TO STANDARD DOCUMENTS

Electronic copies of the cdma2000 release A ballot version can be obtained from the ITU website at http://www.itu.int/imt/2_rad_devt/rspc/CDMA_MC/index.html. This page will be updated with the published version once approved by 3GPP2. All other standard documents referenced in this article can be obtained from the TIA (http://www.tiaonline.org) or from SDO members of 3GPP2 (http://www.3gpp2.org).

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Serge Willenegger received the "Telecommunications Engineer" degree from the Swiss Federal Institute of Technology, Lausanne (EPFL) in 1995. From 1994 to 1995 he studied at the Eurecom Institute, France where he specialized in Mobile Communications.

In 1995 he joined QUALCOMM where he is now a Sr. Staff Engineer and leads QUALCOMM's technical participation in 3GPP-RAN standardization groups. Prior to this, he has been involved in the design of various improvements to TIA/EIA-95 systems. In particular, he worked on coherent reverse link detection and pilot based reverse link structures now adopted in CDMA based 3G standards. He holds or has applied for several patents in these areas. More recently he participated in the 3G harmonization discussions which led to the OHG agreement. He is a member of IEEE Communications Society.