TOPICS IN PCS

Evolution of Wireless Data Services: IS-95 to cdma2000

Douglas N. Knisely, Sarath Kumar, Subhasis Laha, and Sanjiv Nanda

Lucent Technologies

ABSTRACT Existing IS-95-based CDMA systems support circuit-mode and packet-mode data services at a data rate limited to 9.6–14.4 kb/s. Fueled by the explosive growth of the Internet, applications and market opportunities are demanding that higher capacity, higher data rates, and advanced multimedia services be supported in the near future. The evolution of the IS-95 CDMA standard to higher data rates and more advanced services occurs in two steps. The first step, IS-95-B, is an enhancement to the IS-95-A standard and offers the highest possible performance without breaking current IS-95-A air interface design characteristics, thereby maintaining strict compatibility with existing base station hardware. The proposed standard will support a high data rate (64 kb/s) in both directions, to and from the mobile device. A new burst mode packet data service is defined to allow better interference management and capacity utilization. The second evolution step, cdma2000, provides next-generation capacity, data rates, and services. The cdma2000 system includes a greatly enhanced air interface supporting CDMA over wider bandwidths for improved capacity and higher data rates while also maintaining backward compatibility with existing IS-95 CDMA end-user devices. The cdma2000 system also includes a sophisticated MAC feature to effectively support very-high-data-rate services (up to 2 Mb/s) and multiple concurrent data and voice services. This article describes the design and performance of the high-data-rate service provided by second- and third-generation CDMA systems.

The explosive growth of the Internet and the continued dramatic increase in demand for all types of wireless services (voice and data) are fueling the demand for large increases in capacity, data rates, and supported services (e.g., multimedia services). An additional market force that is driving higher data rates over wireless is the "International Mobile Telecommunications in the year 2000" (IMT-2000) international standards development process in the International Telecommunication Union (ITU). The IMT-2000 initiative is defining the long-term technology requirements for next-generation data and voice services that will be supported in new as well as existing (e.g., cellular and personal communications services, PCS) frequency bands.

THE CURRENT STATE OF IS-95 DATA SERVICES

Existing Telecommunications Industry Association (TIA) standards support a wide range of data services in IS-95-A-based [1] code-division multiple access (CDMA) second-generation wireless systems. TIA IS-707 [2] provides the capability of transmitting circuit-switched asynchronous and packet data at a raw data rate of up to 9.6 kb/s or 14.4 kb/s. Many vendors are aggressively developing a wide range of wireless infrastructure equipment and end-user subscriber devices that support these standards. Many wireless data applications that do not need higher data rates will operate efficiently and economically using these systems. Examples of these applications are sending and receiving faxes, simple asynchronous connections to host computers, simple Internet access, and short transaction applications (e.g., vending machine and credit card transactions).

HIGHER DATA RATE SERVICE REQUIREMENTS

Requirements for CDMA high-speed data (HSD) services are specified in terms of supported applications, HSD bearer services, and priorities. Table 1 summarizes the HSD applications and market priorities for those applications. These results are derived from the deliberations of the CDMA Development Group (CDG) and the TIA on requirements of HSD applications. Some conclusions can be reached from these requirements and priorities:

- Higher data rates for *packet data services* (e.g., wireless Internet access) are much higher in priority than for circuit-switched services.
- HSD rate requirements for fully mobile environments are lower than for *fixed* and *semi-mobile environments*.
- The *time to market* for long-term HSD rates is established by IMT-2000 international standards requirements (standards by 1999; products by 2000–2001).

The high data rates promised by third-generation technology will play an important role in enabling mobile operators to offer a broader range of services. Four generic types of services have been identified:

- Basic and enhanced voice services, including applications such as audio conferencing and voice mail
- Low-data-rate services supporting messaging, e-mail, facsimile, and so on
- Medium-data-rate services for file transfer and Internet access at rates on the order of 64–144 kb/s
- High-data-rate services to support high-speed packet and circuit-based network access and to support high-quality video conferencing and networked computing applications at rates higher than 64 kb/s (to 2 Mb/s)

In addition to the above generic service types, the third-generation wireless networks will deliver *multimedia* services, which provide concurrent video, audio, and data services to support advanced interactive applications. These services are also capable of supporting different quality of service (QoS) requirements for different applications.

THE EVOLUTION OF IS-95 TO CDMA2000

The IS-95[1] system has been deployed worldwide because of its superior voice quality, robust performance, and large air interface capacity. Therefore, it is only natural that the design of the next-generation air interface would build on this proven second-generation air interface and would be backward compatible to current IS-95 networks to protect the large capital investment in the already deployed base of networks. The

---

[1] *The term* IS-95 *in this article refers to the already completed* IS-95-A *and* IS-95-B *standards.*

0163-6804/98/$10.00 © 1998 IEEE

third-generation evolution of IS-95, known as cdma2000, uses wideband CDMA technology to meet and exceed all the requirements of IMT-2000. Moreover, cdma2000 provides a graceful transition from second-generation IS-95 systems. Service providers can gradually build up cdma2000 networks in a seamless fashion in selected areas where additional capacity and advanced services are needed.

Two standards and product development phases have been chosen within North American standards activities based on the end date for long-term products (driven by ITU IMT-2000 requirements) as shown in Table 2.

Phase 1 is embodied in the IS-95-B [3] enhancements to IS-95 standards offering backward compatible HSD services, and *Phase 2* is addressed by the cdma2000 [4] third-generation CDMA standard.

The goal of this article is to present this phased evolution of wireless data services. The article points out the general principles and characteristics that are equally applicable to IS-95-B and cdma2000 systems, as well as the enhancements that distinguish cdma2000 from IS-95-B. The following section provides a high-level description of the underlying physical layer that serves as the foundation for the wireless data services. A new burst-mode capability that is the basis of the CDMA high-data-rate packet services is presented, and the layering architecture in IS-95-B and cdma2000 that facilitates an efficient implementation is described. The IS-95-B packet data medium access control (MAC) layer that utilizes the services of the physical layer and the capabilities of the burst mode is described next. This simple MAC layer, although adequate for the moderate data rates of IS-95-B, is inadequate to meet the aggressive demands of very-high-data-rate services. The cdma2000 system, therefore, incorporates a much more sophisticated MAC layer, as reported herein. The resulting data services have performance trade-offs that are mostly common to both IS-95-B and cdma2000 systems. Those trade-offs are presented in the final section.

Application	Priority for mobility types		
	Mobile	Semi-mobile	Fixed
World Wide Web/Internet access	Medium	High	High
Database access	High	High	High
File transfer	Medium	High	High
Electronic mail	Medium	High	High
Broadcast data	Medium	Medium	Medium
Videotelephony	Medium	Medium	Medium
Program sound	Low	Low	Low
Asynchronous circuit data	Medium	Medium	Medium
Rate-adapted V.120 ISDN service	Low	Low	Medium
Group 3 fax (faster than 14.4 kb/s)	Medium	Medium	Medium

Definition of terms

Mobile: Able to be performed with full high-speed capabilities up to vehicular speeds (100 km/h)

Semi-mobile: Able to be performed from any location; however, high-speed access is required only while the MT device is stationary; service may degrade in performance significantly at higher velocities

Fixed: Able to be performed from a single, predefined fixed location (e.g., wireless loop)

■ **Table 1**. *High-speed data applications and market priorities.*

RADIO TRANSMISSION TECHNOLOGY

This section first outlines the HSD-related enhancements of IS-95-Bradio transmission technology (RTT). It then delineates the salient features of the cdma2000 physical layer that provide for higher data rates and better spectral efficiencies than IS-95-B. The cdma2000 system also provides a better MAC functionality that is discussed in detail later.

Phase 1	100% compatibility with existing IS-95-A-based deployments (including base station hardware).
	Extend high-speed data performance to the maximal extent possible without breaking infrastructure hardware compatibility.
Phase 2	Backward compatible with IS-95-A end-user devices (e.g., mobile phones).
	Meet TIA long-term requirements.
	Satisfy ITU IMT-2000 technology requirements.

■ **Table 2**. *Standards and product development phases for North American standards activities.*

ENHANCEMENTS OF IS-95-B FOR HSD

IS-95-B [3] offers high-speed service without changing the physical layer of IS-95-A. High-speed service is provided through code aggregation: up to eight codes may be assigned to a high-speed packet-data-capable mobile for the duration of a burst. An active high-speed packet data mobile always has the *fundamental code channel*. When higher data rates are needed, the mobile could be assigned up to seven *supplemental code channels*. The period of higher-speed operation is referred to as *data burst* in this article. The new service option could be *asymmetric* (i.e., the high-speed packet data mobile *may be capable of different bandwidths in the forward and reverse directions*). The enhancements in IS-95-B that enable HSD service are as follows:

- *Forward code channels:* Up to eight Walsh codes (1 Walsh code per code channel) are assigned for the data burst to the high-rate user.
- *Reverse code channels:* Each reverse supplemental channel is assigned a different pseudo noise (PN) sequence mask derived from its fundamental PN sequence mask. Each mask corresponds to a different PN sequence shift.
- *Power control:* Power control for the supplemental code channels is derived from the fundamental code channel. That is, there is no independent power control loop for the supplemental code channels.
- *Permitted code rates:* During a data burst, all the code channels are transmitted at full rate; partial rates are not permitted.

User Data Rates Supported by IS-95-B — Because up to eight forward or reverse code channels can be assigned simultaneously to a single user, and each code channel operates at 9.6 kb/s using Rate Set 1 (RS1) or 14.4 kb/s using RS2, the data rates offered by IS-95-B are:

- 9.6–76.8 kb/s at RS1
- 14.4–115.2 kb/s at RS2

ENHANCEMENTS OF THE CDMA2000 PHYSICAL LAYER

In order to be backward compatible with IS-95 networks, the cdma2000 [4] radio interface retains many of the attributes of the IS-95 air interface design. As mentioned above, in IS-95-B higher data rates are provided through code aggregation. In cdma2000, higher rates are achieved through either reduced spreading, or multiple code channels. In addition, there are a number of major enhancements in the cdma2000 physical layer that facilitate advanced data services with higher rates and improved capacity. Table 3 contrasts the enhancements with those in IS-95.

The major attributes of cdma2000 are summarized below:

- *Wideband:* Wider channel bandwidth of 5 MHz and beyond offers higher statistical multiplexing gain among multiple users as well as a higher single-user data rate.
- *Supplemental code channel (SCC):* A wide range of data rates (9.6 kb/s–2 Mb/s) is supported over each SCC. In cdma2000, one SCC is assigned per data service. Multiple SCCs can be used to support multiple data streams with different QoS requirements (such as packet data and circuit data services). In IS-95-B, one high-data-rate mobile is assigned up to seven SCCs, each running at 9.6 or 14.4 kb/s.
- *Pilot-based coherent detection:* The incorporation of a pilot channel on the reverse link offers significant performance gain by providing a coherent phase reference for coherent demodulation at the base station (BS). It also reduces the power control loop delay.
- *Fast forward power control:* This forward link feature (800 power updates/s) provides significant performance improvement in the low-mobility environment where most of the high-data-rate applications will occur. Only the reverse link of IS-95 uses fast power control (800 updates/s) to combat the near/far problem.
- *Forward link transmit diversity:* Two spreading options are specified in cdma2000 [4] for the forward link: multicarrier and direct spread. In the multicarrier option with N carriers of 1.25 MHz each ($N = 3, 6, 9, 12$), the different carriers can be transmitted over spatially separated antennas. This increases the effective frequency diversity and provides improvement in link performance without incurring additional complexity at the mobile receiver.
- *Turbo codes:* Turbo codes could be used instead of convolution codes at higher data rates to lower the operating E_b/N_0 value of the receiver, resulting in increased system capacity.
- *Auxiliary pilot channel:* On the forward link, additional pilot channels can be provided for a single mobile or a group of mobiles that are within the same narrow beam. This is of particular interest in systems that employ smart antennas and in wireless local loop applications.

The standardization process for cdma2000 is ongoing. The above attributes are yet to be finalized.

User Data Rates Supported by cdma2000 — Table 4 shows the single-user data rates supported by the cdma2000 physical layer for different channel bandwidths (given by $N \times 1.25$ MHz where N is the number of 1.25 MHz carriers).

This wide range of data rates supports various applications ranging from voice and low-speed data to high-speed packet and circuit data access, described earlier. In addition, cdma2000 also offers a very flexible air interface to support a wide range of operating environments. It meets and exceeds the following requirements of IMT-2000 for data rates in different environments:

- Indoor to 2 Mb/s
- Indoor to outdoor/pedestrian to 144 to 384 kb/s
- Vehicular to 144 kb/s

Feature	IS-95	cdma2000
RF channel bandwidth (MHz)	1.25	1.25/5/10/15/20
Chip rate (Mchips/s)	1.2288	1.2288/3.6864/7.7328/ 11.0592/14.7456
Single-user data rate (kb/s)	9.6–115.2	9.6K–2.4M[1]
Supplemental code channel (SCC)	0–7 SCCs @ 9.6/14.4 kb/s/SCC 0	0 or 1 SCC per Service @ 9.6 kbps up to 2 Mb/s
Frame length (ms)	20	20 (with a 5 ms option)
Modulation	BPSK modulation with quadrature spreading	QPSK modulation with quadrature spreading
Pilot-based coherent detection	Forward link: yes Reverse link: no	Forward link: yes Reverse link: yes
Channel coding	Convolution code, $K = 9$, rate 3/4, 1/2, and 1/3	Convolution code, $K = 9$, rate 1/3 and 1/4
Dedicated control channel	No	Yes
Fast forward power control	No	Yes
Forward link transmit diversity	No	Yes[3]
Use of turbo codes	No	Yes

[1] See "User Data Rates Supported by IS-95-B" for details.

[2] See "User Data Rates Supported by cdma2000" for details.

[3] For RF channel bandwidth 5 MHz or higher.

■ **Table 3.** *Physical-layer characteristics of IS-95 and cdma2000.*

BRIDGE BETWEEN IS-95-B AND WIDEBAND CDMA2000

The cdma2000 radio interface includes the option of 1.25 MHz channel bandwidth. This option provides an easy migration path from IS-95-B to wideband cdma2000 systems. Because the 1.25 MHz option has the same channel bandwidth as IS-95-A/B, this cdma2000 system can be very esily overlaid in the same frequency band with an existing IS-95-A/B system. The 1.25 MHz cdma2000 radio interface offers the benefits of doubling the system capacity (compared to IS-95-B) and providing higher single-user data rates in excess of 144 kb/s. It also enables more graceful migration to higher-bandwidth cdma2000 systems for higher-data-rate services in the future.

BURST MODE FOR CDMA

This section first presents the motivation for burst mode transmission for HSD packet data service, followed by a description of the approach. The general principles and approach described in the following subsections are equally applicable to IS-95-B and cdma2000. A specific implementation for an IS-95-B system is described later. cdma2000 procedures for HSD are not yet standardized, but are expected to be similar.

Channel bandwidth (MHz)	Forward data rates (kb/s)	Reverse data rates (kb/s)
1 x 1.25	9.6–307	9.6–307
3 x 1.25	9.6–1037	9.6–1037
6 x 1.25	9.6–2074	9.6–2074
9 x 1.25	9.6–2458	9.6–2074
12 x 1.25	9.6–2458	9.6–2074

■ **Table 4.** *Single-user data rates supported by cdma2000.*

THE NEED FOR BURST MODE

The advantages of CDMA for cellular voice are well known. Direct sequence spread spectrum can also be used to support higher-data-rate packet services, provided that the following technical challenges can be effectively addressed:

- Signal acquisition for packet access using spread spectrum incurs overhead and delay.
- Bandwidth spreading limits the permissible data rates in the limited wireless spectrum.
- In a reuse environment, dynamic time-division resource sharing across cells can be more efficient for high-data-rate services, compared to CDMA.

A new *burst mode* capability is defined that addresses the above issues. Static allocation of a high data rate (as in a circuit-mode call) to a small number of users can result in inefficient use of CDMA air interface capacity. Dynamic infrastructure-controlled burst allocation, based on aggregate load and interference measurements (see LIDA [5, 6]), makes it possible to efficiently share the bandwidth among several high-speed packet data mobiles without impacting the QoS to voice users. When low loads permit, the burst mode naturally permits a single user to be allocated a substantial fraction of a single cell capacity.

THE SOLUTION APPROACH

The technical challenges listed above are addressed through the burst mode as follows:

- Acquisition delays and overhead are minimized through the assignment of a low-overhead fundamental code channel (circuit) for acquisition and tracking even when idle.
- A single user is permitted to access the entire bandwidth by limiting the spreading. Different data rates and QoS for diverse user classes are managed through variable spreading gain, code aggregation, and channel coding. For the duration of the higher-data-rate burst transmission, in addition to the fundamental code channel, the mobile is assigned SCC(s).
- Efficient use of the RF spectrum with diverse user classes is handled in a distributed manner through the management of aggregate interference or transmit power (over time). This problem has greatly reduced dimensionality compared to dynamic slotted time-division access which requires resource management in the time, frequency, and reuse dimensions.
- The data rate at which the high-speed data user is permitted to transmit is a function of its current path loss and shadow fading conditions to its connected cell as well as neighbor cells. Since the interference environment changes dynamically due to user mobility, it is convenient to define a burst mode for packet data service. High-speed data users are allocated "short" high-data-rate bursts depending on the current interference, load, and path loss conditions.

At any given instant, depending on need and resource availability, a mobile may be assigned different bandwidths on the forward and reverse links. This helps to maximize the efficient use of bandwidth in both directions. Burst allocation on either the forward or reverse link is handled by examining power and interference constraints, and through the use of interference measurements and path loss information gathered from the distributed mobiles and neighbor BSs. Based on computation of the in-cell and out-of-cell interference caused by a high-data-rate user, MAC procedures have been designed to allow burst access at higher data rates, based on the following (see [5–8]):

- The load information in the cell and its neighbors
- The number of legs in soft handoff
- The pilot strength measurements provided by the mobile
- Coordination of the burst rate, burst length, and burst starting time between neighbor cells

Simplified schemes that limit the amount of communication required for burst allocation are also described in references [7, 8]. For example, on the forward link the interference constraint can be translated into a transmit power constraint, and the network can implement a centralized scheduled power allocation to multiple users that guarantees efficient bandwidth utilization. Bandwidth coordination between distributed users is more challenging on the multiple access reverse link. Thus, in the burst mode the infrastructure dynamically assigns higher data rates to requesting users. QoS is handled according to service requirements through power control with a target FER or target E_b/N_0, or by varying the channel coding.

A GENERAL DESCRIPTION OF BURST MODE

High-speed data users are allocated "short" high-data-rate bursts depending on the current interference, load, and path loss conditions. The general features of burst-mode data transfer are:

- An active high rate mobile is assigned a fundamental code channel on origination. Parameters of the high-data-rate service are negotiated at that point. The mobile then goes into a quiescent mode if it has no data to transmit. When a user is quiescent for a short duration, low-rate channels may be maintained for synchronization and power control. In addition, the assigned channel serves as a fast, dedicated signaling channel for requests for and assignment of high-data-rate bursts. Higher data rates are assigned on a demand basis through explicit negotiation between the mobile and the infrastructure.
- On the reverse link, the mobile may signal to request a high-data-rate burst transmission by indicating to the BS its data backlog and the maximum data rate requested. In addition, to assist the BS in deciding if this burst request can be accepted without affecting QoS for other users, the mobile includes pilot strength information for cells in its neighbor list within the access request. The pilot strength measurements received from the mobile indicate to the BS the interference levels which will be seen at that BS and its neighbors due to transmissions from the mobile.
- For forward link burst transmissions as well, the BS may request the mobile to report pilot strength measurements prior to burst allocation. The network can use these measurements to determine the interference seen at the

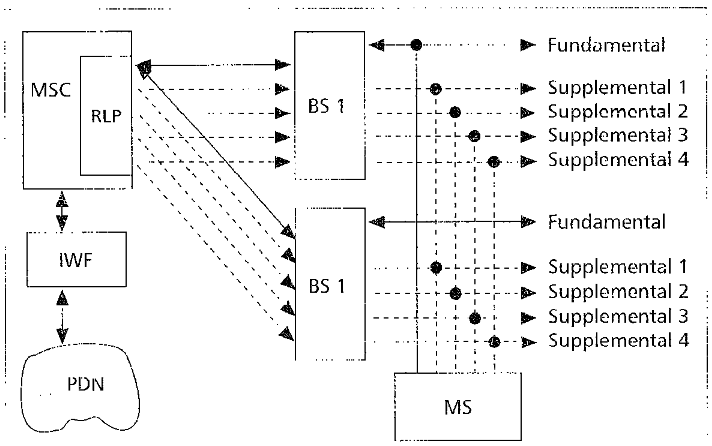


Figure 1. *Architecture diagram describing a mobile (MS) in HSD mode in soft handoff with cells BS1 and BS2 and connected to a switching center (MSC).*

mobile, and exploit light loading in neighbor cells. Pilot strength measurements may also be used by the network to choose a subset of legs to allocate for higher-data-rate burst transmission to the mobile.

- Once the burst request is received at the BS, the network must coordinate access with other burst requests as well as with the voice load already offered to the system. Access control mechanisms using the Burst Admission based on Load and Interference (BALI) [7] procedure can be defined, with varying amounts of complexity. The simplest procedures can be implemented autonomously at each BS. More general procedures require access coordination between neighbor BSs, including instantaneous loading information about neighbor cells.

THE BURST MECHANISM IN IS-95-B

Figure 1 illustrates the system architecture for data services. The figure shows a mobile in soft handoff with two BSs. In soft handoff, the mobile communicates on the fundamental code channel simultaneously with BS1 and BS2. During burst transmission, one or more supplemental code channels are assigned at BS1 or BS2 or both. (In the example, four forward supplemental code channels are assigned at both BS1 and BS2). The mobile switching center (MSC) performs the role of distribution (on the forward link) and selection combining (reverse link) of the signal to/from soft-handoff legs. The radio link protocol (RLP) at the MSC provides reliable transmission mechanism to the upper layers through automatic repeat request (ARQ). The interworking function (IWF) provides an access point to the packet data network (PDN).

Reverse Link Burst Scenario — Figure 2 shows an example of a successful mobile-originated reverse link burst transmission scenario. The mobile remains in the dormant state when there is no data to transmit. When there is backlogged data, the mobile goes into active mode. Subsequently, when the backlogged data exceeds a threshold, the mobile sends a supplemental channel request message (SCRM) to the BS/MSC on the fundamental code channel. The BS/MSC uses the pilot strength measurements reported in the SCRM along with reverse channel load to make burst admission control decisions, as discussed later. Based on the outcome of such admission control, the BS/MSC sends a supplemental channel assignment message (SCAM) on the fundamental code channel. The SCAM specifies the burst length, the number of codes assigned, and the start time of the burst.

The BS/MSC may reject a request by sending a SCAM message with no assignment and a retry delay parameter, which informs the mobile that it may retry its request at a later time. The BS/MSC may also use a SCAM with the number of codes set to zero, to *preemptively terminate* an assigned burst, if, for example, the RF conditions change or the resources need to be preempted by other higher-priority services. The mobile may request extension of an assigned burst by sending another SCRM prior to the end of the assigned burst. If all of the buffered data in the mobile is transmitted before the end of the negotiated burst period, the mobile should send a SCRM (with backlog set to zero) to allow the system to allocate its resources to other users.

Forward Link Burst Scenario — When backlogged data at the IWF exceeds a predefined threshold, and the mobile already has a fundamental code channel, the IWF initiates a request to the BS/MSC, which determines burst admission based on the forward channel load and (optionally) pilot strength measurements from the mobile. The BS/MSC then sends a SCAM to the mobile on the fundamental code channel. The SCAM specifies the burst length, the number of supplemental code channels assigned and the actual Walsh code channels (for each leg on which supplemental code channels are assigned), and the specified start time of the burst. The BS/MSC may prematurely terminate a forward burst by using the SCAM message with number of codes set to zero, as in the case of a reverse burst. If the mobile is not active, the IWF requests the BS/MSC to page the mobile to get it into an active state with the packet data service option and follows the above procedure to initiate burst transmission.

Burst Admission Control — Following the receipt of a burst request by the BS/MSC, the infrastructure uses burst admission control algorithms to determine the start time and duration of the burst and the number of codes assigned. These procedures are referred to as BALI and are discussed in some detail in [7, 8].

On the forward link, burst admission is determined by constraining the maximum transmitter power at each sector. On the reverse link, the admission algorithm is based on limiting the minimum attenuation from the mobile to the cells with which it could potentially interfere. We refer to the entity that computes these load and interference constraints as the *burst allocation function* (BAF). These algorithms are discussed in [8].

The burst allocation determined at each cell with which the mobile is in soft handoff is reported to the burst coordination function (BCF). The BCF determines the allocation that satisfies the constraints at all the cells. This may require coordination between multiple BSs. For example, if there are two soft-handoff legs involved in burst transmission to a mobile, the number of SCCs that can be allocated on the forward link for the burst must satisfy the power constraint at each of the legs.

The burst admission control functions (BAF and BCF) may be implemented in a centralized or distributed manner across the BS/MSC [7].

IS-95 AND CDMA2000 RTT LAYERING STRUCTURE

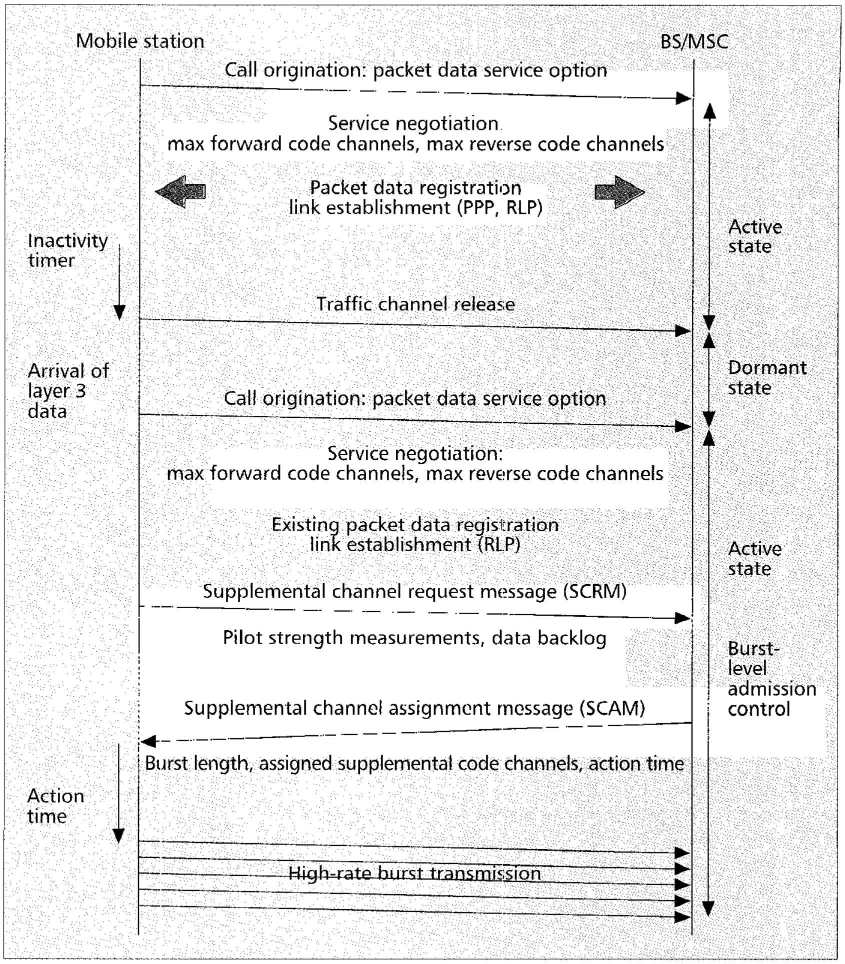
As shown in Fig. 3, IS-95 has a layered structure designed to provide voice, packet data (up to 64 kb/s), simple circuit data (e.g., asynchronous data and fax), and simultaneous voice and packet data service

At the most basic level, the cdma2000 RTT provides protocols and services that correspond to the bottom two layers of the International Organization for Standardization/Open Systems Interconnection (ISO/OSI) Reference Model (i.e., layer 1 — the physical layer, and layer 2 — the link layer) according to the general structure specified by the ITU for IMT-2000 RTTs. Layer 2 is further subdivided into the link access control (LAC) and medium access control (MAC) sublayers. Applications and upper-layer protocols corresponding to OSI layers 3–7 utilize the services provided by the cdma2000 LAC services. Examples include signaling services, voice services, packet data applications, and circuit data applications.

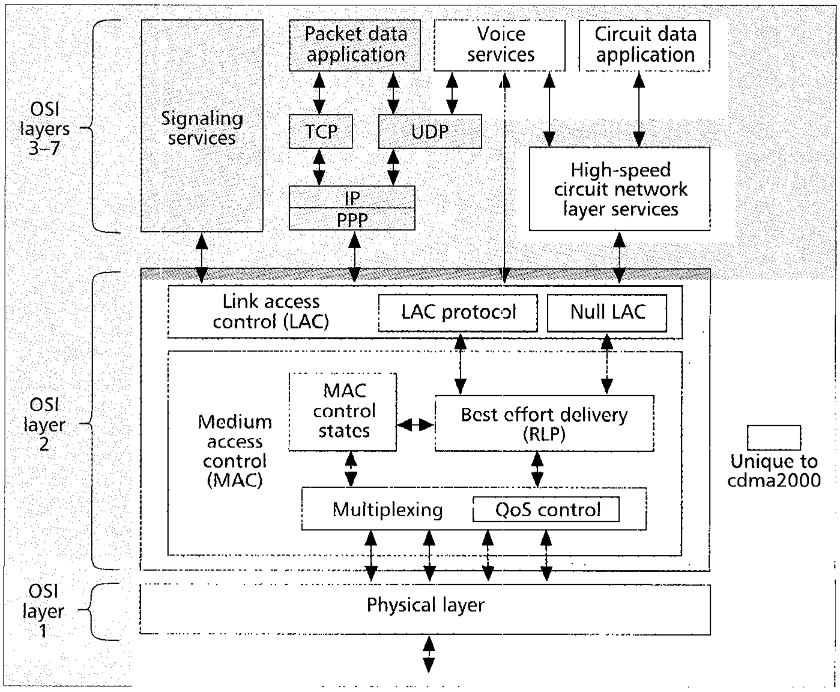
Motivated by higher bandwidths and the need to handle a wider variety of services, several enhancements have been incorporated into cdma2000 (these have been highlighted in Fig. 3). In cdma2000, a fully generalized multimedia service model is supported. This allows virtually any combination of voice, packet data, and high-speed circuit data services to operate concurrently (within the limitations of the air interface system capacity). The cdma2000 system also includes a sophisticated QoS control mechanism to balance the varying QoS requirements of multiple concurrent services, for example, to provide broadband integrated services digital network (B-ISDN) or Resource Reservation Protocol (RSVP) QoS capabilities.

Most significantly, cdma2000 includes a flexible and efficient MAC entity that supports multiple instances of an advanced state machine, one for each active packet or circuit data instance. Along with the QoS control entity, the MAC realizes the complex multimedia, multiservice capabilities of next-generation wireless systems with QoS management capabilities for each active service.

The cdma2000 system also introduces a true LAC protocol entity to support highly reliable point-to-point transmission over the air for signaling services and (optionally) for circuit data services. To provide a high degree of flexibility in the evolution of voice services, the cdma2000 RTT provides the framework and services to transport encoded voice in the form of packet data or circuit data traffic, in a manner that is backward compatible with previous IS-95 standards where the encoded voice is transported



■ **Figure 2.** *A scenario for successful burst transmission.*



■ **Figure 3.** *IS-95 and cdma2000 layer structure.*

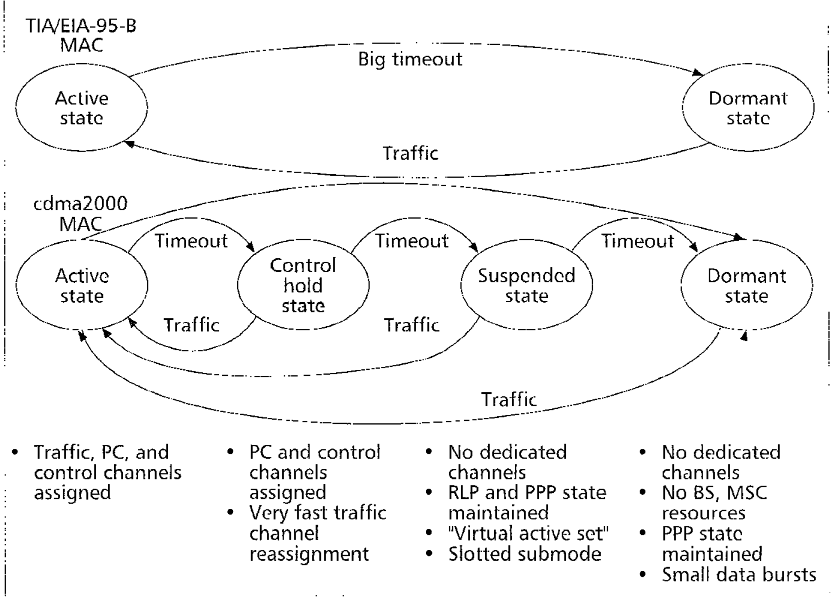


Figure 4. *Comparison between IS-95 and cdma2000 MACs.*

directly by the physical layer. In the latter example, the LAC and MAC services are considered to be null.

The design of the cdma2000 LAC and MAC sublayers is motivated by the following factors:

- The need to support a wide range of upper-layer services
- The requirement to provide high efficiency and low latency for data services operating over a wide performance range (1.2 kb/s to greater than 2 Mb/s)
- Support for advanced QoS delivery of circuit and packet data services (e.g., limitations on acceptable delay and/or bit error rate, BER)
- The demand for advanced multimedia services that support multiple concurrent voice, packet data, and circuit data services — each with varying QoS requirements

As shown in Fig. 3, the cdma2000 LAC sublayer is required to provide a reliable in-sequence delivery transmission control function over the point-to-point radio transmission link. The LAC sublayer service may be accomplished using a suitable ARQ (retransmission) protocol if necessary. Alternatively, if the lower layers provide adequate QoS, the LAC sublayer may be omitted (null).

The cdma2000 MAC sublayer provides three important functions:

- MAC control states — procedures for controlling the access of data services (packet and circuit) to the physical layer (including contention control between multiple services from a single user as well as between competing users in the wireless system)
- Best effort delivery — reasonably reliable transmission over the radio link with a radio link protocol (RLP) that provides a best effort level of reliability
- Multiplexing and QoS control — enforcement of negotiated QoS levels by mediating conflicting requests from competing services and the appropriate prioritization of access requests

IS-95-B PACKET DATA SERVICE MAC LAYER

In IS-95-B, a new service option called the *high-speed packet data service option* is defined. This service option is established between the mobile and the IWF when the mobile requests high-data-rate packet-mode service. During the service option negotiation procedure, the mobile must specify its high-speed data capability to the BS/MSC, that is, its capability in number of code channels on the forward and reverse channels. The BS then specifies the maximum number of codes on the forward and reverse channels it can provide to the mobile. High-data-rate packet service is provided only when the service option is connected.

The packet data MAC functions in IS-95 are based on the concept of providing packet data service over an underlying circuit-data-based call model. In a somewhat simplified form, this MAC service can be reduced to only two states:

- Active — in which a traffic channel is assigned to the mobile, and a link layer and Point-to-Point Protocol (PPP) connection is established between the IWF and the mobile
- Dormant — in which no traffic channel is assigned to the call (however, the knowledge of the user's registration for packet data service is maintained along with the PPP connection)

User data can be transmitted only in the active state. However, since data is expected to be bursty with periods of inactivity, the user is allowed to remain in the active state for a short duration after a burst transmission is complete, to minimize the access time for the next burst. An inactivity timer is defined to conserve the air interface and other network resources. If this timer expires, the user is considered to be in the dormant state. In this state, there are no RF or system resources allocated to the user. The service option still remains connected, and the PPP connection between the mobile, IWF, and BS/MSC remains open during this period. The mobile goes into active mode if packet data traffic destined to or from the user arrives.

CDMA2000 PACKET DATA SERVICE MAC LAYER

The packet data MAC functions for IS-95 have only two states, *active* and *dormant*, as described above. This simple approach works well for fairly low-speed data services with relatively low occupancy for any given user. However, this MAC model is inadequate to meet the aggressive requirements for very-high-speed data services with many competing users in third-generation systems. This is due to the excessive interference caused by idle users in the active state, and the relatively long time and high system overhead required to transition from the dormant to the active state.

To address these requirements, the cdma2000 system incorporates a sophisticated MAC mechanism that includes two intermediate states between the IS-95 active and dormant states (Fig. 4):

- Control hold — In this state, a dedicated control channel is maintained between the user and the BS on which MAC control commands (e.g., to begin a high-speed data burst) can be transmitted with virtually no latency. Power control is also maintained so that high-speed burst operation can begin with no delay due to stabilization of power control.

- Suspended state — In this state, no dedicated channels to or from the user are maintained; however, the state information for RLP is maintained, and the BS and the user maintain a "virtual active set" which permits either the user or the BS to know which BS can best be used (accessed by the user, or paged by the BS) in the event that packet data traffic for the user occurs. This state also supports a slotted substate that permits the user's mobile device to preserve power in a highly efficient manner.

In addition, a short data burst mode is added to the cdma2000 dormant state to support the delivery of short messages without incurring the overhead of transitioning from the dormant to the active state.

Transitions between MAC states can be indicated by MAC control signaling or the expiration of timers. By carefully choosing the values for these timers, cdma2000 MAC can be adapted to a wide variety of data services and operating environments.

PERFORMANCE TRADE-OFFS

Forward and reverse link coverage and capacity are affected differently by users with higher data rates. A variety of these performance trade-offs have been studied and reported separately [7–11]. The trade-off issues considered here are very generic to systems based on CDMA technology and are equally applicable to IS-95-B and cdma2000 systems. For illustration purposes, we consider the IS-95-B system [3]. Examples of these trade-offs are discussed below.

FORWARD LINK CAPACITY AND COVERAGE

On the forward link, a small fraction of the users are assigned a large fraction of the transmit power budget. Hence, the capacity of the cell is limited if the higher-data-rate user is closer to the boundary, while very large capacities are available if the high-data-rate user is in the interior of the cell. Therefore, the large capacity cannot be made available under coverage guarantees.

Assuming a forward link E_b/N_0 requirement of 7 dB and an activity factor of 100 percent, results in [7, 8] show that sufficient forward link bandwidth and power is available to provide up to 76.8 kb/s in 87 percent of the coverage area (when the adjacent cell loading is 60 percent). However, a burst-mode shared access scheme is required to efficiently utilize the available air interface capacity. Much higher capacities are available by relaxing the coverage requirement. Note that the fundamental code channel is always available to an active high-data-rate mobile even when high-data-rate burst cannot be assigned.

SUPPLEMENTAL CODE CHANNELS IN SOFT HANDOFF

Soft handoff provides seamless service and significant performance gains for voice and circuit-mode services. But for packet mode services that involve high-data-rate burst transmission for short durations, it may be beneficial to transmit SCCs on the forward link from the strongest subset of the soft handoff legs chosen at burst allocation. This saves on network and radio resource (forward link power) usage, thereby reducing the blocking and potentially increasing the capacity. The FER on the fundamental code channel is maintained at 1 percent using power control, while the FER on the SCCs may deteriorate during the course of the burst. Sample performance results for 4 s burst duration are reported in [8].

- Performance with a single supplemental leg is acceptable at low speeds. If 5 percent FER is considered acceptable for packet data service, 83 percent of bursts do not need multiple legs at a speed of 65 mph, while 94 percent of bursts do not need multiple legs at 5 mph.
- Increasing the number of legs on which SCCs are assigned still gives a substantial capacity gain with a significant decrease in percentage of bursts that exceed 5 percent FER. However, at higher speeds (65 mph), this percentage is still quite large, and for good performance SCCs must be assigned on all legs.

While there is performance degradation without soft handoff, acceptable performance may be achieved for low- to medium-speed mobiles, especially when the burst durations are short.

REVERSE LINK INTERFERENCE CONSTRAINTS

On the reverse link, the high-data-rate user in one cell causes interference at the neighbors and thus uses up capacity in multiple cells. The magnitude of this interference depends on the position of the user within its cell. Static interference analysis for voice-only systems has been extended to high-data-rate users [5, 8].

For example, suppose that the capacity of the voice-only system is 25 users. If the high-data-rate user is at the boundary between two cells and both cells have 10 voice users, then the data user can be assigned 57.6 kb/s. If the high-data-rate user is three-quarters of the distance to the boundary from one cell, then 57.6 kb/s can be assigned even when there are 17 voice users in the neighbor cell, and 43.2 kb/s can be assigned even if the neighbor cell is at capacity.

REVERSE LINK BURST ADMISSION AND CAPACITY

The important issues associated with reverse link performance are capacity and coverage. The capacity of the system, defined as the average throughput achievable over the cell (average number of users that can be supported times the data rate per user), is smaller for a system with data users than for one with only voice users. This is because the number of high-speed data users that can be supported is small, and this results in higher variance of total received power at the base station. So in order to keep the outage, defined as the probability of total received power exceeding a given threshold, at the same level as for a voice-only system, we have to back off on throughput.

The burst access schemes use current load information in the cells and an estimated resource usage of the data user to determine what data rate is to be permitted. Pilot measurements reported by the mobile can be compared with thresholds based on load to determine the permitted data rate for a burst. This scheme provides a simple *dynamic* mechanism to trade off bandwidth between circuit-mode voice users and packet-mode high-data-rate users. Alternatively, the voice load can be reduced to design an access control that shares bandwidth in a more *static* manner. References [7–9] report on simulation studies to determine the effectiveness of such a scheme. These results show that:

- If the high-data-rate user were to operate in a circuit mode at 57.6 kb/s, there is a small loss (less than 10 percent) in total system throughput. In packet mode data, the burst admission control strategy ensures that the data users which cause excessive interference at the neighbors are not admitted. This results in higher capacities than is the case with circuit-mode data. For the range of parameters considered, the capacity penalty can be completely eliminated.
- The burst acceptance probability is quite high close to the BS, decreasing to around 0.85 as the mobile approaches the edge of the cell. Note again that the fundamental code channel is always available for data transmission.

Better coverage and capacities can be provided by trading off data rates for outage.

REVERSE LINK BUDGET (MOBILE TRANSMIT POWER)

This issue concerns the impact of high data rates on the mobile design. On the reverse link, in order to achieve the same coverage as for a voice user, the mobile transmit power needs to be increased linearly with the data rates. For instance, with M codes assigned per user, the average transmit power of the mobile needs to be M times higher. Moreover, with code aggregation as in IS-95-B, the peak-to-average ratios of the mobile transmitter also increase. In order to accommodate this higher peak-to-average ratio, the mobile needs a power amplifier with a peak power capability more than M times that of a voice mobile. If we use the same amplifier that exists in today's mobiles, the coverage of high-speed data shrinks compared to that of a voice user for the same system loading and similar operating environment. The assigned data rate can be progressively reduced as the mobile hits its peak transmit power limit so that there is full coverage for packet data at the lowest data rate. Alternatively, coverage can be traded off against capacity. That is, by reducing the load in the system, the reach of the mobile can be increased for higher data rates.

REVERSE LINK POWER CONTROL

CDMA systems rely on tight reverse link power control, with deleterious effects on capacity when the power control is not effective. Each mobile runs its own independent power control to combat the path loss variations and aggregate interference. With higher-data-rate operation, the statistics of aggregate interference are different.

In [8, 10] we examine the reverse link power control performance for multiplexing high-speed data users with voice on the same CDMA carrier. There are several factors that permit reduction in the average E_b/N_0 requirement for high-speed data users. The smaller E_b/N_0 requirement translates to increased capacity (in terms of kb/s/cell/CDMA carrier). Our findings from [8, 10] are summarized as follows:

1 Any given supplemental code channel of an HSD user encounters aggregate interference power of other codes that is correlated with the signal power. This results in a lower average E_b/N_0 requirement for HSD users compared to voice or circuit-mode data users. Voice users see a small increase in E_b/N_0 requirement when sharing a CDMA carrier with high-data-rate users. However, there is an overall capacity gain reflected in a smaller noise rise.
2 The E_b/N_0 requirements are smaller by almost 2 dB at 1 mph than at 30 mph. This implies a larger capacity if high-data-rate mobiles are stationary or fixed wireless users.
3 There is a further decrease in E_b/N_0 requirement (almost 1 dB) and gain in capacity by decreasing the power control step size to 0.5 dB. There is a further gain of over 0.6 dB in E_b/N_0 requirement by setting a higher FER target for delay-tolerant data services allowing for recovery through ARQ.

Item 1 is applicable to IS-95-B only, while 2 and 3 are applicable to both IS-95-B and cdma2000 systems.

MOBILITY METRIC

User mobility imposes many constraints on the system. For example, an active user has network resources allocated even when not in burst transmission During burst transmission a handoff add trigger is an indication that the mobile may be approaching a new sector/BS. In addition to allocating resources at the new cell, the interference caused by the high-rate mobile needs to be reevaluated. There is a large infrastructure overhead associated with signaling and reallocation/deallocation of resources for such a user. The mobility of the user determines the frequency of such triggers, and hence the probability of resource reallocation. With this in mind, resource allocation schemes may be designed so that the length of the burst and number of codes assigned to a packet data user could be made a function of user mobility [5]. Fixed or low-mobility users may be assigned higher numbers of codes for longer durations than high-mobility users. Low-mobility users may also be assigned SCCs on fewer legs than the fundamental code channel to save on the resources. The mobile's handoff activity is an excellent mobility metric that directly relates to the issues discussed above. A running average of the number of handoff events by a mobile can be used to optimize the resource usage.

CONCLUDING REMARKS

We describe the evolution of wireless data services from IS-95 to cdma2000. The two-step evolution consists of IS-95-B, which maintains strict compatibility with existing BS hardware, followed by cdma2000, which meets or exceeds the requirements specified for IMT-2000.

A new burst mode packet data service is described that allows better interference management and capacity utilization. We show that the burst mode addresses many of the technical challenges that have previously resulted in CDMA being considered unsuitable for high-data-rate services. The burst access procedures described here have already been standardized in IS-95-B. We believe these load and interference management methods are quite powerful, and may provide the best engineering solution for high data rate access in an interference-constrained outdoor cellular environment. The scheme is general, and we expect that several emerging-third generation cellular technologies based on CDMA will incorporate these schemes as well.

The second evolution step, cdma2000, provides next-generation capacity, data rates, and services. The cdma2000 system includes a greatly enhanced air interface supporting CDMA over wider bandwidths for improved capacity and higher data rates while also maintaining backward compatibility with existing IS-95 CDMA end-user devices. The cdma2000 system also includes a sophisticated medium access control feature to effectively support very high data rate services (up to 2 Mb/s) and multiple concurrent data and voice services. Enhancements over IS-95-B include the introduction of the suspended and control hold states in addition to the IS-95-defined active and dormant states for packet data MAC.

The viability of high-speed packet data services over CDMA has been shown through extensive performance evaluation studies that are reported in the references [5–11]. Here, we have provided a brief discussion of the variety of trade-offs involved and direct the reader to the references for a more thorough understanding of the technical issues.

ACKNOWLEDGMENTS

We acknowledge valuable comments from our colleagues Edward Chao, Richard Ejzak, Quinn Li, Maria Palamara, Nallepilli Ramesh, and Joseph Tarallo.

REFERENCES

[1] EIA/TIA-95 Rev A, "Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," 1995.
[2] TIA IS-707, "Data Services Standard for Wideband Spread Spectrum Cellular System."
[3] EIA/TIA-95 Rev B, " Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," 1997.
[4] D. Knisely, Q. Li, and N. Ramesh, "cdma2000 — Evolution of cdmaOne to IMT-2000," to appear, *Bell Labs Tech. J.*, 1998.

[5] C.-L. I and S. Nanda, "Load and Interference Based Demand Assignment for Wireless CDMA Networks,"" *Proc. IEEE GLOBECOM*, 1996.

[6] C.-L. I and S. Nanda, "Cellular Interference Control for Integrated Services over CDMA," *Proc. Int'l. Teletraffic Cong.*, Washington, DC, June 1997.

[7] R. P. Ejzak *et al.*, "BALI: A Solution for High-Speed CDMA Data," *Bell Labs Tech. J.*, vol. 2, no. 3, Summer 1997, pp. 134–51.

[8] S. Kumar and S. Nanda, "High Data Rate Packet Communications for Cellular Networks using CDMA: Algorithms and Performance," submitted to *IEEE JSAC*, June 1998.

[9] S. Kumar and S. Nanda, "An Access Scheme for High Speed Packet Data Service on IS-95 based CDMA," WINLAB Wksp. 1997, *Proc. Advances in Wireless Commun.*, Kluwer, 1998, pp. 241–52.

[10] S. Kumar, S. Nanda, and A. Falconi, "Reverse Link Power Control Performance for High Speed Data over CDMA," *Int'l. Conf. Telecommun.*, Porto Carras, Greece, June 22–25, 1998.

[11] S. Kumar and S. Nanda, "A Simulation Technique to Study CDMA System Performance with Integrated Voice and Data Services," Advanced Simulation Techniques 1998, Boston, MA, Apr. 5–9, 1998.

BIOGRAPHIES

DOUGLAS N. KNISELY (dnk@lucent.com) is a distinguished member of technical staff in the Wireless Standards Organization at Lucent's Network Wireless Systems in Naperville, Illinois. He is currently responsible for the development of TIA cdma2000 third-generation standards, specializing in high-speed data services and the MAC layer. He holds a B.S. in music and physics from Heidelberg College, Tiffin, Ohio. His previous responsibilities have included the design and development for the high-speed CDMA data services in the EIA/TIA-95-B standard. Prior accomplishments include video conference system design and implementation in AT&T Global Information Systems, and network architecture, protocol design, and communication software development in AT&T Computer Systems. He was also responsible for managing the system architecture and performance analysis activities for the AT&T StarServer E symmetric multiprocessor system.

SARATH KUMAR (sarath@lucent.com) received his B. Tech. degree in electrical engineering from Indian Institute of Technology (I.I.T.), Kanpur in 1988, and his M.Tech. degree from I.I.T, Bombay, in 1990. He obtained his Ph.D. in electrical engineering in 1993 from the University of Pennsylvania, Philadelphia. From October 1993 to April 1994 he worked as a research associate at the Wireless Information Networks Laboratory (WINLAB), Rutgers University. Since May 1994 he has been with the Performance Analysis Department at Bell Laboratories, Lucent Technologies in Holmdel, New Jersey. For his Ph.D. thesis he worked on multi-user transmitter/receiver design, and at WINLAB he looked at the resource allocation issues in cellular communications. At Bell Laboratories he is currently involved in the design and analysis of CDMA networks.

SUBHASIS LAHA (slaha@lucent.com) received his B.Tech degree from I.I.T., Kharagpur, and his M.S. and Ph.D. degrees from the University of Illinois, Urbana, all three in electrical engineering. In 1987 he joined AT&T Computer Systems where he was involved in the system architecture, design, and performance analysis of symmetric multiprocessor systems and desktop videoconference systems. He has been working on the design of wireless data systems since the inception of Lucent Technologies in late 1995.

SANJIV NANDA (nanda@lucent.com) received his B.Tech. degree in electrical engineering from I.I.T., Kanpur, in 1983; his M.S. degree in mathematics in 1986; and M.S. and Ph.D. degrees in electrical engineering in 1985 and 1988, respectively, all from Rensselaer Polytechnic Institute, Troy, New York. During 1989–1990 he was with the Wireless Information Network Laboratory (WINLAB) at Rutgers University, Piscataway, New Jersey. He joined the Performance Analysis Department at Bell Laboratories (now Lucent Technologies) in 1990, where he is currently technical manager. At Rensselaer he worked on rate distortion theory and image coding. His work at WINLAB was concerned with multiple access and resource allocation for wireless microcellular networks. At Lucent he is involved in design, performance study, and modeling of wireless communications systems of the future, with particular focus on wireless data services.