MOBILE COMMUNICATIO

CELLULAR DIGITAL PACKET DATA

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CELLULAR DIGITAL PACKET DATA

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To my mother, who perished during the 1987 Sri Lankan army's onslaught on Jaffna; to my father, who taught me, by example, the important values in life; and to young Tamil men and women who gave their lives defending the freedom and dignity of the people of Thamil Eelam.

— M. Sreetharan

To my wife, Amy, and daughter, Sonali, without whose support I would not have known about CDPD.

— Rajiv Kumar

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CHAPTER 1

INTRODUCTION

Cellular digital packet data (CDPD) is a wireless technology that provides packet-switched data transfer service using the radio equipment and spectrum available in the existing analog mobile phone system (AMPS)–based analog cellular networks. AMPS technology is used mainly in the United States and therefore initial deployment and use of CDPD will predominantly be in the U.S. markets. Demand for wireless data transmission capabilities is rising sharply, and currently available wireless data technologies have not been popular with the wireless users because of their coverage, cost, and throughput (speed) limitations. Overlaid on the widely deployed AMPS radio infrastructure in the United States, CDPD has the potential to provide users with nationwide coverage that cannot be met by other competing wireless technologies. Further, CDPD promises a low cost service to its subscribers because:

- CDPD shares the use of the AMPS radio equipment on the cell sites;
- CDPD uses excess capacity in the allocated spectrum for the analog voice systems;
- CDPD network usage cost is based on the volume of data transferred and not on the connection time.

The protocol architecture of CDPD is chosen so that the available infrastructure of the terrestrial data network can be integrated as an extension to the CDPD network, as shown in Figure 1.1. In effect, the CDPD network provides a connectionless routing framework—an Internet protocol (IP) or connectionless network proto-

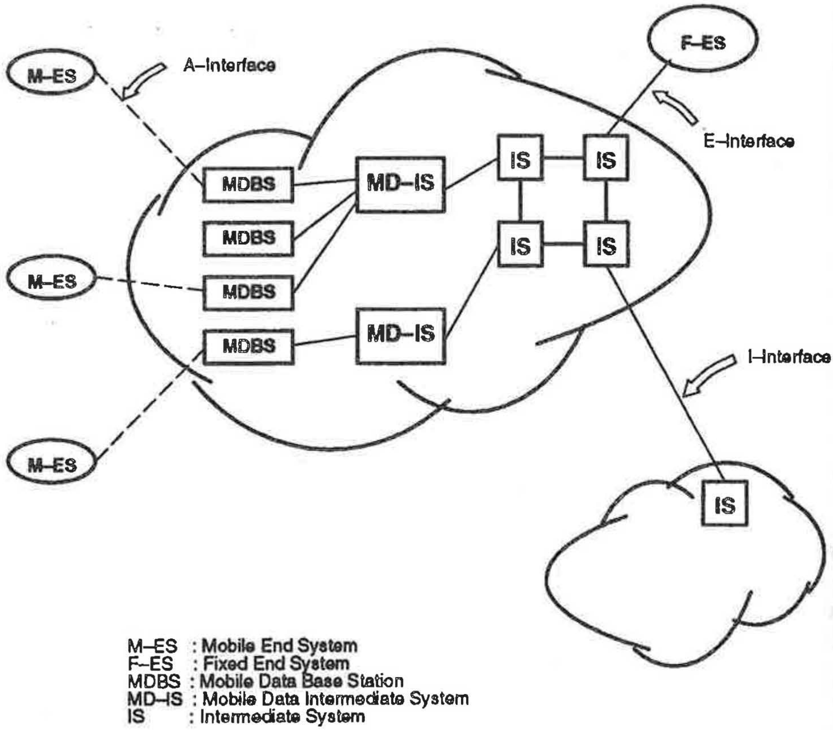

FIGURE 1.1 Overall CDPD network architecture. (*Source:* [1].)

col (CLNP) network layer packet transfer facility—to allow a mobile end system to connect to another end system via the IP-based Internet or CLNP-based OSI networks.

This chapter provides a brief historical background to the cellular networks that serve as the basic framework for the deployment and the operation of the CDPD networks. The architecture and operation of the CDPD networks are also introduced so that the core differences between competing or complementing wireless data technologies can be identified for engineering or managerial decision making.

1.1 BACKGROUND

Within the last 20 years the wireless field has experienced unprecedented growth into a new industry. Fueled by advances in radiofrequency, satellite, and microelectronic technologies, and aided by the convenience of instant and tetherless access to telephony and messaging portable devices, wireless technology will spawn mass markets for wireless communication devices and applications.

Table 1.1 lists the chronology of landmark events in RF spectrum allocation and in the growth of the cellular technology reveals that most of the advances are relatively recent.

TABLE 1.1
Landmark Events in the Cellular/Wireless Field

Year	*Event*
1925	2 MHz was believed to be the highest usable frequency and the National Association of Broadcasters warn of impending frequency shortage.
1934	FCC was set up as an independent regulatory body to allocate spectrum, to define rules for services, to provide licenses to users, to certify wireless products, and to police the radio spectrum.
1958	Bell System proposal to the FCC for a 75-MHz spectrum in the 800-MHz band for use in cellular.
1970	FCC tentatively allocates 75 MHz for a wireline common carrier.
1971	Cellular system design with cells, frequency reuse schemes submitted by AT&T Bell Laboratories.
1974	FCC allocates 40-MHz spectrum with 666 channel pairs with one cellular system per market.
1978	First cellular trials conducted in Chicago.
1981	FCC implements the two-carrier per geographic area licensing.
1982	First meeting of the Groupe Special Mobile (GSM) group.
1985	Personal communication services concept emerges as a future technology.
1986	FCC allocates additional 5 MHz for each band, allowing 83 additional channels per band (A and B).
1991	CDPD patent was filed by three IBM staff members.
1993	Initial specification of CDPD by the consortium of carriers and IBM.
1994	Number of wireless users in U.S. reaches 20 million.
1995	Narrowband and broadband PCS spectrum auctioned by the FCC with the promise for near universal access to messaging, mobile telephony, and data exchange. Beginning of extensive deployment of CDPD infrastructure, third-party CDPD modem development, and third-party application software development.

Although the United States serves as the main market for the AMPS technology (over 85% of the worldwide AMPS subscribers are in the U.S.), other countries such as Australia, New Zealand, several Asian countries (such as Indonesia, the Philippines, Hong Kong, and Singapore), and several South American countries (such as Chile and El Salvador) also use AMPS as their primary wireless cellular technology [2]. CDPD, within its current stage of development, can be easily deployed in these foreign markets once the technical success and the cost advantage to the CDPD customer are demonstrated in the U.S. markets.

In 1993, anticipating the growth in the demand for wireless access to exchange data, a consortium consisting of the following carriers was formed to generate a specification for the CDPD technology:

- Ameritech Mobile Communications, Inc.;
- Bell Atlantic Mobile Systems Contel Cellular, Inc.;
- GTE Mobile Communications, Inc.;
- McCaw Cellular Communications, Inc.;
- NYNEX Mobile Communications, Inc.;
- PacTel Cellular;
- Southwestern Bell Mobile Systems;
- U S West Cellular.

The CDPD specifications embody the following major design goals:

- Compatibility with existing data networks;
- Ability to support present and future data network services and facilities through standardized access to CDPD network;
- Allowance of maximum use of the existing commercial data network infrastructure and provision of support to multiple data network protocols.

In addition, more generic goals associated with mobile systems, which include seamless roaming, security/privacy, protection of the network from fraudulent users, and support of a wide range of mobile stations (such as portable, low-power handheld) are also part of the design goals of the CDPD network.

1.2 CELLULAR DIGITAL PACKET DATA (CDPD)

The original idea for using the spare bandwidth in AMPS system to transmit data is credited to Robert Miller, Victor Moore, and Thomas Pate (IBM, Florida) and described in a U.S. patent filed in 1991. The abstract of the patent, which contains Figure 1.2, is given below:

> A method for performing Cellular Data Networking (CDN) in an Advanced Mobile Telephone System (AMPS), wherein said AMPS includes a set of cellular telephone voice transceivers, each tuned to one of a pre-

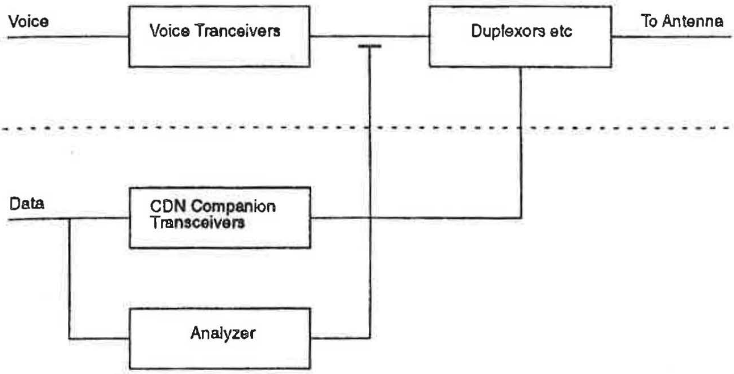

FIGURE 1.2 Organization of transceivers. (*Source:* [3].)

selected set of communication channels, and means for coupling each transceiver in said set of transceivers to an antenna to facilitate the performance of duplex radio communications over said set of channels, including at least one data transceiver, and a set of sensors coupled to each transceiver in said set of transceivers, comprising the steps of:

a) determining when there is unused air time to switch said data transceiver onto the channel to which a particular one of the transceivers in said set of transceivers is tuned;

b) determining when to turn said given data transceiver off based on sensing a demand for the channel to which the given data transceiver is tuned by said particular transceiver;

c) identifying time slots that are unused by said AMPS on each of said channels; and

d) assigning selected unused time slots identified in step (c) for data transmission purposes.

It has to be noted that the AMPS system has been in operation since 1978, and no one suggested the overlay possibility until this patent was filed. Therefore, what appears to be a straightforward evolution of the AMPS system may not have happened if not for the above "invention."

1.2.1 A Brief History

In the early part of 1990, under a project called CelluPlan I, researchers at IBM (Boca Raton, Florida) started looking into employing cellular phones as a means to transfer data (circuit-switched cellular) using a data modem built by Communicate and a cellular phone from Novatel. They soon discovered that modem attributes, terrain, and the noisy airlink affected the reliability of the data transfer. While analyzing the air channel in AMPS cell sites to characterize its behavior, they found that even in the busiest cell sites a significant portion of the time individual RF channels were not used, giving rise to the idea that it may be possible to use the idle time on an RF-channel to transfer data with the ability to hop to different "free" RF channels when voice system began using the channel. IBM and Novatel built a simple prototype to demonstrate the feasibility of the idea and CelluPlan-II was born. Attracting the consent of McCaw to commit to wireless data as an important technology, IBM in partnership with McCaw and subcontracting to PCSI, started specifying the Celluplan-II technology. The task of convincing the carriers to adopt to the IBM-McCaw plan was left to Machaley of McCaw and Moore of IBM, and this effort culminated in the consortium being formed with all major carriers with the exception of Bell South, which had a vested interest in RAM Data. Concerns about possible RF interference of the new technology with the operational AMPS system were dismissed after some internal tests were conducted by McCaw. During 1992, IBM's involvement in the project diminished. A field trial of the initial technology derived from CelluPlan-II was held in the San Francisco Bay Area in the second half of 1992 and early part of 1993. Meanwhile, an improved version of the CDPD technology, which was more tailored to the Internet world, was developed by a team led by Mark Taylor (McCaw) for the CDPD forum. The consortium, later including Bell South, announced the availability of the CDPD specifications in San Jose (1993) in the presence of some major companies such as Sears, which expressed commitment to CDPD as a user. By patenting the technology, IBM ensured that the technology transfer was accomplished at no cost to the carriers and was able to serve as a neutral third party to bring the carriers together to build the infrastructure necessary to support CDPD. The technology specification that defined the airlink as Gaussian minimum shift keying (GMSK) and a data rate of 19.2 Kbps was based on the premise that an inexpensive CDPD modem is key to the success of CDPD. These requirements allow off-the-shelf components available in the cellular industry to be used, minimizing the modem cost.

1.2.2 Overlay on Analog Cellular

Utilizing the unused bandwidth in the AMPS system and the ability to share cell-site hardware are the two factors that gave birth to the CDPD technology as a low-cost alternative to existing private packet data technologies.

In sharing the same set of frequencies allocated to the AMPS, no additional functionality is imposed on the AMPS. The implication is that the AMPS system will continue to allocate and use frequencies assuming that there are no other potential users of its frequencies. It is the responsibility of the CDPD system to continuously monitor ("sniff") the AMPS frequencies and employ the unused frequencies. However, when the AMPS radio is independently assigned the frequency the CDPD system is using, the sniffing subsystem in the CDPD has the responsibility to switch the carrier off within 40 ms, thereby not causing interference with AMPS operation. The CDPD system then has to find another unused frequency. The mobile-end systems (M-ESs) that were tuned to the older frequency will recognize the disappearance of the CDPD carrier and have to identify a "new" available CDPD frequency and continue the session with minimal interruption to the data flow. The CDPD network will assist the M-ESs in providing a variety of information related to CDPD frequency pools and so forth so that M-ESs can acquire CDPD channels efficiently.

The extent to which CDPD is overlaid on the AMPS system ends with the air segment. In the area of sharing the cell-site hardware, one of the most expensive components in a cell site is the real estate for the cell site and the associated antenna subsystem. The CDPD can fully share the AMPS antenna subsystem by suitably combining the RF transmit signals and splitting the RF receive signals. The sharing of power amplifiers (PAs) is also possible depending on the availability and compatibility of the AMPS PAs. In the mobile telephone switching office (MTSO), the AMPS voice calls carried by the T1 links from the cell sites are multiplexed and connected to the public switched telephone network (PSTN). The CDPD network traffic from the cell site is also carried by the same shared T1 links, and in the MTSO this multiplexed data traffic uses a configured router as the gateway to the terrestrial IP/OSI data networks. Figure 1.3 shows the relationship of the CDPD overlay with the AMPS infrastructure.

1.2.3 Dedicated and Shared RF Channels

The frequency allocation scheme in a carrier's AMPS network and the carrier's preference in phasing in of the CDPD network will largely determine the configuration of frequencies for use by the CDPD network. In an AMPS system, each cell will have multiple radios and a set of frequencies assigned to the cell. Similarly, the CDPD system will have a frequency pool configured for each of the cell. In a typical AMPS/CDPD setup, the cell configuration (sectored, omni, etc.), and the RF foot print for the AMPS and CDPD will be as closely matched as possible.

The CDPD use of the frequencies allocated for AMPS fall into two different groups: dedicated frequencies and shared frequencies.

Dedicated Frequencies

These are frequencies assigned by the carrier for sole use by the CDPD network. The CDPD hardware/software do not implement special procedures to monitor the use of these "dedicated" frequencies by other network(s).

In this case, the cooperating AMPS system RF-engineering personnel must manually enforce that the AMPS frequency pool does not include any dedicated frequencies marked for use by the CDPD system. Failure to continually establish this mutually exclusive frequency allocation condition every time a new frequency plan

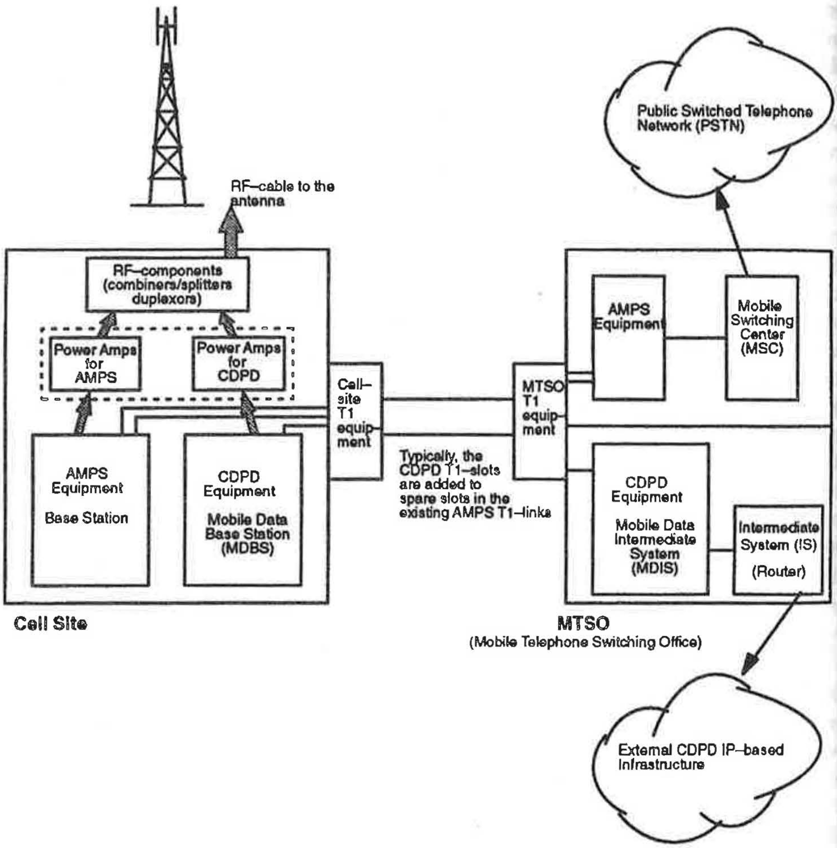

FIGURE 1.3 CDPD overlay with AMPS.

for AMPS is established and implemented will result in the CDPD system interfering with voice.

Shared Frequencies

The frequencies that the AMPS and the CDPD can share are called shared frequencies. The AMPS system is not expected to be aware of any other potential users of its frequencies. It is the responsibility of the CDPD system to use the shared frequencies when the AMPS system is not using it (a call is not active on that frequency) and to relinquish the frequency when the AMPS starts using it before causing any undue interference with the voice system. Special hardware that sniffs voice frequencies and triggers a carrier switchoff within 40 ms from the time of detection needs to be employed in the CDPD network for harmonious sharing of frequencies. This stringent switchoff time requirement eliminates any audible interference in the voice system by removing the CDPD carrier from the air during the initial setup time of the voice call, before the beginning of any voice activity.

CDPD design allows the switched off carrier (on detection of voice activity) to be replaced with another "available" frequency by the base station, and has procedures implemented in the M-ESs to search and tune to a new frequency, making the transition transparent to the application. In CDPD implementations we can find both configurations. In markets where there are frequencies available for exclusive use by the CDPD, the carriers tend to prefer a dedicated channel CDPD setup. This simplifies the CDPD hardware, and hence the cost, as sniffing subsystem hardware is not required. In addition, this simplifies the operational software in the CDPD system and minimizes the chance for interference with the more important (revenue-wise) voice system. The inefficiency in the data transfer mechanism arising from interruptions due to channel "hopping" that occurs in a shared frequency CDPD configuration is also avoided.

1.2.4 Network Connectivity

One of the main objectives in the CDPD network specification and design is to use the functionally proven and extensively deployed existing data network infrastructure as an integral part of the CDPD network.

The open system interconnection (OSI) protocol suite is based on the OSI reference model defined by the International Organization for Standardization and International Electrotechnical Committee (ISO/IEC). Although OSI is predicted to become the primary networking solution of choice in the next several years, existing OSI implementations are few and skeletal. In contrast, TCP/IP-based networks have proven to be operationally successful, and in the last two years have attracted a mass consumer market with Internet access and the World Wide Web possibilities. Thus, the CDPD specification provides facilities to use either the OSI protocol suite with ISO 8473 (connectionless network protocol (CLNP)), or the TCP/IP protocol suite with IP (Internet protocol) as the network layer protocol.

Current M-ES implementations and associated applications exclusively use the TCP/IP protocols. However, communication between CDPD components, primarily mobile data-intermediate systems (MD-ISs), the specification requires the CLNP protocol be used.

1.2.5 CDPD System Performance

The primary component that governs the performance of the CDPD network is the airlink. With the given bandwidth of 30 kHz, and the choice of Gaussian minimum shift keying (GMSK) modulation, CDPD networks operate at a 19.2-Kbps data rate. This data rate has been demonstrated to be superior to those obtained from the current working speeds of existing private wireless networks like ARDIS and RAM Data. However, the private packet service providers are busy upgrading the data rates supported by their networks, and a 19.2-Kbps RAM Data network is being deployed.

The raw data rate translates to the following effective data rates after accounting for the air-link MAC level overhead:

- Link level throughput in a forward direction: 12.7 Kbps;
- Link level throughput in a reverse direction: 11.8 Kbps (based on a half-duplex M-ES, averaged over a single transmission);
- Half-duplex M-ES can send only a limited amount of information in each of its reverse transmissions (274 bits, which is equivalent to approximately 34 octets).

These are approximate throughput values to provide an indication of the overall performance of the CDPD network and apply to one channel stream. The following list indicates why the users have to be careful in interpreting the above throughput values:

- The throughput applies to a CDPD channel stream (one frequency pair). If multiple mobile stations are using the same channel, the mobile units have to share the bandwidth.
- If the same channel stream is shared by multiple M-ESs (all half-duplex), then due to the multi-access protocol constraints, the reverse direction throughput will be less than 11.8 Kbps. The more the number of M-ESs, the less the value of the aggregate throughput of the channel stream.
- The network can be configured to allow the full-duplex M-ESs to send longer streams of information in each of their reverse bursts, thereby achieving some improvement in the reverse channel throughput.
- If multiple channel streams are available in a cell, then the CDPD network can assign M-ESs to different channel streams based on the load-balancing algorithm being implemented. The throughput, in the M-ES's perspective, will then be dependent on total channel utilization and the effectiveness of the load balancing.

Further, the above throughput applies to the link-level frames. Accounting for the link level and network-level overhead would leave the effective application throughput 10% to 20% less than the figures shown above. Other aspects related to throughput to take note of are as follows:

- CDPD operation allows for header compression when using the TCP/IP or the OSI protocols. A standard 40-octet header in each packet in the TCP/IP session is compressed to an average of 3 octets. Throughput as seen by the application will have marked improvements if header compression is enabled.

- CDPD Specification 1.1 specifies V42.bis compression by the network layers. Applications that require transfer of large volumes of data and do not employ compression in any form at the application level can again experience larger effective throughput. The CDPD networks currently in operation use only one channel stream per cell. Therefore, the effective distribution of M-ES loads across multiple channel streams has not become a hotly debated topic yet.

1.3 CDPD APPLICATIONS

Cost and available bandwidth are two key factors that will have an impact on the type of applications that will use the CDPD technology for wireless data transfer. Two major categories of applications can be identified that can be expected to dominate the CDPD market: embedded systems with bursty data transfer requirements and handheld interactive computing [4–8].

1.3.1 Embedded Systems With Bursty Data Transfer Requirements

CDPD technology is ideally suited to applications where small amounts of data need to be transferred from remote locations to a central system. These applications benefit from the fact that the applications can be "registered" with the CDPD network once during the initial power-up, and can send data without any delay when necessary. The continuous connectivity maintainable by the application without incurring any cost makes CDPD different from circuit-switched cellular where maintaining a continuous connection will be expensive; further, for bursty data transfers, the circuit connection has to be set up and cleared, adding delay in transferring data.

Application types that will fall into this category include both manned and unmanned types. Examples are as follows:

- *Telemetry.* Monitoring of pipelines and so forth as part of interconnection of supervisory control and programmable logic controllers (PLCs) across CDPD networks.
- *Vehicle tracking.* As an inexpensive alternative implementation for satellite-based global positioning system (GPS), vehicles/trucks can use CDPD-based position location system.
- *Credit card authorization.* CDPD can replace the traditional wireline connections used in the credit card authorization system used in the stores. The CDPD system will be faster (does not have to set up the call) and allow authorization stations to be set up anywhere (provided there is CDPD coverage).

1.3.2 Handheld Interactive Computing

This group of applications represents a traditional computing setup where a user and handheld computing equipment are involved. These full-function mobile personal computers are likely to have full screens, keyboards, and different disk configurations (hard and removable and PC-card features). Tablet computers, which will replace multipart forms and possess signature capture capability, will dominate some sectors of the field application market. The following major application categories can be identified within this group.

Personal Messaging

With corporate users increasingly using remote access to enterprise networks to share information and to coordinate/manage activities via electronic mail, peer-to-peer wireless messaging will soon become a business standard. The average consumer who is currently enjoying the convenience of cellular voice and pagers is soon going to discover the similar benefits of electronic messaging and instant access to information (stock quotes, hotel information, etc.), creating a surge in demand for easy-to-use new wireless products and the infrastructure capacity to support the data transfer requirements.

Field Automation

Applications where productivity is increased and the service quality is enhanced by the ability to instantly query or modify information remotely from the field will increasingly employ wireless technology. Police officers, real estate/insurance agents, sales representatives, and field service technicians are examples of the kinds of workers who work away from their offices, are highly mobile, and are bound to benefit from the capability to access information instantly. Police departments in some areas (Connecticut and Pittsburgh) have already adopted or are experimenting with CDPD already.

Computer-aided dispatching (CAD) is another market that could benefit from CDPD. Continuous communication is possible between the office worker and the dispatched field personnel. Taxicab firms and the trucking industry are increasingly embracing CAD, and CDPD can be the cost-effective technology for the needs of these industries.

Internet Access

The popularity of the Internet among computer users has risen sharply in the last year. Accompanying this popularity is the availability of instant information in fields ranging from newspapers to music. The potential of applications and markets built around World Wide Web (WWW) is enormous. At best, a mobile user will be able to obtain throughput performance similar that of a 14.4-Kbps wireline modem. Interacting with WWW facility is still feasible and is practical where only a moderate amount of graphics is involved. For high-resolution, graphics-intensive browsing activity, the CDPD speed will be a definite limitation.

Spurring further growth in wireless applications and use of wireless infrastructures will be the pen-only tablets and personal digital assistants. These would come in a variety of forms with different input and communications capabilities, enticing users with their capability to provide instant access to mail, calendar maintenance, and management functions, and corporate information. CDPD technology's growth will assist the wireless application field; in addition, the CDPD's survival will depend on the popularity of the above applications and how the pricing structure, availability, and reliability compare with other competing technologies.

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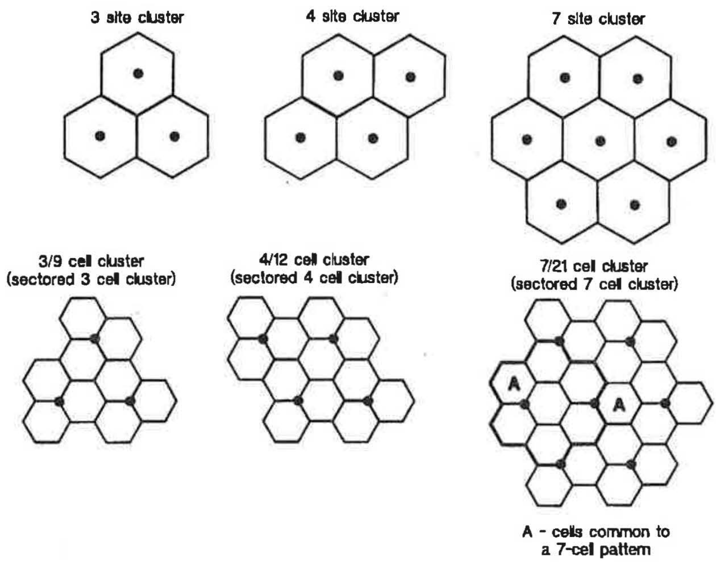

FIGURE 7.3 Cell clusters. (*Source:* [1].)

A set of several frequencies are used in one cell and other mutually exclusive sets are used in other cells in the cluster. This arrangement forces one to examine the criteria as to when a frequency can be reused again. Figure 7.4 provides an example of the popular 7-cell cluster arrangement, with six clusters surrounding a cluster in the middle. In the middle of each cluster is a base station that must have the same frequency set if the network is being built with the 7-cell cluster as the basis.

It can be shown that if the cluster size is N and the cell radius is R, the reuse distance D is given by

$$D = R\,(3N)^{1/2}$$

The cluster sizes need not be the same throughout the network. Cells can be split to provide increased capacity (number of subscribers per square area) towards city centers. Figure 7.5 shows such a plan with representative cluster sizes of 4, 7, and 12.

7.1.4 Adjacent Areas

Each MD-IS and the MDBSs that it supports in a CDPD network belong to an *area*, as illustrated in Figure 7.6. When an M-ES moves from a cell to another cell that is

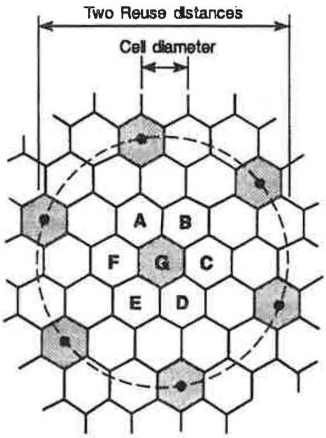

FIGURE 7.4 Frequency reuse distance. (*Source:* [1].)

supported by a different MD-IS, the M-ES is expected to reregister with the new MD-IS.

The reregistration requirement during interarea cell transfers is an overhead the M-ESs will attempt to avoid when selecting RF channels. If an acceptable cell is available within the same area, the intra-area transfer is given priority.

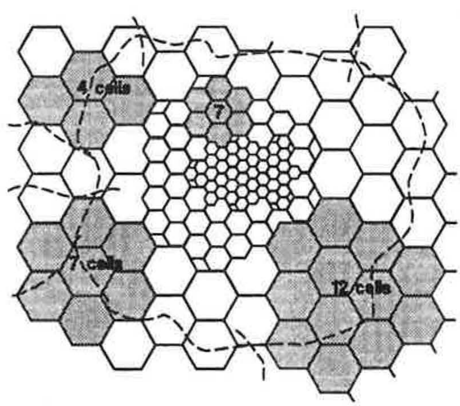

FIGURE 7.5 Typical cell layout plan for a city. (*Source:* [1].)

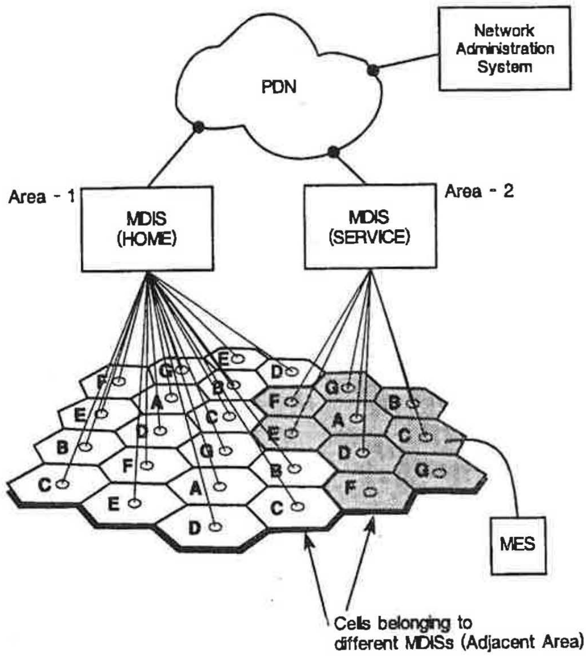

FIGURE 7.6 MD-ISs and adjacent areas.

Each M-ES has a home MDIS, the significance of which will be detailed when the mobility aspects of M-ESs are covered in the next chapter.

7.1.5 CDPD Frequency Pools and AMPS System

CDPD deployment is normally carried out in regions where the AMPS system is already in operation. Operational AMPS systems will have an established frequency plan. However, the frequency plans continually change if the network is being expanded by adding cell sites or splitting existing cells. A complete network-wide reassignment of frequencies is not uncommon. In this scenario, carriers have several alternatives when assigning frequencies for an overlaid CDPD system.

- *Dedicated frequencies.* If one or more spare frequencies are available that are not required for use in the AMPS system, these frequencies can be assigned for use by CDPD. These are called *dedicated* frequencies. The CDPD network can assume that these frequencies will not be used by any non-CDPD system.

- *Shared frequencies.* These frequencies are shared by both the voice system and the CDPD system. The CDPD system is expected to employ mechanisms to detect the use of these frequencies by non-CDPD systems. While CDPD is using an RF channel, if non-CDPD use is detected, the CDPD system is expected to relinquish using the RF channel within 40 ms.

In multiple channel streams per sector configurations, a mix of dedicated and shared frequencies can be used within a cell. The RF channel selection algorithms are expected to give priority to dedicated channels over shared channels.

When shared frequencies are used in a CDPD system, one of two methods can be employed to manage their use.

- *Sniffer hardware.* Hardware can be added to the CDPD MDBS to continuously scan the shared frequencies to detect presence of energy. This status information can assist the channel allocation portion of the software. More importantly, the hardware also has to provide information on the shared frequencies that are currently used by the CDPD system; this information has to be provided at a faster rate so that the MDBS can perform a forced hop when voice activity is detected within the 40 ms required by the specifications.
- *Channel status protocol (CSP).* Close coordination between the voice and the CDPD system can be organized by implementing a channel status protocol between them. Messages exchanged between the two systems can avoid both systems choosing the same frequency together. This protocol has not been widely implemented in CDPD and AMPS systems yet.

7.1.6 Color Codes

Color codes in the CDPD system perform the same function as the supervisory audio tones (SATs) in the analog cellular system. In addition to facilitating the detection of co-channel interference, the CDPD color code also is used when an M-ES performs an interarea cell transfer.

7.1.6.1 Group Color Code

The CDPD specification defines the group color code as follows. Each cell in a group of cells may be assigned the same cell group color code if both of the following conditions apply:

- The cell is adjacent to another cell in the same group.

- No radiofrequency (RF) channel available for CDPD use in the cell is also available for CDPD use in any other cell in the group.

The concept behind the group color code is the same as the supervisory audio tones (SATs) used in the voice network. It helps the receiving element (cell or an M-ES) to distinguish between two transmitting elements (M-ESs or cells, respectively) that are using the same frequency.

The CDPD group is equivalent to a cell cluster in the voice network and is therefore associated with the frequency assignment strategy employed by a carrier. Frequency reuse patterns determine the cell groups. Frequency reuse refers to the use of radio channels on the same frequency to cover different areas that are separated from one another by sufficient distances so that co-channel interference is not significant enough to disturb the operation of the system. A set of cells that have mutually exclusive frequency sets and are geographically contiguously located to satisfy the neighbor criterion above will be labeled as a group and will be given the same group color code. Since the group color code can have 31 distinct values (5 bits), it would not be a difficult task to assign the color codes so that no two cells transmitting on the same frequency within the hearing range of a single M-ES have the same color code.

The group color code is encoded in each RS block transmitted on the forward channel stream and is used by the M-ES to detect co-channel interference from a remote MDBS. Similarly, the group color code encoded in the first block of a burst transmitted on the reverse channel stream is used by the MDBS to detect co-channel interference from a remote M-ES.

7.1.6.2 Area Color Code

Area color code is a unique identifier of 3 bits in length assigned to an MD-IS. The area color code has to be unique only within MD-ISs that geographically cover areas adjacent to each other. This is assigned by the network service provider when defining the network topology and the geographic placement of the MD-ISs. Along boundaries of the networks operated by different service providers, coordination in assignment of the color codes may be necessary to ascertain smooth operation when M-ESs roam from one service provider's network to another's network.

The area color code is broadcasted in the cell configuration messages. In addition, the area color code (3 bits) and the cell group color code (5 bits) are also transmitted together as the first data byte of each Reed-Solomon (RS) block in the forward channel. The area color code allows an M-ES to identify during a cell transfer whether it is about to move into an area controlled by a different MD-IS. Since an interarea cell hop requires the M-ES to reregister, the area color code can be used by the M-ES to favor a cell that has the same area color code as the current cell the M-ES is currently tuned to in order to prevent the reregistration overhead.

7.2 RADIO RESOURCE MANAGEMENT: MAIN GOALS

The radio resource management entity (RRME) is the part of the layer management entity whose function is to manage the available radio resources for efficient and correct operation of the CDPD system. RRME entities with differing management responsibilities reside in both MDBS and M-ES to achieve the following major goals:

- As an overlay technology on AMPS, the CDPD cell boundaries should be made to coincide with that of the AMPS system.
- With the use of passive techniques, the CDPD transmissions should avoid interfering with transmissions of the voice network.
- In situations where dedicated channels cannot be allocated to CDPD, the CDPD system should be able to use the bandwidth available during the idle time of frequencies (not used by voice) for CDPD transmissions. Switching the frequency used by a channel stream (RF port) is called a *channel hop*.
- Scarcity of bandwidth necessitates the requirement for using in-band control, unlike the voice system where dedicated control channels are available.
- An M-ES must be able to acquire a channel for its use within an acceptable delay without any prior knowledge of the frequencies in use, and to continue to maintain connectivity and exchange information with its remote end in the presence of channel hops.
- A moving M-ES must maintain connectivity and continue exchanging information with its remote end as it moves across cell boundaries, across areas operated by the same or different network service providers. In this scenario, the M-ES must be able to account for terrain effects in its selection of the best radio channel to use.

CDPD system employs three components of radio resource management methodology that combine to achieve the above main goals:

1. The RRME that resides in the M-ES;
2. The RRME that resides in the MDBS;
3. The radio resource management protocol (RRMP). This encompasses a set of messages exchanged between the RRMEs in the MDBS and in the M-ES, and the associated set of procedures that facilitate coordinated execution of radio resource management.

The RRME is distributed in different components of the CDPD architecture, as illustrated in Figure 7.7.

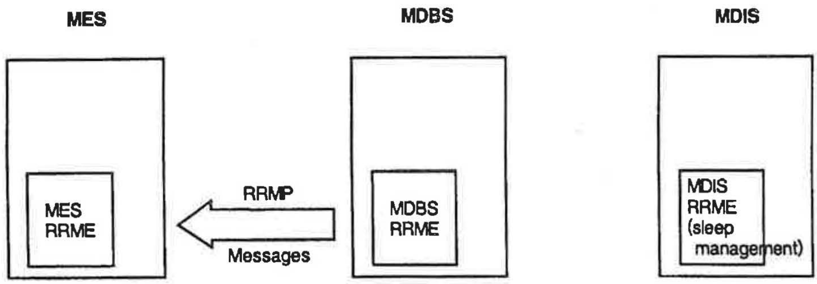

FIGURE 7.7 Different components of radio resource management.

7.3 RADIO RESOURCE MANAGEMENT PROTOCOL

The radio resource management protocol consists of a set of MDLP-level messages transmitted from the MDBS RRME to the M-ES RRME. The simplicity of this protocol is evident from the following:

- The RRMP messages are transmitted in the forward direction only. There are no RRMP messages from the M-ES RRME to the MDBS.
- The RRMP frames are carried as unnumbered information (UI) frames as part of the MDLP link, so that the RRME in the MDBS can easily insert the MDLP frames within the forward direction MDLP packets handled by the MDLP relay entity that will be normally resident in the MDBS.

The RRMP frames mainly carry network, cell, and channel identification information and the parameters necessary for the M-ES to perform its radio management functions. These frames are broadcast to all M-ESs. The following messages fall into this category:

1. Channel stream identification message;
2. Cell configuration message;
3. Channel quality parameters message;
4. Channel access parameters message.

A significant amount of configuration information is necessary to allow the MDBS RRME to construct these messages.

The switch channel message is the only other RRMP message sent as a command to the selected set of M-ESs.

The message formats are defined and the component fields in each messages are described. These parameters will provide the framework for describing the RRMEs and their respective functionalities.

7.3.1 Message General Format

The general format of an RRMP message, including the MDLP information is shown in Figure 7.8.

All RRMP messages have the TEI defined as 0, indicating that it is a broadcast message targeted to layer management entities. The messages are typed as commands and the effective address extension is 1 (no additional address bytes), making the first byte in the MDLP frame 0×03.

The frame type is unnumbered information, and in the extended mode of operation takes one byte, 0×03.

The Information field in the UI frame has two header bytes to define the following:

Byte-1
  Layer management entity identifier
    0×2A: RRME

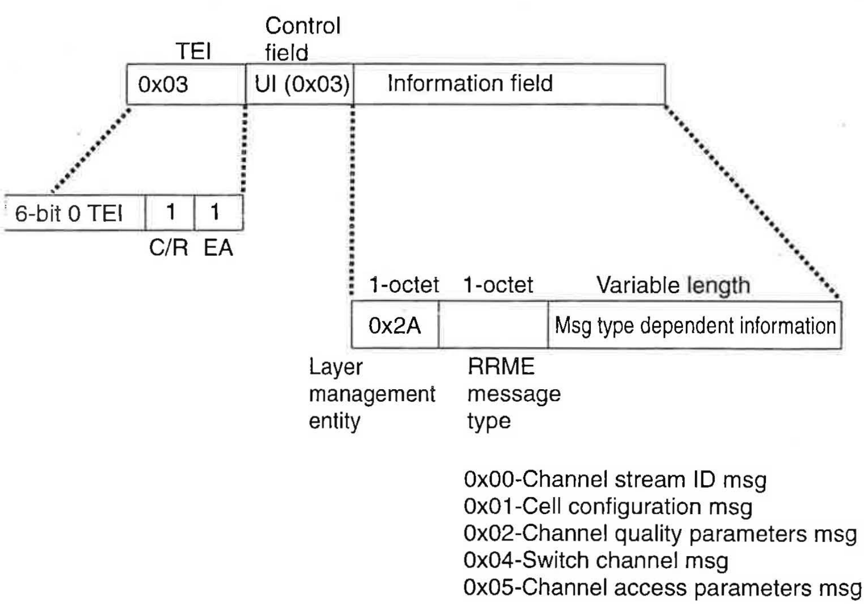

FIGURE 7.8 RRMP message format.

Byte-2

RRME Message Type

0×00: Channel stream identification
0×01: Cell configuration
0×02: Channel quality parameters
0×05: Channel access parameters
0×04: Switch channel message

At the MDLP frame level, the first five bytes of the different RRMP messages are, therefore:

Channel identification message:	03 03 2A 00...
Cell configuration message:	03 03 2A 01...
Channel quality parameters Msg:	03 03 2A 02...
Channel access parameters Msg:	03 03 2A 05...
Channel switch message:	03 03 2A 04...

7.3.2 Information in RRME Messages

7.3.2.1 Channel Stream Identification

The channel stream identification message is broadcast by the MDBS RRME in each channel stream at a periodic interval of, typically, 2–5 seconds. This message contains information for the M-ESs to identify the network, the cell, and the channel stream. The parameters in the message are shown in Figure 7.9 and described next:

- *Protocol version.* RRM protocol version. CDPD Specification 1.1 definition sets this value to 1.
- *RF channel type.* Defines whether the currently used RF channel on this channel stream is a CDPD dedicated frequency (bit set to 1) or a shared frequency that can undergo channel hops (0).
- *Channel capacity.* MDBS indicating to the listening M-ESs whether the current channel stream capacity is full (1) or not (0). M-ESs are not supposed to attempt to register on this channel if the bit is set.
- *Channel stream identifier.* A unique identifier (0–63) of a channel stream within a given cell.
- *Cell identifier.* This value is a globally unique identifier of a cell and consists of two 16-bit subfields made up of the service provider network identifier (SPNI) and the cell identifier. The cells within a single service provider network are assigned the same SPNI.

Bit	8	7	6	5	4	3	2	1
Octet 1	LMEI (=42_{16})							
Octet 2	Type = Channel Stream Identification (0)							
Octet 3	Protocol Version							
Octet 4	Dedicated	Capacity	Channel Stream Identifier					
Octet 5	Cell Identifier (= Service Provider Network Identifier + Cell number)							
Octet 6								
Octet 7								
Octet 8								
Octet 9	Service Provider Identifier							
Octet 10								
Octet 11	Wide Area Service Identifier							
Octet 12								
Octet 13	Power Product							
Octet 14	Max Power Level							

FIGURE 7.9 Parameters in the channel id message. (*Source:* [2]. © CDPD Forum.)

- *Service provider identifier.* The service provider identifier (SPI) uniquely identifies a licensed facilities-based cellular service provider offering CDPD services.
- *Wide area service identifier.* Service providers can define cooperating agreements to provide service over large geographic areas that may comprise several SPNIs. In such cases, the wide service area is identified by a unique wide service area identifier (WASI).
- *Power product.* Represents unsigned 8-bit value of the power product, expressed in decibels. The absolute value of the power product will be adjusted by adding –143 dB to keep the result always positive for the RRMP frame.
- *Maximum power level.* This is an unsigned value between 0 and 10 representing the maximum power level an M-ES can use for reverse transmission. The 0–10 levels are mapped to absolute power values.

7.3.2.2 Cell Configuration

The cell configuration message is broadcast on every channel stream by the RRME in the MDBS at periodic intervals of 5–10 sec. One cell configuration message pertaining to the current cell is broadcast on each channel stream. In addition, a cell configuration message for each of the neighbor cells configured for the current cell is also broadcast on each channel stream. These messages provide the M-ES information of

Bit	8	7	6	5	4	3	2	1
Octet 1	LMEI (= 42_{10})							
Octet 2	Type = Cell Configuration (1)							
Octet 3	Cell ID (= Service Provider Network Identifier + Cell number)							
Octet 4								
Octet 5								
Octet 6								
Octet 7	Face	0	Active Channel Streams			Area Color Code		
Octet 8	Reference Channel							
Octet 9								
Octet 10	ERP Delta							
Octet 11	RSSI Bias							
Octet 12	Power Product							
Octet 13	Max Power Level							
Octet 14	Dedicated	Reserved						
Octet 15	RF Channel Number 1							
•••••••	(RF Channel Numbers 2 to N-1)							
Octet 2N+12	Dedicated	Reserved						
Octet 2N+13	RF Channel Number N							

FIGURE 7.10 Parameters in the cell configuration message. (*Source:* [2]. © CDPD Forum.)

the RF channel configuration of the current and neighbor cells and other parameters that assist the M-ES during channel hops and cell transfers.

The parameters carried in the cell configuration message are shown in Figure 7.10 and described next.

- *Cell identification.* Unique cell id that includes the SPNI.
- *Face of a sectored cell.* This bit is 1, if the cell is a face of a sectored cell.
- *Active channel streams.* This number defines the number of active channel streams in a cell. Zero means CDPD is not active in that cell, and 7 means that there are 7 or more channel streams in that cell.
- *Area color code.* Denotes the area color code of that cell to facilitate the M-ES to identify cells supported by different MD-ISs.
- *Reference channel.* A valid RF channel number referring to a continued keyed channel in a defined cell that can be used in the best cell selection by the M-ES.

- *ERP delta.* This value defines the difference in the nominal effective radiated power (ERP) between the reference channel and the CDPD channels in that cell. The expected signal strength of a CDPD channel in a cell is calculated by subtracting the ERP delta value from the received signal strength indication (RSSI) value of the reference channel.
- *RSSI bias.* Effective RSSI value of an adjacent cell is calculated by adding the RSSI bias value to its expected RSSI value. A positive value for a neighbor cell shrinks the boundary of the current cell.
- *Power product:* The same quantity is broadcast as part of the channel stream id message.
- *Maximum power level.* The same quantity is broadcast as part of the channel stream id message.
- *RF channel type.* Dedicated or shared channel type.
- *RF channel number.* RF channel number (1–1,023). There will be as many pairs of these entries <channel type, channel number> as there are number of entries in the frequency pool of this cell.

7.3.2.3 Channel Quality Parameters

The channel quality parameters message is broadcast at periodic intervals, typically on the order of 60 seconds. This message contains information that assists the M-ES in determining the quality of the channel for continuing to use it for data transfer.

The parameters in the channel quality parameters message are shown in Figure 7.11 and described next.

- *RSSI hysteresis.* This parameter takes a value between –127 dB and 127 dB and is used as an adjustment to the current channel's RSSI value when select-

Bit	8	7	6	5	4	3	2	1
Octet 1	LMEI (=42_{10})							
Octet 2	Type = Channel Quality Parameters (2_{10})							
Octet 3	RSSI HYSTERESIS							
Octet 4	RSSI SCAN TIME							
Octet 5	RSSI SCAN DELTA							
Octet 6	RSSI AVERAGE TIME							
Octet 7	BLER THRESHOLD							
Octet 8	BLER AVERAGE TIME							

FIGURE 7.11 Channel quality parameters message format. (*Source:* [2]. © CDPD Forum.)

ing the best server channel. A positive hysteresis value forces the M-ES to favor the current channel, avoiding unnecessary flip-flops between two channels that have roughly equivalent signal strengths at the location of the moving M-ES.

- *RSSI scan time.* This represents the maximum time that may elapse before the M-ES RRME initiates an adjacent cell scan procedure.
- *RSSI scan delta.* This value defines the upper and lower ranges for the variation of the RSSI value of the current channel.
- *RSSI average time.* Averaging time for the RSSI value.
- *BLER threshold.* Channel exception condition is generated if the current averaged block error rate (BLER) exceeds this value, invoking an adjacent cell scan. BLER is defined as the ratio of the number of uncorrectable blocks compared to the total number of blocks received.
- *BLER average time.* Time for calculating moving average of the BLER value.

7.3.2.4 *Channel Access Parameters*

The channel access parameters message contain parameters related to the operation of the MAC layer. These parameters define the operational characteristics of multiple M-ESs sharing a given channel stream and the error-recovery procedures carried out by the MAC layer.

The parameters in the channel access parameter message are shown in Figure 7.12 and described next.

- *Maximum transmit attempts.* This parameter defines the number of retries the MAC layer should attempt to retransmit, either if channel busy when it tries to check the channel condition when it has data to transmit or an actual trans-

Bit	8	7	6	5	4	3	2	1
Octet 1	LMEI (=42_{10})							
Octet 2	Type = Channel Access Parameters (5_{10})							
Octet 3	MAX_TX_ATTEMPTS							
Octet 4	MIN_IDLE_TIME							
Octet 5	MAX_BLOCKS							
Octet 6	MAX_ENTRANCE_DELAY							
Octet 7	MIN_COUNT							
Octet 8	MAX_COUNT							

FIGURE 7.12 Channel access parameters message format. (*Source:* [2]. © CDPD Forum.)

mission is notified as decode failure in the forward channel. When the maximum transmission attempts fail, the MAC layer is expected to generate a channel exception condition triggering the mechanisms that perform frequency rescan.

- *Minimum idle time.* After a successful transmission of a burst, the M-ES is required not to access the reverse channel for a minimum period defined by the minimum idle time (in microslots units).
- *Maximum blocks.* Maximum number of blocks that can be transmitted in a burst by an M-ES.
- *Maximum entrance delay.* If an M-ES has data to transmit and senses the channel is busy, it defers, checking the channel again after a random number of microslots defined within 0 and the max entrance delay parameter.
- *Minimum count.* If a there is a collision in the reverse channel transmission detected by the decode failure flag, the M-ES backs off for a number of microslots selected within a uniformly distributed random number between 0 and $2^{\text{minimum count}} - 1$.
- *Maximum count.* During each successive failure to transmit, the random backoff delay parameter will be selected between 0 and $2^x - 1$, where x is the exponent used in the previous backoff calculation incremented by 1. Maximum count defines the upper limit to the incrementing exponent x. Thus, the valid range of x is

$$\text{minimum count} <= x <= \text{maximum count}$$

7.3.2.5 *Switch Channel Message*

This message contains the new RF channel number and a list of TEIs. This message is used by the MDBS RRME to force the selected M-ESs to switch to the new channel defined in the message.

In CDPD implementation, the switch channel message can be employed in the following operating scenarios:

- When a shared RF channel is being used in a channel stream and the dwell timer is set to nonzero, the MDBS will initiate a planned hop to a new channel. To make an orderly transition, the MDBS will transmit the switch channel message. In this case, since all the M-ESs using the current channel need to hop to the new channel, the message will contain ONE TEI value defined as 0.
- In a typical load balancing algorithm where periodically an RRME algorithm evaluates the load on different channels of the same cell, it may determine a new distribution of M-ESs to channels that may provide more efficient use of the RF bandwidth. In this case, the list of M-ESs may be identified and a switch channel message sent to the selected list.

Bit	8	7	6	5	4	3	2	1
Octet 1	LMEI ($=42_{10}$)							
Octet 2	Type = Switch Channels (04_{10})							
Octet 3	Reserved							
Octet 4	RF Channel Number							
Octet 5	Number of TEIs							
Octet 6...	TEI 1							
•••	TEIs 2 to N							

FIGURE 7.13 Switch channel message format. (*Source:* [2]. © CDPD Forum.)

The message parameters are shown in Figure 7.13.

7.4 KEY FUNCTIONS OF RADIO RESOURCE MANAGEMENT

7.4.1 RRMEs

The MDBS radio resource management serves as the primary entity that collects configuration information and broadcasts the relevant information as required by the RRMP protocol. The RRME in the MDBS will use the services of the physical layer, the MAC layer, and the MDLP layer to carry out its functions. These functions include RF channel selection, managing the tuned channel (including initiation of planned and forced hops), and channel congestion management.

The RRME in the M-ES will extensively use the services of the physical layer, the MAC layer, and the MDLP layer to carry out its functions. The RRME functions in the M-ES include processing of RRMP messages and selecting the best RF channel for setting up and maintaining the MDLP connection with the network.

An additional RRM function that is related to sleep management of appropriately equipped M-ESs is carried out by cooperating entities that reside in the MD-IS and in the M-ES.

7.4.2 MDBS RRME Functions

In addition to broadcasting the RRMP messages, the RRME entity resident in the MDBS assigns frequencies to traffic channels. The RRME also manages re-assignment of frequencies due to implementation-dependent conditions or when frequencies are forced out from CDPD by voice activity.

7.4.2.1 Channel Selection

One of the main functions of the MDBS RRME is to select and assign an RF channel for each channel stream configured in a cell.

A typical CDPD cell will have a frequency pool containing a subset of frequencies assigned to the associated AMPS cell. The RRME will select a dedicated channel if one is found in the RF pool. The availability of shared RF channels in the frequency pool for use by a channel stream will be determined by one of the following implementation dependent factors:

- CDPD systems can employ sniffers to detect the presence of a chosen RF channel in the transmitter output of the associated voice cell. Periodic scan of the shared RF channels in the CDPD frequency pool by the sniffer hardware can be used to update the availability status of the shared channels for CDPD use.
- Where the voice system implements a defined channel status protocol (CSP), the CDPD system can exchange CSP messages with the AMPS system and can update the shared RF channel status.

Once the basic availability of a shared RF channel for CDPD use is determined, implementation of specific algorithms can attempt to select an RF channel that has the lowest probability of being chosen for use in the non-CDPD (voice) system. In this respect, knowledge of the behavior of the selection algorithm in the voice system will be useful in choosing a matching algorithm for the CDPD system. The following possibilities are easily accommodated in a CDPD implementation:

- If the voice system uses a static list and selects the first unused RF channel scanning from top to bottom, the CDPD RF pool can be organized in the inverse order. Then, the best RF channel for CDPD use will be the first available when the RF pool is scanned from top to bottom.
- If the voice system uses a roundrobin algorithm, then dynamic reordering of the CDPD RF pool will become necessary. The reordering criterion is to move the RF channel that is released by the voice system to top of the CDPD list. The best RF channel for CDPD use will be the first available when the RF pool is scanned from top to bottom.
- If the voice system uses a top to bottom scanning for selection and the order of the list is not known, the CDPD system can dynamically create the best list for CDPD use by moving the RF channel when released by the voice system to the bottom of the CDPD list. The RF channels in the top of the list will then be the ones that have not been used by voice for the longest period of time. In addition, more sophisticated algorithms can be conceived that can use the continuous voice usage information provided by the sniffer subsystem to derive the long-term statistics on the channel allocation dynamics of the voice system.

7.4.2.2 *Directed Channel Hops (Planned Hops)*

A directed channel hop is a planned RF channel switching procedure initiated by the RRME on a particular channel stream. The reasons for initiating planned hops are configuration and implementation dependent.

In a directed channel hop, the RRME does the following:

- Selects the new RF-channel for use in the channel stream.
- Sends a switch channel message, and waits till the switch channel message is transmitted in the old RF channel. A burst of identical switch channel messages may be necessary to ensure that all the M-ESs tuned to the RF channel receive them.
- Ceases transmission on the channel stream and tunes to the new frequency within 40 ms of turning off the carrier on the old frequency.

The expectation of this procedure is that the M-ESs previously using this channel stream, remain on the channel stream after switching to the new frequency, thus avoiding the overhead of channel search by the affected M-ESs.

Several implementation-specific examples can be thought of where planned hops can be used:

- With each shared RF channel, a maximum channel time (swell time) value is defined. This timer, if configured as a positive value, specifies the maximum time the channel stream can use the RF channel once it has been tuned on a channel stream. On the expiration of this timer, the MDBS RRME should use the planned hop procedure to switch the channel stream to another RF channel. This timer may be set for the following reasons:
  1. The frequency assignment in the voice system may be time of the day–based and that information can be used within the CDPD system to derive a dwell-time parameter for associated CDPD RF channels.
  2. If some degree of co-channel or adjacent channel interference from an RF channel is expected based on the network design, and if there is a maximum allowed time of tolerance of this interference, the dwell time can be used to limit the amount of continuous use of the RF channel.
- If the CSP is used to interact with the voice system, the planned hop procedure may be used within the CDPD system when the voice system sends a channel busy message to the CDPD system indicating that the voice system is about to use a specific RF channel.

Associated with the dwell time, the shared RF channels are also configured with a layoff time. The layoff time defines the time a released RF channel after a planned hop cannot be used for CDPD, unless there are no other RF channels available for CDPD use.

In many CDPD networks deployed and providing commercial service, the dwell time for shared channels are configured as 0. This implies that if a shared channel is selected for use, it will continue to be used until forced out by voice activity in the AMPS system.

7.4.2.3 Undirected Hops (Forced Hops)

Undirected hops or forced hops are used by the MDBS RRME when time constraints prevent the MDBS from being able to carry out the planned hop procedure. When the non-CDPD activity is detected on an RF channel currently being used in the CDPD system, the requirement mandates that the CDPD should relinquish using the RF channel within 40 ms. This stringent time constraint, which includes the latency in detecting the presence of non-CDPD (primarily voice) activity by the sniffer subsystem employed in the MDBS, does not allow the MDBS sufficient time to find a new RF channel, and generate and transmit a switch channel message before ceasing transmission on the old RF channel.

Typical sequence of operations that is carried out during a forced hop is as follows:

- Non-CDPD activity is detected on an RF channel used by the CDPD system. The latency between the start of non-CDPD activity and the detection of it depends on the sniffing hardware and the sniffing methodology employed. To reduce cost in the deployment of the sniffing hardware, the worst case latency will be designed to be closer to 30–35 ms so that there is little time left to do any additional processing.
- The RRME uses the physical layer to immediately turn off the carrier to satisfy the 40-ms time constraint. If the overall time constraint allows, then an attempt can be made to minimize the loss of transmissions by suspending the forward data transfer before turning the carrier off.
- The M-ES will detect a channel exception condition primarily as loss of synchronization detected by the MAC layer and will choose a new channel stream for continuation of its activity.

Implementation of an efficient and fail-safe system for detecting non-CDPD activity is a critical requirement for a successful CDPD system. Extensive use of self-testing methodology needs to be implemented so that the system marks the shared frequencies unusable if failure is suspected in any part of the sniffing subsystem.

Even in cases where the CSP is used with the voice system, scenarios can be identified where forced-hop procedures have to be used during channel hops so that the delays in the CSP protocol messages do not violate the 40-ms limit on CDPD channel switch-off time.

7.4.2.4 *Channel Congestion Management*

The channel capacity flag in the channel stream identification message provides the MDBS RRME with the capability to inhibit additional M-ESs from registering on a channel stream.

The capacity flag reflects the internal determination of the CDPD system whether the specific channel is congested. The specification requires that if there is only one channel stream in a cell, the capacity flag should be 0, indicating that the channel is never congested. The strategy used in the MDBS (and possibly in the MD-IS) to manage congestion in a channel will increasingly become important as the number of traffic channels per cell increases in deployed networks to handle increasing CDPD traffic.

When multiple channel streams per cell are employed, an efficient channel congestion management strategy should take into account the following scenarios:

- Channel congestion depends on the traffic volume carried by the channel in the forward and reverse direction. Thus, to build a congestion control scheme that can adapt to changing traffic flow conditions, continuous measurement of the forward and reverse channel traffic on a per M-ES basis becomes necessary.
- In M-ES applications where only bursty traffic is used, the number of M-ESs registered on a specific channel stream may also be important.

A workable algorithm will use a suitable combination of the number of M-ESs and their throughput to derive a dynamic congestion control strategy. In addition to making the channels that are carrying excessive traffic marked as capacity full, switch channel messages can be targeted to selected M-ESs, forcing them to change to other channels.

7.4.3 M-ES RRME Functions

The RRME resident in the M-ES uses the RRMP messages broadcast by the MDBS for performing its radio management functions.

7.4.3.1 *RRMP Broadcast Message Processing*

Processing the received RRMP messages and maintaining the current cell and its neighbor information is one of the main activities of the M-ES RRME.

7.4.3.2 *Wide Area Channel Search*

When an M-ES is first powered up, the procedure the M-ES RRME executes to initially acquire channel is called a wide area channel search. The order of search for a usable RF channel is implementation-dependent and some possible algorithms are as follows:

- The most simple form will be a sequential search of all possible RF channels (800 channels of 2–5 ms/channel taking up to 3 sec), or to limit the search to carrier A or B based on the configuration of the M-ES with the knowledge of the carrier (WASI) operating in the geographic location.
- A search order based on the retained knowledge of the RF channels in cells previously acquired by the M-ES.

The following is the sequence of operations the RRME schedules during the initial acquisition of an RF channel:

1. The RRME selects the next frequency from its search list and invokes the physical layer function to measure the RSSI value of the selected RF channel.
2. If the RSSI value is not within an acceptable range determined by implementation-dependent criteria, the next channel is selected and the procedure is repeated from step 1.
3. On acceptable RSSI value, the RRME invokes the MAC layer function to synchronize on the chosen RF channel (MAC-OPEN request).
4. If the MAC layer is unable to synchronize (if a MAC-CLOSE indication is received), then the procedure again continues from step 1.
5. If the MAC layer is able to synchronize to the RF channel (i.e., the sync patterns on the forward channel are detected by the receiver), the RRME continues to measure the quality of the channel. The quality parameters are implementation-dependent and are generally based on a combination of sync error rate, block error rate, and symbol error rate.
6. The RRME then waits until it receives the channel stream identification message.

At this stage, the RRME continues to execute what is defined as a cell transfer procedure, which is also used in several other operational scenarios, and therefore is described as a separate sequence of operations in Section 7.4.3.4.

Since the wide area channel search is a fallback, all-inclusive search strategy, the M-ES will execute this as a last resort when more efficient strategies, such as adjacent cell scan, fail.

7.4.3.3 Adjacent Cell Scan

In the newer version of the CDPD specification, the M-ES RRME is required to "continuously" measure the signal quality of the current cell and neighbor cells. In these periodic evaluations, if the M-ES locates a "better server" channel, then the current channel the M-ES is expected to switch to that channel and to execute a cell transfer procedure. This scheme provides the best CDPD channel for an M-ES since the channel selection method is based on relative strengths of RSSI values.

Terrain Effects and Scan Efficiency

Terrain effects can produce adequate signal quality from a distant cell well into the *cell boundaries* of an adjacent cell. An M-ES continuation of using this channel from a distant cell can cause interference from its strong reverse channel transmissions on the CDPD or voice transmissions in other cells. The best server channel selection helps to avoid this possibility. Further, adjacent cell scan allows techniques for adjusting the measured signal quality to account for terrain, traffic conditions, and unnecessary switch-over flipflops between two cells. The specific parameters and strategies that allow the M-ES to deal with the terrain conditions and make the adjacent cell scan efficient are as follows.

Reference Channels and ERP Delta During the best channel selection, initially only the reference channel defined for the neighbor cells needs to be scanned to select the best cell. These reference channels are carried in the cell configuration broadcasts relevant to each neighbor cell. During comparison of RSSI measurements, the measured value of the RSSI level has to be adjusted by the ERP delta parameter before the value is compared those of other neighbor cells. The ERP delta value represents the difference in the RSSI values of a CDPD broadcast channel and the reference channel, which can be an AMPS control channel or a CDPD dedicated channel. The ERP delta is a configurable parameter and is broadcast along with the value of the reference channel in the cell configuration broadcast.

RSSI Bias The RSSI bias value is defined for each neighbor relationship and is broadcast in the cell configuration message. When comparing the RSSI levels of the different neighbor cells, each reference channel RSSI value is further adjusted by the neighbor's RSSI bias value before comparison. The effect of this adjustment is to effectively move the cell boundary towards or away from the specific neighbor cell depending on the sign and magnitude of the RSSI bias value. This feature can be used for load sharing between neighbors by moving the cell boundary of the higher traffic cell towards its center.

RSSI Hysteresis When there is a heavy volume of traffic along a boundary of two cells with equal power levels, best channel selection may cause unnecessary flipflops between the cells. This parameter provides a hysteresis effect during the best channel selection and avoids superfluous channel reacquisitions.

The best server channel selection, therefore, begins with a best cell selection followed by the channel selection within that cell, and subsequently channel acquisition.

Reference Channel Scan Procedure

The reference channel scan procedure, whereby the RRME in the M-ES selects the best cell for CDPD use can be described as follows:

1. For the next adjacent cell for the current cell, find the RSSI value of its reference channel, $RSSI_{RefCh}$.
2. Compute the effective RSSI value of this neighbor cell.

$$RSSI_{Eff} = RSSI_{RefCh} - ERP_{Delta} + RSSI_{Bias}$$

   Note that smaller ERP_{Delta} and larger $RSSI_{Bias}$ will make the neighbor a more attractive cell for CDPD use in the current scan.

3. Compute the $RSSI_{Eff}$ for all neighbors (repeat steps 1 and 2) of the current cell and select the best cell or cells with the highest $RSSI_{Eff}$.
4. Compare the highest neighbor to the RSSI value of the current cell ($RSSI_{Curr}$) taking into account the $RSSI_{Hysteresis}$ value to determine whether the M-ES should hop to another cell. The M-ES must proceed to reacquire the current channel if

$$RSSI_{Curr} + RSSI_{Hysteresis} > \text{Max } RSSI_{Eff}$$

5. If the current cell is the best cell, then the RRME:
   - Tunes to the previously used channel stream;
   - Restarts the RSSI scan timer to trigger the next adjacent cell scan;
   - Sets the internal RSSI value, $RSSI_{InternalRef}$, to the mean RSSI value of the current channel. As described in the next section, this value is used in determining another triggering condition for the adjacent cell scan, and the adjacent cell scan procedure terminates. The M-ES continues to use the same channel stream.
6. If there is more than one best candidate cell group, the ones with the same area color code are given priority over the others. The RF channels in the chosen cell are scanned one after the other until an RF channel stream is found which satisfies:
   - $RSSI_{New\text{-}Stream} > RSSI_{RefCh} - ERP_{Delta}$;
   - Implementation-dependent channel quality criteria such as block error rates are acceptable.

The RRME then executes the cell transfer procedure.

Reference Channel Scan Triggers

The best server channel selection and the adjacent cell scan are triggered by two different conditions:

1. A configurable periodic timer determines the maximum time between two adjacent cell scans. It is started during the initial power up of the RRME application, and is retriggered after each adjacent cell scan. The recommended value of this timer is 90 seconds.
2. Rate of change of RSSI value: If the RSSI average value of the current cell traverses outside the range defined by $RSSI_{InternalRef}$ + $RSSI_{ScanDelta}$, and $RSSI_{InternalRef}$ − $RSSI_{ScanDelta}$ for a period longer than the configured RSSI average time, an adjacent cell scan procedure is executed. In the case when the RSSI average is increasing (condition where current RSSI value exceeds $RSSI_{InternalRef}$ + $RSSI_{ScanDelta}$), only the face neighbors are scanned.

When the adjacent cell scan is initiated by an increasing RSSI average value, the likely scenario is that the M-ES is moving towards the center of a sectored cell. As shown in Figure 7.14, the positively increasing RSSI average trigger forces the M-ES to perform a face neighbor scan so that M-ES chooses the face neighbors channel as it crosses the face boundary. Without this trigger condition, the M-ES is likely to hold on to the current channel well into the face neighbor's territory.

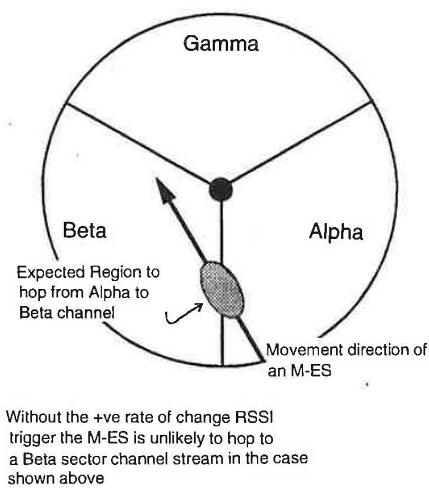

FIGURE 7.14 Increasing RSSI trigger of face neighbor cell scan.

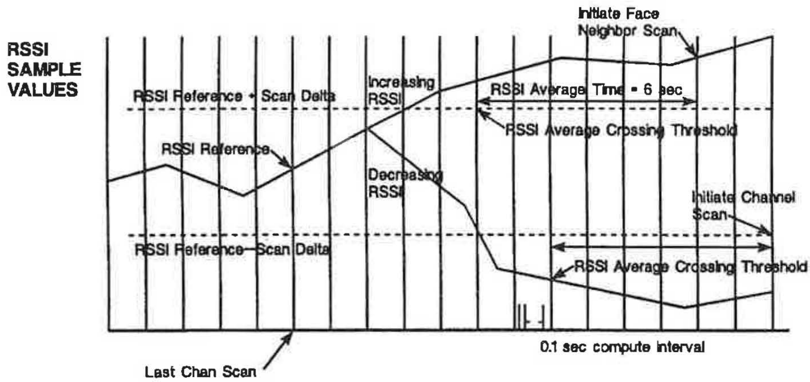

FIGURE 7.15 RSSI measurement procedure.

RSSI Measurements

Figure 7.15 illustrates the technique employed by the M-ES RRME to measure the RSSI values of the current channel and shows the conditions when adjacent cell scan procedure is triggered.

As shown in Figure 7.15:

- RSSI value is computed ten times every second.
- Only samples taken in the last 5 secs are used in computing the RSSI average.
- RSSI samples are flushed when the RF channel is changed.
- If the time elapsed is less than 6 sec, only the samples collected are used in computing the average.
- RSSI average must be outside the range for more than the RSSI average time to initiate face neighbor scan or the adjacent cell scan.
- If RSSI average value exceeds the defined range (positive rate of change), only the face neighbors are chosen for the cell scan.

BLER Measurements

Figure 7.16 illustrates the technique employed by the M-ES RRME to measure the block error rates. This procedure is carried out by the RRME as it continuously assesses the quality of the channel that it is using.

As shown in Figure 7.16:

- BLER is computed once every second.
- BLER computation is initialized when the RF channel is changed.

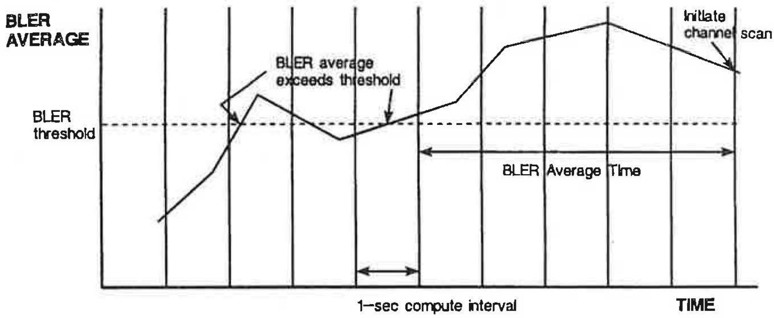

FIGURE 7.16 BLER measurement procedure.

- Only the number of intervals within the BLER average time is used in the calculation of the average BLER.
- If less time has elapsed than the configured BLER average time, BLER the averaging procedure will assume the rest of the intervals as having no errors.
- BLER average must be above the configured BLER threshold for a length of BLER average time to result in a channel exception condition and to initiate an adjacent cell scan.

Channel Quality

Channel quality is continuously monitored by the RRME, and several conditions can render the channel unusable. These channel exception conditions initiate the adjacent cell scan procedure. The following is a list of channel exception conditions:

- Measured mean block error rate exceeding configured threshold value.
- MAC layer reporting error due to loss of channel synchronization.
- MAC layer reporting error due to the reception of invalid group or area color code.
- MAC layer reporting error due to failure of maximum transmit attempts (configurable number).
- Other implementation-dependent error conditions, such as number of decode failures reported by the MDBS as decode flags in the forward channel stream or number of forward sync words in error, may also trigger the MAC layer to report channel exception error.

In a properly designed network with adequate radio coverage, cell hops triggered by channel exception conditions should be rare.

7.4.3.4 Cell Transfer Procedure

The cell transfer procedure is a sequence of actions carried out by the RRME after the reception of the channel stream identification message, subsequent to the selection of a new RF channel, for continuation of the M-ES use of the CDPD network. The following events will typically trigger the M-ES to select a new RF channel:

- Completion of a wide area channel search;
- Completion of an adjacent cell scan;
- Completion of a directed channel hop that moves the M-ES to a different channel stream.

The set of operations executed by the RRME as part of the cell transfer procedure are as follows:

1. A check is made if the SPNI, SPI, or WASI received as part of the channel stream identification message are acceptable to the M-ES. If it is unacceptable, the M-ES will select the next best channel from the list (wide area scan or adjacent cell scan) and continue the search.
2. The internally maintained value of the RSSI reference to the mean RSSI of the selected channel is set and the RSSI scan timer is started.
3. The power product and the maximum power level value are set to that of the current cell.
4. The RRME initializes for BLER and RSSI measurements, and, if it is a new cell, initializes the internal cell configuration information base.
5. If the area color code has remained unchanged, the RRME instructs the MDLP layer to resume operation. If the M-ES has a new area color code, then interarea cell transfer procedure is followed.

Interarea cell transfers require the RRME to clear the current MDLP connection, to set up a new MDLP connection, and to reregister using the mobile network registration protocol (MNRP) with the new MD-IS supporting the newly acquired channel stream.

7.4.3.5 Switch Channel Message Processing

A switch channel message is sent from the MDBS typically during a planned hop triggered by the expiration of the dwell timer or as required by the specific implementation of a load balancing scheme in the MDBS. The message contains the new RF-channel number and a list of TEIs associated with the M-ESs. If all M-ESs that are tuned to the channel stream are supposed to switch, the TEI list will contain one entry, a TEI value of 0.

On reception of a switch channel message, the receiving M-ES is expected to switch to the new frequency. If the new frequency is supported in a different traffic channel, as in the case of M-ES load balancing scheme, the carrier is likely to be already active, and the procedure of tuning to the new frequency will be straightforward. However, in the case of dwell timer expiration, the MDBS has to transmit one or more switch channel messages, turn the current carrier off after the last message has been transmitted, and tune to the new frequency. At the M-ES end, as soon as the M-ES processes the switch channel message, it will attempt to tune to the new frequency contained in the message. A fast M-ES may attempt to tune to the new frequency before the MDBS has time to tune its carrier and may fail in acquiring the intended frequency. Strict timing requirements to ensure successful channel switching are not defined in the CDPD specifications.

7.4.3.6 Power Control

The MDBS controls the power transmitted by the M-ES with the use of two parameters, power product and maximum power level, broadcasted in the channel stream identification and the cell configuration RRMP messages broadcast on the channel stream. The maximum power level value limits the transmit power of the M-ES; the power product allows the MDBS to control the transmit power of the M-ES, if necessary. A constant power product itself has the effect of reducing the transmit power of the M-ES as it moves closer to the MDBS cell site.

Effective radiated power for the M-ESs are mapped to different power levels. These ERP values correspond to the M-ES Class-I as shown in Table 7.1.

TABLE 7.1
Power Levels of a Class-I M-ES

M-ES Maximum Power Level	*Maximum ERP (dBW)*
0	6
1	2
2	–2
3	–6
4	–10
5	–14
6	–18
7	–22
8	–22

TABLE 7.1 (continued)

M-ES Maximum Power Level	*Maximum ERP (dBW)*
9	
	–22
10	–22

The MDBS, on determining the power level at which it would like to receive transmissions from the M-ES, will send a power product value to the M-ES. In simple terms, the power product defines the following:

Power product [dBW^2] = M-ES transmit power [dBW] + mean received signal strength of the forward channel at the M-ES [dBW]

As we can see, if the MDBS is transmitting at a constant power, the closer the M-ES is to the cell, the greater will be the received signal strength of the forward stream. The above rule will force the M-ES to reduce its transmit power to maintain the defined power product value.

To allow easy implementation (to avoid dealing with negative numbers), the power product value that is transmitted is computed by how much it is in excess of –143 dBW. That is,

$$\text{Power product}_{\text{Transmitted}} = \text{power product}_{\text{Actual}} - (-143 \text{ dBW})$$

Therefore, the M-ES uses the following rule to determine its transmitter power:

M-ES transmit power [dBW] = power product$_{\text{Transmitted}}$ – 143 – RSSI of fwd channel at M-ES

The configured power product value may be adjusted seasonally, but otherwise no dynamic power control by the MDBS is deemed necessary.

7.4.3.7 Sleep Management

Sleep management procedures are defined in the CDPD specifications for implementing power conservation strategies for M-ESs. For implementation of the sleep-mode procedures, the RRME on the network side is made a subcomponent of the MD-IS software that has access to the link states managed by the MDLP layer in the MD-IS.

The overall concept is to allow the M-ES to transit into a power conservation state if there has been no messages to transmit on the reverse channel for a configured

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