North American Cellular System Based on Time Division Multiple Access

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Introduction

- 3 ways to expand the capacity of a cellular system
  - New spectrum bands
  - Split existing cells into smaller cells by installing new base stations
  - Introduce new technology to make more efficient use of existing bandwidth and base stations
- The original AMPS authentication procedure, based on verifying electronic serial numbers, proved vulnerable to fraud.

IS-54

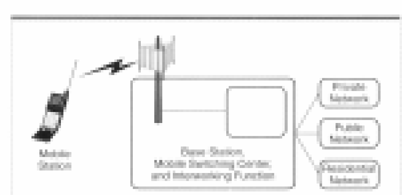
- Interim Standard 54 (IS-54): Cellular System Dual Mode Subscriber Equipment.
- Under IS-54, new terminals have all of the attributes of 1G AMPS terminals, with the added ability to transmit user information in digital format over "digital traffic channels."
- The technology advances that make IS-54 at least three times as efficient as AMPS are mainly in the area of digital signal processing.
- While calls are in progress, IS-54 telephones have access to associated control channels that perform some of the functions of AMPS transmissions on forward voice channel (FVC) and reverse voice channel (RVC).
- A sleep mode, in which terminals can turn off their receivers for a significant fraction of the time when they do not have a call in progress ,is introduced

IS-136

- The digital control channel (DCCH) specification is TIA/EIA Interim Standard 136 (IS-136), which is a revised version of IS-54.
- IS-136 specifies analog and digital traffic channels and the AMPS out-of-band control channels (FOCC and RECC).
- The publication of IS-136 opens the way to the production of all-digital TDMA telephones, rather than the dual-mode units specified in IS-54.
- A revised version of IS-136, published in October 1996, specifies TDMA operation in the North American PCS bands at 1900 MHz.

Architecture

- IS-136 (NA-TDMA) systems are capable of operating with AMPS terminals, dual-mode terminals, and all-digital terminals.
- BMI: Base Station, Mobile Switching Center, and Interworking Function.
- NA-TDMA specifies three types of external network: public systems, residential systems, and private systems.
  - function as a cellular telephone with access to the BS of cellular operating companies (public network).
  - function as a cordless telephone operating with a specific residential BS (residential network).
  - function as a business phone operating with a specific wireless private branch exchange (private network).



NA-TDMA Identifiers

- All of the AMPS identifiers are included in the NA-TDMA specifications.
- The 64-bit A-key plays a critical role in promoting network security and communication privacy in a dual-mode TDMA system.
- The system divides its service area into clusters of cells, referred to as location areas. LOCAID is a 12-bit location area identifier.
- The IMSI (international mobile subscriber identification) is a telephone number with up to 15 decimal digits.
- The value of PV (protocol version) reflects the standards document that governs the operation of a base station or terminal.
- The SOC (system operator code) transmitted by a BS identifies to terminals the company that operates the BS.
- The BSMC (BS manufacturer code) indicates the manufacturer of the BS.
- The DVCC (digital verification color code) plays the same role in digital traffic channels as the SAT transmitted in analog traffic channels.

Radio Transmission

- NA-TDMA specifies carries spaced at 30 kHz.
- The frame duration is 40 ms. Each frame contains 6 time slots. The length of each time slot is 40/6=6.67 ms.
- A receive time slot (base-to-mobile) begins approximately 1.9 ms after the end of the corresponding transmit time slot.

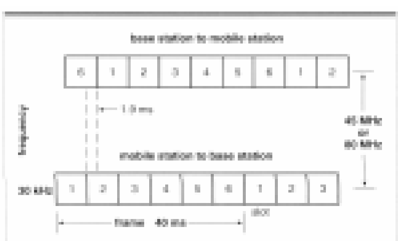
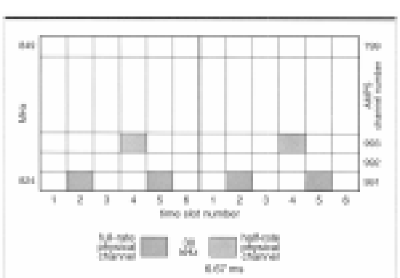
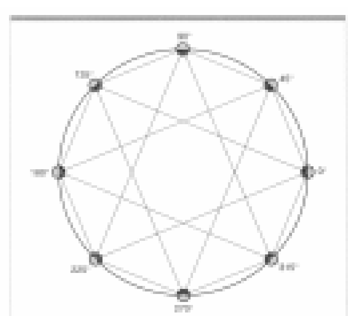


Figure 5.3 Frames and time slots.

Physical Channels

- Each time slot carries 324 bits, so that the data rate per carrier is (324*6)/40=48.6 kb/s.
- NA-TDMA defines 4 types of physical channels.
  - A full-rate channel can occupy slots 1 and 4, slots 2 and 5, or slots 3 and 6. The bit rate of a full-rate physical channel is (324*2)/40=16.2 kb/s.
  - Half-rate channel (8.1 kb/s) consisting of one slot per frame
  - Double full-rate digital channels (32.4 kb/s) with 4 slots per frame
  - Triple full-rate digital channels that occupy an entire carrier (48.6 kb/s)
- NA-TDMA has no fixed assignment of physical channels to digital control channel operation.
- On arriving in a new cell, a TDMA terminal without a call in progress performs a scanning procedure to search for a digital control channel.





Radiated Power

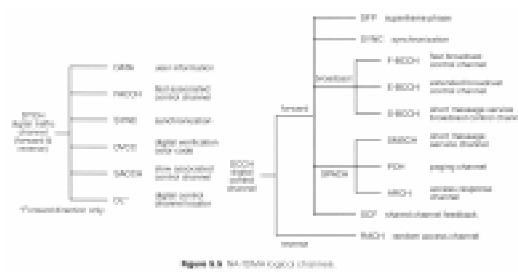
- NA-TDMA specifies 11 radiated power levels for terminals, including the eight power levels of AMPS terminals.
- The highest power level is 4W (6 dBW) and the levels differ by increments of 4 dB, ranging to a low of -34dBW (0.25mW).
- In dual-mode system, the three lowest power levels can be assigned only to digital traffic channels and digital control channels specified in IS-136.
- The transmitter of a terminal using a TDMA full-rate physical channel is active only one-third of the time.
- The average transmitted power lower than the specified radiated power level.

Spectrum Efficiency

- The most common reuse factor is N=7 cells per cluster with three antenna sectors in each cell.
- An all-digital network occupying half of the AMPS band has 416 carriers and 3*416=1248 full-rate physical channels.
- A practical network with N=7 frequency reuse will operate at least 21 digital control channels. This leaves a maximum of 1248-21=1227 full-rate digital traffic channels, which corresponds to an efficiency of E=1227/(7*25)=7.01 conversations/cell/MHz, approximately 3 times the efficiency of AMPS.

Logical Channels

- As a dual-mode system, NA-TDMA is capable of supporting all of the AMPS logical channels in addition to the digital control channels and digital traffic channels specified in IS-136.
- A digital traffic channel transmits information in 6 formats in the forward direction and 5 formats in the reverse direction.
- Forward digital control channels multiplex information in 9 distinct formats, including 3 broadcast control channels and 3 point-to-point channels. They also broadcast 2 types of synchronization information (SFP and SYNC) and carry feedback on the results of random access transmissions from terminals (SCF).
- The RACH random access channel is a many-to-one channel carrying messages from terminals to a base station.



Logical Channels (cont.)

- The FACCH uses a blank-and-burst technique to transmit information on a digital traffic channel.
- The broadcast control channels and the SPACH all occupy their own time slots on a forward digital control channel.
- Terminals contend for access to the RACH. Shared channel feedback plays an important role in the contention process.

Digital Traffic Channel (DTCH)

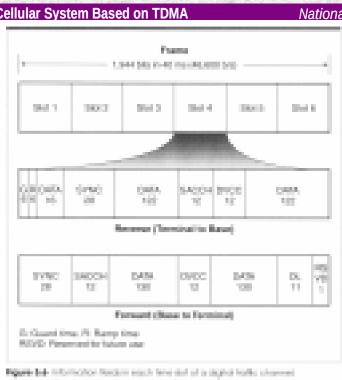
- The format for forward transmissions differs from the format for reverse transmissions.
  - NA-TDMA BSs transmit continuously while terminals turn their transmitters on at the beginning of each transmitting time slot and turn them off at the end of the slot.
  - Three terminals share the same carrier and it is important to prevent their signals from arriving at the BS simultaneously.

DTCH (cont.)

- The 6-bit guard time (G, 0.123 ms) in the reverse time slot prevents the signal transmitted at beginning of one time slot from interfering with the signal transmitted at the end of the previous time slot.
- The 6-bit ramp time (R) allows the transmitter to come up to its full radiated power level.
- In the forward time slots, the 11digital control channel locator (DL) bit 1 RSVD bit take the place of guard and ramp intervals in reverse time slots.

DTCH (cont.)

- In addition to the reverse time slots, the terminal transmit a shortened burst (50 bits, 1.03 ms) when they acquire a new physical channel.
- The long guard time presents the signal from one terminal from interfering with signals from other terminals using adjacent time slots.
- Based on time alignment information in the PHYSICAL LAYER CONTROL message, the terminal adjusts its transmitter timing relative to the nominal timing (1.9 ms).



Synchronization

- The 28-bit SYNC field in each time slot serves 2 purposes.
  - It contains frame synchronization information.
  - It enables a receiver to train an adaptive equalizer.
- NA-TDMA traffic channels achieve frame synchronization by means of 6 different 28-bit SYNC sequences, one assigned to each time slot.
- On recognizing the SYNC pattern for that time slot, the receiver has an indication of when to receive the information in the time slot and when to transmit reverse DTCH information to the BS.
- An adaptive equalizer in the receiver examine the received waveform in the SYNC field and compares it with the known transmitted waveform.

Digital Verification Color Code (DVCC)

- Like the SAT, the DVCC informs MSs and BSs that they are receiving the desired signal and not a signal from another cell using the same physical channel.
- In contrast to the 3 SATs of AMPS, NA-TDMA has a total of 255 different DVCCs (8-bits).

DATA Fields

- The DATA fields contain 260 bits of user information per time slot.
  - Forward: the DATA bits occupy 2 fields, each with 130 bits.
  - Reverse: there are 3 DATA fields, one with 16 bits, and the other two with 122 bits each.
- A full-rate user channel occupies 2 time slots per frame carries 2*260/0.040=13,000 b/s.

Speech Coding

- An analog-to-digital converter produces digital speech samples at a rate of 8000 samples per second in a linear format quantized to at least 13 bits/sample.
- The VSELP algorithm produces a 159-bit representation of the 160 samples.

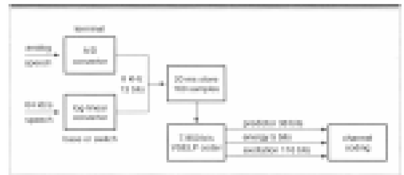


Figure 5.7 Speech coding summary

Error Protection for Coded Speech

- Among the 159 VSELP bits in a vocoder frame, there are 77 Class 1 bits that are especially vulnerable to transmission errors.
- 12 bits in the Class 1 bits are designated the "Most Perceptually Significant" bits.
- These bits are protected by 7-bit CRC error-detecting code.

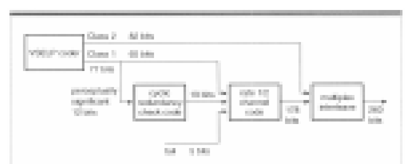


Figure 5.8 Error protection for coded speech.

Repetition Speech Block

- If the bit stream fails the CRC, the decoder generates a "bad frame" indication.
- The bad frame causes the VSELP decoder to ignore the received information and to repeat the most recent block of speech bits received without a CRC failure.
- If the decoder requires 3 or more consecutive repetitions of a speech block, it attenuates the received signal.
- If there are six or more successive bad frame indications, the receiver completely mutes the received signal.

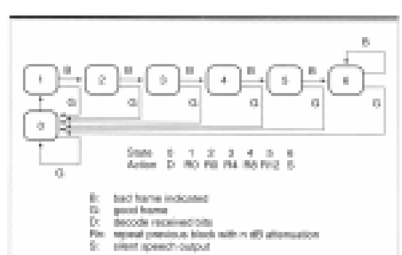
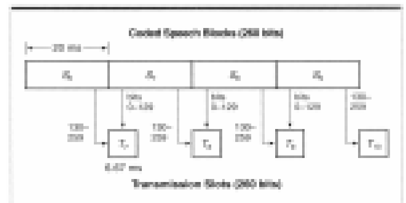
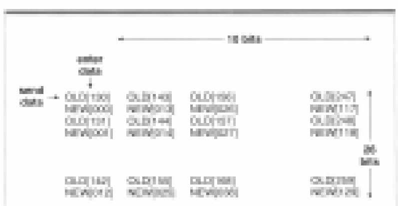


Figure 5.9 Bad frame masking.

Interleaving Code Bits

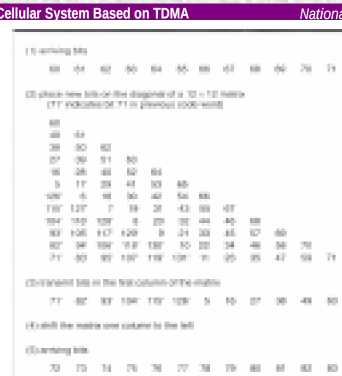
- To combat the effects of fading.
- NA-TDMA collects the final 130 bits from an "old" VSELP block and multiplexes them with the first 130 bits from a "new" block.





Slow Associated Control Channel (SACCH)

- The SACCH is an out-of-band signaling channel carrying information to and from a terminal while a call is in progress.
- FVC and RVC in AMPS are in-band signaling channels that operate in a blank-and-burst mode, interrupting user information each time they carry a message.
- In the SACCH, 132 bits, corresponding to the contents of 11 time slots, comprise a code word.
- The code word contains a 50-bit network control message protected by an error-detecting CRC and an error-correcting convolutional code.



Digital Control Channel Locator (DL)

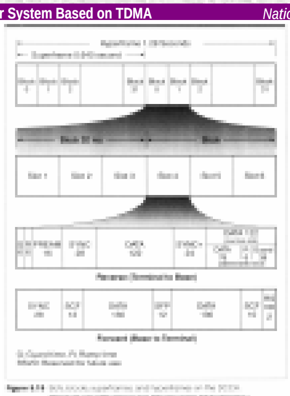
- The DL field in the forward digital traffic channel helps terminals locate a digital control channel (DCCH).
- The 11-bit DL field contains 7-bit digital locator value protected by an (11,7;3) error-correcting code.

Fast Associated Control Channel (FACCH)

- An in-band signaling channel to handle faster communications.
- The code word replaces the 260 bits from a speech coder block.
- The FACCH information is transmitted in 1/6 the time of SACCH information.
- The reliability of the information is considerably higher.

Digital Control Channel (DCCH)

- A block, consisting of 3 slots, is half of a frame.
- A full-rate control channel occupies 1 slot per block.
- There are 32 blocks per superframe and 2 superframes per hyperframe.
- A full-rate DCCH occupies 32 time slots per superframe. A half-rate DCCH occupies 16 slots per superframe.



DCCH (cont.)

- The SYNC field is identical to the SYNC field of a DTCH.
- SYNC+ and PREAM are fixed bit patterns that provide additional synchronization information on the random access channel.
- SPF informs terminals of the location of the current block in the 32-block DCCH superframe. The block number is represented as an 8-bit word.
- Because SFP differs from the code protecting the DVCC, terminals can inspect this 12-bit field to determine whether the current time slot carries a DCCH or a DTCH.
- SCF appears in 22 bits of each forward DCCH time slot.
  - A busy/reserved/idle (BRI) indication (6 bits) informs terminals of whether the current slot is being used by a random access channel.
  - A received/not-received (R/N) indication (5 bits) informs terminals of whether the BS has successfully decoded the information transmitted in a time slot on the reverse DCCH.
  - A coded partial echo (CPE, 11 bits) acknowledge receipt of information on the reverse DCCH.

Multiplexed Logical Channels on the Forward DCCH

- Each time slot on a forward DCCH carries information from one of the six logical channels.
- The logical channels share each superframe with F-BCCH, E-BCCH, S-BCCH, and SPACH ordered.

Figure 5.16 Logical channels in a digital traffic channel superframe.

Paging Channel Operation, Sleep Mode

- Monitoring paging messages has a strong influence on the standby time of the terminal's battery.
- NA-TDMA improves this situation with a way to make the terminals to operate in sleep mode when there is no call in progress.
- The terminal wakes up for a short time interval in the sleep mode.
- If there is a paging message for the terminal, the BS schedules the message to arrive during this brief wake-up interval.

RACH Access Protocol

- Dispersed terminals contend for access to the RACH under the control of the shared channel feedback (SCF) information transmitted in forward DCCH time slots.
- 2 modes for RACH
  - Random access
  - Reserved access

Random Access

- Success
  - A terminal with information to transmit waits for an IDLE indication in the BRI bits of a forward DCCH time slot.
  - The terminal then transmits its information in a specified slot of the reverse DCCH.
  - The BS reports the result of this transmission with the IDLE indication that stimulated the transmission by the terminal.
  - The BS indicates a successful result by means of a BUSY indication in the BRI bits of the response slot.
- Failure
  - The terminal waits a random time and attempts again to transmit its information to the BS.
  - The transmission attempts continue until the BS receives the RACH information and successfully transmits an ACK to the terminal.

Reserved Mode

- The BS prompts the terminal for a transmission by means of a RESERVED indication in the BRI bits and the last 7 bits of the MS identifier in the CPE portion of the shared channel feedback.
- This prompt from BS grants the terminal exclusive access to a time slot in the reverse DCCH.

Data Field of the DCCH

- DCCH purpose
  - To carry network control messages and SMS messages.
- Messages are contained in the DATA fields of each slot.
- In addition to the message content, the DATA fields carry headers that describe the message.
  - Indicates whether the message content begins a new message or is a continuation of a message in progress.
  - Indicates the length of the message portion of the DATA field.
- 260 bits in a forward DCCH time slot.
  - There are 260/2=130 bits at the input to the convolutional coder.
  - With a 16-bit CRC and 5 tail bits, this leaves 130-16-5=109 bits available for the header and message information.

Messages

- 3 sets of messages classified by the logical channels
  - Messages transmitted on AMPS logical channels
  - Messages transmitted on the in-band (FACCH) and out-of-band (SACCH) signaling channels associated with TDMA traffic channels.
  - Messages transmitted on the digital control channels.

Messages on AMPS logical Channels

- The main purposes of the added messages and information fields:
  - Control NA-TDMA authentication procedures
  - Direct dual-mode terminals to digital traffic channels
  - Inform the BS and switch of the capabilities of a terminal.
- Preferred call mode information, in call setup messages, informs the system of the capabilities of a terminal.
- LOCAID, a location area identifier carried in GLOBAL ACTION messages, plays an important role in area-based registration, a mobility management protocol available in NA-TDMA.

Additional Messages on AMPS Control Channels

Base-to-Mobile Messages (FOCC and FVC)	Mobile-to-Base Message (RECC and RVC)
Authentication Messages	
SERIAL NUMBER REQUEST CONFIRM BASE STATION CHALLENGE UNIQUE CHALLENGE ORDER SHARED SECRET DATA UPDATE	SERIAL NUMBER RESPONSE BASE STATION CHALLENGE CONFIRM UNIQUE CHALLENGE CONFIRM SHARED SECRET DATA UPDATE
Call Management Messages	
PAGE WITH SERVICE MESSAGE WAITING	ORIGINATION WITH SERVICE PAGE RESPONSE WITH SERVICE
Radio Resources Management Message	
INITIAL DIGITAL TRAFFIC CHANNEL	

Messages Carried on Associated Control Channels

- Most the messages stimulate ACK responses from the receiving network element.
  - Some ACK messages simply inform the sending BS or terminal that the message was received.
  - Other ACKs contain information specific to the purpose of the original message.
- Messages on the associated control channels share a common format, which is similar to the formats of messages exchanged in other systems, such as ISDN and SS7.
- All of the messages are carried in 49-bit code words.
- The first bit in each code word indicates whether this code word is the final code word in a message (0) or if additional code words follow (1).

Message Structure

- Each message begins with a 2-bit preamble. NA-TDMA refers to this preamble as a protocol discriminator.
- The next 8 bits comprise a message type field that specifies the nature of the message.
- The remainder of the message contains variable data specific to the purpose of the message.

Contents of a 48-Bit HANDOFF Message Carried on the FACCH

Bit Position	Information
1-2	00 protocol discriminator
3-10	11011100 HANDOFF message
11-21	AMPS channel number (specifies carrier)
22	Full rate of half rate
23-25	Time slot
26-35	SAT if handoff to analog channel, DVCC if handoff to digital channel
36-39	Transmit power level
40-44	Time alignment
45-46	Shortened burst indicator
47	Voice privacy mode
48	Message encryption mode

Message Content

- ACK and retransmission
  - The waiting time for a confirmation is 200 ms for messages on an FACCH and 1.2 seconds for SACCH messages.
  - For transmissions from a MS, the maximum number of attempts is 3.
  - For BS transmissions, there is no standard maximum.
- The DTMF messages refer to the dual-tone multiple-frequency sounds produced by push-button telephones.
- The MEASUREMENT ORDER, CHANNEL QUALITY, and STOP MEASUREMENT ORDER messages are all part of the mobile-assisted handoff protocol.
- R-DATA messages are part of the short message service.

Messages Carried on Digital Control Channels

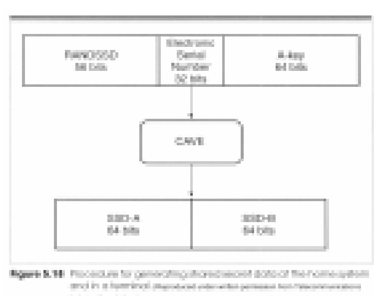
- There are 58 messages defined for the DCCH in contrast to the 16 FOCC/RECC messages in AMPS.
- All DCCH messages share a common format.
- The length of each message is an integer multiple of 8 bits, up to a maximum length of 255*8=2040 bits (255 octets).
- Each message begins with a protocol discriminator of length 2 bits, which for IS-136 messages are 00.
- The following 6 bits comprise a message type that specifies the nature of the message.
- The remainder of the message contains data specific to the purpose of the message.
  - The data fields begin with mandatory data carried in every message of a specific type.
  - This data is followed by optional parameters, which are carried in some message.

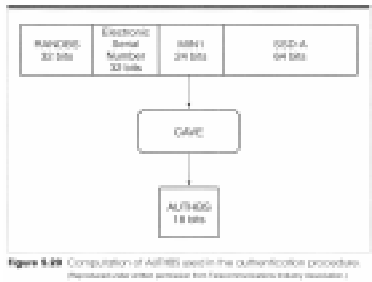
Contents of a SYSTEM IDENTITY Message on a BCCH

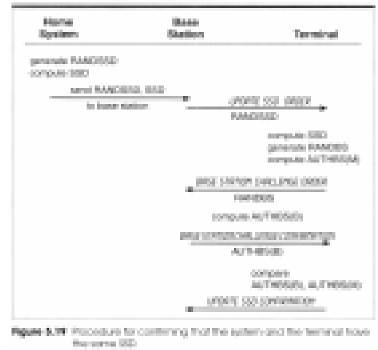
Bit position	Information
1-2	00 protocol discriminator
3-8	001011 SYSTEM IDENTITY message
	Mandatory Data
9-23	System identifier (SID)
24-26	Network type
27-30	Protocol version
	Optional Data
Variable	PSID/RSID set
Next 14 bits	Mobile country code
Variable	Alphanumeric system name

Authentication and Privacy

- At the heart of network security is a secret key (A-key), 64-bit binary number, stored in each telephone.
- The authentication center and the terminal both use the same A-key, in combination with a random number generated at the AC, to compute a 128-bit word, denoted shared secret data (SSD).
- SSD is the cryptographic key used by a terminal and a BS to protect transmitted information.
- CAVE (cellular authentication and voice encryption) is a cryptographic algorithm that operates on 152-bit inputs.
- RANDSSD is a random number generated at the AC.
- RANDBS, 32-bit random number, is a random number generated at the terminals.
- The BS sends an SSD UPDATE ORDER message to the terminal.







Network Security Mechanism for Verifying the Identity of a Terminal

- The BS controls the contents of a memory register, COUNT, 8-bit call-history register, in the terminal by means of a PARAMETER UPDATE message.
- To gain access to the system, the terminal transits COUNT to the BS, which verifies that the terminal has the correct value of this parameter.

Mobile-Assisted Handoff (MAHO)

- 4 types of handoff: from one analog channel to another analog channel, from analog to digital, from digital to analog, and from digital to digital.
- Each terminal reports its measurement to its own BS in CHANNEL QUALITY messages on the slow associated control channel.
- The MEASUREMENT ORDER messages identify either 6 or 12 active channels in surrounding cells. The terminal then tunes to these channels and observes their signal strengths.

MAHO (cont.)

- The terminal performs two measurements on the active traffic channel.
  - BER, the binary error rate
  - RSSI, received signal strength indication
- An initial CHANNEL QUALITY message contains the BER estimate (3 bits), the RSSI estimate of the active channel (5 bits), and the RSSI measurements of the first 6 surrounding channels.

MAHO (cont.)

- The adv. of MAHO
  - MAHO can initiate a handoff in response to signal-quality problems at the terminal.
  - MAHO responds more promptly to signal-quality problems.
  - MAHO provides BER to allow the system to perform handoffs in response to excessive interference on traffic channels.
  - MAHO moves some of the information processing necessary for network control from switches to BSs and terminals.

Mobile-Assisted Channel Allocation (MACA)

- MACA is a radio resources management procedure related to MAHO.
- The BCCH transmits a MACA message to all the terminals in a cell. The message contains a list of idle channels that available to handle new calls.
- Terminals tune to channels and perform signal-strength measurement and transmit the measurement to the BS in MACA REPORT messages on the RACH.
- The system uses these signal-strength measurements, as part of a channel allocation algorithm, to assign an appropriate physical channel to a conversation.

Call Management

- ALERT WITH INFO directs the terminal to produce an audible signal.
- When a subscriber responds to an alerting signal, the terminal sends a CONNECT message to the BS.
- The CONNECT message replaces the on-hook, off-hook indications provided by the AMPS 10 kHz supervisory tone.
- The FLASH messages indicate to the system that a telephone user wishes to initiate a special action during an ongoing call.

Mobility Management

- Whenever a terminal that does not have a call in progress enters a new location area, it sends a REGISTRATION message to the local base station.
- When a call arrives for a terminal, the system pages the terminal only in the location area where it last registered.
- The terminal compares this identifier with the stored identifier of the previous BS to determine the terminal has entered a new location area and is therefore required to send a REGISTRATION message to the system.