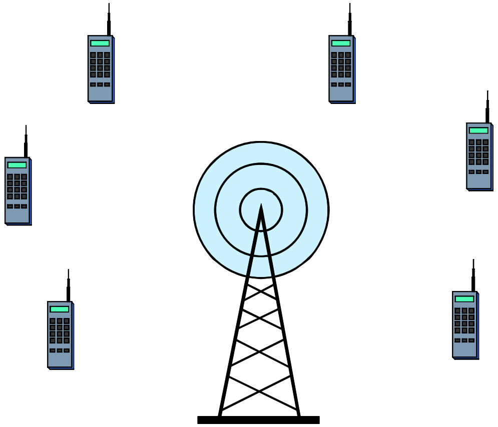
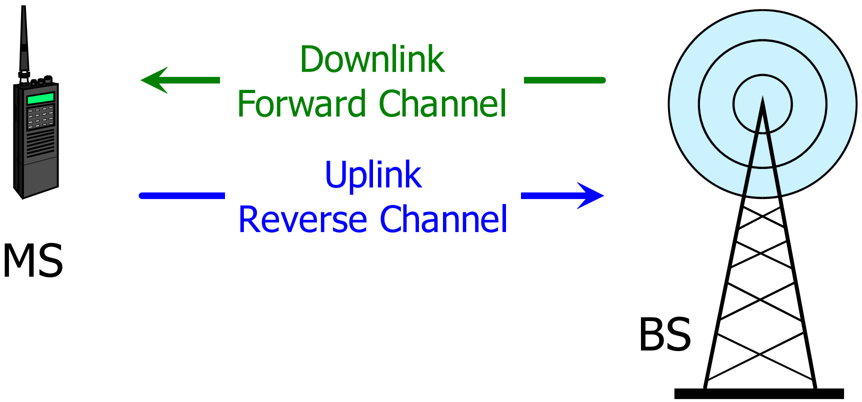
2G Cellular Telephony

Zero Generation System (1975 – 1990)



- **3 kHz voice bandwidth (like POTS)**
- **Frequency Division Multiple Access (FDMA)**
  - Analog FM modulation
  - Total bandwidth divided into hundreds of channels
- **Full duplex transmission**
  - 2 frequencies per telephone during call
  - Dedicated Base Station (BS) transmission frequency (uplink)
  - Dedicated Mobile Station (MS) transmission frequency (downlink)
- **Various non-compatible national and commercial systems**
  - 2G systems evolved from
    - US AT&T AMPS
    - British Telecom TACS



1G — Advance Mobile Phone Systems (AMPS)

North American first generation analog system — IS-553

25 MHz transmission band per direction

20 MHz frequency band per direction (1976)

Mobile Station (uplink): 825 - 845 MHz

Base Station (downlink): 870 - 890 MHz

Additional 5 MHz band per direction (1986)

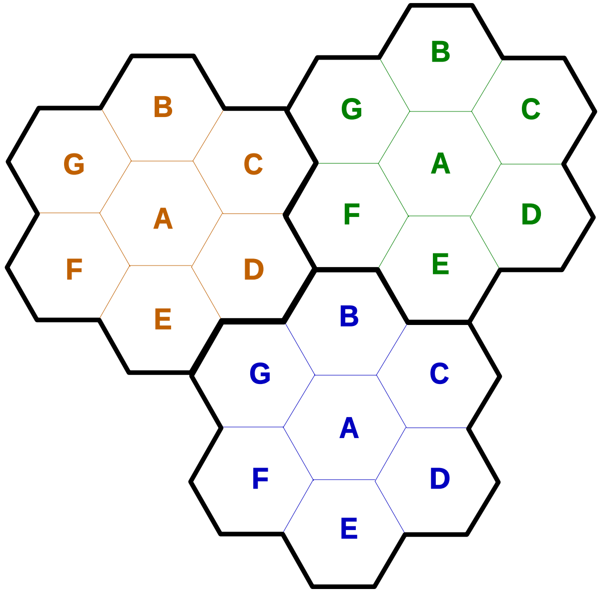
Mobile Station (uplink): 845 - 849 MHz

Base Station (downlink): 890 - 895 MHz

Frequency Division Multiple Access (FDMA)

Divide band into 30 kHz RF voice channels

$$\frac{25\text{ MHz per cluster}}{30\text{ kHz per channel}} = 832\text{ channels per cluster}$$



7 cell frequency reuse pattern (A, B, ..., G)

832 channels / 7 cells < 118 channels per cell

Typically 90 useful channels per cell

Commercial Diversity (Competition)

Split 25 MHz band for 2 service providers

B band for the established Telco

A band for a second cellular operator

832 channels / 2 bands = 416 channels per service provider

118 channels per cell / 2 bands < 59 channels per cell per provider

Band	Frequency Range (MHz)	Use
A	824 to 835 and 845 to 846.5	MS: Transmit from mobile
	869 to 880 and 890 to 891.5	BS: Receive at mobile
B	835 to 845 and 846.5 to 849	MS: Transmit from mobile
	880 to 890 and 891.5 to 894	BS: Receive at mobile

AMPS Digital Call Control

AMPS similar to POTS

- Most channel capacity allocated to voice
- Limited call control

Call control channel

- 10 kbps FSK (digital FM)
- Registration
- Authentication
- Operations, Administration, Maintenance (OAM)

Control information

- From phone
  - Mobile Identification Number (10 digit phone number)
  - Electronic Serial Number (32-bit ID of telephone)
  - Home System Identification (15-bit provider code)
- From network
  - Frequencies available to phone

Total Access Communications System (TACS)

British first generation analog standard

25 MHz transmission band

MS (uplink):	890 - 915 MHz
BS (downlink):	935 - 960 MHz

Not compatible with AMPS

25 kHz per channel

25 MHz per cluster / 25 kHz per channel = 1000 channels per cluster

7 cell reuse pattern

1000 channels / 7 cells = 140 channels per cell

Second Generation Systems

2G Analog systems

- Triple number of channels per cell
- Motorola proprietary products
  - Narrowband Advance Mobile Phone Systems (N-AMPS)
  - Motorola Integrated Radio System (MIRS)

Time Division Multiple Access (TDMA)

- Divide FDMA radio channel into time slots
- MS transmits digitized voice in one time slot on one frequency
- North American d-AMPS
- European GSM

Code Division Multiplex Access (CDMA)

- Create orthogonal binary digital transmission codes
- MS transmits in one code on one frequency

Narrowband AMPS (N-AMPS)

Based on AMPS standard

- Developed by Motorola

Allocate 10 kHz per channel — instead of 30 kHz in AMPS

- Triples number of channels
- Combines data compression and lower voice quality

First standard Short Message Service (SMS)

- Alphanumeric characters in control channel

Standards

- N-AMPS is IS-88, 89, 90
- Combined with AMPS as IS-91

Review of E1 Time Division Multiplexing (TDM)

Analog voice channel (300 Hz to 3300 Hz)

Sampled at 8000 samples/second

Round-off to 1-byte sample

Digital voice bit stream (DS-0)

$$\frac{8000\text{ samples}}{\text{second}} \times \frac{8\text{ bits}}{\text{sample}} = 64\text{ kbps}$$

E1 frame contains 32 bytes

1 byte each from 30 DS-0 streams

2 control bytes

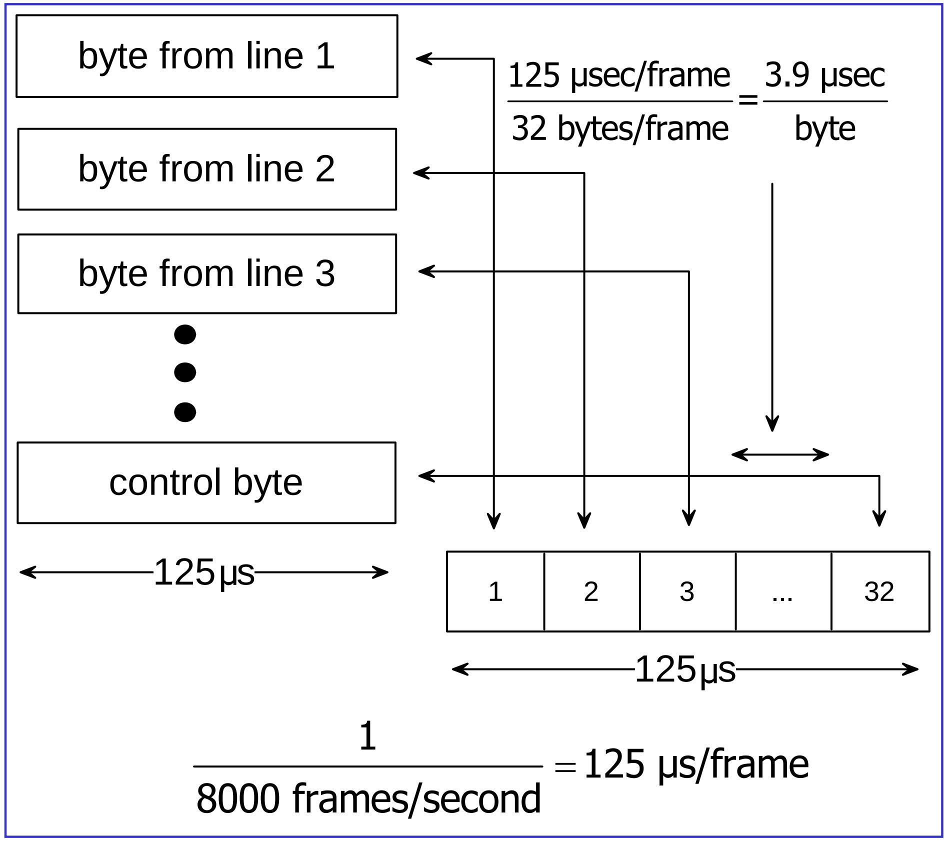
Isochronous real time

1 byte sample every 125 μsec

32 bytes per frame

E1 bit rate = 32 × 64 kbps = 2.048 Mbps

Squeeze 125 μsec sample into 125 μsec / 32 = 3.9 μsec transmission time



$$\frac{125\ \mu\text{sec/frame}}{32\text{ bytes/frame}} = \frac{3.9\ \mu\text{sec}}{\text{byte}}$$

$$\frac{1}{8000\text{ frames/second}} = 125\ \mu\text{s/frame}$$

Digital AMPS (d-AMPS)

North American 2G digital cellular on AMPS infrastructure

AMPS-based FDMA

$$\frac{\text{25 MHz per cluster}}{\text{30 kHz per voice channel}} = \text{832 voice channels per cluster}$$

Digital transmission

Transmit 48,600 bps in each 30 kHz voice channel

Voice channel modulation — DQPSK (encoded PSK)

Control channel modulation — AMPS compatible FSK

Time Division Multiple Access (TDMA)

Divide each voice channel into 6 time slots

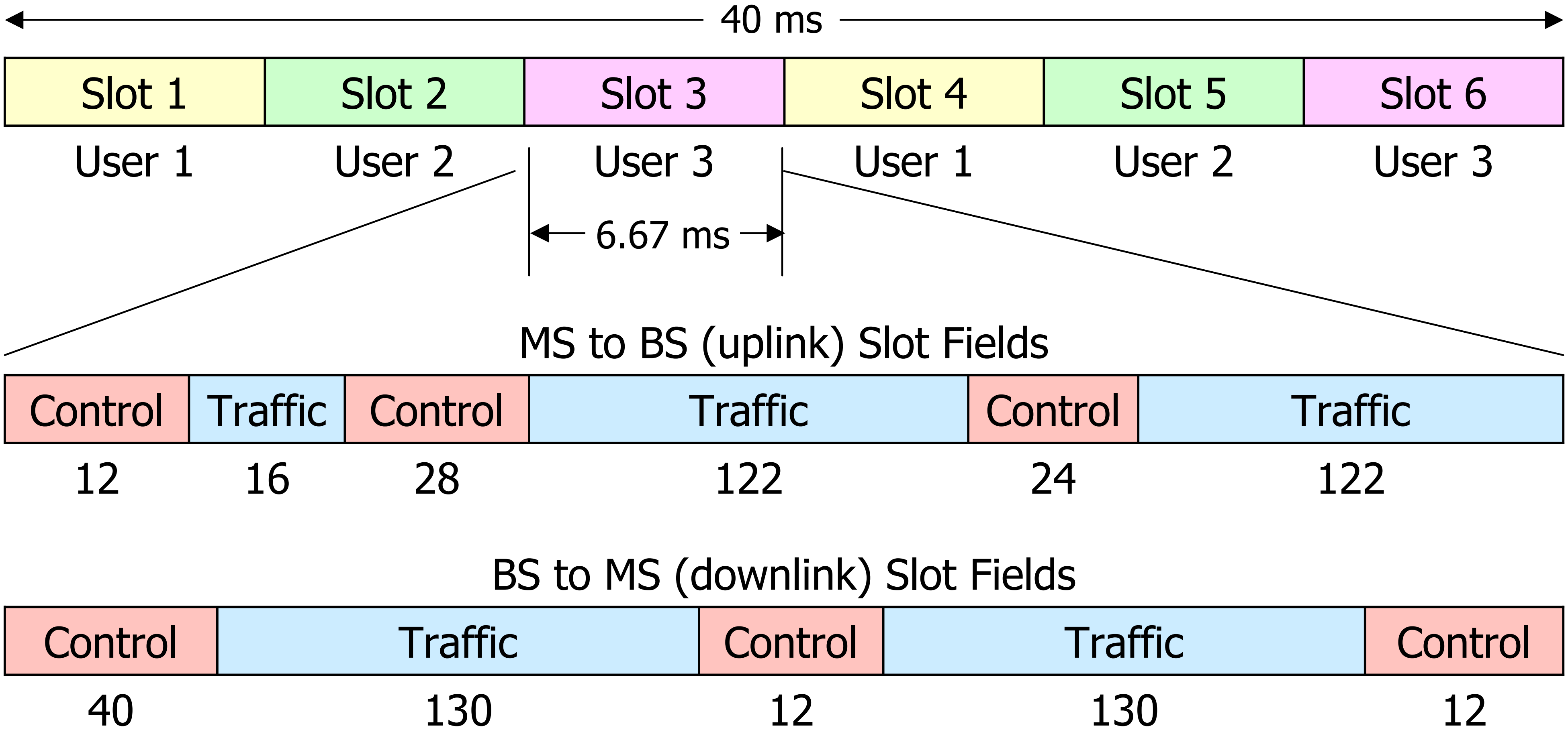
Allocate 2 time slots per user

- 3 users per voice channel
- 48,600 bps per channel / 3 users per channel = 16,200 bps per user

Standards

IS-54 replaced by IS-136

d-AMPS Digital Frames



40 ms

Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
User 1	User 2	User 3	User 1	User 2	User 3

6.67 ms

MS to BS (uplink) Slot Fields

Control	Traffic	Control	Traffic	Control	Traffic
12	16	28	122	24	122

BS to MS (downlink) Slot Fields

Control	Traffic	Control	Traffic	Control
40	130	12	130	12

Time slot contains

260 traffic bits (digitized voice)

64 control bits (call control, synchronization, OAM)

d-AMPS Data Rates

Slot width

260 data bits + 64 control bits = 324 bits per slot

Frame size

324 bit per slot × 6 slots per frame = 1,944 bits per frame

Frame and slot rates

40 ms per frame / 6 time slots per frame = 6.67 ms per time slot

40 ms per frame ⇒ 25 frames per second

Total transmission rate

25 frames per second × 1,944 bits per frame = 48,600 bps

User rates

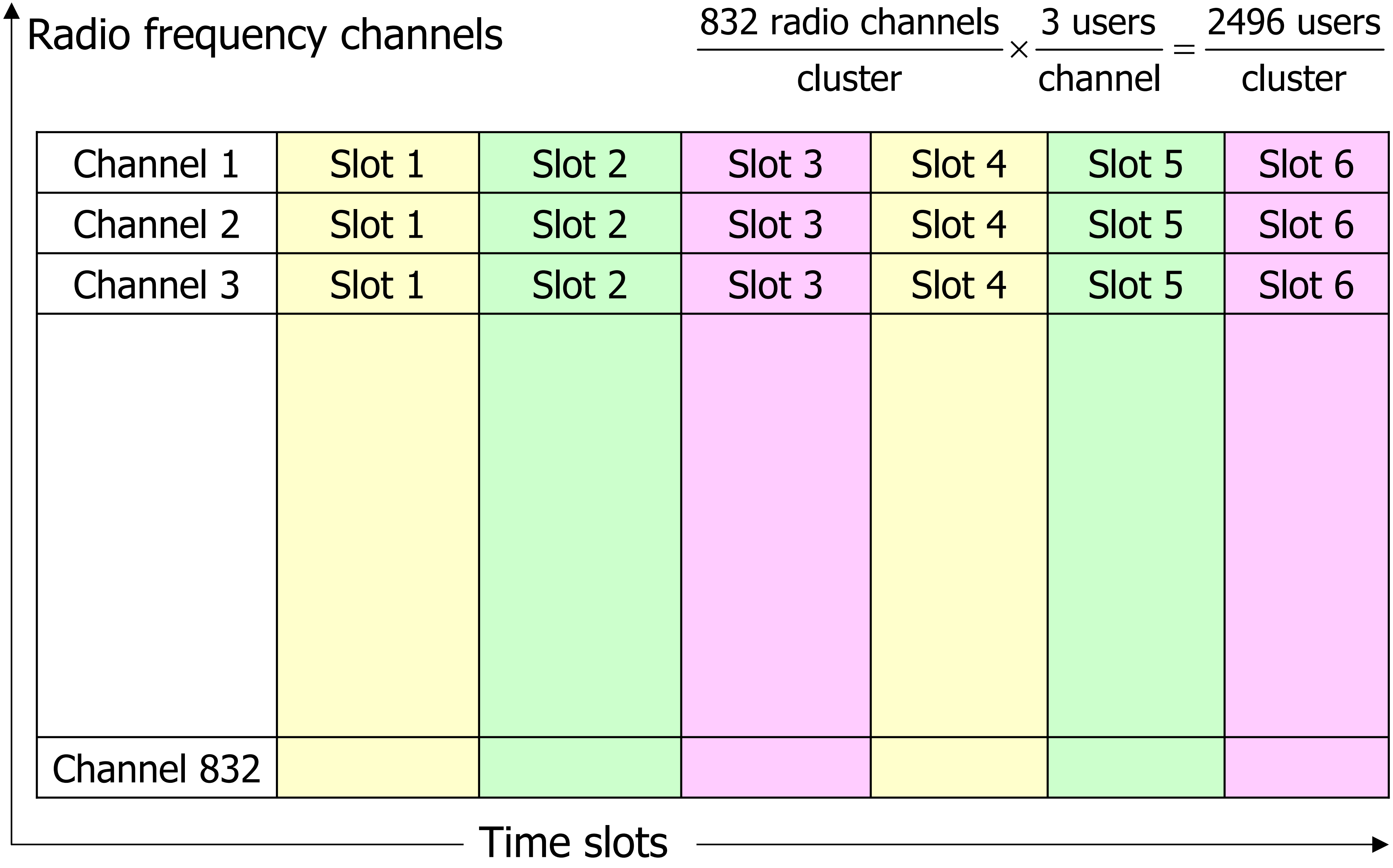
$$\frac{25\text{ frames}}{\text{second}}\times\frac{2\text{ user slots}}{\text{frame}}\times\frac{260\text{ traffic bits}}{\text{user slot}}=13{,}000\text{ bps (user traffic rate)}$$

$$\frac{25\text{ frames}}{\text{second}}\times\frac{2\text{ user slots}}{\text{frame}}\times\frac{64\text{ control bits}}{\text{user slot}}=3{,}200\text{ bps (user control rate)}$$

$$\text{total user rate}=16{,}200\text{ bps}$$

d-AMPS Channels

$$\frac{832 \text{ radio channels}}{\text{cluster}} \times \frac{3 \text{ users}}{\text{channel}} = \frac{2496 \text{ users}}{\text{cluster}}$$



Radio frequency channels

Channel 1	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
Channel 2	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
Channel 3	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
Channel 832						

Time slots

Voice Encoding

Analog to digital

Vector Sum Excited Linear Prediction

Generates 159-bit sample every 20 ms

Data rate = 159 bits / 20 ms = 7,950 bps

Forward error correction (protection)

Encoding permits error correction at receiver

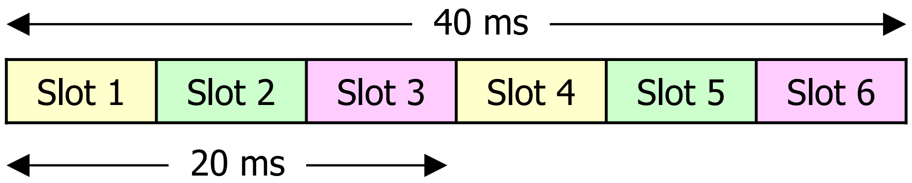
77 most significant speech bits encoded to 178 bits

159 – 77 = 82 less significant bits not encoded

Encoded data = 178 + 82 bits = 260 bits

260 bits / 20 ms = 13,000 bps

User time slots



Transmit frame every 40 ms

Frame contains two time slots per user

Time slot contains 260-bit digitized 20 ms voice sample

GSM

Global System for Mobile Communications

European Union 2G digital cellular on TACS frequencies

Non-TACS channelization

Divide band into 200 kHz RF channels (8 TACS voice channels)

25 MHz per cluster / 200 kHz per channel = 125 channels per cluster

Digital transmission

Transmit 270.883 kbps in each 200 kHz radio channel

Voice and control modulation

- Gaussian minimum-shift keying (GMSK) — optimized FSK

Time Division Multiple Access (TDMA)

Divide each channel into 8 time slots

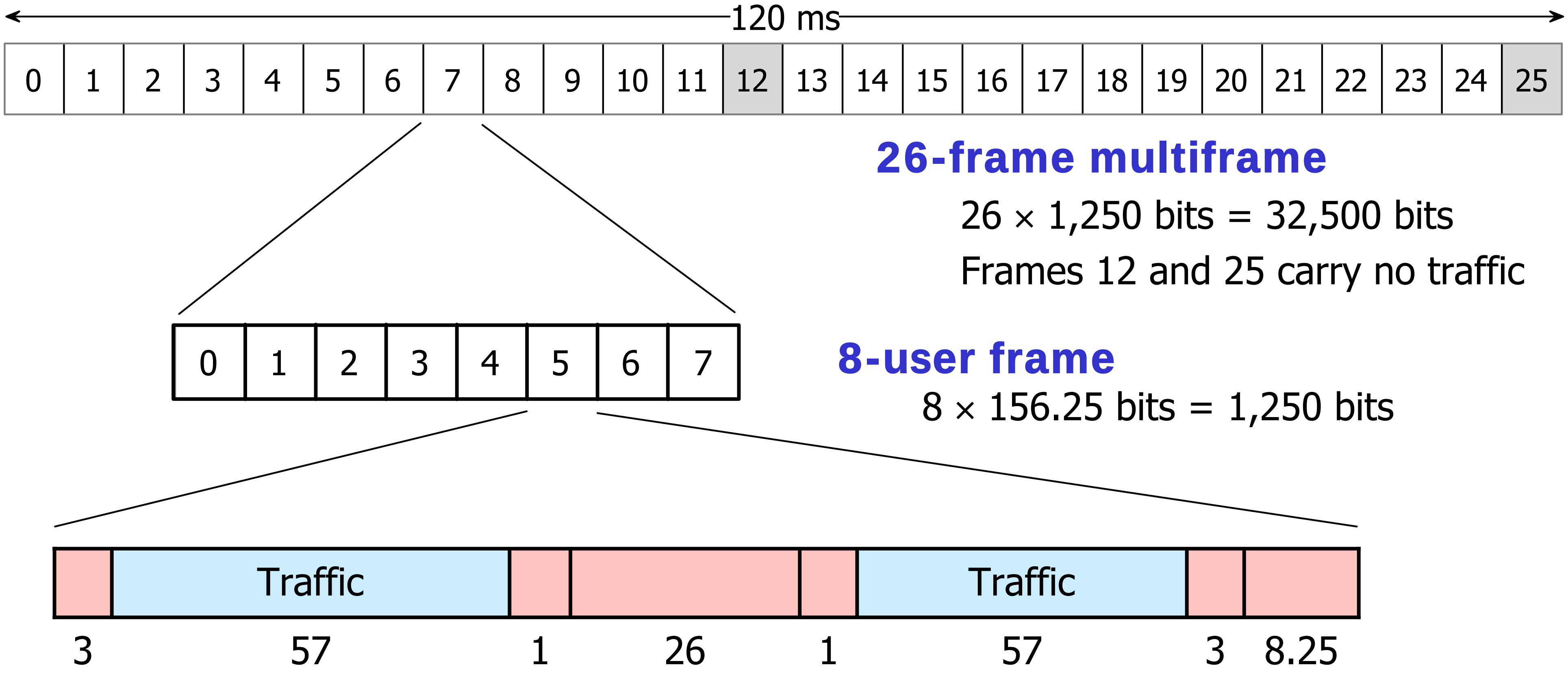
Allocate 1 time slot per user

- 270.883 kbps per channel / 8 users per channel = 33,086 bps per user

Standards

European Telecommunications Standards Institute (ETSI)

GSM Digital Frames



26-frame multiframe

26 × 1,250 bits = 32,500 bits

Frames 12 and 25 carry no traffic

8-user frame

8 × 156.25 bits = 1,250 bits

User time slot

156.25 bits

Time slot contains

57 + 57 = 114 traffic bits (digitized voice or data)

42.25 control bits for call control, synchronization, OAM

8.25-bit field — variable no-transmission interval between frames

Total bits in time slot = 114 + 42.25 = 156.25

GSM Data Rates

Time slot width

114 traffic bits + 42.25 control bits = 156.25 bits

Frame width

8 time slots per frame × 156.25 bits per slot = 1,250 bits per frame

Multiframe width

26 frames × 1,250 bits per frame = 32,500 bits per multiframe

Total transmission rate

32,500 bits per multiframe / 120 ms = 270.833 kbps

User traffic rate

Traffic in 24 frames — frames 12 and 25 carry no traffic

$$\left(\frac{2\times 57\text{ bits}}{\text{time slot}}\times\frac{24\text{ time slots}}{\text{multiframe}}\right)\bigg/\frac{120\text{ ms}}{\text{multiframe}}=22.8\text{ kbps}$$

GSM Voice Encoding

A/D conversion

Analog voice signal filtering at 3.3 kHz

Sampling at 8000 samples / second

Rounded off to 13-bit quantization (2^{13} level encoding)

8000 samples/second × 13-bits/sample = 104 kbps

Voice Encoding

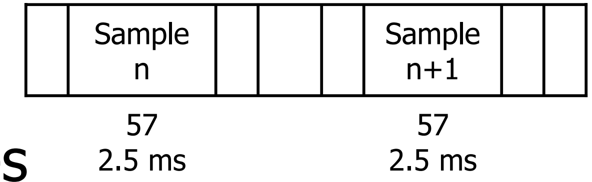
Regular Pulse Excited Long Term Prediction (RPE-LTP)

8-times voice compression

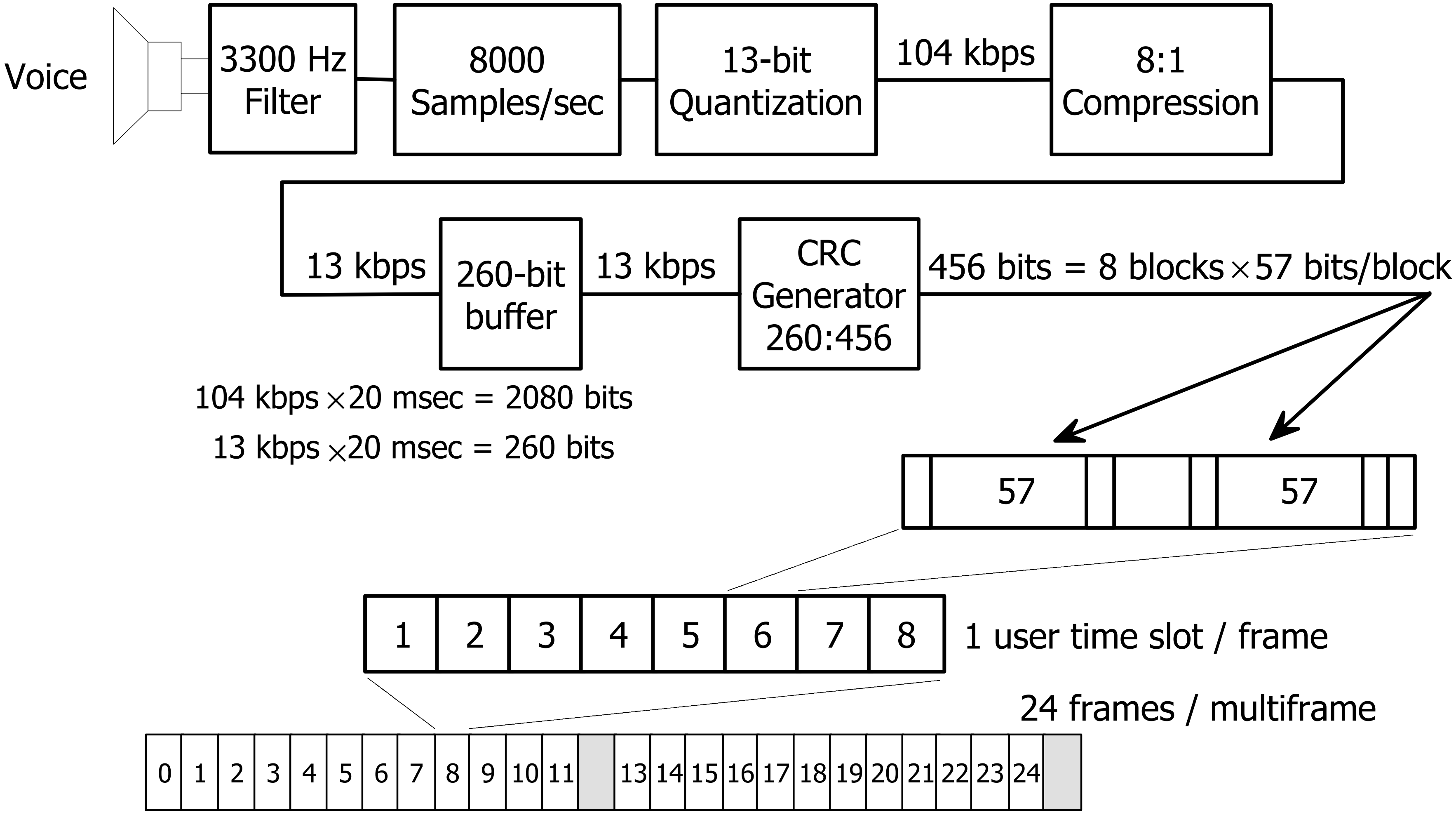
104 kbps / 8 = 13 kbps compressed data rate

GSM Voice Error Protection

- **Compressed 20 ms sample**
  - Uncompressed sample size = 104 kbps × 20 ms = 2080 bits
  - Compressed sample size = 13 kbps × 20 ms = 260 bits
- **Error protection on most significant bits**
  - 260-bit sample → 456-bit protected sample
- **Protected sample transmitted in 8 time sequential slots**
  - 20 ms sample / 8 slots = 2.5 ms sample per slot
  - 456 bits / 8 time slots = 57 bits per time slot
- **2 × 57-bit traffic fields per time slot**
  - Each time slot holds 1/8 of 2 sequential samples
  - 2 fields per time slot × 2.5 ms per field = 5 ms traffic per time slot
- **On large (uncorrectable) error at receiver**
  - Sample replaced with previous sample
  - Large error in 1 sample worse than small errors in 2 samples



GSM Voice Transmission Summary



Voice

3300 Hz Filter

8000 Samples/sec

13-bit Quantization

104 kbps

8:1 Compression

13 kbps

260-bit buffer

13 kbps

CRC Generator 260:456

456 bits = 8 blocks × 57 bits/block

104 kbps × 20 msec = 2080 bits

13 kbps × 20 msec = 260 bits

57 | 57

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8

1 user time slot / frame

24 frames / multiframe

0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24

57 user bits per field × 2 fields per frame × 24 frames per multiframe = 2736 user bits per multiframe

2736 bits per multiframe / 120 ms per multiframe = 22.8 kbps

22.8 kbps / (456/260) = 13 kbps

GSM Transmission Rate vs Service Rate

24 user frames serviced in 120 ms multiframe

$$\frac{120\text{ ms}}{24\text{ user frames}} = 5\text{ ms user traffic per frame}$$

Squeeze 8 user slots into frame transmission time

$$5\text{ ms user traffic serviced in }\frac{5\text{ ms}}{8} = 0.625\text{ ms}$$

26 physical frames per multiframe transmission

$$\frac{120\text{ ms}}{26\text{ frames}} = \frac{60}{13}\text{ ms per frame} = 4.62\text{ ms per frame}$$

Squeeze 8 user slots into physical frame transmission time

$$\frac{60}{13}\text{ms} \times \frac{1}{8} = \frac{15}{26}\text{ ms} = 0.58\text{ ms per slot transmission}$$

Comparing d-AMPS and GSM

Feature	**d-AMPS**	**GSM**
Total bandwidth	25 MHz per direction per cluster	25 MHz per direction per cluster
Frequency bands	MS (uplink): 825 - 849 MHz BS (downlink): 870 - 895 MHz	MS (uplink): 890 - 915 MHz BS (downlink): 935 - 960 MHz
Voice encoding	13 kbps (compressed protected)	22.8 kbps (compressed protected)
FDM (radio) channels per cluster	$\frac{25\text{ MHz}}{\text{cluster}} \Big/ \frac{30\text{ kHz}}{\text{channel}} = \frac{832\text{ channels}}{\text{cluster}}$	$\frac{25\text{ MHz}}{\text{cluster}} \Big/ \frac{200\text{ kHz}}{\text{channel}} = \frac{125\text{ channels}}{\text{cluster}}$
Digital capacity per FDM channel	48.6 kbps per 30 kHz channel	270.833 kbps per 200 kHz channel
TDMA (digital) slots per channel	3 digital voice streams/channel	8 digital voice streams/channel
TDMA channels per cluster	$\frac{832\text{ channels}}{\text{cluster}} \times \frac{3\text{ slots}}{\text{channel}} = \frac{2{,}496\text{ slots}}{\text{cluster}}$	$\frac{124\text{ channels}}{\text{cluster}} \times \frac{8\text{ slots}}{\text{channel}} = \frac{992\text{ slots}}{\text{cluster}}$
Protocol Structure	Simple — comparable to POTS	Complex — comparable to ISDN

Comparison of User Slots

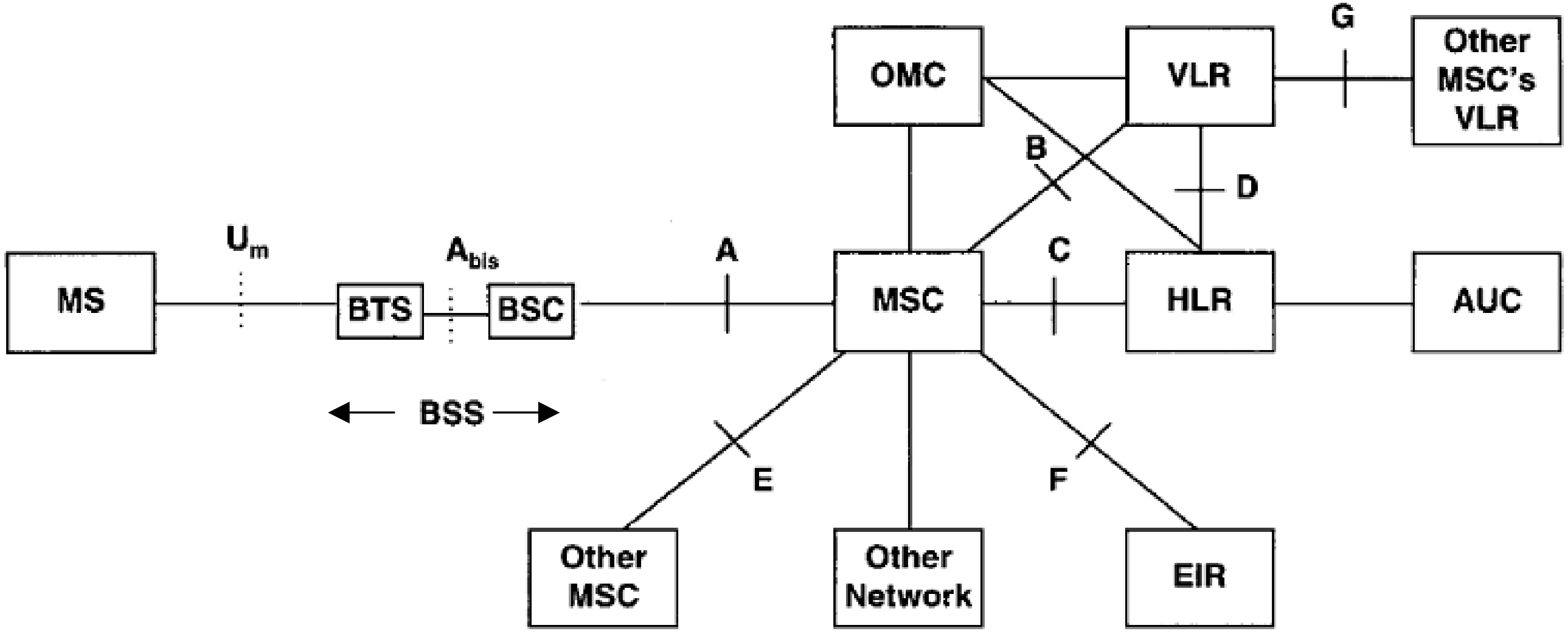
	d-AMPS	**GSM**	**d-AMPS to GSM Ratio**
User slots	2496	992	2.5
Bits / Hz	48.6 / 30 = 1.62	270.8 / 200 = 1.35	1.2
Used slots	100%	24 / 26 = 92%	1.08
Traffic / total	260 / 324 = 0.80	114 / 156 = 0.73	1.09
Bits per 20 ms voice sample	20 ms × 13 kbps = 260 bits	20 ms × 22.8 kbps = 456 bits	
20 ms voice samples per 1000 bits	1000 / 260 = 3.85	1000 / 456 = 2.19	1.75

Breakdown of d-AMPS to GSM user slot advantage

$$1.2 \times 1.08 \times 1.09 \times 1.75 = 2.5$$

Basic GSM Architecture

← Air Interface → ← Public Land Mobile Network (PLMN) →



MS	Mobile Station	HLR	Home Location Register
BSS	Base Station Subsystem	VLR	Visitor Location Register
BTS	Base Transceiver Station Radio system for one cell	AUC	Authentication Center User authentication / encryption keys
BSC	Base Station Controller Controller for one or more BTS	EIR	Equipment Identity Register Hardware ID database (theft control)
MSC	Mobile Switching Center	OMC	Operations and Maintenance Center

Mobility Management

Registration

Performed when mobile station (MS) activated in Service Area

Authentication

Verify authenticity of Mobile Station

Call Establishment

Performed when the user initiates or receives call

Handoff (handover)

Performed when MS changes connection point to network

Security

Protects from fraud and eavesdropping

GSM Registration Procedure

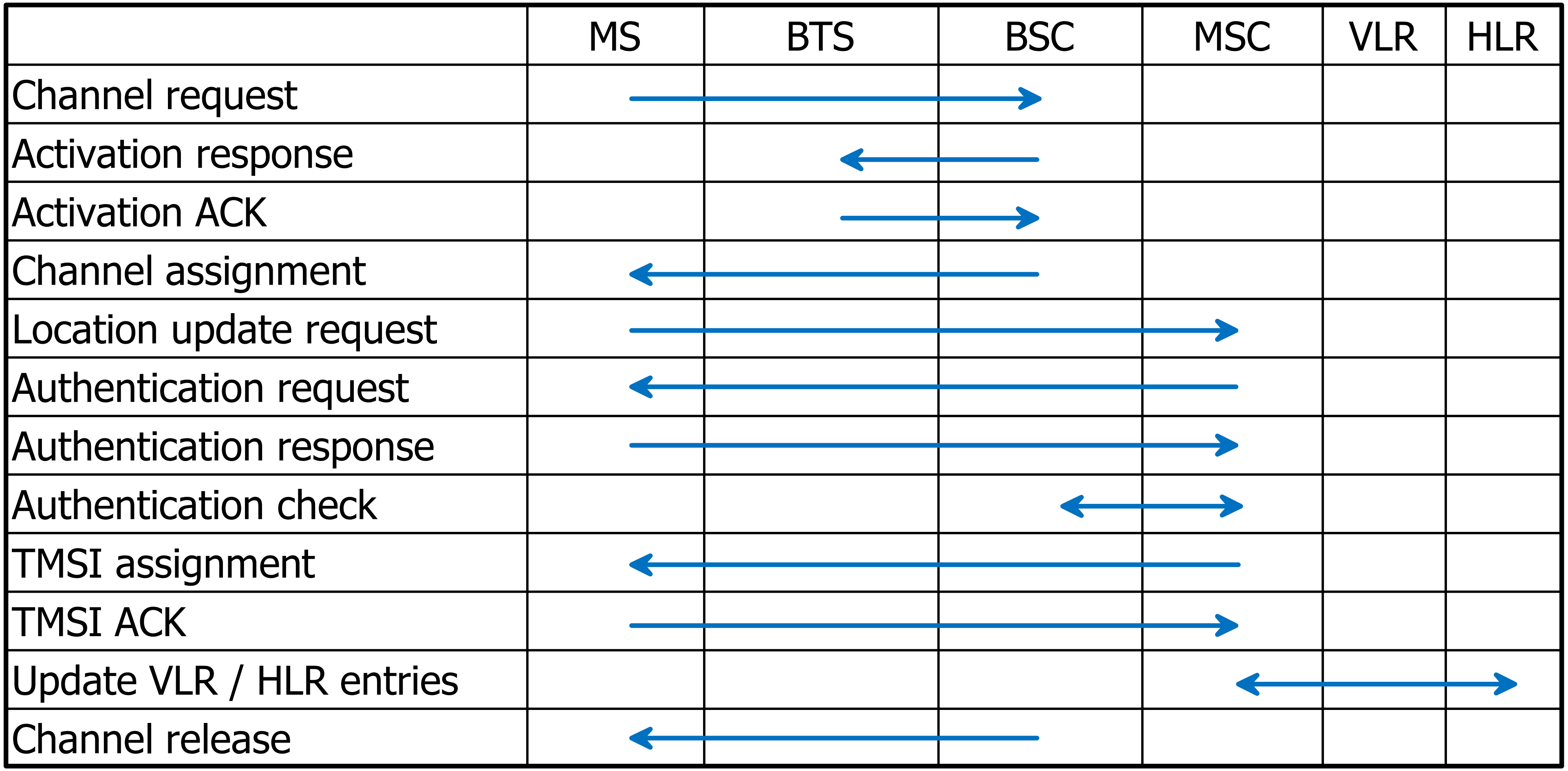
MS activated

- Scans all possible frequencies
- Synchronizes to BS beacon message
    - Beacon — control frame within larger data frame
- MS learns frame timings

MS initiates registration procedure

- Requests registration on control channel
- Base station system (BSS) authenticates MS
    - Checks ID number on SIM (subscriber identity module) card
- BSS assigns TMSI (Temporary Mobile Subscriber Identity)
- BSS updates VLR against HLR
- BSS closes control channel

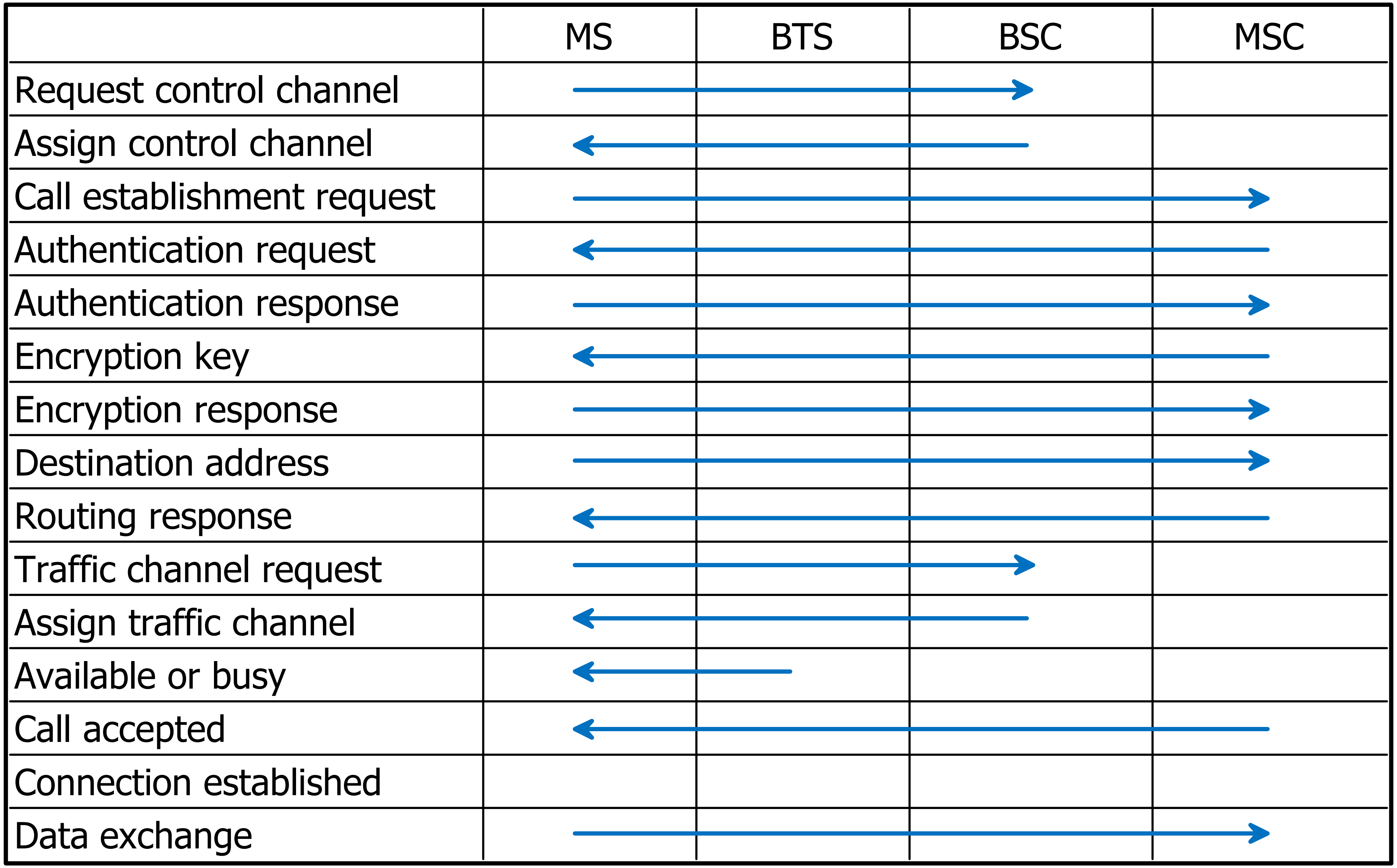
GSM Registration



	MS	BTS	BSC	MSC	VLR	HLR
Channel request	—	—	→			
Activation response		←	—			
Activation ACK		—	→			
Channel assignment	←	—	—			
Location update request	—	—	—	→		
Authentication request	←	—	—	—		
Authentication response	—	—	—	→		
Authentication check			←	→		
TMSI assignment	←	—	—	—		
TMSI ACK	—	—	—	→		
Update VLR / HLR entries				←	—	→
Channel release	←	—	—			

GSM Call Establishment

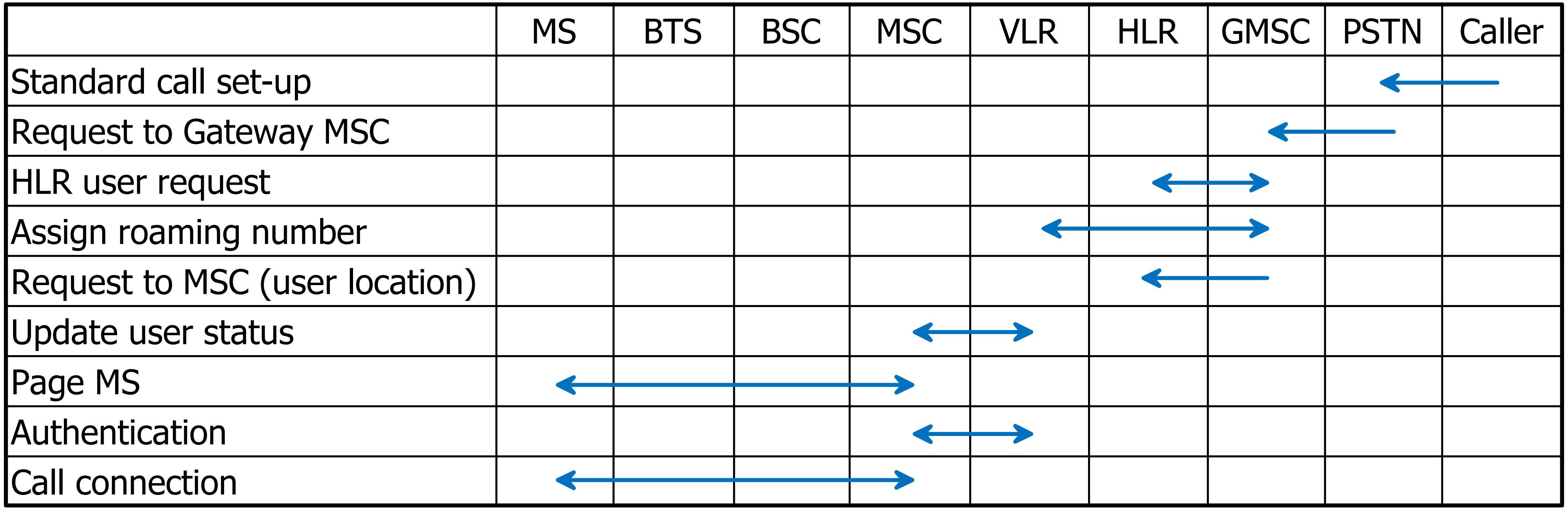
MS Initiated



	MS	BTS	BSC	MSC
Request control channel	→	→	→	
Assign control channel	←	←	←	
Call establishment request	→	→	→	→
Authentication request	←	←	←	←
Authentication response	→	→	→	→
Encryption key	←	←	←	←
Encryption response	→	→	→	→
Destination address	→	→	→	→
Routing response	←	←	←	←
Traffic channel request	→	→	→	
Assign traffic channel	←	←	←	
Available or busy	←	←		
Call accepted	←	←	←	←
Connection established				
Data exchange	→	→	→	→

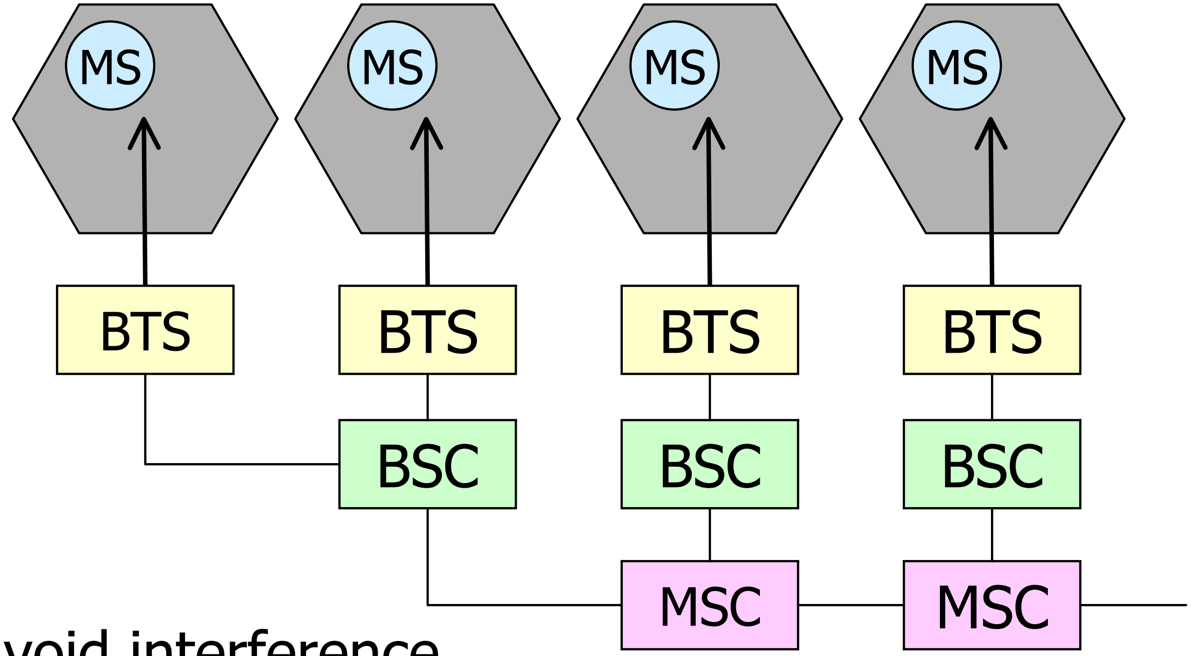
GSM Call Establishment

Mobile Terminated



	MS	BTS	BSC	MSC	VLR	HLR	GMSC	PSTN	Caller
Standard call set-up								←	←
Request to Gateway MSC							←	←	
HLR user request						↔	↔		
Assign roaming number					↔	↔	↔		
Request to MSC (user location)						←	←		
Update user status				↔	↔				
Page MS	↔	↔	↔	↔					
Authentication				↔	↔				
Call connection	↔	↔	↔	↔					

Handoff



Intra-cell

Change frequencies to avoid interference

Inter-cell — Intra-BSC

MS moves between cells within control of one BSC

Inter-BSC — Intra-MSC

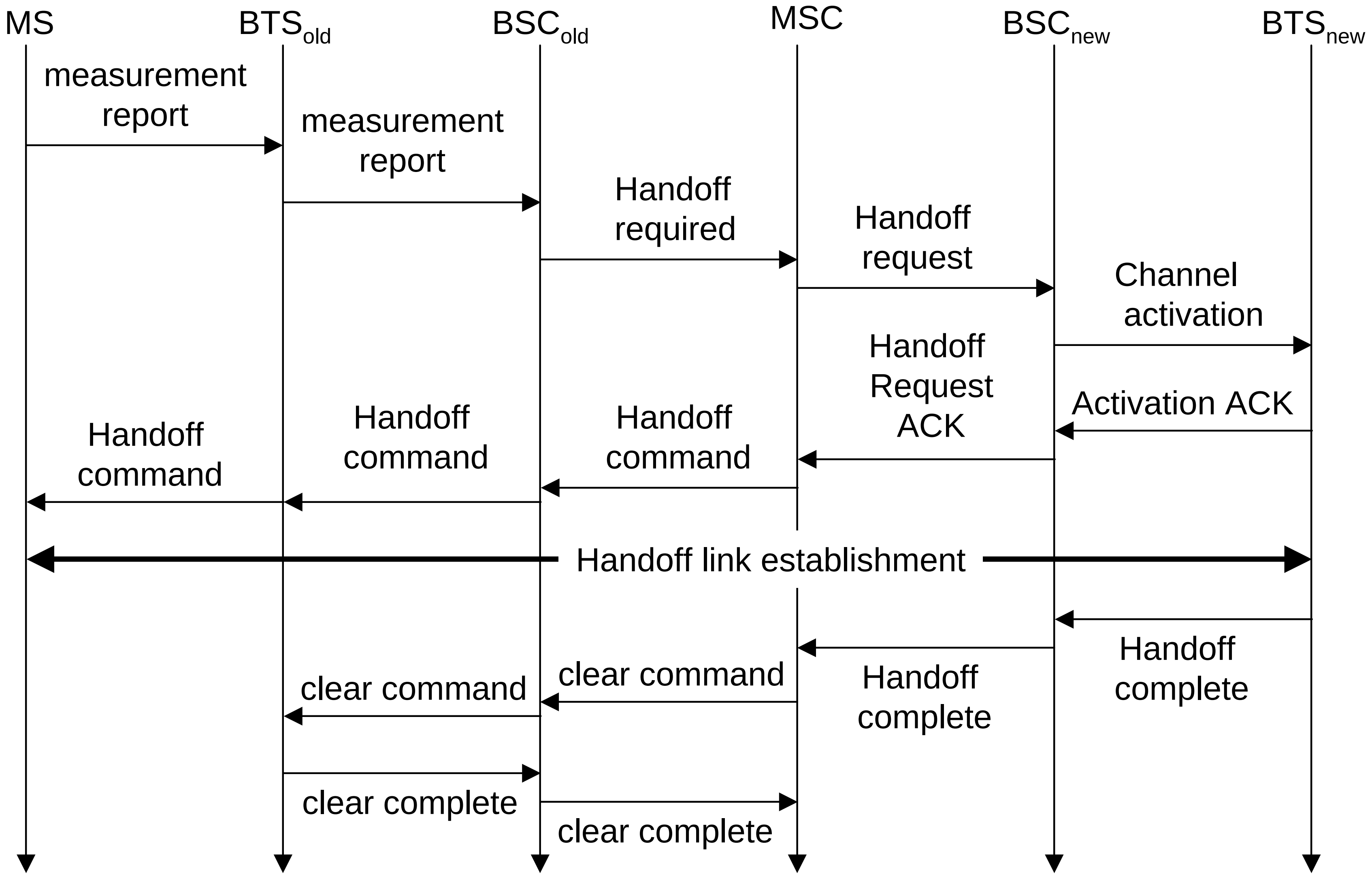
MS moves between cells controlled by different BSCs

MSC controls handover

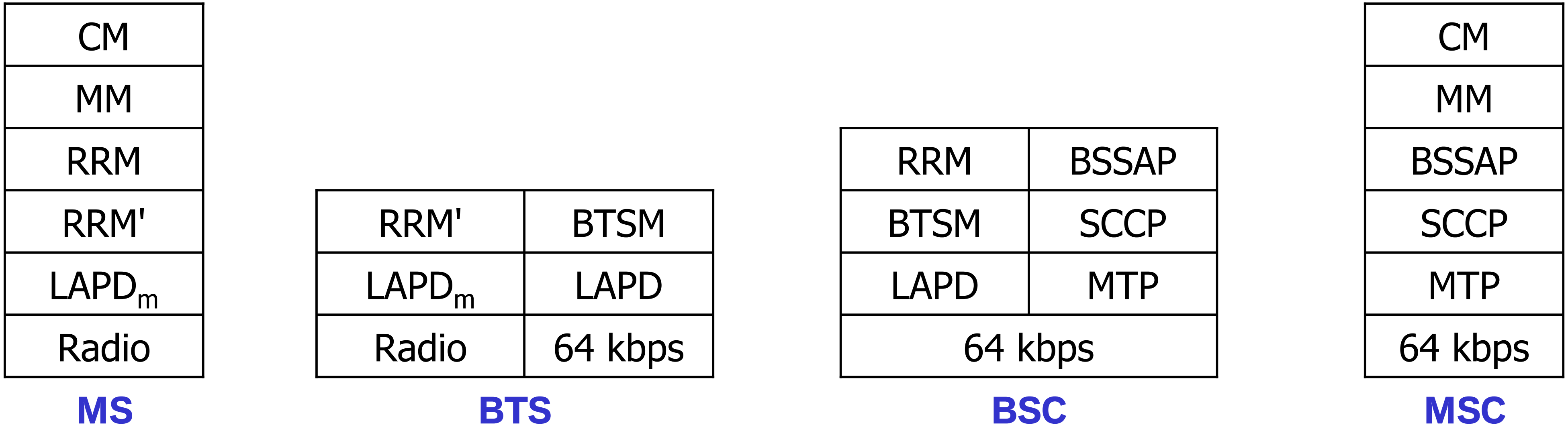
Inter MSC

MS moves between cells controlled by different MSCs

Handoff Procedure



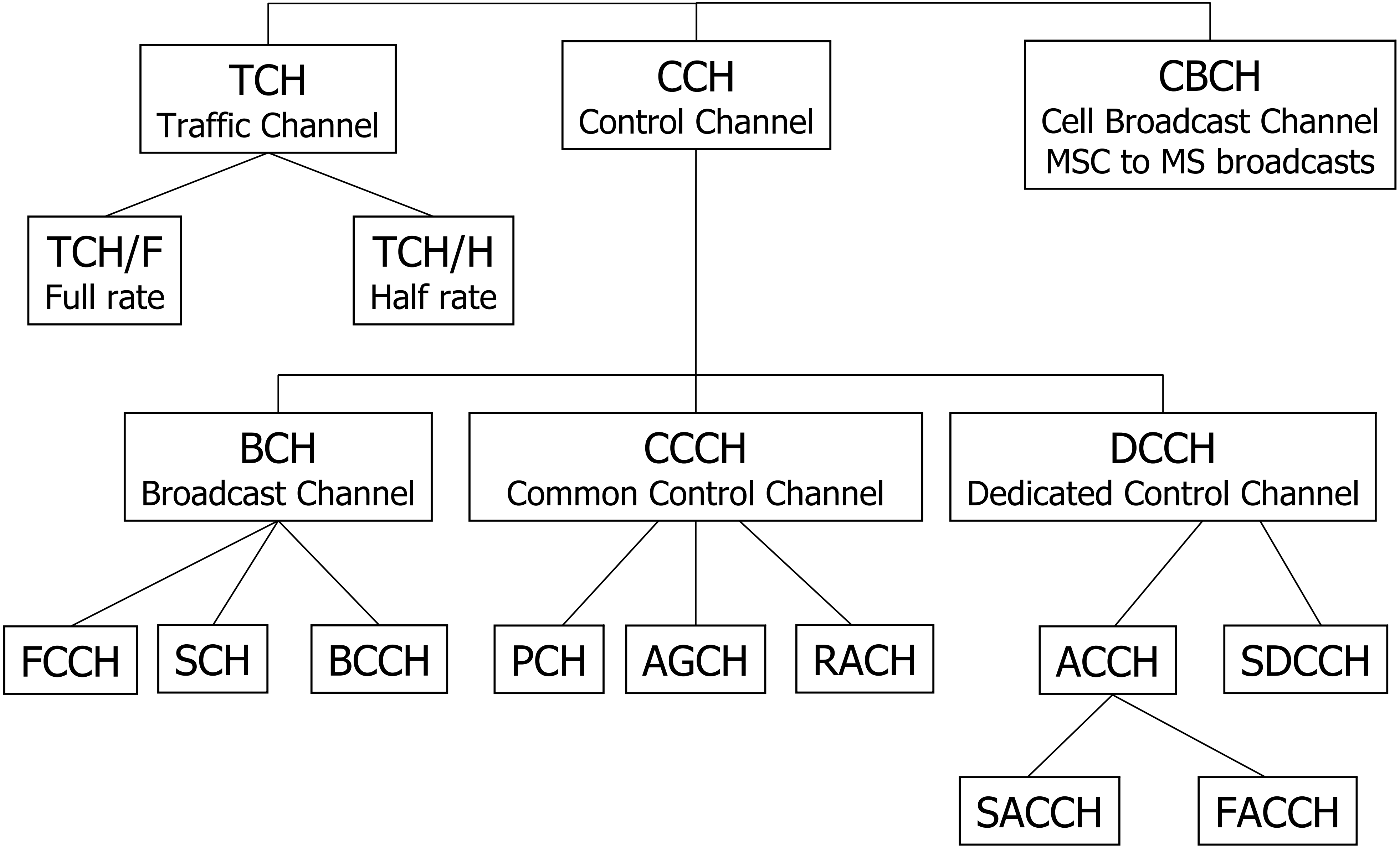
GSM Protocol Stack



CM					CM
MM					MM
RRM			RRM	BSSAP	BSSAP
RRM'	RRM'	BTSM	BTSM	SCCP	SCCP
LAPD$_m$	LAPD$_m$	LAPD	LAPD	MTP	MTP
Radio	Radio	64 kbps	64 kbps		64 kbps
MS	**BTS**		**BSC**		**MSC**

CM	Connection Management
MM	Mobility Management
RRM	Radio Resource Management Separate protocol instances at MS/BTS layer and MS/BSC layer
LAPD	Link Access Protocol D — ISDN layer 2 protocol (Q.920/921)
BTSM	Base Transceiver Station Management
BSSAP	BSS Application Part
SCCP	Signaling Connection Control Part (SCCP) — MSC/BSS management
MTP	Message Transfer Part — standard PSTN signaling and management

GSM Logical Channel Structure



- TCH Traffic Channel
  - TCH/F Full rate
  - TCH/H Half rate
- CCH Control Channel
  - BCH Broadcast Channel
    - FCCH
    - SCH
    - BCCH
  - CCCH Common Control Channel
    - PCH
    - AGCH
    - RACH
  - DCCH Dedicated Control Channel
    - ACCH
      - SACCH
      - FACCH
    - SDCCH
- CBCH Cell Broadcast Channel MSC to MS broadcasts

GSM Control Channels

BCH — Broadcast Channel

- Frequency Correction Channel (FCCH)
- Synchronization Channel (SCH) — frame numbers and cell ID
- Broadcast Control Channel (BCCH) — broadcast services and cell ID

Common Control Channel (CCCH)

- Paging Channel (PCH)
- Access Grant Channel (AGCH) — BTS assigns control channel to MS
- Random Access Channel (RACH) — MS requests to BTS

DCCH (Dedicated Control Channel)

- SDCCH (Stand-alone Dedicated Control Channel)
  - Service requests, authentication, traffic channel assignment
  - Call establishment and mobility management
- F/SACCH (Fast / Slow Associated Control Channel)
  - Preemptive / background messages for maintenance and handoff

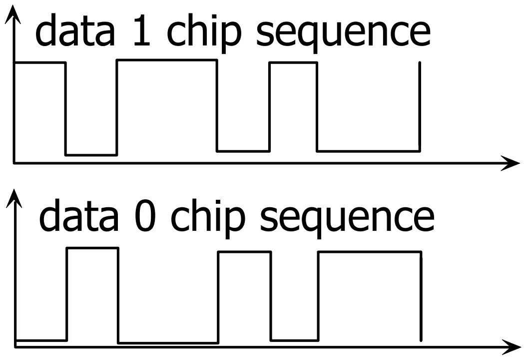
Direct Sequence Spread Spectrum (DSSS)

Transmit data bit as chip sequence

- Chip
  - Shortest binary pulse on transmission channel
  - n-chip sequence is symbol for one data bit

Multiplies transmission rate

- User generates data at m bits per second
- Transmit n-chip sequence for every user bit
- Example
  - 1-sequence for data 1 = 10110100
  - 0-sequence for data 0 = 01001011
- Chip rate = n bps × m chips per bit = n × m chips per second (cps)



Receiver easily distinguishes 1-sequence from 0-sequence

- Bit error requires > n / 2 chip errors
- Works well in noisy environment

CDMA

Code Division Multiple Access

- Commercial system developed by Qualcomm
- Operates on AMPS frequencies

Non-AMPS channelization

- 25 MHz radio band per direction
- Divide band into 1.25 MHz RF channels
- 25 MHz per cluster / 1.25 MHz per channel = 20 channels per cluster

DSSS digital transmission

- Transmit 1.2288 Mcps in 1.25 MHz radio channel
- Voice and control modulation — QPSK

Code division

- Users transmit simultaneously using independent chip sequences
  - Orthogonal (Walsh) Codes / Pseudorandom noise (PN) codes
- Receiver separates channels by decoding chip sequences

Standards

- IS-95 — now called CDMAone

Orthogonal CDMA Codes

m-dimensional vector space with inner product

$$\mathbf{U}\cdot\mathbf{V}=\frac{1}{m}\sum_{i=1}^{m}U_i\times V_i$$

m orthonormal basis vectors

$$S_i\,,i=1,\ldots,m$$

$\mathbf{T}=\sum_{i=1}^{m}t_i\times S_i\,,$ with coefficient t_i for any vector $\mathbf{T}$

$$S_i\cdot S_j=m\times\delta_{ij}=\begin{cases}0,\ i\neq j\\ m,\ i=j\end{cases}$$

$$t_i=S_i\cdot\mathbf{T}=S_i\cdot\frac{1}{m}\sum_{j=1}^{m}t_j\times S_j=\frac{1}{m}\sum_{j=1}^{m}t_j\times\left(S_i\cdot S_j\right)=\frac{1}{m}\sum_{j=1}^{m}t_j\times m\delta_{ij}=t_i$$

Code scheme

Basis vector S_i is code assigned to station i

Station i transmits $t_i\times S_i$ with coefficient

$$t_i=\begin{cases}-1\text{, data 0}\\ 0\text{, no transmission}\\ +1\text{, data 1}\end{cases}$$

Total transmission from all stations

$$\mathbf{T}=\sum_{i=1}^{m}t_i\times S_i$$

Example — 4-Chip CDMA

Code vectors for m = 4 stations

$$S_1 = \begin{bmatrix} -1 \\ -1 \\ -1 \\ -1 \end{bmatrix} \quad S_2 = \begin{bmatrix} -1 \\ +1 \\ +1 \\ -1 \end{bmatrix} \quad S_3 = \begin{bmatrix} -1 \\ -1 \\ +1 \\ +1 \end{bmatrix} \quad S_4 = \begin{bmatrix} -1 \\ +1 \\ -1 \\ +1 \end{bmatrix}$$

4-bit transmission levels (chips)

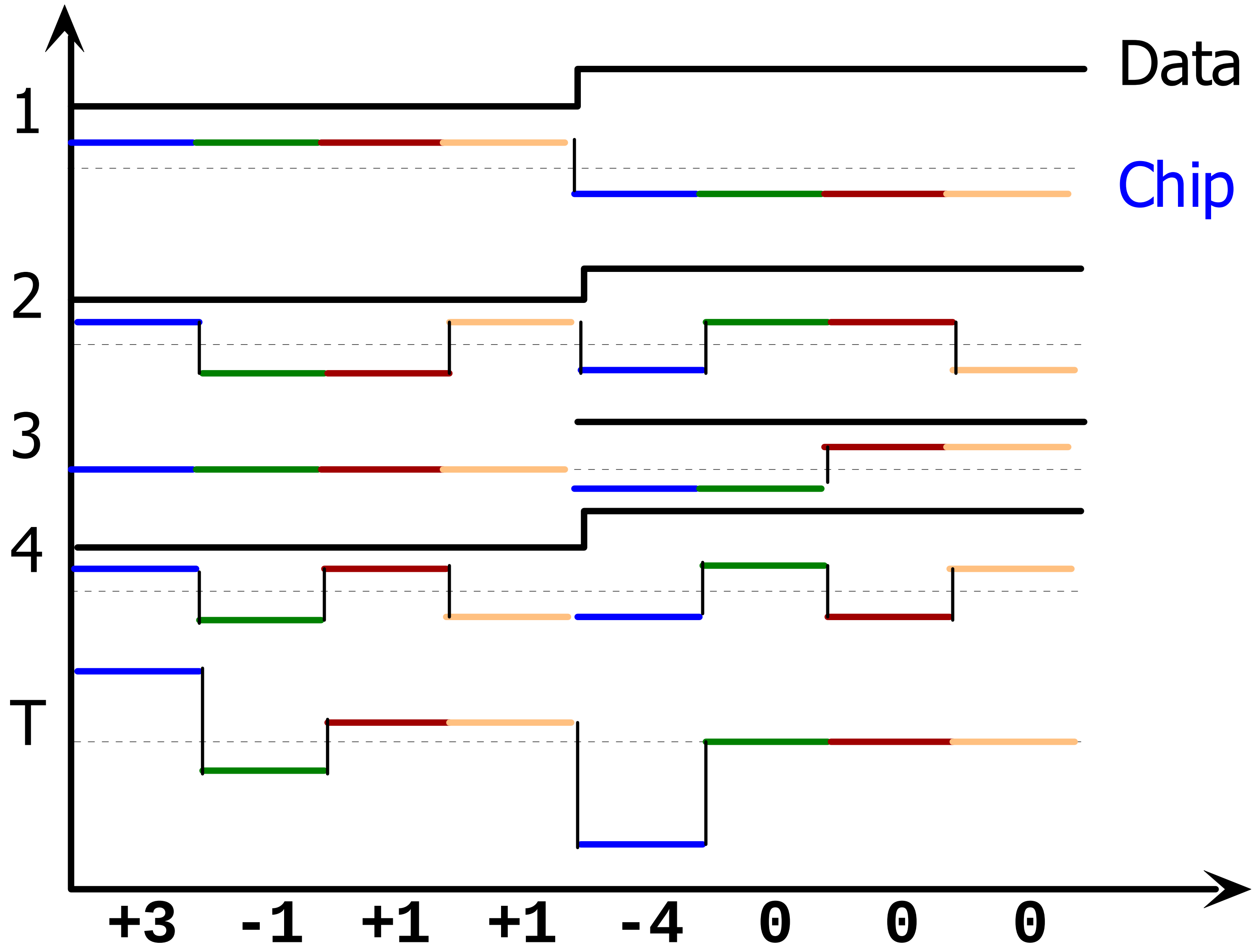
	Binary 1	Binary 0
Station 1	**–1 –1 –1 –1**	**+1 +1 +1 +1**
Station 2	**–1 +1 +1 –1**	**+1 -1 -1 +1**
Station 3	**–1 –1 +1 +1**	**+1 +1 -1 -1**
Station 4	**–1 +1 -1 +1**	**+1 -1 +1 -1**

Radio signal amplitudes added together

Example — 2-bit Transmission

Station 1	Data	0	1
	Signal	+1 +1 +1 +1	-1 -1 -1 -1
Station 2	Data	0	1
	Signal	+1 -1 -1 +1	-1 +1 +1 -1
Station 3	Data	no data	1
	Signal	0 0 0 0	-1 -1 +1 +1
Station 4	Data	0	1
	Signal	+1 -1 +1 -1	-1 +1 -1 +1
Total Transmission	Signal	+3 -1 +1 +1	-4 0 0 0

Example — 2-bit Transmission



Example — Decoding

Inner Product $\mathbf{U}\cdot\mathbf{V} = \frac{1}{4}\sum_{i=1}^{4} U_i V_i$ $t_j = \mathrm{T}\cdot \mathrm{S}_j$

First bit $\mathbf{T}$ = (+3, -1,+1,+1)	$t_1 = \tfrac{1}{4}(3,-1,+1,+1)\cdot(-1,-1,-1,-1) = \tfrac{1}{4}[-3+1-1-1] = -1 \Rightarrow 0$ $t_2 = \tfrac{1}{4}(3,-1,+1,+1)\cdot(-1,+1,+1,-1) = \tfrac{1}{4}[-3-1+1-1] = -1 \Rightarrow 0$ $t_3 = \tfrac{1}{4}(3,-1,+1,+1)\cdot(-1,-1,+1,+1) = \tfrac{1}{4}[-3+1+1+1] = 0 \Rightarrow$ no data $t_4 = \tfrac{1}{4}(3,-1,+1,+1)\cdot(-1,+1,-1,+1) = \tfrac{1}{4}[-3-1-1+1] = -1 \Rightarrow 0$
Second bit $\mathbf{T}$ = (-4,0,0,0)	$t_1 = \tfrac{1}{4}(-4,0,0,0)\cdot(-1,-1,-1,-1) = \tfrac{1}{4}[4] = +1 \Rightarrow 1$ $t_2 = \tfrac{1}{4}(-4,0,0,0)\cdot(-1,+1,+1,-1) = \tfrac{1}{4}[4] = +1 \Rightarrow 1$ $t_3 = \tfrac{1}{4}(-4,0,0,0)\cdot(-1,-1,+1,+1) = \tfrac{1}{4}[4] = +1 \Rightarrow 1$ $t_4 = \tfrac{1}{4}(-4,0,0,0)\cdot(-1,+1,-1,+1) = \tfrac{1}{4}[4] = +1 \Rightarrow 1$

Orthogonal Walsh Codes

Walsh 0

$W_0 = \boxed{1}$ $\quad W_0' = \boxed{-\ 1}$

Walsh 1

$$W_1 = \begin{array}{|c|c|}\hline W_1 & W_1 \\ \hline W_1 & W_1' \\ \hline\end{array} = \begin{array}{|c|c|}\hline 1 & 1 \\ \hline 1 & -1 \\ \hline\end{array}$$

Walsh 2

$$W_2 = \begin{array}{|c|c|}\hline W_2 & W_2 \\ \hline W_2 & W_2' \\ \hline\end{array} = \begin{array}{|c|c|c|c|}\hline 1 & 1 & 1 & 1 \\ \hline 1 & -1 & 1 & -1 \\ \hline 1 & 1 & -1 & -1 \\ \hline 1 & -1 & -1 & 1 \\ \hline\end{array} = \begin{array}{|c|}\hline S_1 \\ \hline S_4 \\ \hline S_3 \\ \hline S_2 \\ \hline\end{array}$$

Walsh 3

$$W_3 = \begin{array}{|c|c|}\hline W_4 & W_4 \\ \hline W_4 & W_4' \\ \hline\end{array}$$

Walsh N

$$W_N = \begin{array}{|c|c|}\hline W_{N-1} & W_{N-1} \\ \hline W_{N-1} & W_{N-1}' \\ \hline\end{array}$$

Walsh N is $2^N \times 2^N$ matrix

Pseudo-Noise (PN) Coding

Pseudorandom Bernoulli sequence of 1 or –1

- Equivalent to sequence of m coin tosses
- Nearly equal number of 1 and –1 in each code
  - By central limit theorem

$$P_{-1}=P\left(-1\right)=\frac{1}{2}+\delta \qquad P_{+1}=P\left(+1\right)=\frac{1}{2}-\delta \qquad \left|\delta\right|<\frac{1}{\sqrt{m}}$$

Codes are "nearly orthogonal"

- For codes A and B with chip patterns $C_i^{(A)}$ and $C_i^{(B)}$

$$A=B\ \Rightarrow\ \frac{1}{m}\sum_{i=1}^{m}C_i^{(A)}\times C_i^{(B)}=\frac{1}{m}\sum_{i=1}^{m}\left[\pm 1\right]^2=1$$

$$A\neq B\ \Rightarrow\ \frac{1}{m}\sum_{i=1}^{m}C_i^{(A)}\times C_i^{(B)}$$

$$=\frac{1}{m}\sum_{i=1}^{m}\left[P_{+1}\times P_{+1}-P_{+1}\times P_{-1}-P_{-1}\times P_{+1}+P_{-1}\times P_{-1}\right]=4\delta^2<\frac{4}{m}$$

Channel Coding

Forward channels

- 64 orthogonal Walsh codes to 64 users
  - Theoretically perfect separation between users
- All signals in same cell scrambled using PN sequence
  - Reduces interference between same Walsh code in neighboring cells
  - Short PN sequence uses cell ID as seed
  - Paging and traffic scrambled with long PN sequence before Walsh

Reverse channels

- Orthogonal codes not applicable in uplink
  - Orthogonality requires time synchronization
  - MSs transmit asynchronously
- Long PN sequence
- Stream is scrambled using short PN sequence
- Carries cell ID

Power Control

Near / far problem

- Signal from MS close to BS stronger than same signal from far MS

Solution — dynamic control of MS signal power

Open loop power control at MS

- MS senses strength of pilot signal and adjusts power
- Strong signal
  - MS close to BS
  - Power lowered

Closed loop power control at MS

- Power control information sent to MS from BS
- Requests transition up or down in power

Open loop power control at BS

- BS decreases power gradually (to avoid interference in other cells)
- Raises power when MS reports high frame error rate (FER)

North American IS-95 CDMA

25 MHz AMPS frequency band

1.25 MHz per FDM band ⇒ 20 FDM bands

In every 1.25 MHz FDM band

64 users transmit in same 1.25 MHz band (on same carrier frequency)

Each station has unique 64-bit chip sequence

Digital channel

Allocate 19.2 kbps / user for voice, data, control

19.2 kbps/channel × 64 channels = 1.2288 Mbps

All cells use all frequencies and all codes (reuse = 1)

Transmissions from neighboring cells are not time-synchronized

Unsynchronized codes are close to orthogonal

Users

$$\frac{64\text{ users}}{\text{radio channel}} \times \frac{20\text{ channels}}{\text{cell}} \times \frac{7\text{ cells}}{\text{cluster}} = 8{,}960\ \frac{\text{users}}{\text{cluster}}$$

Reuse Pattern in GSM and CDMA

GSM

- Transmit 8 time slots on 1 FDM channel
  - Channels on different FDM channels do not interfere
  - Channels in different time slots do not interfere
- Each cell uses 1/7 to 1/3 of all FDM channels to avoid interference
- Minimum distance between cells on same frequency = 2

CDMA

- Transmit 64 different codes on 1 FDM channel
  - Channels on different FDM channels do not interfere
  - Channels using different codes do not interfere
- All codes and FDM channels used in all cells
  - Most codes do not interfere when not synchronized
  - User at cell boundary assigned a non-interfering code
  - Multipath signals are not synchronized

GSM and CDMA Multiplexing

	GSM	**CDMA**
Total Bandwidth	25 MHz	25 MHz
FDM Bandwidth	200 kHz	1.25 MHz
Radio channels	25 MHz / 200 kHz = 125	25 MHz / 1.25 MHz = 20
User bit rate	22.8 kbps	19.2 kbps
Users per channel	8	64
Bit rate in channel	8 × 22.8 kbps = 182.4 kbps	64 × 19.2 kbps = 1.2288 Mbps
Total Bit Rate	182.4 kbps × 124 = 22.6 Mbps	1.2288 Mbps × 20 =24.6 Mbps
Reuse	2, 3, 7	1
Channels per cell	124 / 7 ≈ 17	20
Users per cell	(124 / 7) × 8 ≈ 141	20 × 64 = 1280
Users per cluster	(124 / 7) × 8 × 7 = 992	20 × 64 × 7 = 8960

CMDA principal advantage — reuse

GSM with reuse = 1 ⇒ 992 users / cell × 7 cells / cluster = 6944 users per cluster

CDMA Codes Compared to TDMA

CMDA

Each station transmits a 64-bit code

All stations transmit continuously at the same

Transmissions are separated by orthonormality of codes

CMDA codes

2^{64} different 64-bit sequences

- 64 orthogonal 64-bit sequences
- Orthogonal transformation on orthogonal code is an orthogonal code

$S_i^{(j)} = i$'th chip in code basis vector j

$S'^{(j)}_i = \sum_{k=1}^{64} T_{ik} S_k^{(j)} = i$'th chip in new code basis vector j

Orthogonal matrix $T_{ik} = T_{ki}^{-1}$

Pick $S'^{(j)}_i = \delta_{ij}$

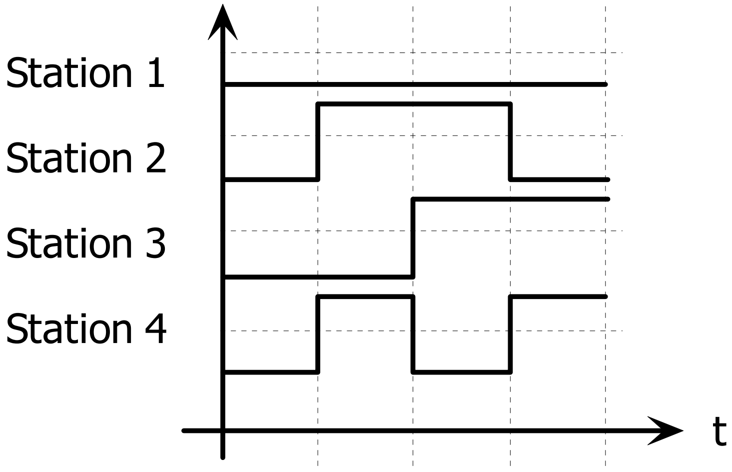
System looks like TDMA

Station i only transmits on chip i

Station i transmits 1 bit per chip sequence

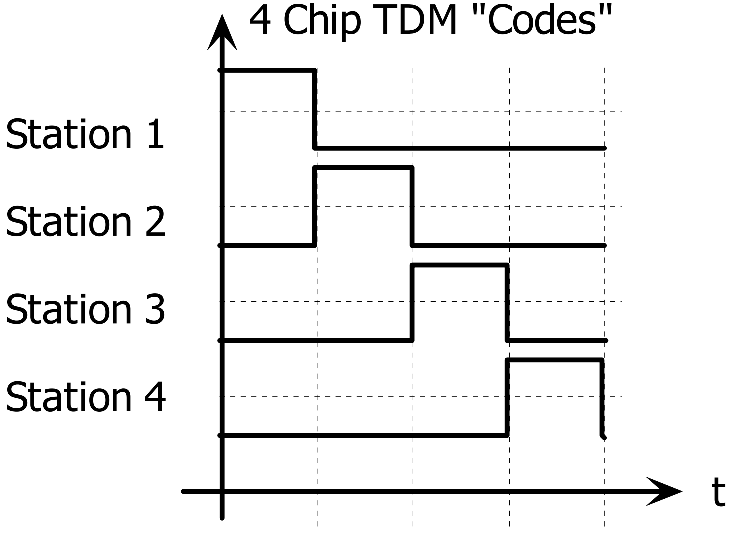
CDMA Codes and TDMA "Codes"

4 Chip Walsh Codes



-1	-1	-1	-1
-1	+1	+1	-1
-1	-1	+1	+1
-1	+1	-1	+1

4 Chip TDM "Codes"



+1	-1	-1	-1
-1	+1	-1	-1
-1	-1	+1	-1
-1	-1	-1	+1

Noise Immunity in GSM and CDMA

GSM transmits

- 8 user samples transmitted in time required to make 1 sample
  - Each 5 ms sample transmitted in 5 × (24/26) × (1/8) = 0.58 ms
- 8 voice streams of 22.8 kbps = 182.4 kbps in 200 kHz
  - Shannon: Required SNR = $2^{182.4/200} - 1 = 0.88$

CDMA transmits

- 1 user voice sample transmitted in time to make 1 voice sample
  - No time multiplexing
  - Every user transmits a different set of symbols
  - 64 symbols transmitted at one time with multilevel modulation
- 64 voice streams of 19.2 kbps = 1.2288 Mbps in 1.25 MHz
  - Shannon: Required SNR = $2^{1.2288/1.25} - 1 = 0.98$
- Better noise immunity because of noise averaging

Noise Averaging in CDMA

Total transmitted data from 64 users

$$\mathbf{T} = \sum_{i=1}^{64} t_i\ S_i$$

Total received signal

$$\mathbf{T} = \sum_{i=1}^{64} t_i\ S_i + \text{noise} = \sum_{\text{i=1}}^{64} t_i\ S_i + N_i\ 1_i$$

Calculated coefficient for user i is

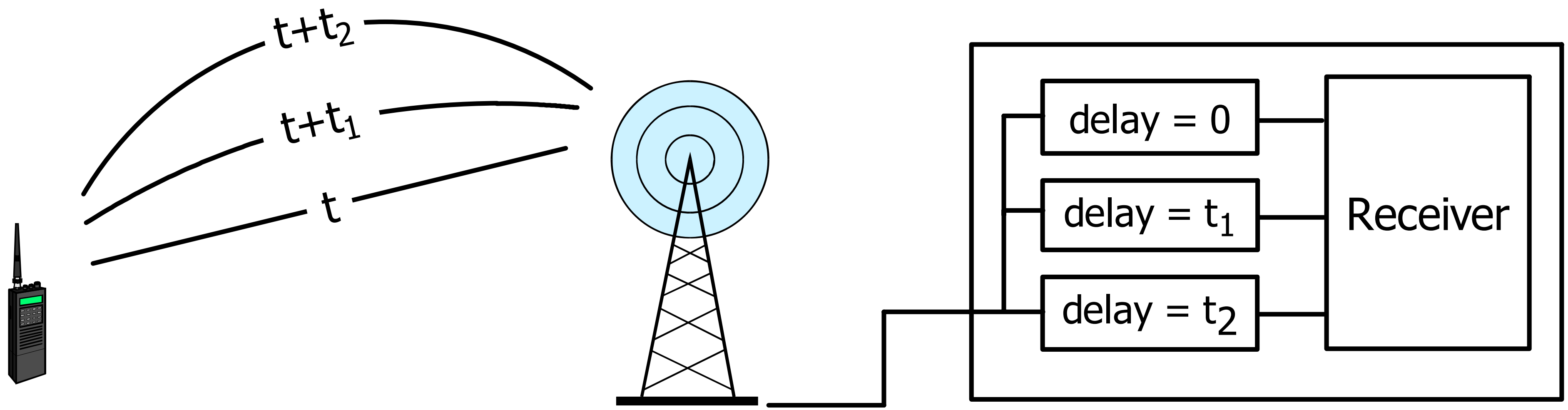
$$\begin{aligned}
\text{Calculated } t_j &= (\mathbf{T} + \text{Noise}) \cdot S_{(j)} = \left(\sum_{i=1}^{64} t_i\ S_{(i)} + N\right) \cdot S_{(j)} \\
&= \sum_{k=1}^{64} \left(\sum_{i=1}^{64} t_i\ S_{(i)}{}^k + N^k\right) \cdot S_{(j)}{}^k \ ,\ N^k \text{ is noise amplitude on chip } k \\
&= \sum_{i=1}^{64} t_i \sum_{k=1}^{64} S_{(i)}{}^k \cdot S_{(j)}{}^k + \sum_{k=1}^{64} N^k \times S_{(j)}{}^k \\
&= \sum_{i=1}^{64} t_i\ \delta_{ij} + \sum_{k=1}^{64} N^k \times 1\,(if\ \ S_{(j)}{}^k = 1) - N^k \times 1\,(if\ \ S_{(j)}{}^k = -1) \\
&= t_j + \langle \text{Noise} \rangle_{\text{chip} = +1} - \langle \text{Noise} \rangle_{\text{chip = -1}}
\end{aligned}$$

Rake Receiver

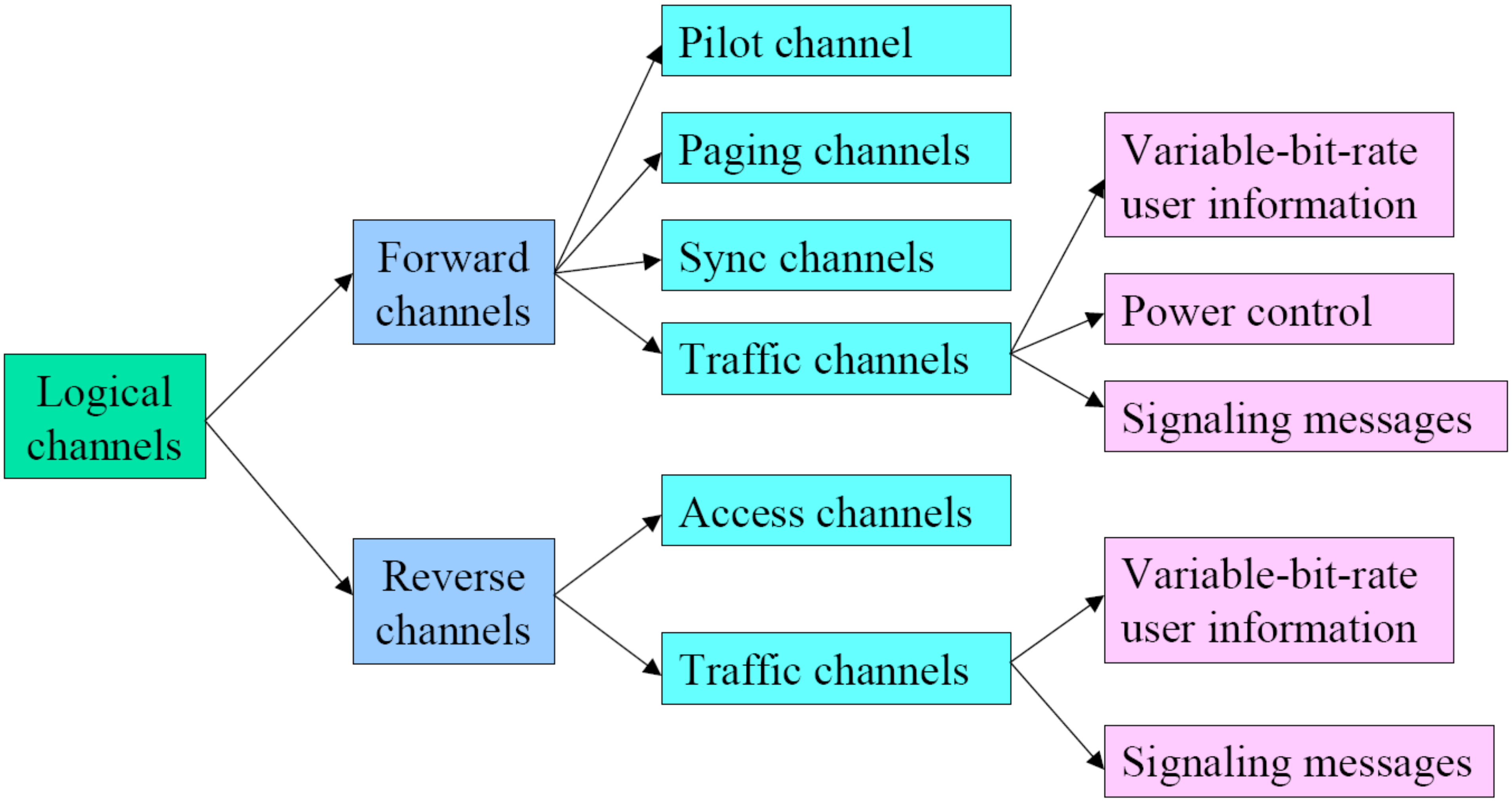
Overcomes multipath interference

Captures delayed signals in multipath reception

Adds contributions from all paths



Logical Channels



Forward Logical Channels

Pilot channel

- Transmitted in all frames
- Phase and timing reference for MS
- Provides signal strength to MS for channel acquisition
- Reused in every cell with local short PN code offset
- 1 pilot frame per 64 channel system

Sync channel

- Timing, system and, network IDs to MS
- Can be received by MS after locking onto pilot signal
- 8 synch frames per 64 channel system

Forward traffic channels

- User data and signaling data
- Two modes
  - Blank and burst — signaling data instead of voice
  - Dim and burst — multiplexes signaling data with voice data
- 55 traffic frames per 64 channel system

Reverse Logical Channels

Access channel

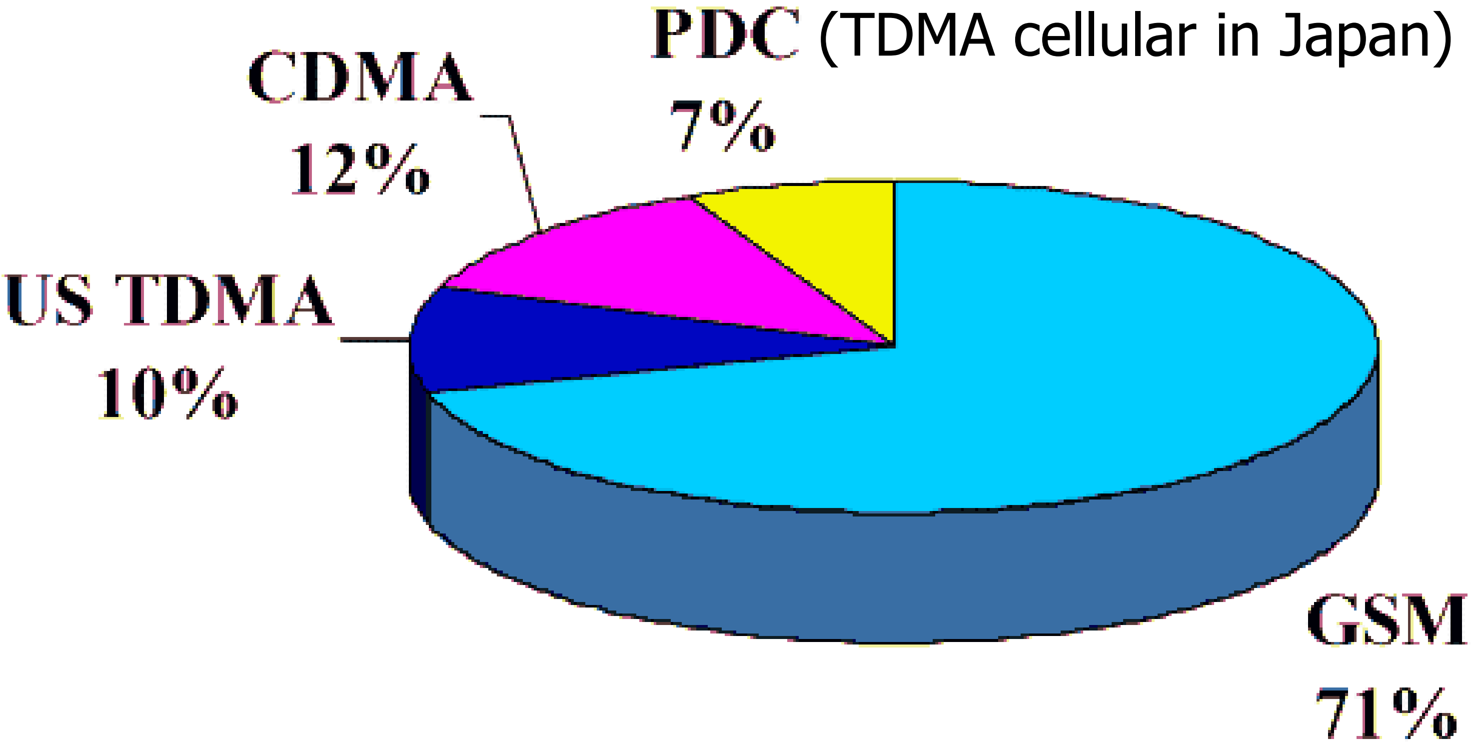
- Random access channel used by MS for messages to BS
- Contention access
  - Choose access channel at random
  - Collision ⇒ lost data → no ACK → retry after random wait
- Paired with up to 32 paging channels
  - MS responds to paging message on corresponding access channel

Reverse traffic channel

- User data (primary and secondary) and signaling
- Signaling information multiplexed with user data
- Variable data rates

Distribution of 2G Systems

Cellular telephones in use — July 2001



Source: EMC World Cellular / GSM Association