Lecture 9

Traffic Engineering for Circuit Switched Connections

Traffic Engineering

- Cells - deploy a large number of low-power base stations - each having a limited coverage area
- Reuse the spectrum several times in the area to be covered to increase capacity
- Issues:
  - Capacity (traffic load) in a cell
    - One measure = number of ***communication channels*** that are available
  - Performance
    - Call blocking probability, handoff dropping probability, throughput etc.
  - Interference

+ GSM Logical Channels

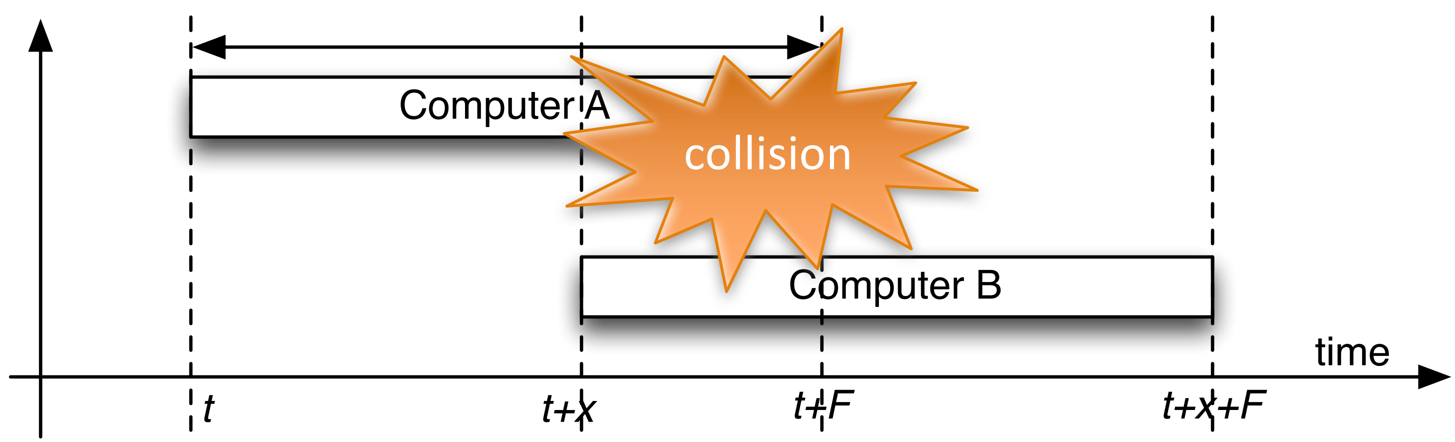
- No RF carrier or time slot is reserved for a particular task except the BCCH
  - Any time slot on any carrier can be used for almost any task
  - Framing structure has to be maintained
- Channels are of two types:
  - Traffic Channels (TCH)
    - Voice at 13 kbps
    - Data at 9.6, 4.8 or 2.4 kbps
  - Control Channels (CCH)
    - Broadcast, Common and Dedicated

Broadcast Control Channels (Unidirectional)

- BCCH (Broadcast Control Channel)
  - Used to transmit cell identifier, available frequencies within and in neighbouring cells, options (like FH) etc.
  - Continually active "beacon"
  - Has two sub-channels
- FCCH (Frequency Correction Channel)
  - Uses a frequency correction burst
- SCH (Synchronization Channel)
  - Time synchronization information

+ ALOHA

- Transmit whenever you want
  - If you are acknowledged, everything is fine
  - Otherwise retransmit packets
- Low throughput (18%)
- Slotted versions are slightly better
  - Transmission attempts can take place only at discrete points of time



Use of ALOHA in Cellular Networks

- To set up a call, MSs initially employ slotted ALOHA to send some information to the BS
  - Called “random access channel” or something similar
  - In LTE, a preamble is transmitted (unique or may collide)
- If successful, they are “assigned” a frequency channel and time slot or spread-spectrum code
- If unsuccessful, they try again
  - MS gives up if repeated tries fail
    - Collisions (congestion), poor channel quality, etc.

Common Control Channels (Unidirectional)

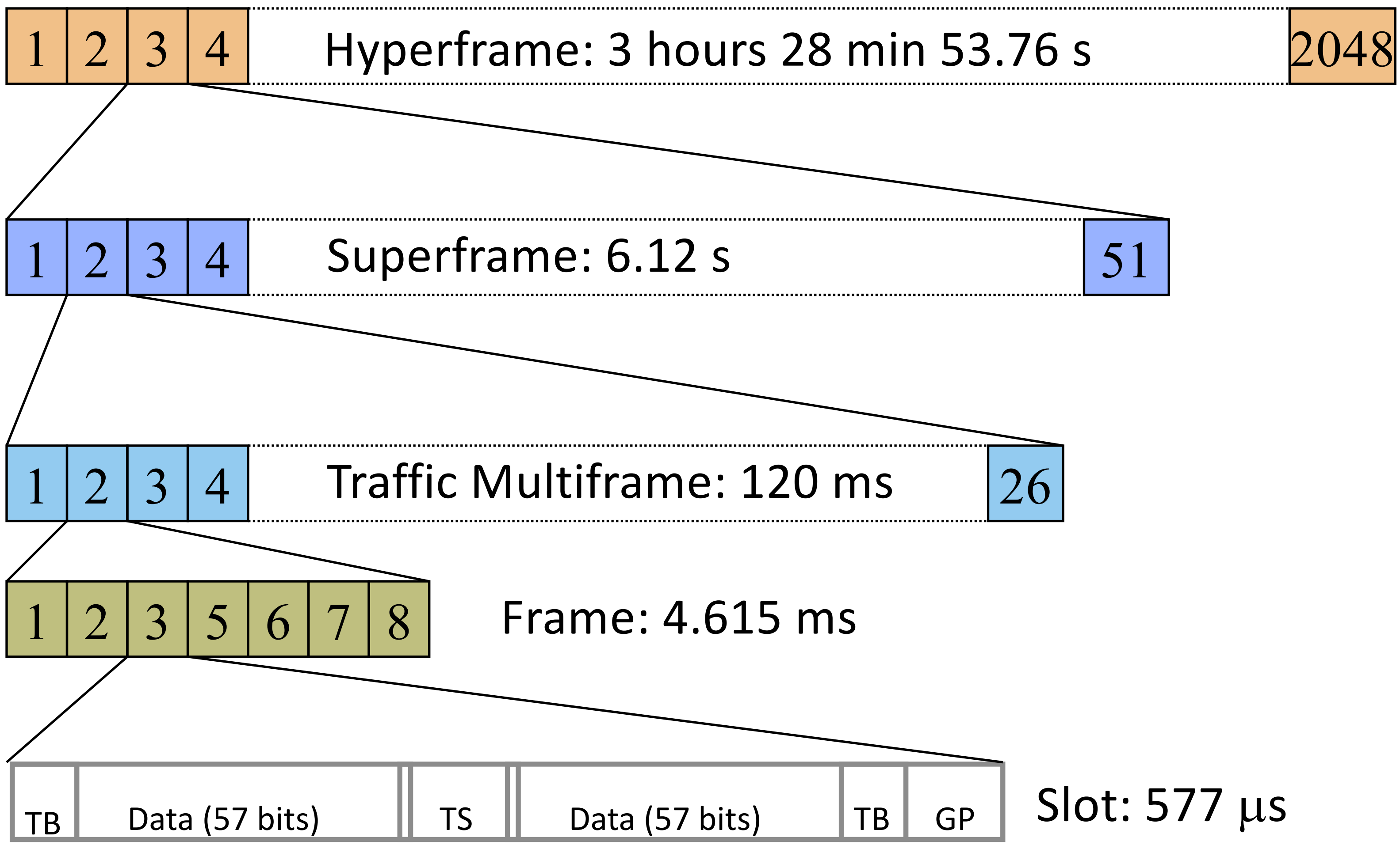
- Used for all connection set up purposes
- The paging channel (PCH) is used for paging a mobile when it receives a call
- The random access channel (RACH) is used by the MS to set up a call
  - Slotted ALOHA on the RACH
- Access grant channel (AGCH) is used by the BTS to allocate a channel to the MS
  - This can be a TCH (start using voice)
  - Or a SDCCH (negotiate further for connection setup)

SDCCH: Stand alone dedicated CCH

Dedicated Control Channels (Bidirectional)

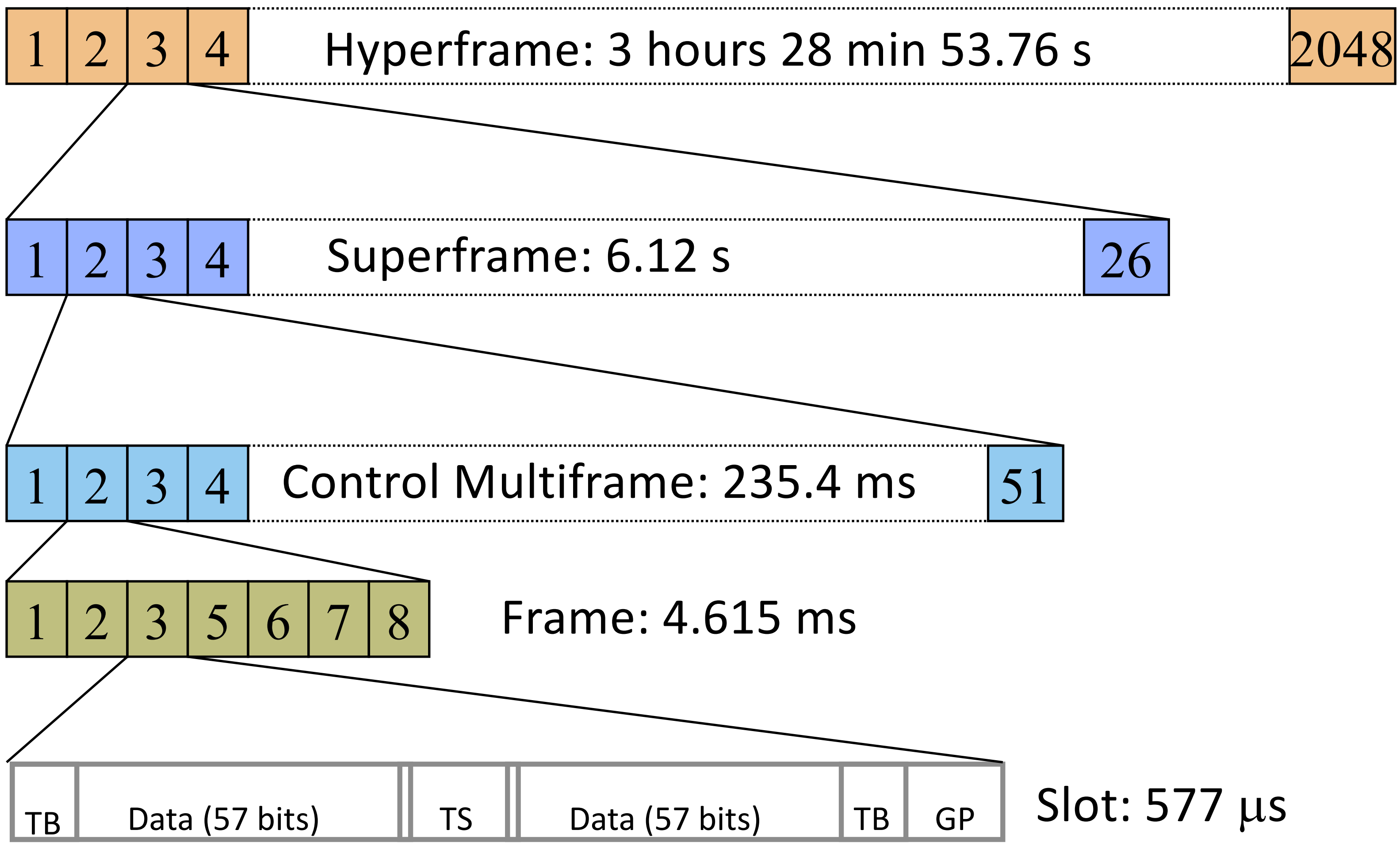
- As long as a MS has not established a TCH, it will use a stand-alone dedicated control channel (SDCCH) for signaling and call set up
  - Authentication
  - Registration, etc.
- Each TCH has a Slow Associated Control Channel (SACCH)
  - Exchange system information like channel quality, power levels, etc.
- A Fast Associated Control Channel (FACCH) is used to exchange similar information urgently (during handoff for instance)

Framing Scheme in GSM (Traffic Channels)



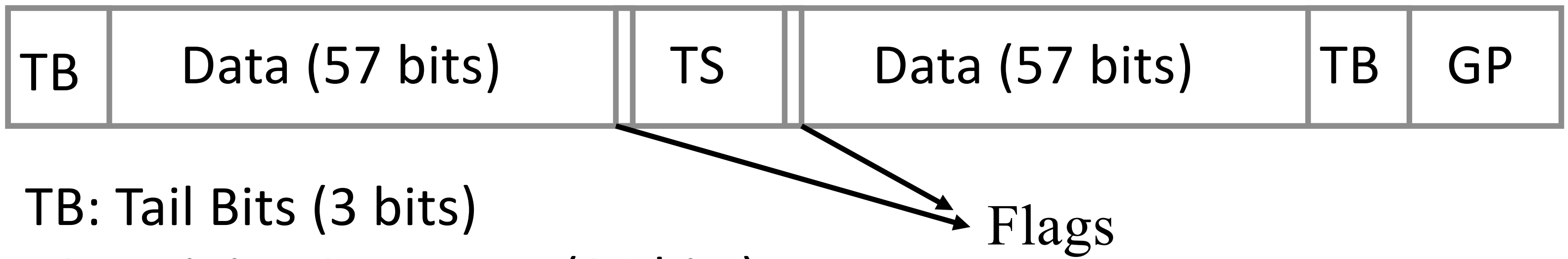
Framing scheme is implemented for encryption and identifying time slots

Framing Scheme in GSM (Control Channels)



Framing scheme is implemented for encryption and identifying time slots

One Time Slot (typical)



TB: Tail Bits (3 bits)

TS: Training Sequence (26 bits)

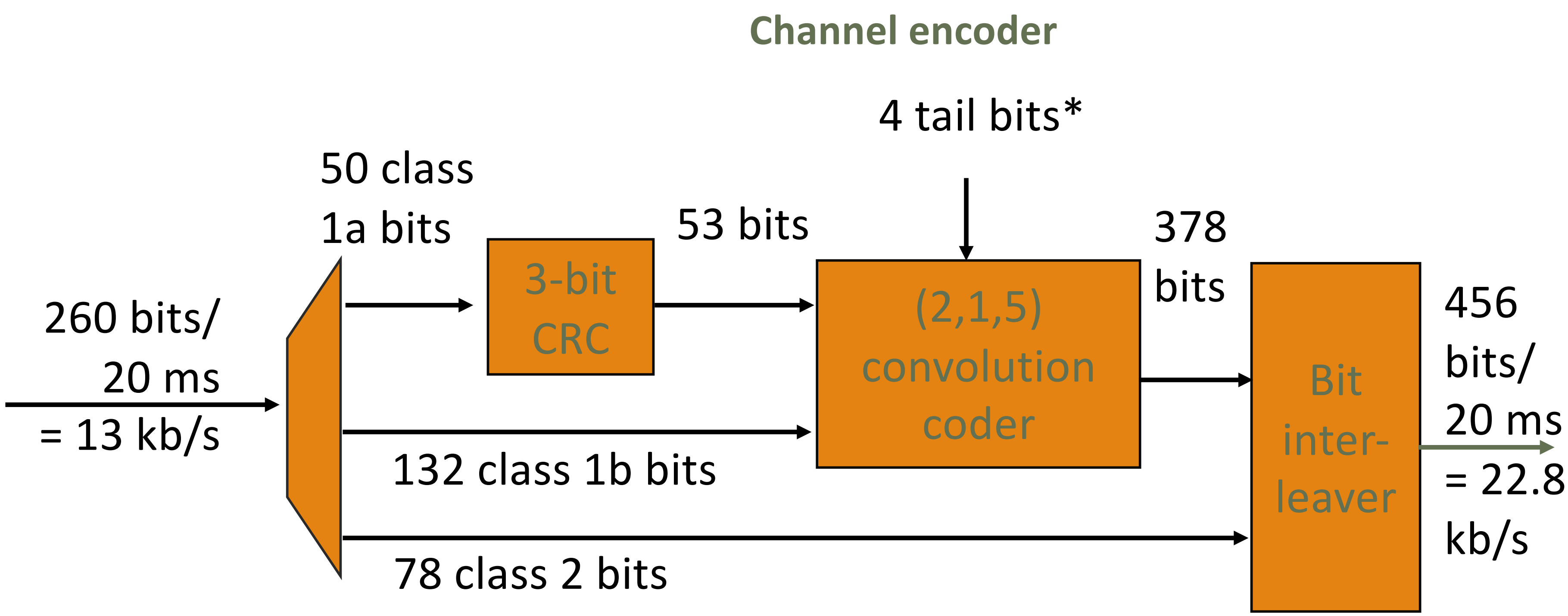
GP: Guard Period (8.25 bits)

- A time slot lasts 577 μs (546.5 μs of data and 30.5 μs of guard-time)
- Bits per slot = 3+57+1+26+1+57+3+8.25 = 156.25
- Bit rate = 156.25/577 μs = 270.79 kbps

+ Traffic Channel

- 20 ms of voice (260 bits @ 13kbps) is converted to 456 bits after CRC and convolutional encoding
- Effective data rate = 22.8 kbps
- 456 bits = 8 × 57 bits
  - (Reminder: a time slot has two 57 bit units separated by a training sequence)
- Voice samples are interleaved and transmitted on the TCH
- Data and Control bits are also encoded to end up with 456 bits over 20 ms

GSM Coding for Voice Traffic



- Class 1a: CRC and convolutional coding
  - 3-bit error detection & error correction
- Class 1b: convolutional coding
- Class 2: no error protection

*tail bits to periodically reset convolutional coder

Example: Mobile Initiated Call in 2G GSM

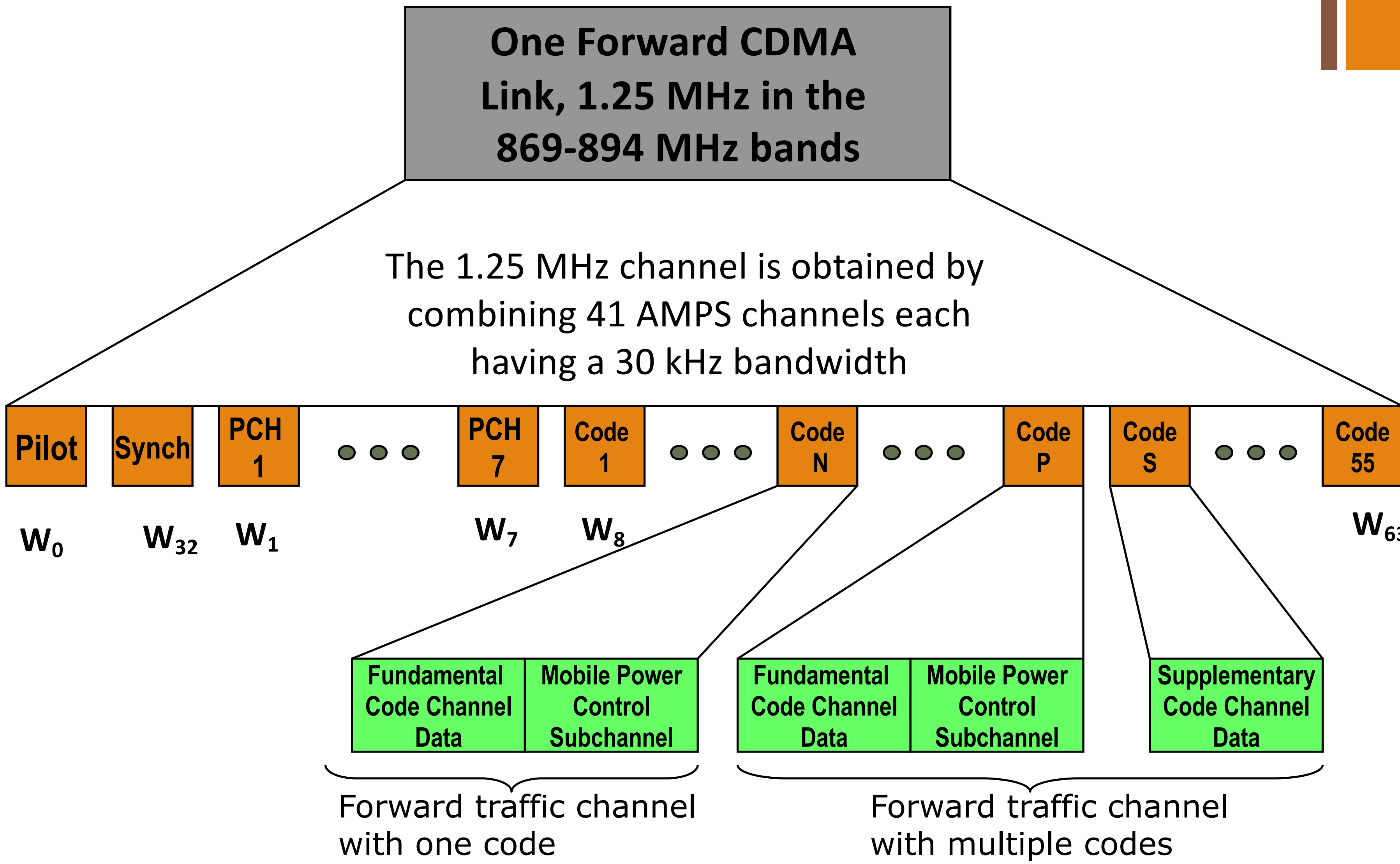
Message Name	Category
1. Channel Request	RRM
2. Immediate Assignment	RRM
3. Call Establishment Request	CM
4. Authentication Request	MM
5. Authentication Response	MM
6. Ciphering Command	RRM
7. Ciphering Ready	RRM
8. Send Destination Address	CM
9. Routing Response	CM
10. Assign **Traffic Channel**	RRM
11. **Traffic Channel** Established	RRM
12. Available/Busy Signal	CM
13. Call Accepted	CM
14. Connection Established	CM
15. Information Exchange	voice bits

Security Related (rows 4–7)

Traffic Channel = Circuit

This is all control signaling

IS-95 Forward Channel

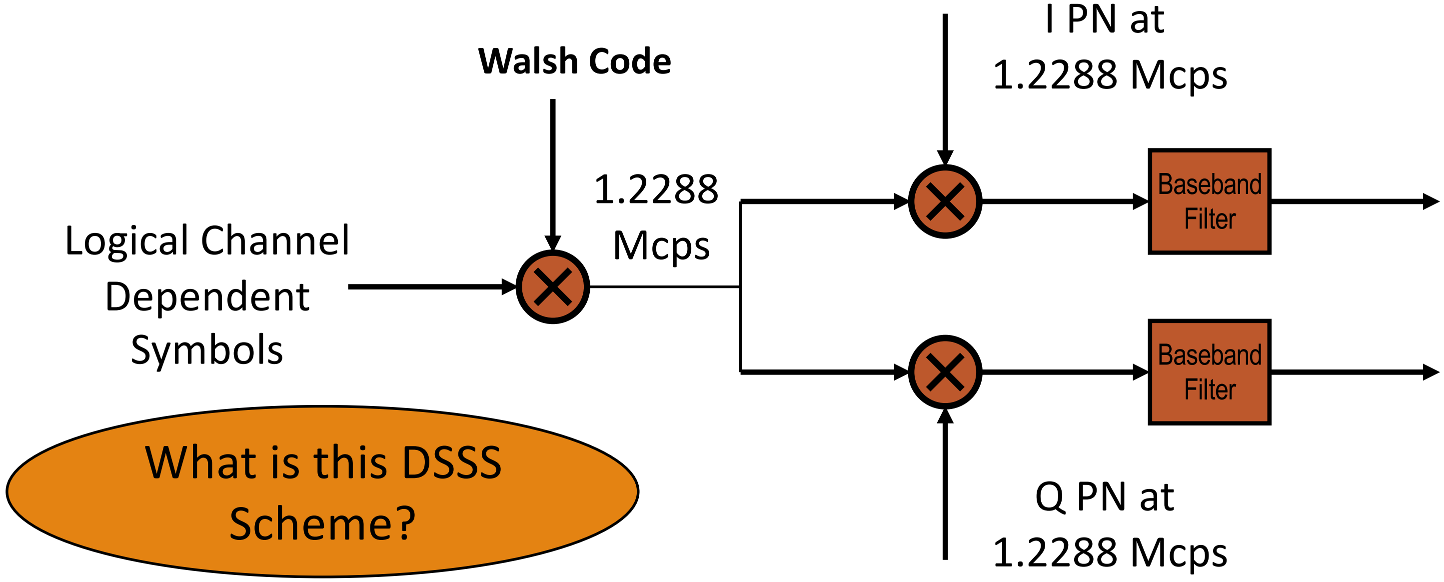


The IS-95 Forward Link (I)

- There are four types of *logical channels*
  - They are created by using *orthogonal* Walsh codes
- Broadcast channels without power control
  - Pilot Channel (assigned Walsh code W_0)
  - Synch Channel (assigned Walsh code W_{32})
  - Paging Channel – PCH (up to 7 in number)
- Dedicated channels with power control
  - Forward traffic channels – FTCH (many)
    - Fundamental code channel
    - Up to seven supplemental code channels

Basic Spreading Procedure on the Forward Channel in IS-95

- Symbols are generated at different rates
- For the spread signal to be at 1.2288 Mcps, the incoming stream must be at: $1.2288 \times 10^6/64 = 19.2$ kbps
- What happens if the incoming stream is at a lower rate?
  - Example: Incoming stream is at 4.8 kbps
  - Number of chips per bit = $1.2288 \times 10^6/4.8 \times 10^3 = 256$

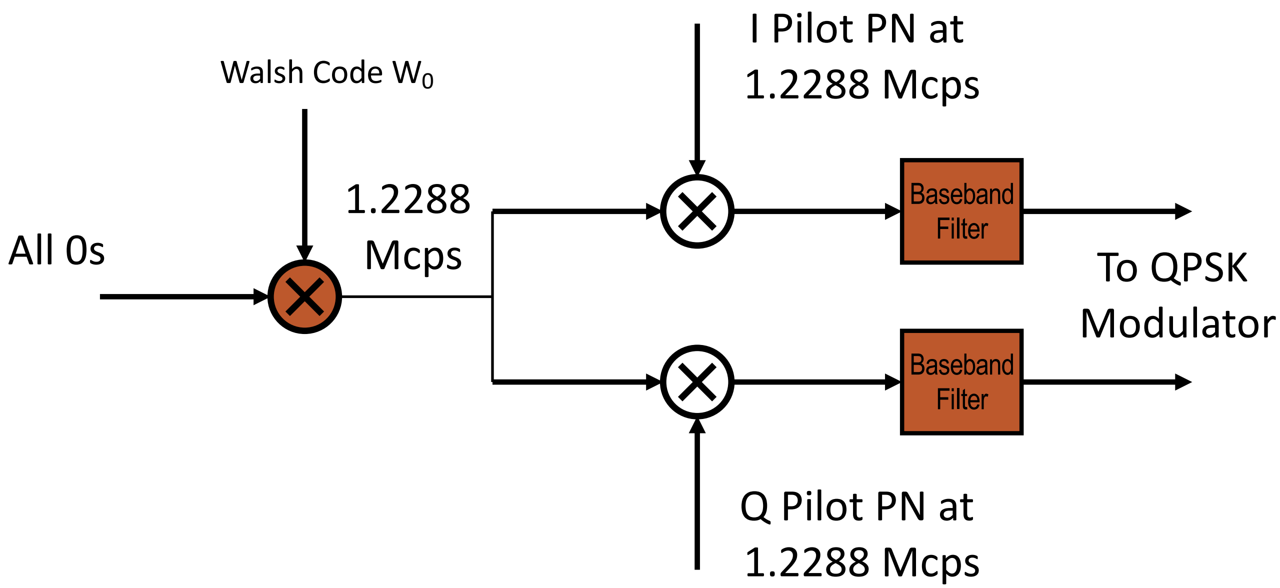


Channelization, Scrambling, and Error Correction Codes

- CDMA systems use a variety of codes for spreading the signal
- Channelization Codes
  - Walsh codes and OVSF codes
  - Used to separate user transmissions in the same cell on the forward link
  - Used to separate multiple signals of *same* user on reverse links in 3G systems
- Scrambling Codes (PN codes)
  - M-sequences, Gold sequences, Kasami sequences
  - Used to separate signals on the reverse link from multiple users
  - Used to separate signals from different base stations on the forward link

Pilot Channel

- It is continuously transmitted by a BS on the forward link
  - Like a “beacon” (Compare BCCH)
  - Acts as the reference signal for all MSs
  - Used in demodulation and coherent detection

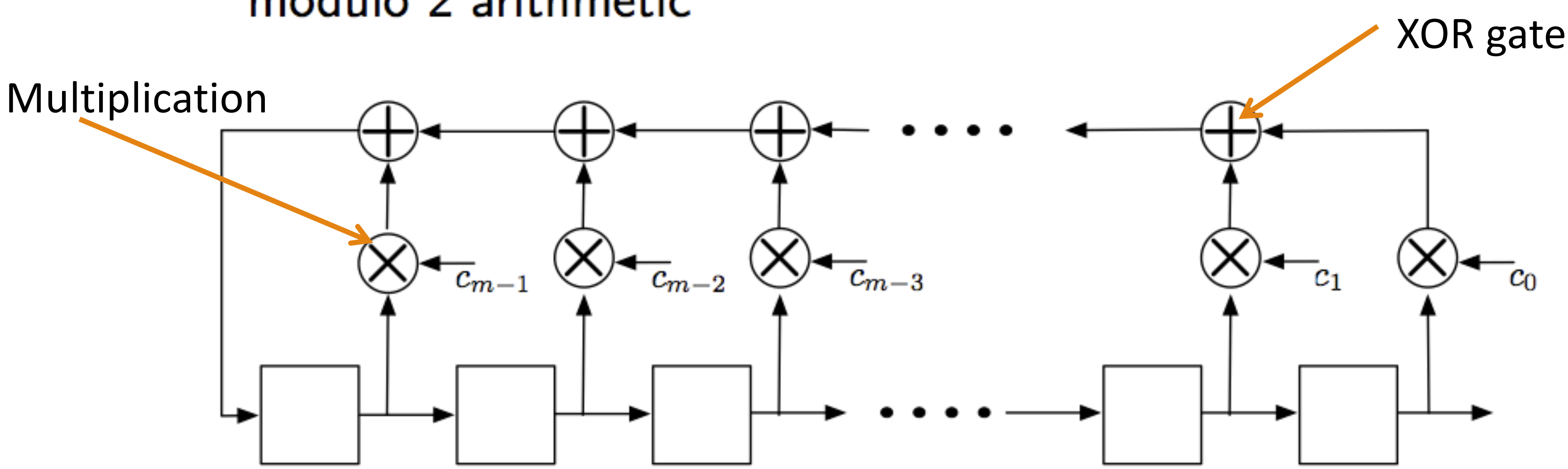


The Pilot Channel (II)

- It carries NO information but it is a very important signal
- It has 4-6 dB higher transmit power than any other channel
- The transmit power of the pilot channel is constant (No power control)
- The I and Q PN sequences
  - Are generated using a LFSR of length $m = 15$
  - The period is $2^{15} - 1 = 32767$
    - An extra zero is added after a run length of 14 zeros once within the period
  - In time, one period is $32768 \times 0.8138\ \mu s = 26.67$ ms
  - Number of repetitions/second = $1/26.67 \times 10^{-3} = 37.5$
  - Number of repetitions in 2 seconds = 75

PN Sequences are generated using Linear Feedback Shift Registers (LFSRs)

- The general form of an *m*-stage linear feedback shift register is as shown below
- All operations in LFSRs are based on binary numbers and modulo 2 arithmetic



$$c(x) = \sum_{j=0}^{m-1} c_j x^j + x^m$$

Polynomial Representation: $c_i \in \{0,1\}$

Use of the PN sequences in IS-95

- The PN sequences are defined by the following LFSRs
  - $PNI(X) = X^{15} + X^{13} + X^{9} + X^{7} + X^{5} + 1$
  - $PNQ(X) = X^{15} + X^{12} + X^{11} + X^{10} + X^{6} + X^{5} + X^{4} + X^{3} + 1$
- All base stations use the same PN sequences but with a different "offset"
- The offsets are by multiples of 64 chips
  - Total number of possible offsets = 32768/64 = 512
  - Duration of 64 chips = $64 \times 0.8138 \times 10^{-6} = 52\ \mu s$
    - Light travels 3×10^{8} m/s => 15630 m in 52 μs

More on the Offset

- The base stations in IS-95 are completely synchronized using GPS
  - Transmitted chips on the downlink are all synchronized from all base stations
  - The Base Station "System Time" is synchronized to a "Universal Coordinated Time" or UTC
    - UTC is loosely what used to be GMT
    - The time is specified in terms of a 24 hour cycle
    - System time is not the same as UTC because it does not include leap seconds
- The Walsh codes are used without any offset
  - They are aligned such that the first bit always starts at the even second in the IS-95 system

The Synch Channel

- The synch channel is locked to the offset of the PN-sequence used in the pilot channel
  - It contains information pertinent to the associated base station
  - MS can retrieve the information for subsequent use
- The very first bits demodulated by the MS are from the synch channel
  - Important in synchronizing to the base station
  - Example 1: Reverse PN codes have zero offset relative to even numbered seconds of the system time
  - Example 2: MS must synch its long code generator with the one used at the BS

The Paging Channel

- Transmits control information to the MS
  - Page message to indicate incoming call
  - System information and instructions
    - Handoff thresholds
    - Maximum number of unsuccessful access attempts
    - List of surrounding cells (how are they identified?)
    - Channel assignment messages
  - Acknowledgments to access requests
- It operates at either 4.8 kbps or 9.6 kbps
  - It is passed through a rate ½ convolutional encoder to go up to 9.6 kbps or 19.2 kbps
  - If the output is 9.6 kbps, it is repeated to go up to 19.2 kbps

The forward traffic channel

- Carries user traffic and control messages to specific MSs
  - Dedicated exclusively to one MS
- Can carry traffic at different rates
  - Rate Set 1
    - 1.2 kbps, 2.4 kbps, 4.8 kbps and 9.6 kbps
    - Ideal to support Q-CELP that varies the voice code rate (maximum of 8 kbps) based on the voice activity
    - Used primarily in IS-95
  - Rate Set 2
    - 1.8 kbps, 3.6 kbps, 7.2 kbps and 14.4 kbps
    - Ideal to support better voice quality at a maximum of 13 kbps
    - Suggested for PCS (but also allowed in IS-95)

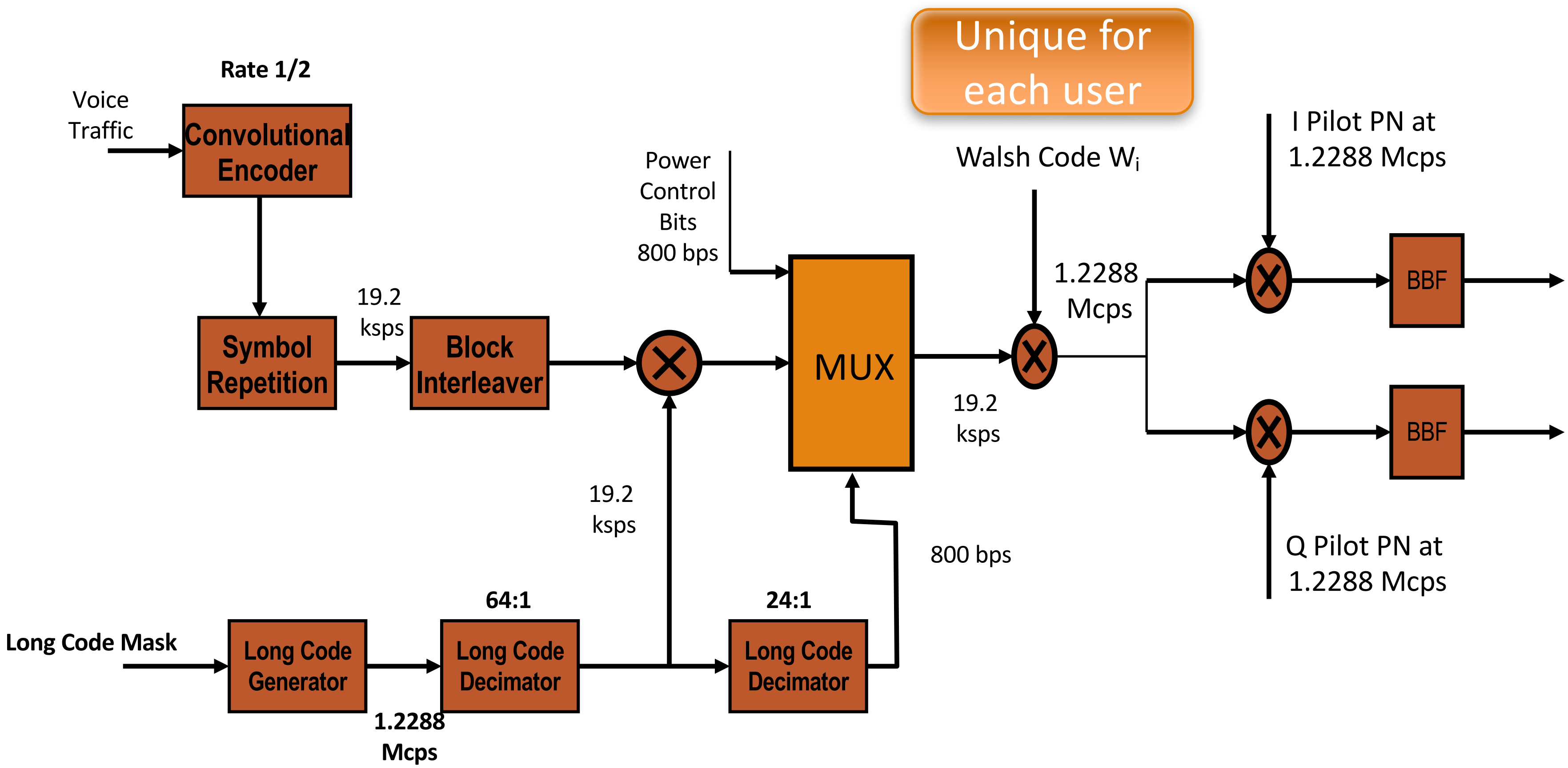
Coding of the speech signal

- The speech signals are encoded into **20 ms frames**
  - The frames contain 192 bits of speech at 9.6 kbps
    - High voice activity
  - The frames contain 24 bits at 1.2 kbps
    - Background noise or low voice activity
  - The frames contain 48 & 96 bits at 2.4 and 4.8 kbps
    - Provide smooth transition between the other two data rates
- There are 8 tail bits in the frame that are used to reset the convolutional encoder
- At 9.6 kbps and 4.8 kbps there is a CRC code as well to indicate the "quality" of the frame
  - Frame quality indicator (12,10,8 or 6 bits)
  - Only detect frame errors

Frame Quality Indicator (FQI)

- In CDMA, the frame error rate specifies the required SIR for the system
  - Typically 1% or 2% (depending on rate set)
- The FQI in the frame allows the BS to detect whether or not a frame is in error

Operation of the Forward Traffic Channel (Rate Set 1)

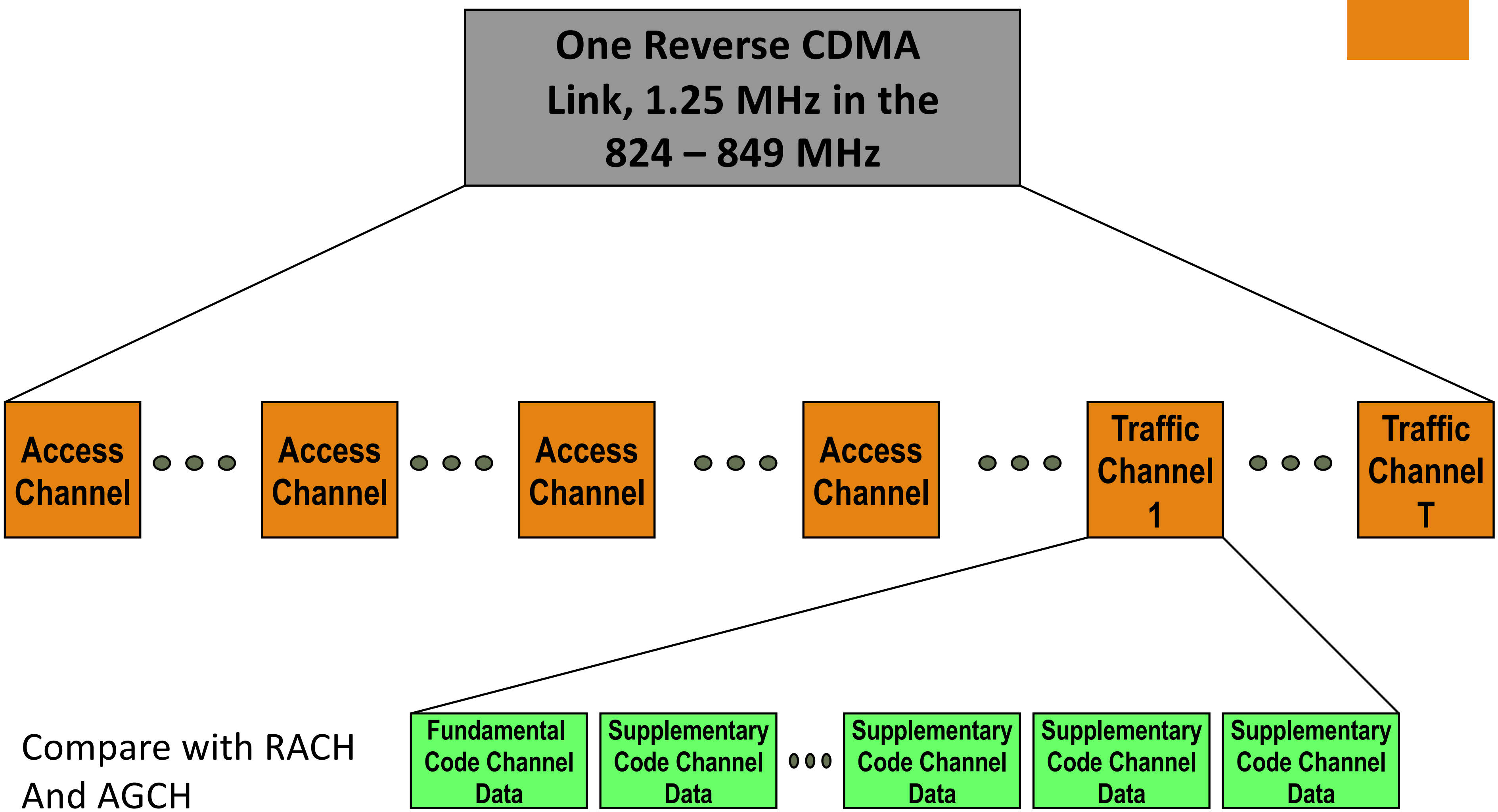


Control signals and data over FTCHs

Compare with SACCH and FACCH in GSM

- IS-95 supports transmission of
  - Signaling data and user data over the same frame
  - Primary user data (voice) and secondary user data (e.g. Fax) over the same frame
  - This is allowed only for the 9.6 kbps frames
    - Only speech can be carried at lower rates
- Dim and burst
  - Signaling or secondary user data occupies part of the frame along with speech
- Blank and burst
  - Signaling or secondary user data occupies the entire frame

Reverse CDMA Channel



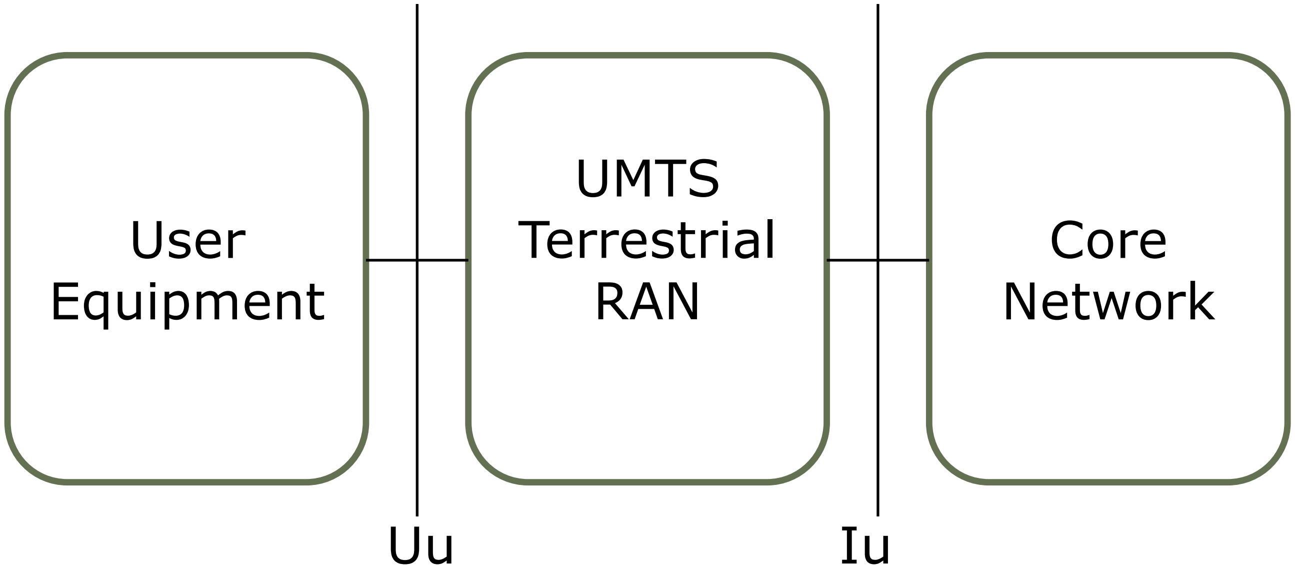
Compare with RACH
And AGCH

What is UMTS?

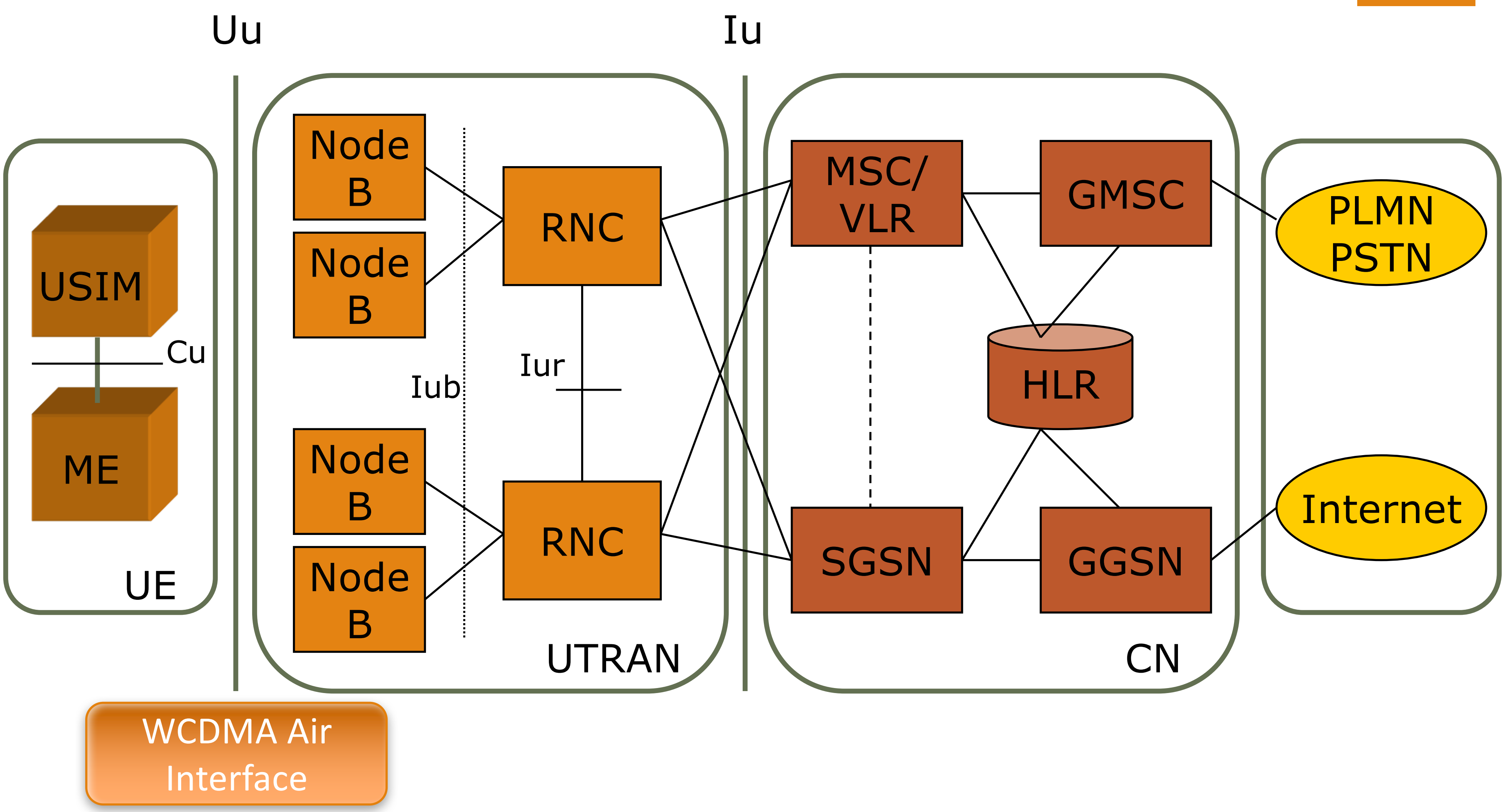
- UMTS stands for Universal Mobile Telecommunications System
  - 3G cellular standard in the US, Europe, and Asia
- Outcome of several research activities in Europe
  - Generated trial systems and basic understanding of WCDMA
  - Assisted the standardization efforts
- Most of the standardization work was focused in 3GPP
  - 3GPP refers to the physical layer as UTRA – UMTS Terrestrial Radio Access
  - There are two modes – FDD and TDD
- UMTS can support both GSM-MAP and IS-41 core networks
  - An all-IP third alternative is available now

UMTS Architecture

- The UMTS System
  - Consists of many logical network elements similar to the 2G systems
  - Logical network elements have "open interfaces"
- There are three components
  - User Equipment (UE)
  - UMTS Terrestrial Radio Access Network (UTRAN)
  - Core Network (CN)
    - Heavily borrows from GSM



Detailed Network Elements



Summary of WCDMA

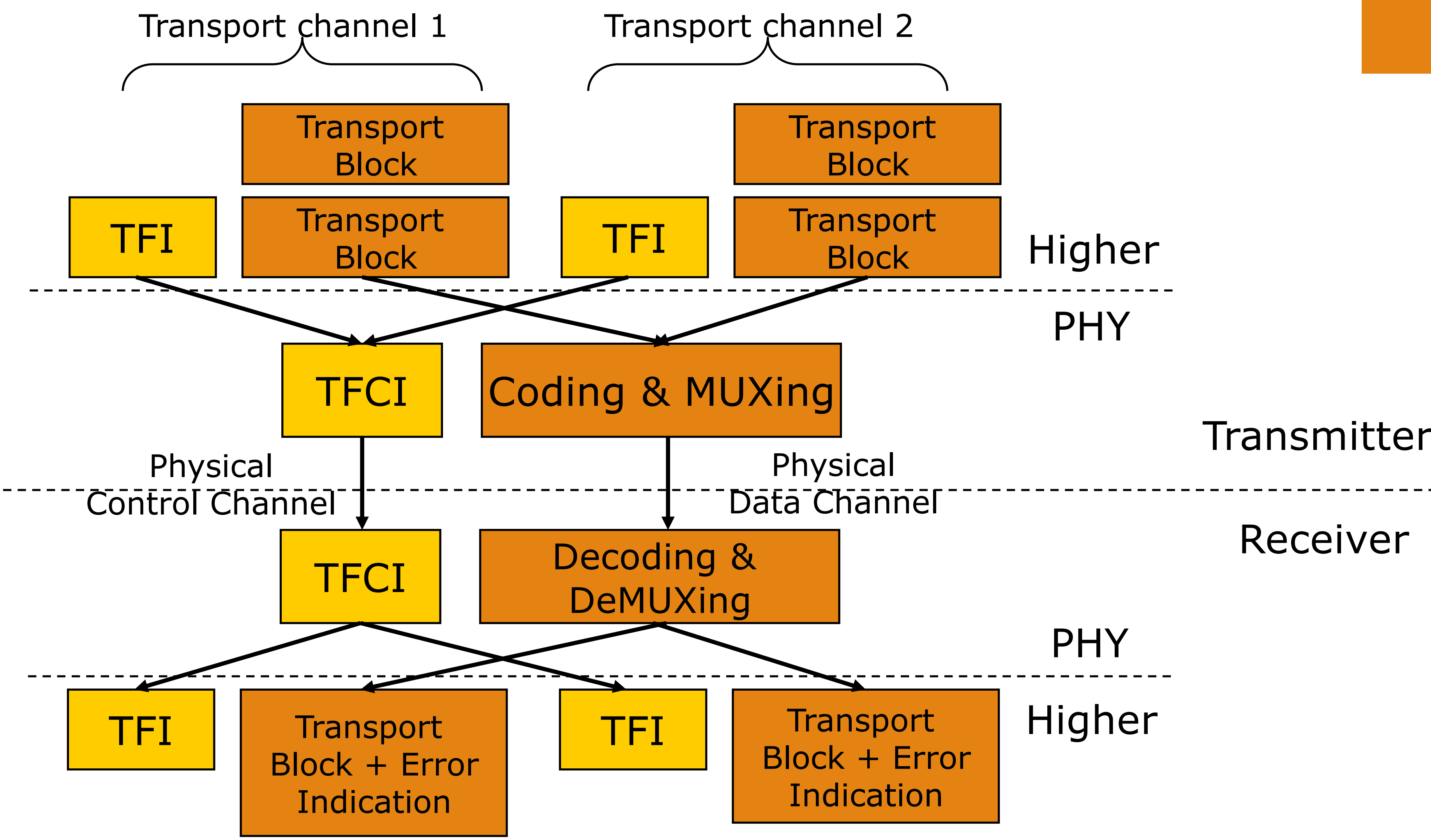
- WCDMA is somewhat different compared to IS-95
- It is a "wideband" direct sequence spread spectrum system
  - Supports up to 2 Mbps using
    - Variable spreading
    - Multicode connections
- The chip rate is 3.84 Mcps
  - Approximate bandwidth is 5 MHz
  - Carrier spacing is on a raster of 200 kHz
  - Supports higher data rates/capacity
  - Increased multipath diversity (proportional to chip duration)

UTRA General Interface – II

- Higher layer data is carried in transport channels
  - The data is carried in chunks called "transport blocks"
  - Each transport channel is mapped to a physical channel (later)
  - The frames are 10ms long
- A transport channel has
  - A TFI – Transport Format Indicator
    - Time dependent field
    - Contains **parameters** of the associated transport channel
  - TFI's are combined into TFCIs
    - Transport Format Combination Indicator
    - TFCI's tell the receiver what transport channels are active
  - Blind transport format detection (BTFD) is also possible
    - Usually happens only on the forward link
- There are two types of transport channels
  - Dedicated transport channels
  - Common transport channels

Control Signaling

UTRA General Interface

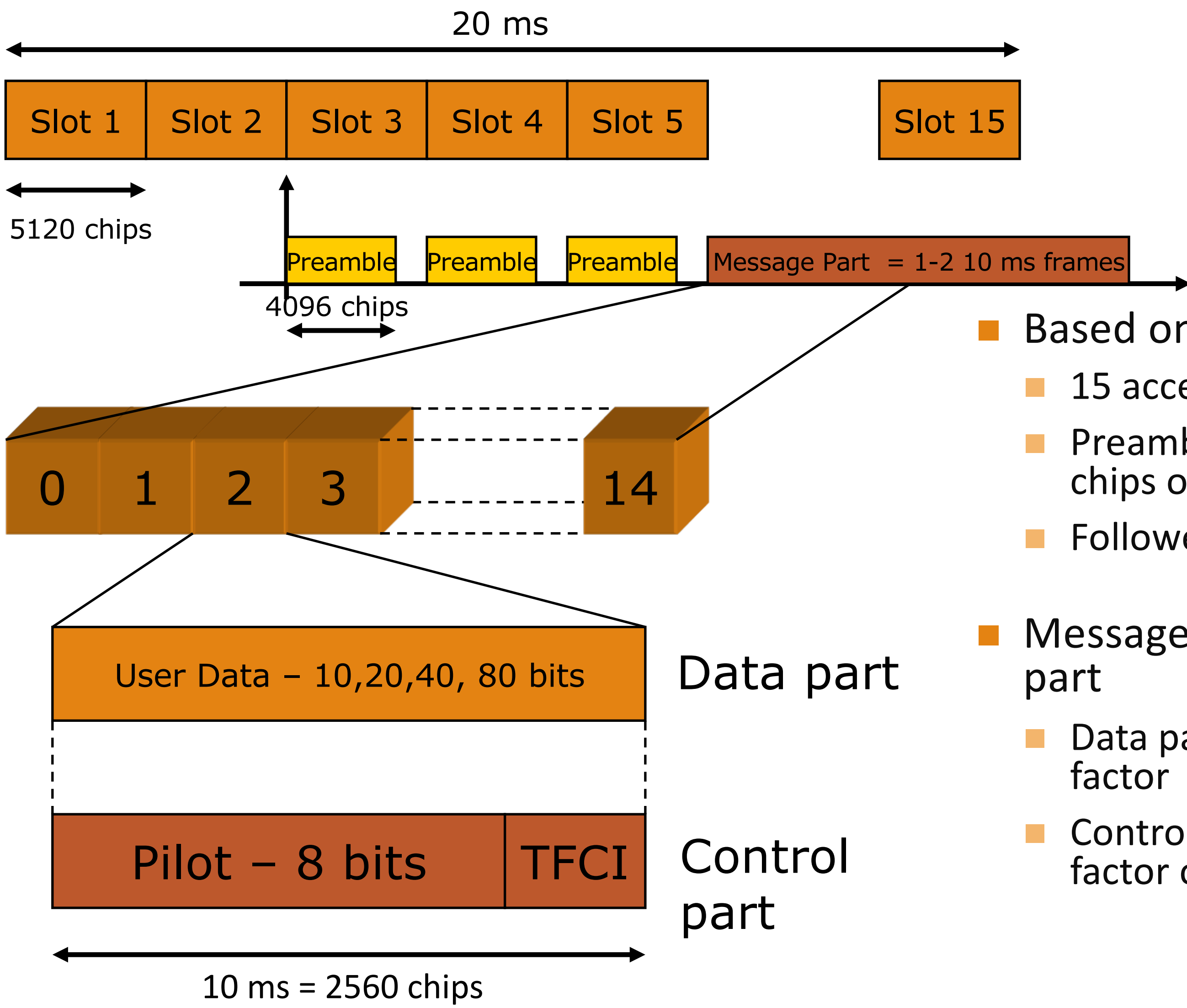


Mapping of Transport Channels to Physical Channels

Broadcast Channel (BCH)	→	Primary Common Control Physical Channel (PCCPCH)
Forward Access Channel (FACH) Paging Channel (PCH)	→	Secondary Common Control Physical Channel (SCCPCH)
Random Access Channel (RACH)	→	Physical Random Access Channel (PRACH)
Dedicated Channel (DCH)	→	Dedicated Physical Data Channel (DPDCH) Dedicated Physical Control Channel (DPCCH)
Downlink Shared Channel (DSCH)	→	Physical Downlink Shared Channel (PDSCH)
Common Packet Channel (CPCH)	→	Physical Common Packet Channel (PCPCH)

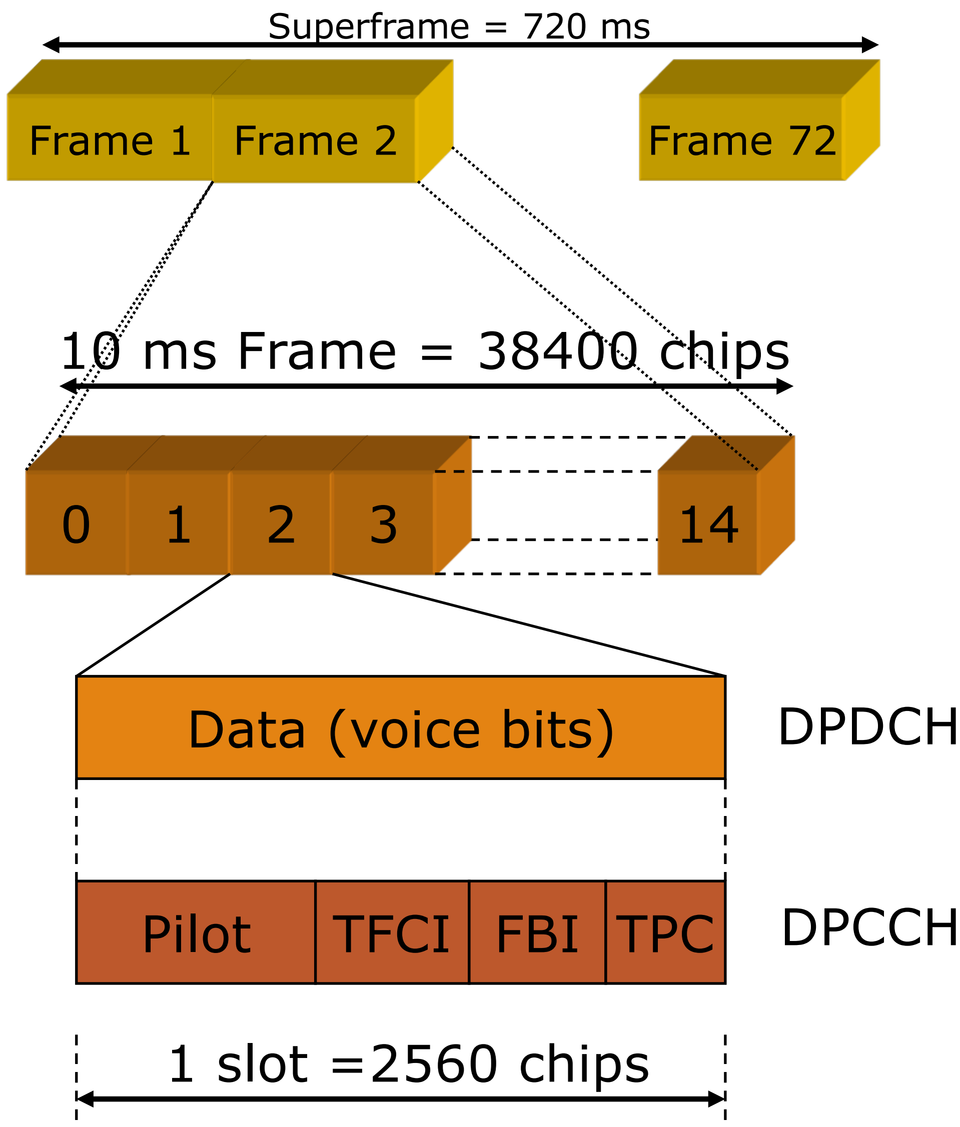
Forward Only   Reverse Only   Both Reverse and Forward

Random Access Channel



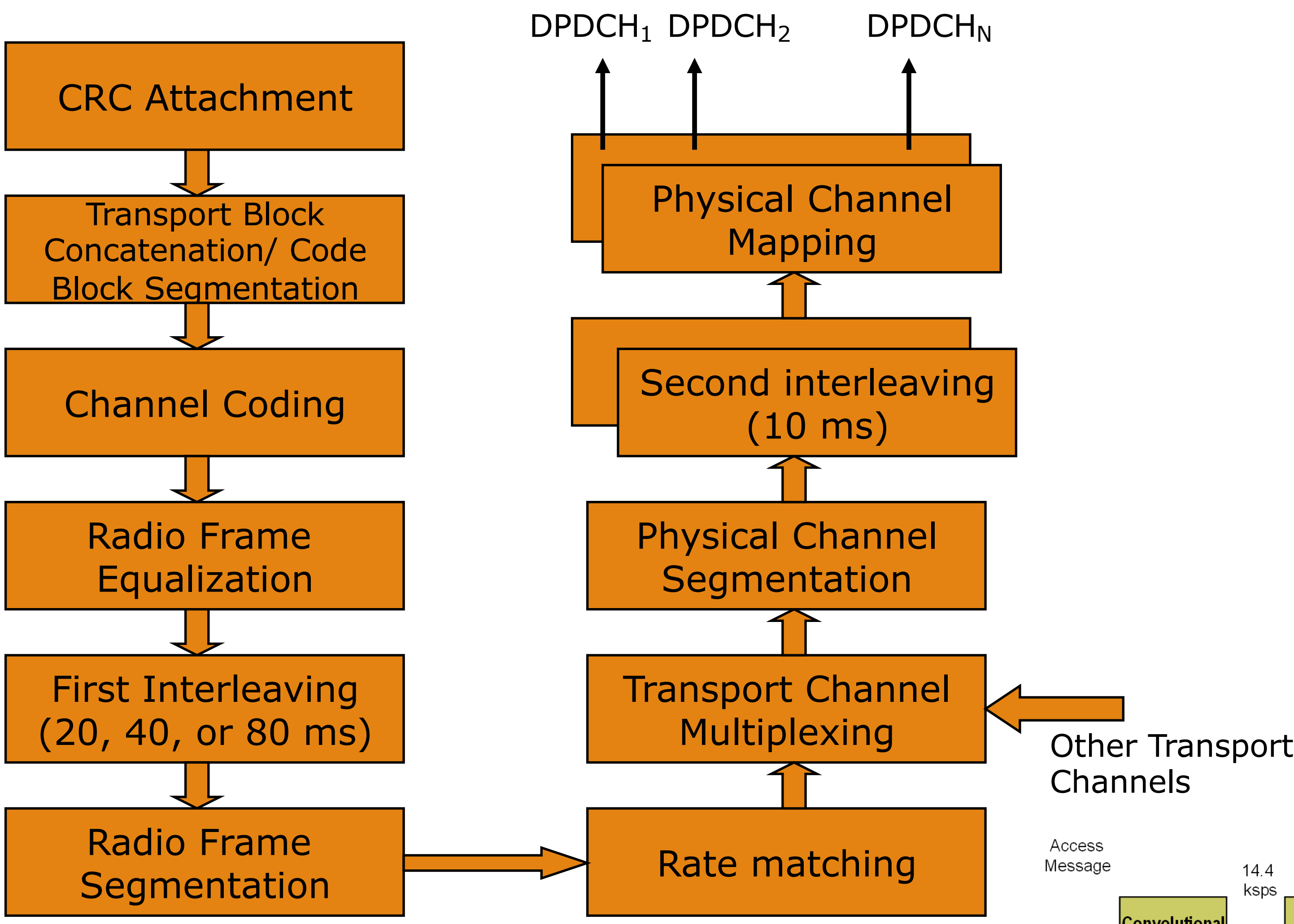
- Based on slotted ALOHA
  - 15 access slots every 20 ms
  - Preambles are transmitted for 4096 chips of 5120 chips in an access slot
  - Followed by the access message
- Message has a data and a control part
  - Data part has a variable spreading factor
  - Control part has a fixed spreading factor of 256

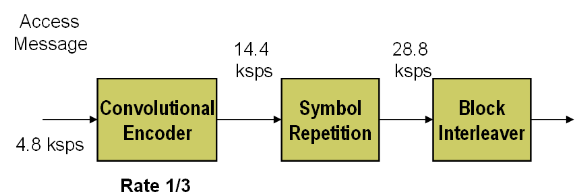
Reverse DPCH Structure



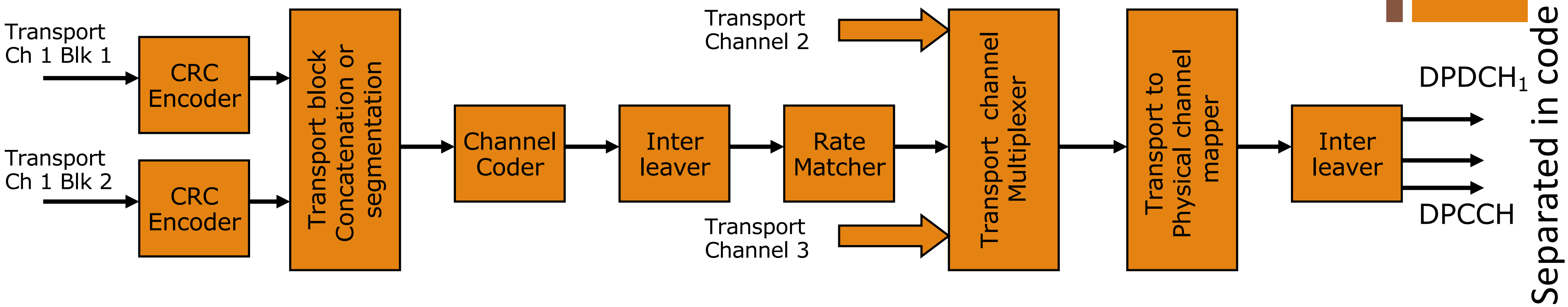
- The DPCCH carries physical layer control information
  - It has a fixed spreading factor of 256
- The DPDCH carries higher layer information
  - Spreading factor can range between 4 and 256
- TPC – Transmission Power Control
- FBI – Feedback Information

+ Reverse multiplexing and channel coding chain in UMTS





More details



Reverse Link Example

- Figure shows reverse link
- Forward link is similar, but control and user data are *separated in time*
- Includes power control for some channels, and not for others

Reverse chain in UMTS details – I

- A transport block is received from the higher layers
  - A CRC is attached (0, 8, 12, 16 or 24 bits)
  - Used to provide error indication to higher layers
- The transport blocks are either concatenated or segmented based on their size as compared to the channel coding block
  - Two types of channel coding are provided
    - ½ and 1/3 rate convolutional coding
    - 1/3 rate turbo coding
- Channel coding is performed

Reverse chain in UMTS details – II

- Radio frame equalization
  - Ensures that data is divided into equal sized blocks when transmitted over many 10 ms frames
  - Data is padded with zeros till it can be divided into equal sized blocks that fit in a frame
- First interleaving
  - Used only when the delay budget is acceptable
  - Depends on how often data arrives from higher layers (called the transmission time interval or TTI)
  - If different transport channels have different TTI's, they must be time aligned before multiplexing
- Rate matching
  - This is similar to the puncturing/repetition operations in IS-95
  - It is used to match the number of bits to be transmitted to the number available on a single frame
  - The TFCI contains the rate matching attribute

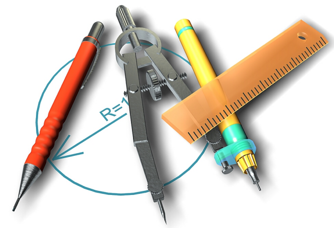
Reverse chain in UMTS details – III

- Transport channel multiplexing
  - Different transport channels are multiplexed here
    - Spreading codes are used to separate the channels
    - Serial multiplexing is also possible
- Second Interleaving
  - Also called intra-frame interleaving
  - Lasts for 10 ms
  - Applied separately for each physical channel
- The output is a mapping to a physical channel
  - The number of bits given for a physical channel at this stage is exactly equal to the number that the spreading factor of that frame can transmit

Traffic Engineering (2)

- Questions:
  - If I want to place a call, what is the probability that I will NOT get a communication channel?
    - "New call admission"
  - If I am moving from cell to cell, what is the probability that during a call, I will NOT find a communication channel in the new cell to continue my call?
    - "Handoff call admission"

Grade of Service



- Grade of service
  - Usually 2% blocking probability during busy hour
  - Busy hour may be
    1. Busy hour at busiest cell
    2. System busy hour
    3. System average over all hours
- Given $c = T/N_c$ traffic channels per cell – what is the grade of service (GoS)?
  - How many users can be supported for a specific GoS?
- Basic analysis called *Traffic Engineering or Trunking*
  - Same as circuit switched telephony
  - Use **Erlang B** and Erlang C Models

Erlangs - 1

- Let there be $c = T/N_c$ channels per cell
- In a given time period, suppose there are Q users making a call
  - If $Q = c$, any new call will be blocked with probability 1
  - If $Q < c$, then your call may get a channel
- How do we quantify this better?
  - Erlangs

Erlangs - 2

- How do you estimate traffic distribution?
  - Traffic intensity is measured in Erlangs
  - One Erlang = completely occupied channel for 60 minutes
- Examples
  - 30 kHz voice channel occupied for 30 min/hour carries 0.5 Erlangs
  - 100 calls in one hour each lasting 3 minutes = 100 calls/hour × 3/60 = 5 Erlangs

- Agner Krarup Erlang
- Scientist with the Copenhagen Telephone Company
- Studied data from a village's telephone calls to arrive at his conclusions

More on Erlangs

- Let traffic intensity per user = A_u
  - A_u = average call request rate × average holding time = $\lambda \times t_h$
- Total traffic intensity = traffic intensity per user × number of users = $A_u \times n_u$
- Example:
  - 100 subscribers in a cell
  - 20 make 1 call/hour for 6 min => 20 × 1 × 6/60 = 2E
  - 20 make 3 calls/hour for ½ min => 20 × 3 × .5/60 = 0.5E
  - 60 make 1 call/hour for 1 min => 60 × 1 × 1/60 = 1E
  - 100 users produce 3.5 E load or 35 mE per user

n_u = 20; λ = 1;
t_h = 6/60

Notation associated with queues

- Written as P/Q/R/S
  - P: Description of arriving traffic
  - Q: Description of service rates or times
  - R: Number of servers
  - S: Number of users that can be in the system (includes those being served and those waiting)
- M => Markov (Poisson arrival times, exponential service times)
  - Commonly used as it is tractable and it fits voice calls
- If the number of users that can be in the system (S) is infinite, it is dropped from the notation

Erlang B Model: M/M/c/c queue

- To estimate the performance of a trunked system use the Erlang B queueing model
- The system has a finite capacity of size *c*
  - Customers arriving when all servers (channels) busy are dropped
- *Blocked calls cleared model (BCC)* (no buffer)
- Assumptions
  - *c* identical servers (channels) process customers in parallel
  - Customers arrive according to a Poisson process (average of λ calls/s)
  - Customer service times exponentially distributed (average of $1/\mu$ seconds per call)
- The offered traffic intensity is $a = \lambda/\mu$ in Erlangs

Erlang B Formula or Blocking Formula

- Probability of a call being blocked B(c,a)

$$B(c,a) = \frac{a^c}{c!} / \sum_{n=0}^{c} \frac{a^n}{n!}$$

- Erlang B formula can be computed from the recursive formula

$$B(c,a) = \frac{a \times B(c-1,a)}{c + a \times B(c-1,a)}$$

- Usually determined from table or charts

Example of Erlang B Calculation

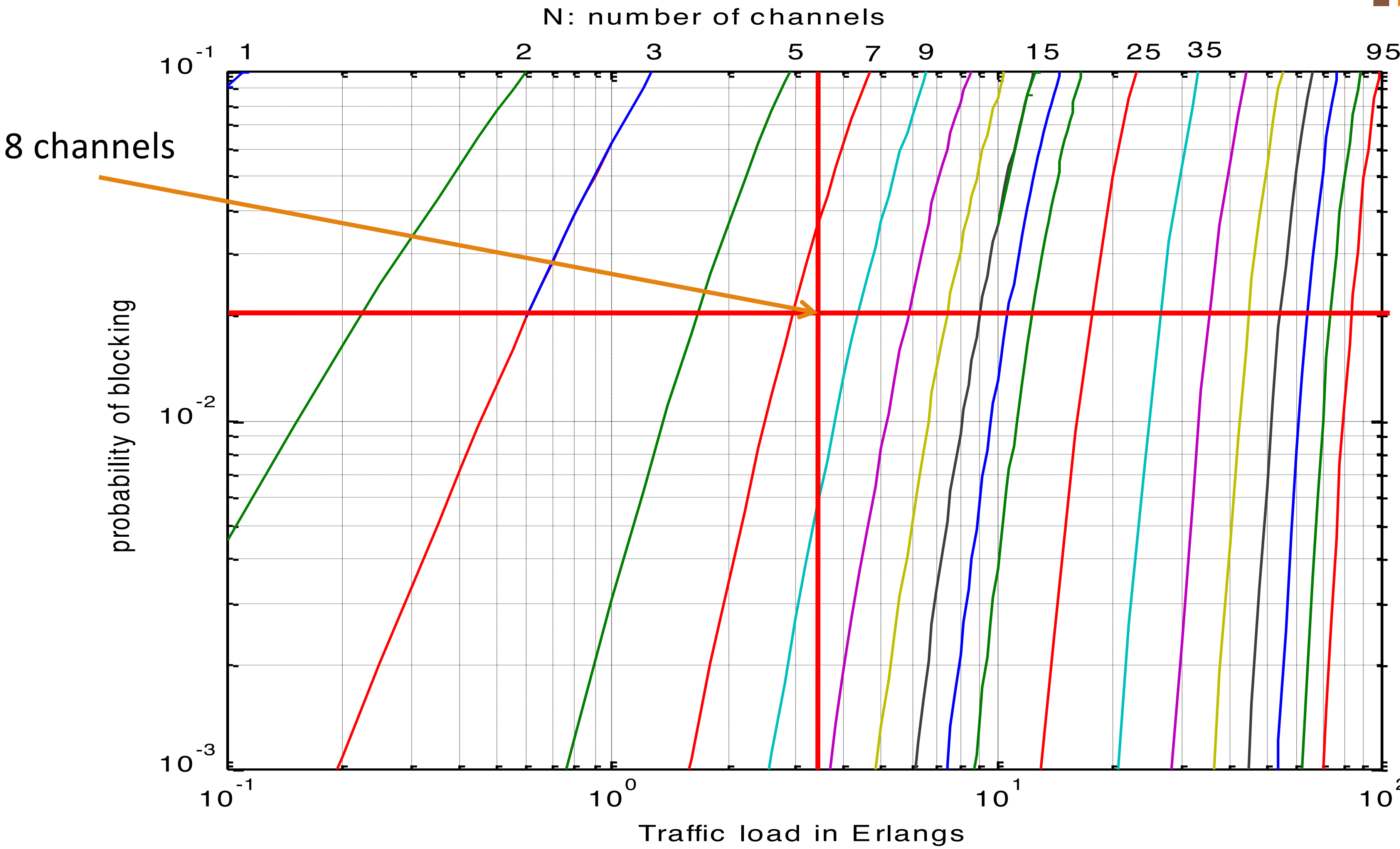
- For 100 users with a traffic load of 3.5 E, how many channels are needed in a cell to support 2% call blocking ?
  - Use Erlang B tables or charts
  - With a 2% call blocking, we need 8 channels

Sample Erlang B table

(Erlang *B*)

	A, erlangs												
	B												
N	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%
1	.0101	.0121	.0152	.0204	.0309	.0526	.0753	.111	.176	.250	.429	.667	1.00
2	.153	.168	.190	.223	.282	.381	.470	.595	.796	1.00	1.45	2.00	2.73
3	.455	.489	.535	.602	.715	.899	1.06	1.27	1.60	1.93	2.63	3.48	4.59
4	.869	.922	.992	1.09	1.26	1.52	1.75	2.05	2.50	2.95	3.39	5.02	6.50
5	1.36	1.43	1.52	1.66	1.88	2.22	2.50	2.88	3.45	4.01	5.19	6.60	8.44
6	1.91	2.00	2.11	2.28	2.54	2.96	3.30	3.76	4.44	5.11	6.51	8.19	10.4
7	2.50	2.60	2.74	2.94	3.25	3.74	4.14	4.67	5.46	6.23	7.86	9.80	12.4
8	3.13	3.25	3.40	3.63	3.99	4.54	5.00	5.60	6.50	7.37	9.21	11.4	14.3
9	3.78	3.92	4.09	4.34	4.75	5.37	5.88	6.55	7.55	8.52	10.6	13.0	16.3
10	4.46	4.61	4.81	5.08	5.53	6.22	6.78	7.51	8.62	9.68	12.0	14.7	18.3
11	5.16	5.32	5.54	5.84	6.33	7.08	7.69	8.49	9.69	10.9	13.3	16.3	20.3
12	5.88	6.05	6.29	6.61	7.14	7.95	8.61	9.47	10.8	12.0	14.7	18.0	22.2
13	6.61	6.80	7.05	7.40	7.97	8.83	9.54	10.5	11.9	13.2	16.1	19.6	24.2
14	7.35	7.56	7.82	8.20	8.80	9.73	10.5	11.5	13.0	14.4	17.5	21.2	26.2
15	8.11	8.33	8.61	9.01	9.65	10.6	11.4	12.5	14.1	15.6	18.9	22.9	28.2
16	8.88	9.11	9.41	9.83	10.5	11.5	12.4	13.5	15.2	16.8	20.3	24.5	30.2
17	9.65	9.89	10.2	10.7	11.4	12.5	13.4	14.5	16.3	18.0	21.7	26.2	32.2
18	10.4	10.7	11.0	11.5	12.2	13.4	14.3	15.5	17.4	19.2	23.1	27.8	34.2
19	11.2	11.5	11.8	12.3	13.1	14.3	15.3	16.6	18.5	20.4	24.5	29.5	36.2
20	12.0	12.3	12.7	13.2	14.0	15.2	16.3	17.6	19.6	21.6	25.9	31.2	38.2

Erlang B Chart



+ Example: Using Erlang B for traffic engineering

- Consider a single analog cell tower with 56 traffic channels
  - When all channels are busy, calls are blocked
  - Calls arrive according to a Poisson process at an average rate of 1 call per active user per hour
  - During the busy hour ¾ of the users are active
  - The call holding time is exponentially distributed with a mean of 120 seconds

Example: Continued

- What is the maximum load the cell can support while providing 2% call blocking?
  - From the Erlang B table with *c*= 56 channels and 2% call blocking, the maximum load = 45.9 Erlangs
- What is the maximum number of users supported by the cell during the busy hour?
  - Load per active user = (1 call/3600 s) × (120 s/call) = 33.3 mErlangs
  - Number of active users = 45.9/(0.0333) = 1377
  - Total number of users = 4/3 number active users = 1836

Another Example

- Consider an AMPS system with 30 kHz channels, 4 sectors/cell, frequency reuse of N_c = 9, and 12.5 MHz of bandwidth.
  - Number of channels = $12.5 \times 10^6 / 30 \times 10^3$ = 416 channels
  - Say 20 are control channels => total number of voice channels = 396
  - Number of channels/cell = 396/9 = 44
  - Number of channels/sector = 44/4 = 11
- If an IS-136 system is used, assuming 3 time slots per carrier, the number of channels/sector = 33

Example (Continued)

- For a 2% blocking probability, from the Erlang B tables, the maximum traffic load is
  - For AMPS: 5.84 E
  - For IS-136: 24.6 E
- If the average call duration is 3 minutes, and each call is 3/60 = 0.05 E
  - AMPS can support 5.84/0.05 = 116 calls/hour/sector
  - IS-136 can support 24.6/0.05 = 492 calls/hour/sector

Handoff and Mobility

- A call will occupy a channel as long as a user is in the cell
  - If we assume cell residence time is exponential, then the channel occupancy = min(call holding time, cell residency time)
  - Also exponentially distributed
- Similar calculations can be done, but we ignore mobility and handoff here

Traffic Engineering in CDMA

- It is more complicated!
- Determining Erlang capacity is not trivial
  - One approximation is to use the number of channels from the "pole point"
  - To be more accurate, we have to characterize the impact of call arrivals and holding time on the interference
  - See for example: A. M. Viterbi and A. J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System," IEEE JSAC, Vol. 11, No. 6, August 1993.