Cellular Networks and Mobile Computing
COMS 6998-8, Spring 2012

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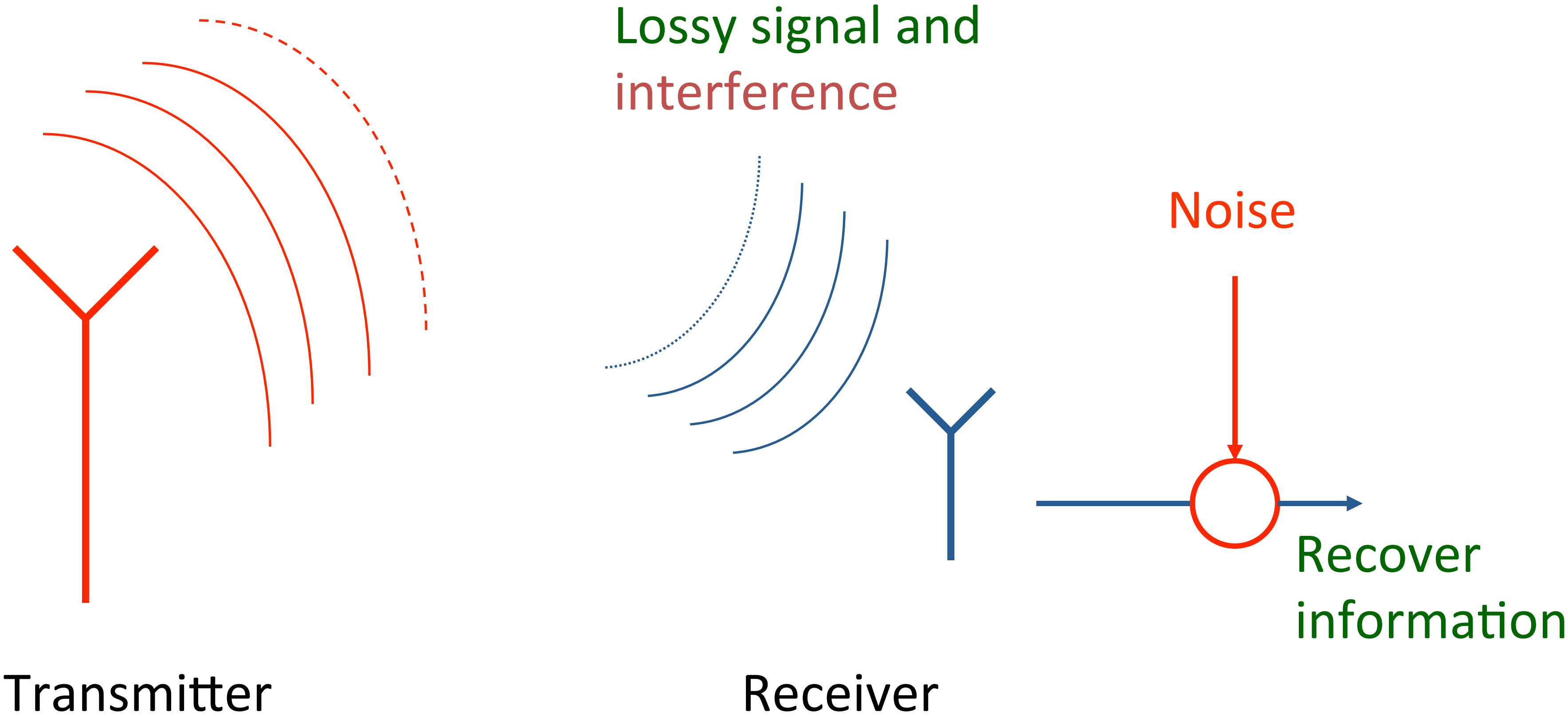
1/30/2012: Cellular Networks: UMTS and LTE

Outline

- Wireless communications basics
  - Signal propagation, fading, interference, cellular principle
- Multi-access techniques and cellular network air-interfaces
  - FDMA, TDMA, CDMA, OFDM
- 3G: UMTS
  - Architecture: entities and protocols
  - Physical layer
  - RRC state machine
- 4G: LTE
  - Architecture: entities and protocols
  - Physical layer
  - RRC state machine

Basic Wireless Communication

Information is embedded in electromagnetic radiation

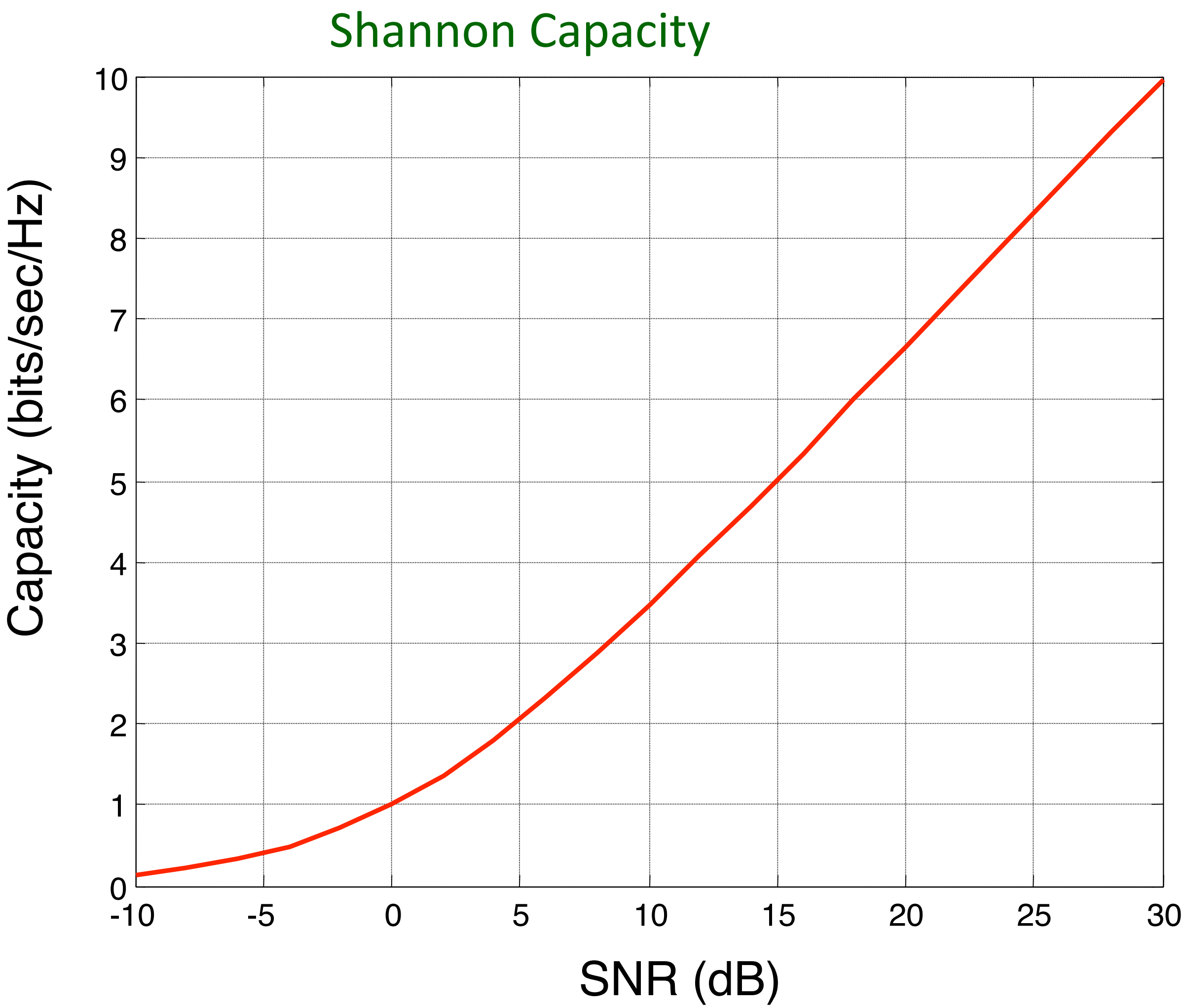


Noise & Interference

- Thermal Noise
  - Generated due to random motion of electrons in the conductor and proportional to temperature
  - $N_o = K_o T$ dBm/Hz where K_o is Boltzmann's constant
  - Receiver Noise Figure – extent to which thermal noise is enhanced by receiver front end circuitry ~ 10 dB
- Interference – signals transmitted by other users of the wireless network
- Signal transmitted by other wireless devices from different wireless networks
  - Example: Microwave ovens near 802.11 network

Courtesy: Harish Vishwanath

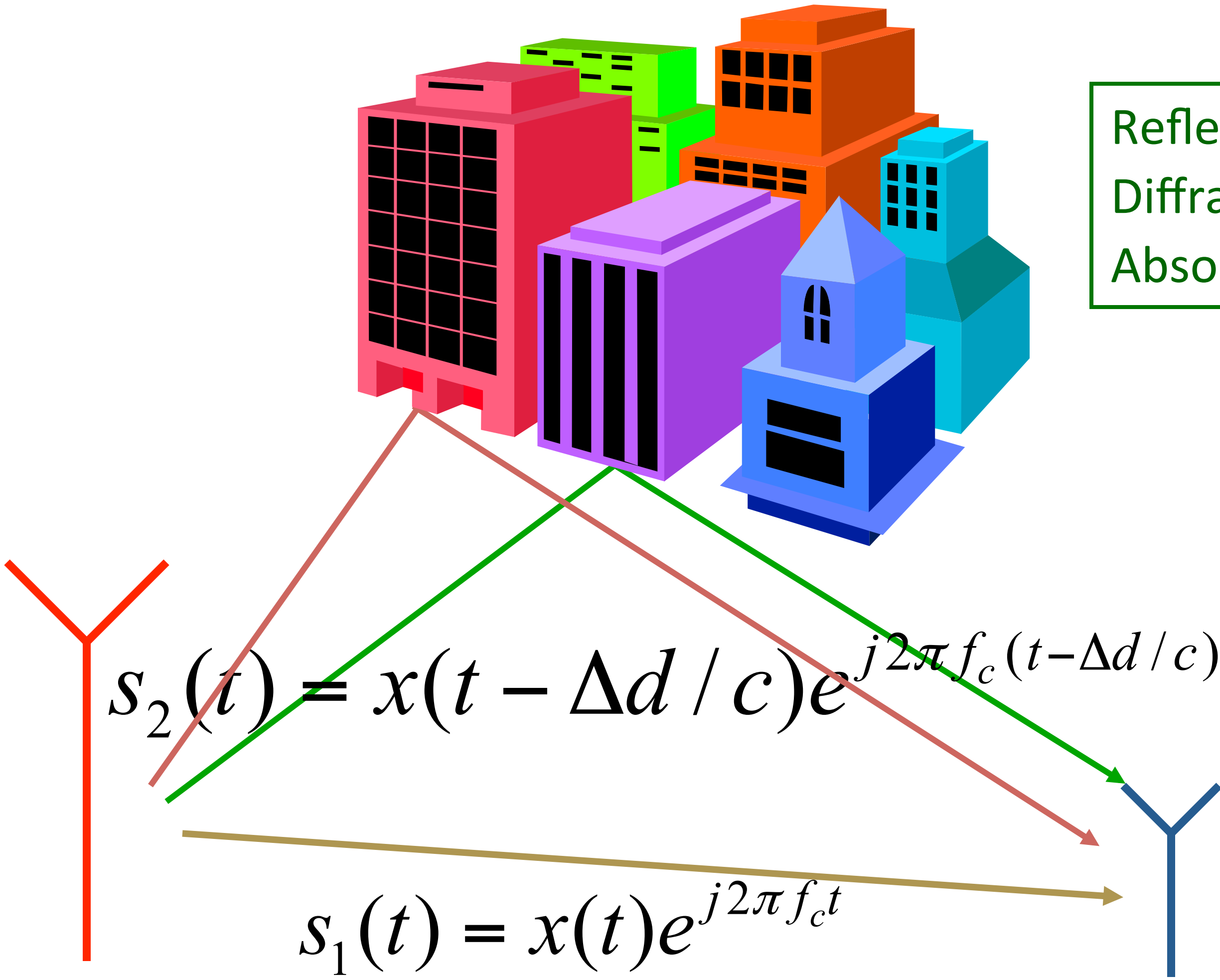
Impact of White Gaussian Noise



$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}}$$

$$C = \log(1 + SNR)$$

Scattering of Signals - Multipath Fading



Reflection
Diffraction
Absorption

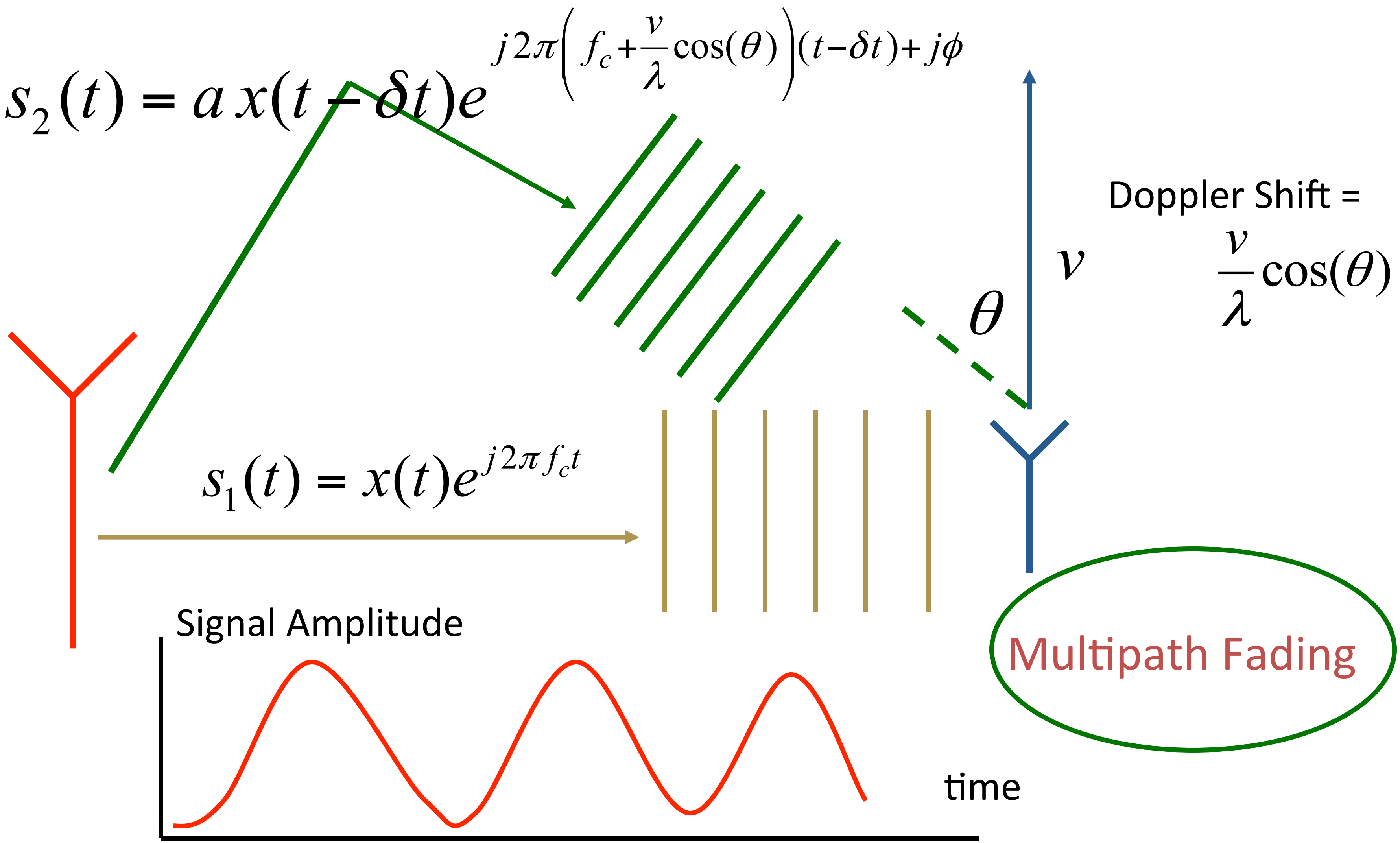
$$s_2(t) = x(t - \Delta d / c)e^{j2\pi f_c (t - \Delta d / c) + j\phi}$$

$$s_1(t) = x(t)e^{j2\pi f_c t}$$

Multiple paths with random phases and gains combine constructively and destructively to cause significant amplitude variations

Courtesy: Harish Vishwanath

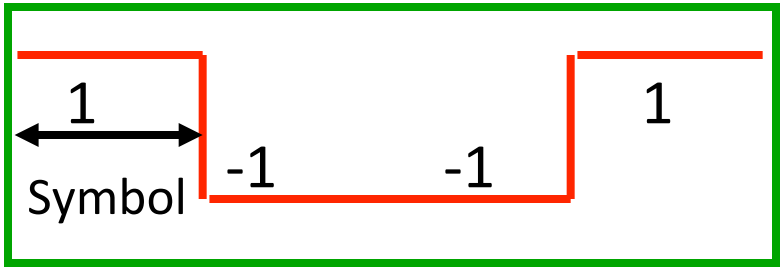
Impact of Mobility



Flat & Frequency Selective Fading

- When the multipath delay is small compared to symbol duration of the signal, fading is flat or frequency non-selective

$$x(t - \delta t_{\max}) \approx x(t)$$

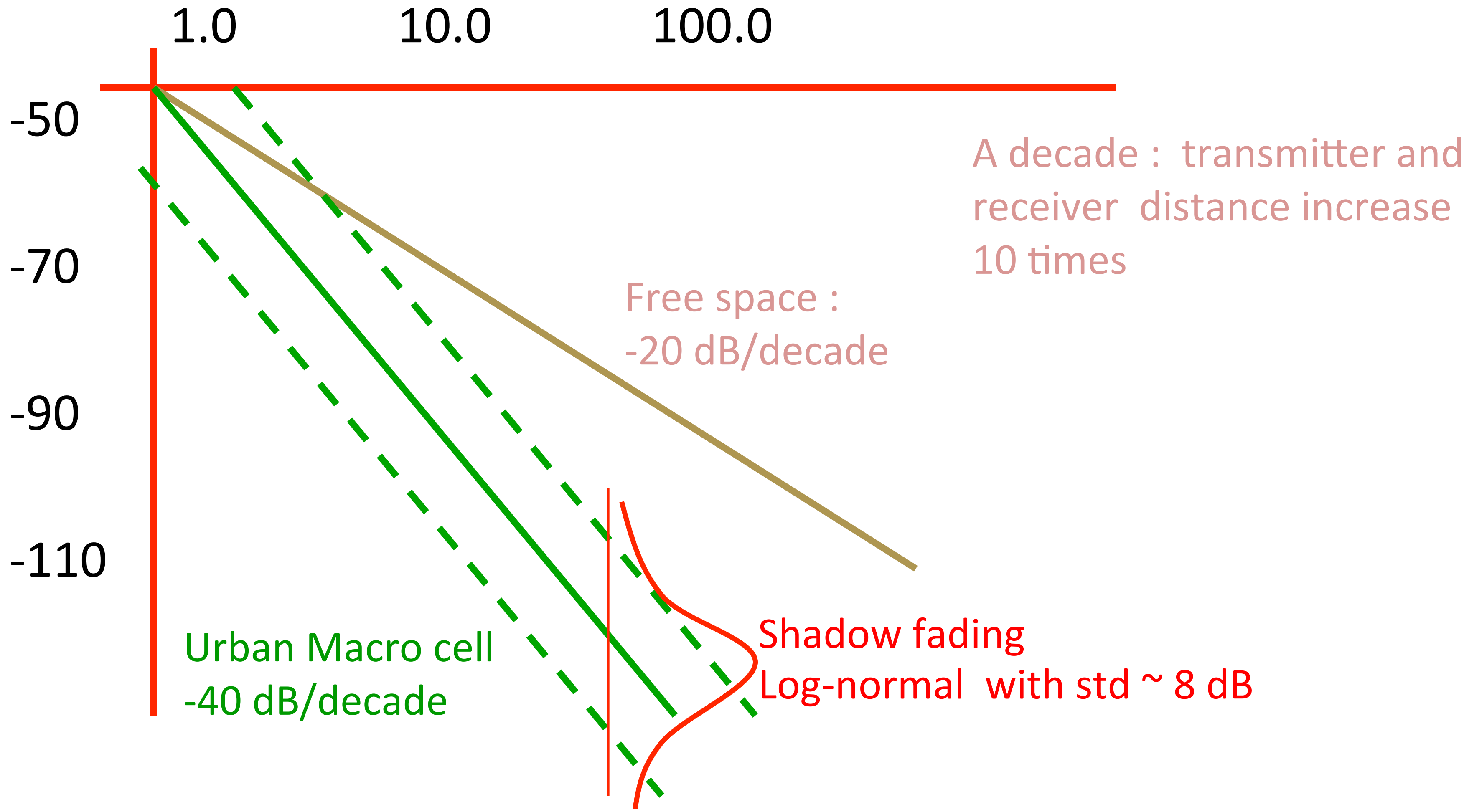


- Happens when signal bandwidth is small

$$B_x = \frac{1}{\delta t_{\max}}$$

- Urban macro-cell delay spread is 10 micro seconds
- When signal bandwidth is large different bands have different gains – frequency selective fading

Typical Pathloss



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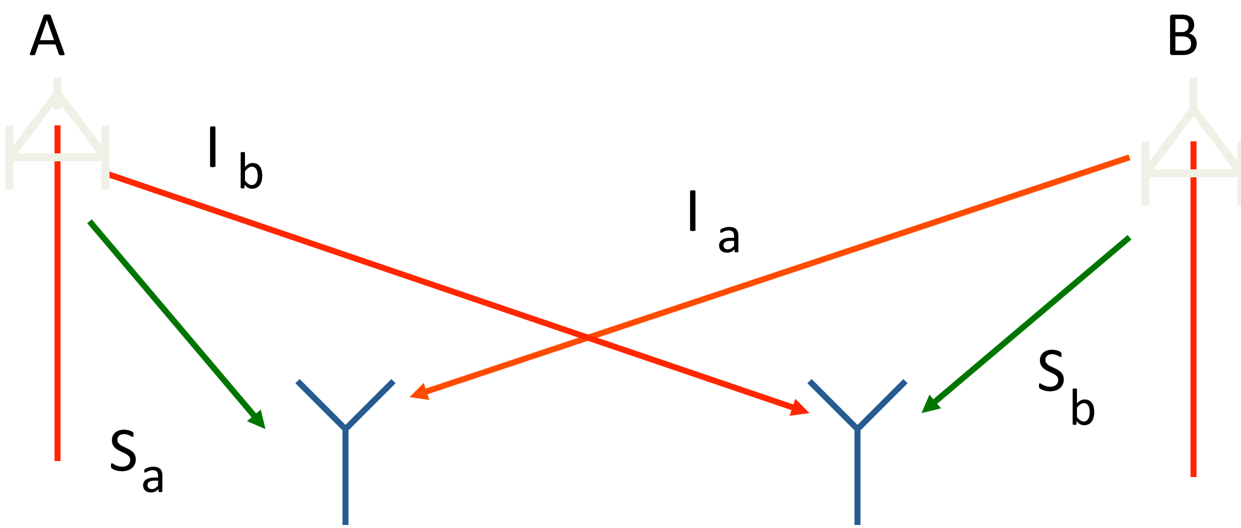
Spectrum Reuse



$$SINR_a = \frac{S_a}{I_a + N}$$

a and b can receive simultaneously on the same frequency band if $SINR_a$ and $SINR_b$ are above required threshold

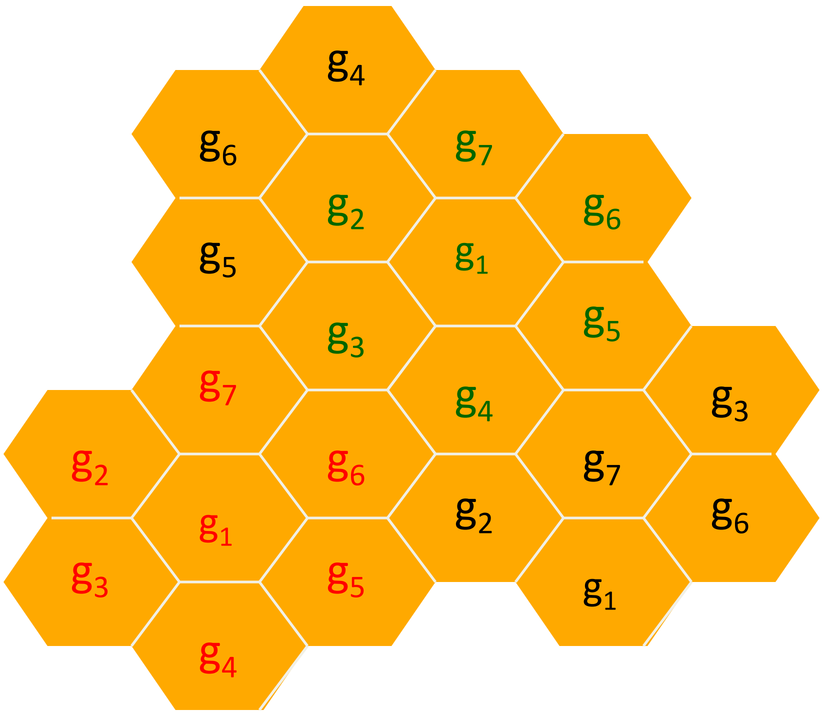
This happens if the respective transmitters are sufficiently far apart

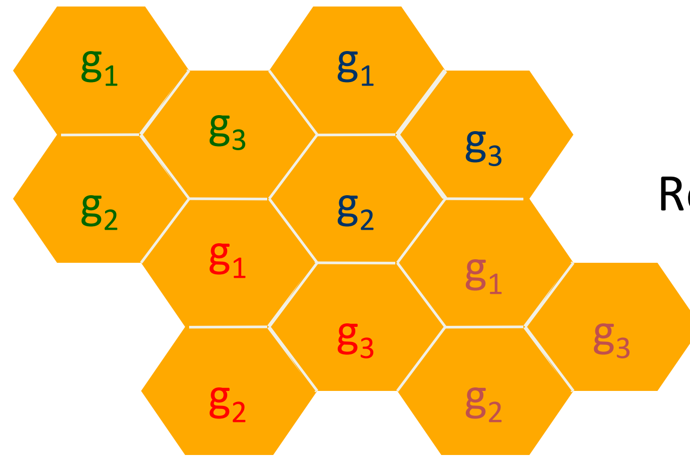
The Cellular Principle

- Base stations transmit to and receive from mobiles at the assigned spectrum
  - Multiple base stations use the same spectrum (spectral reuse)
- The service area of each base station is called a cell
- The wireless network consists of large number of cells
  - Example – The network in Northern NJ is about 150 base stations for a given operator
- Cells can be further divided into multiple sectors using sectorized antennas
- Each terminal is typically served by the "closest" base station(s)

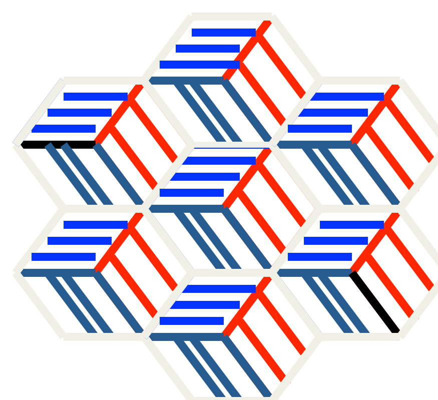
Fixed Frequency Planning

Each base is assigned a fixed frequency band





Reuse of 3

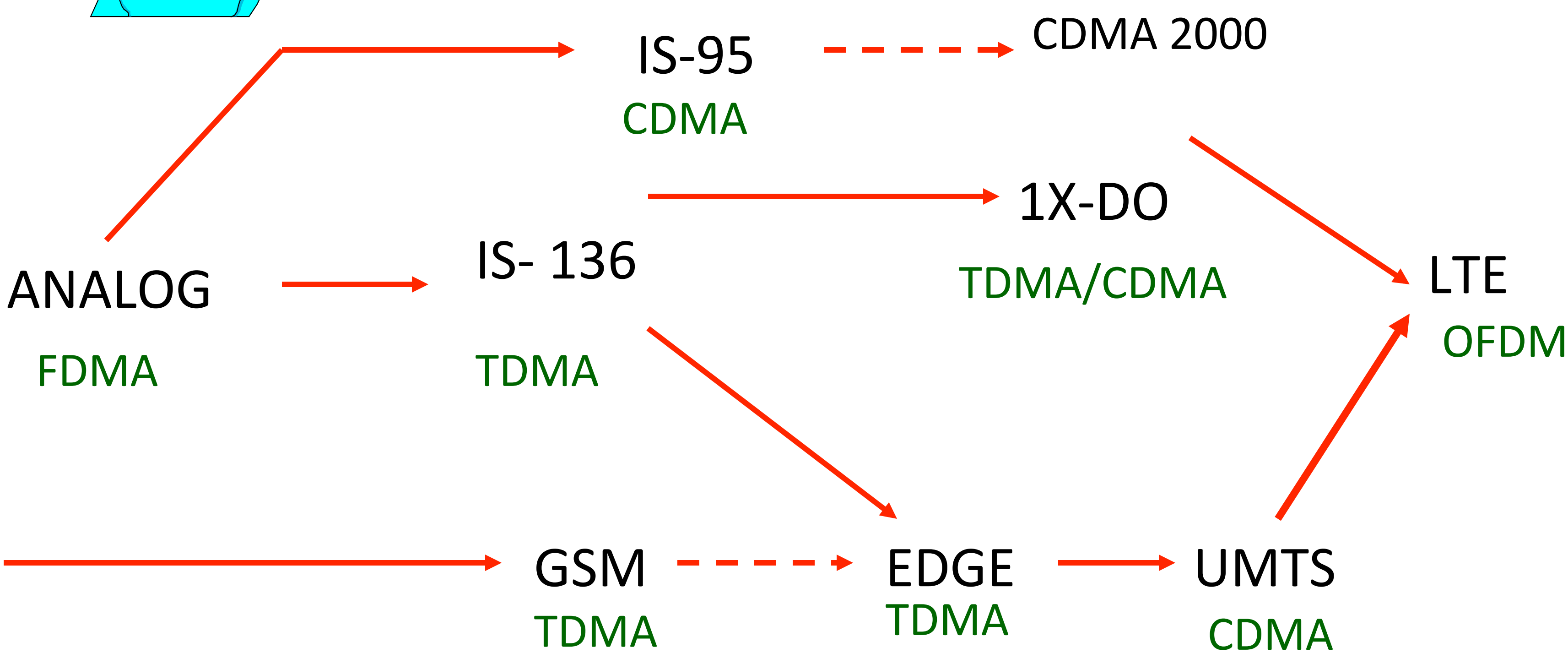


Reuse of 1/3

Reuse of 7 – nearest co-channel interferer is in the second ring

Courtesy: Harish Vishwanath

Cellular Network Evolution



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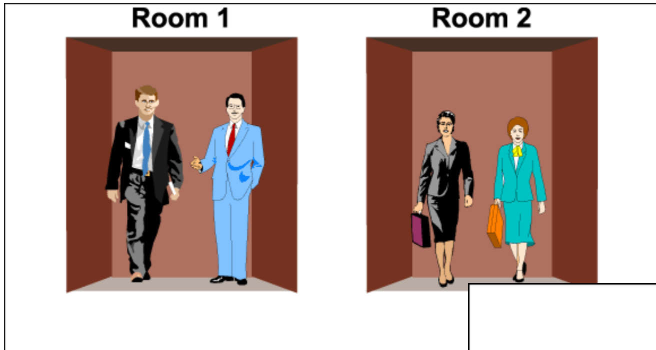
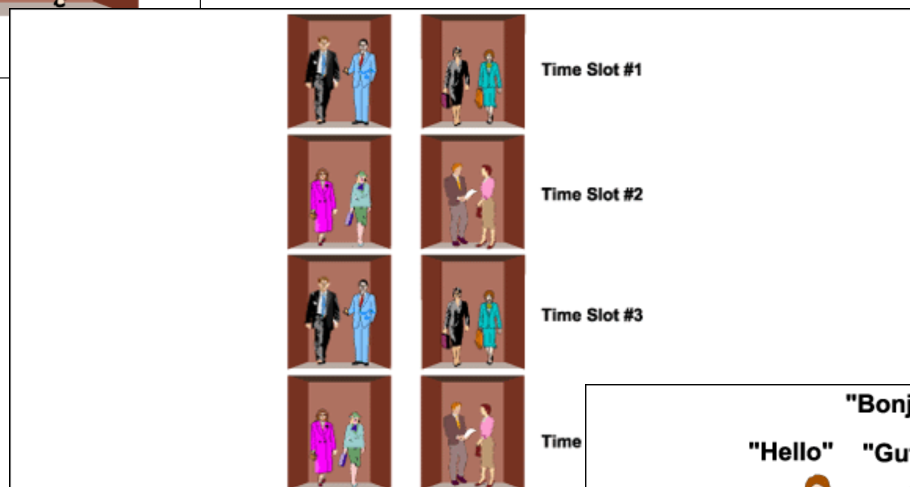
The Multiple Access problem

- The base station has to transmit to all the mobiles in its cell (downlink or forward link)
  - Signal for user a is interference for user b
  - Interference is typically as strong as signal since a and b are relatively close
  - How to avoid interference?
- All mobiles in the cell transmit to the base station (uplink or reverse link)
  - Signal from a mobile near by will swamp out the signal from a mobile farther away
  - How to avoid interference?

Meeting Room Analogy



Simultaneous meetings in different rooms (FDMA)

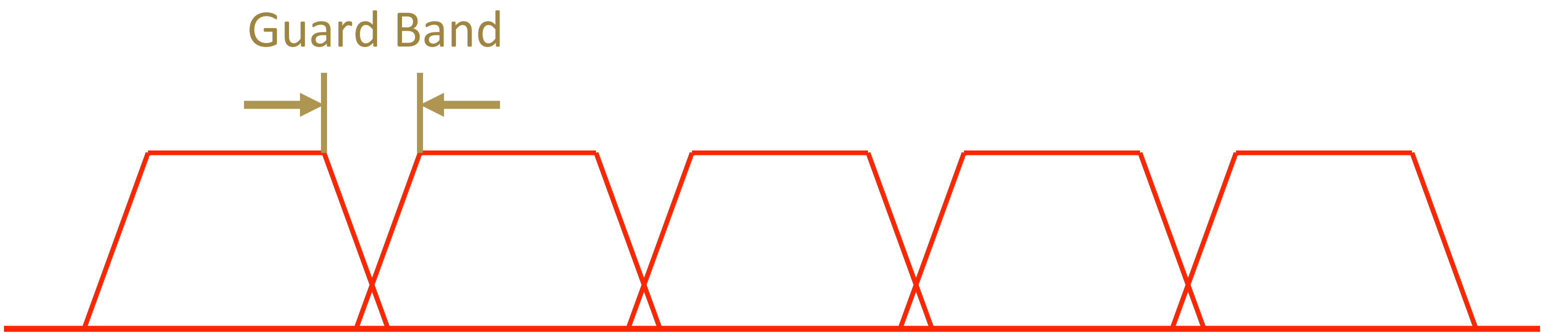


Simultaneous meetings in the same room at different times (TDMA)

Multiple meetings in the same room at the same time (CDMA)

Courtesy: Harish Vishwanath

Frequency Division Multiple Access



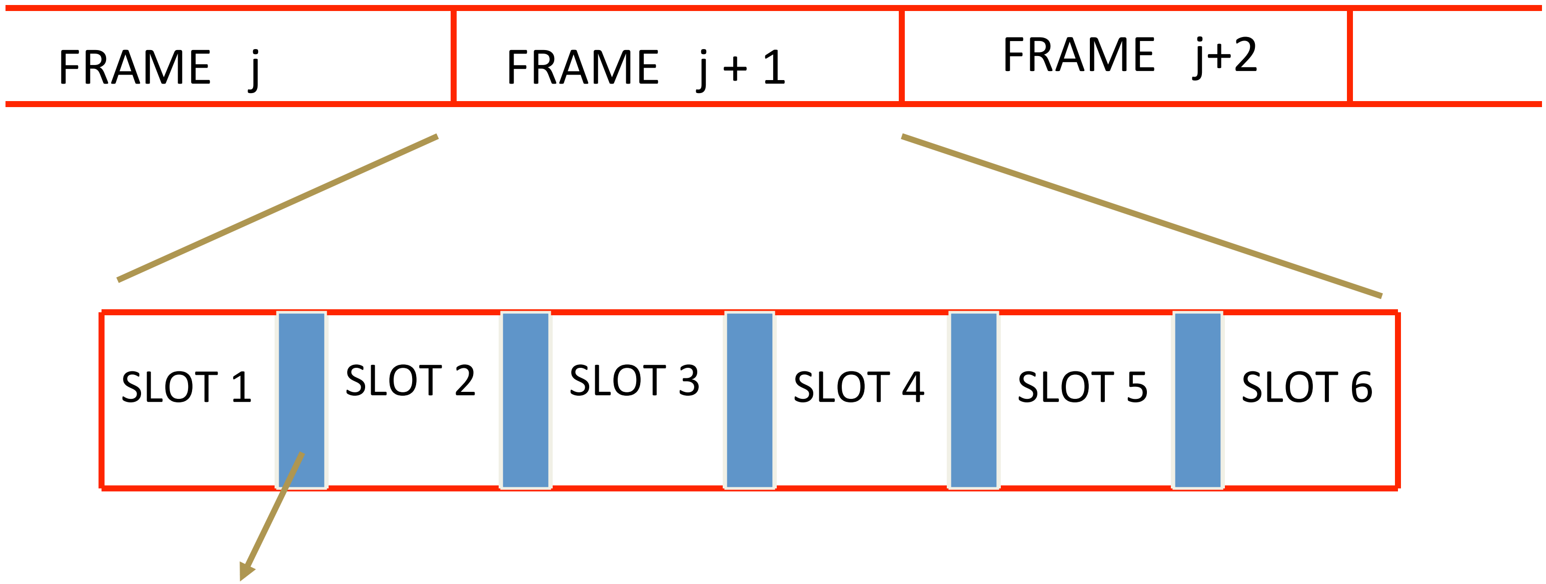
Each mobile is assigned a separate frequency channel for the duration of the call

Sufficient guard band is required to prevent adjacent channel interference

Mobiles can transmit asynchronously on the uplink

Time Division Multiple Access

Time is divided into slots and only one mobile transmits during each slot



Guard time – Signal transmitted by mobiles at different locations do not arrive at the base at the same time

Courtesy: Harish Vishwanath

TDMA Characteristics

- Discontinuous transmission with information to be transmitted buffered until transmission time
  - Possible only with digital technology
  - Transmission delay
- Synchronous transmission required
  - Mobiles derive timing from the base station signal
- Guard time can be reduced if mobiles pre-correct for transmission delay
  - More efficient than FDMA which requires significant guard band

Orthogonality in TDMA/FDMA

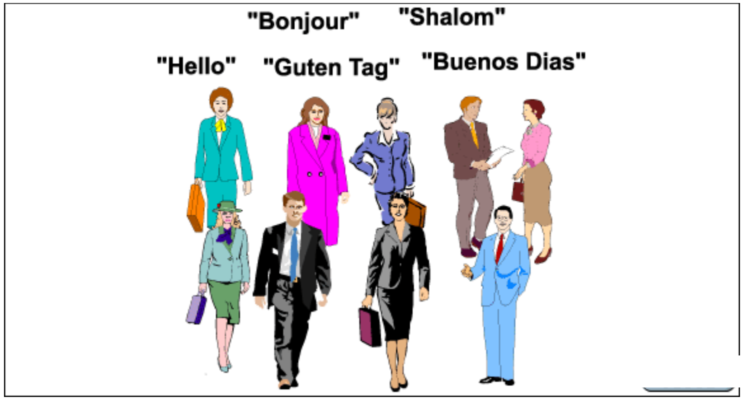
Every information signal lasts a certain duration of time and occupies a certain bandwidth and thus corresponds to a certain region in the time-frequency plane

Granularity is determined by practical limitations

Time division and frequency division are invariant under transformation of the channel and retain the orthogonality

Any orthogonal signaling scheme for which orthogonality is preserved will be a useful multiple access technique

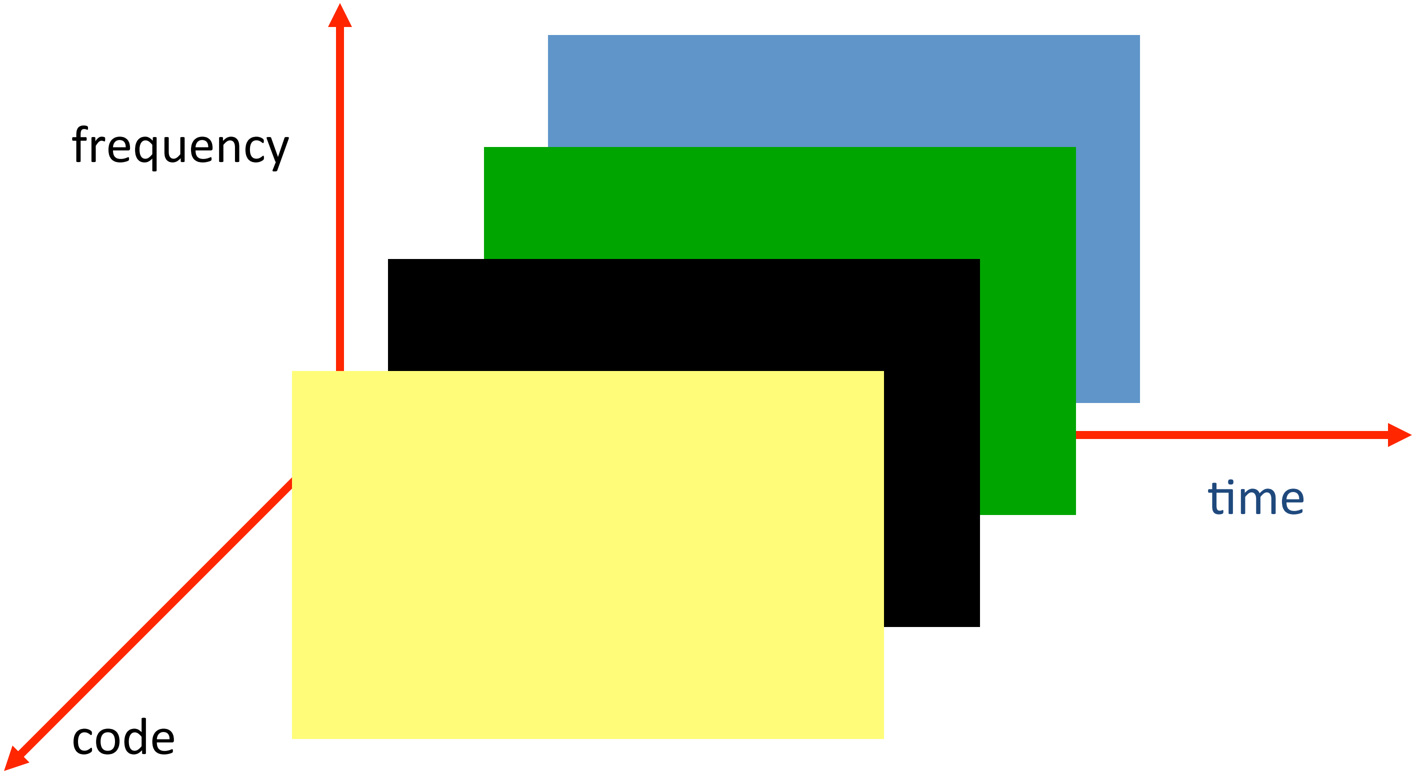
Code Division Multiple Access



- Use of orthogonal codes to separate different transmissions
- Each symbol or bit is transmitted as a larger number of bits using the user specific code – Spreading
- Spread spectrum technology
  - The bandwidth occupied by the signal is much larger than the information transmission rate
  - Example: 9.6 Kbps voice is transmitted over 1.25 MHz of bandwidth, a bandwidth expansion of ~100

Courtesy: Harish Vishwanath

Spread Spectrum systems

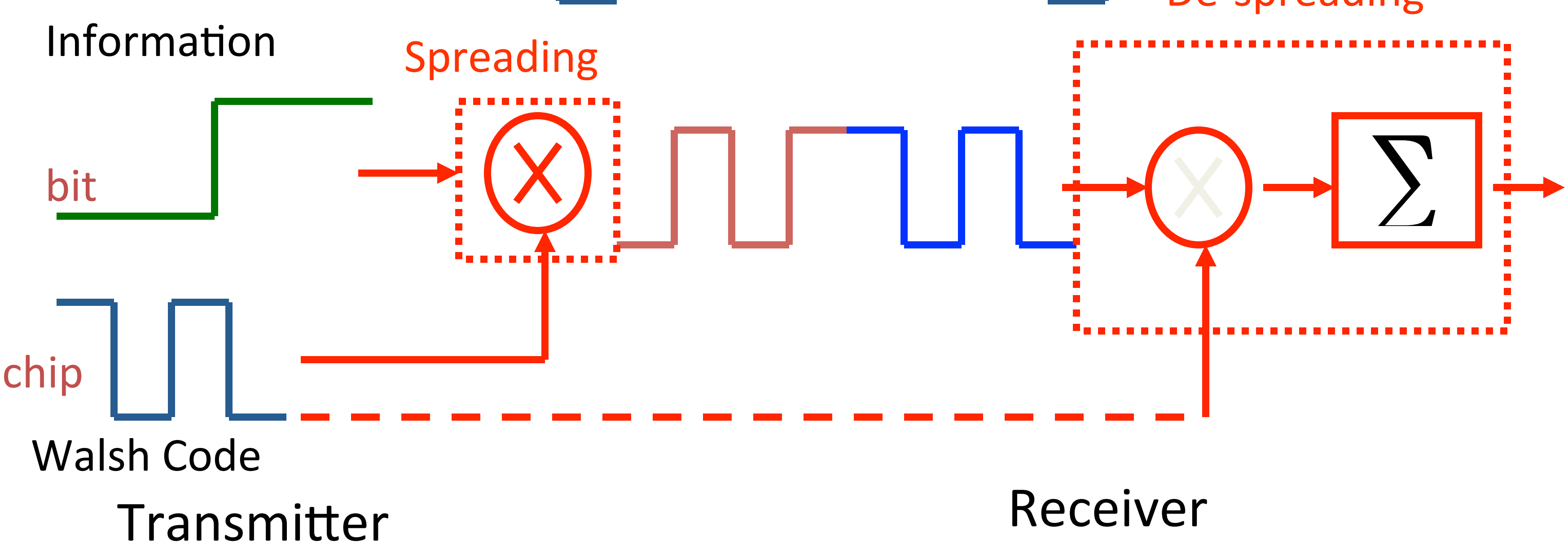


Code orthogonality is preserved under linear transformations and hence near orthogonality is preserved under signal propagation

Orthogonal Walsh Codes

Spread factor 4
Walsh Array

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

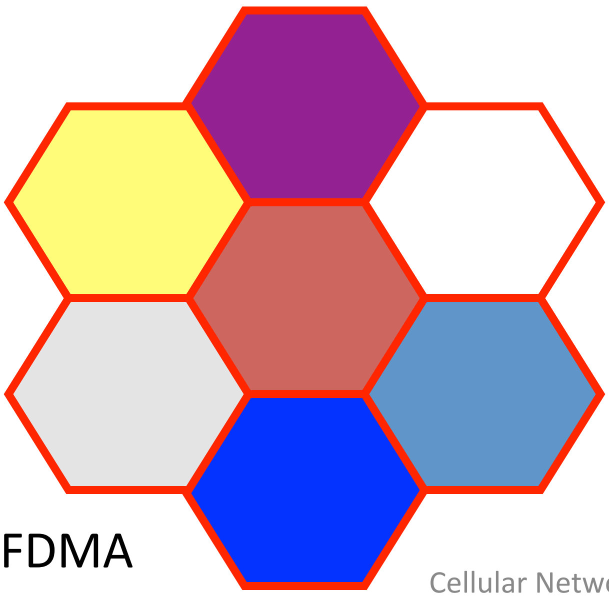


Power Control is critical

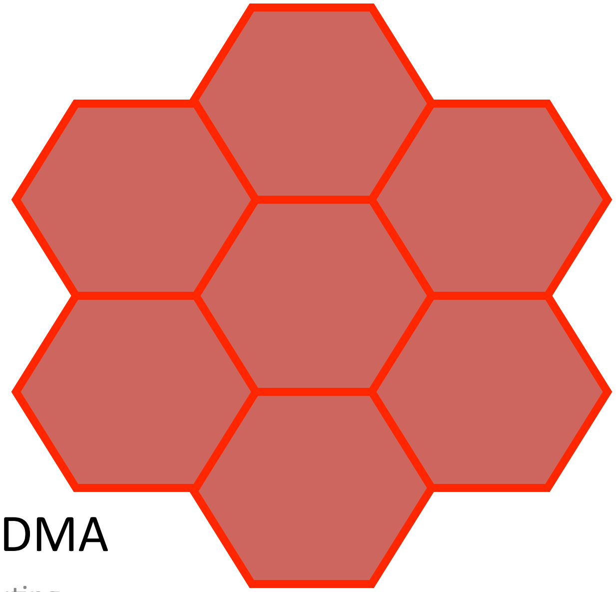
- The dynamic range of the pathloss for a typical cell is about 80 dB
- The signal received from the closest mobile is 80 dB stronger than the farthest mobile without power control
  - Code orthogonality is not sufficient to separate the signals - Near-far problem in CDMA
  - Strict orthogonality in TDMA/FDMA makes power control not critical
- Power Control – Mobiles adjust their transmit power according to the distance from the base, fade level, data rate

Why CDMA?

- Simplified frequency planning
  - Universal frequency reuse with spreading gain to mitigate interference
  - Interference averaging allows designing for average interference level instead of for worst case interference



TDMA / FDMA



CDMA

Courtesy: Harish Vishwanath

Why CDMA?

- Variable rate Vocoder with Power Control
  - Advanced data compression technology is used to compress data according to content
  - Typical voice activity is 55% - CDMA reduces interference by turning down transmission between talk spurts
  - Reduced average transmission power increases capacity through statistical multiplexing
  - Compensate for fading through power control - transmit more power only under deep fades avoiding big fade margins

Why CDMA?

- Simple multipath combining to combat fading

Each signal arriving at a different time can be recovered separately and combined coherently

The resulting diversity gain reduces fading

$$s_2(t) = x(t - T_c)e^{j2\pi f_c (t - T_c) + j\phi}$$

$$s_1(t) = x(t)e^{j2\pi f_c t}$$

Spreading sequence in $x(t)$ is offset by one chip compared to spreading sequence in $x(t - T_c)$

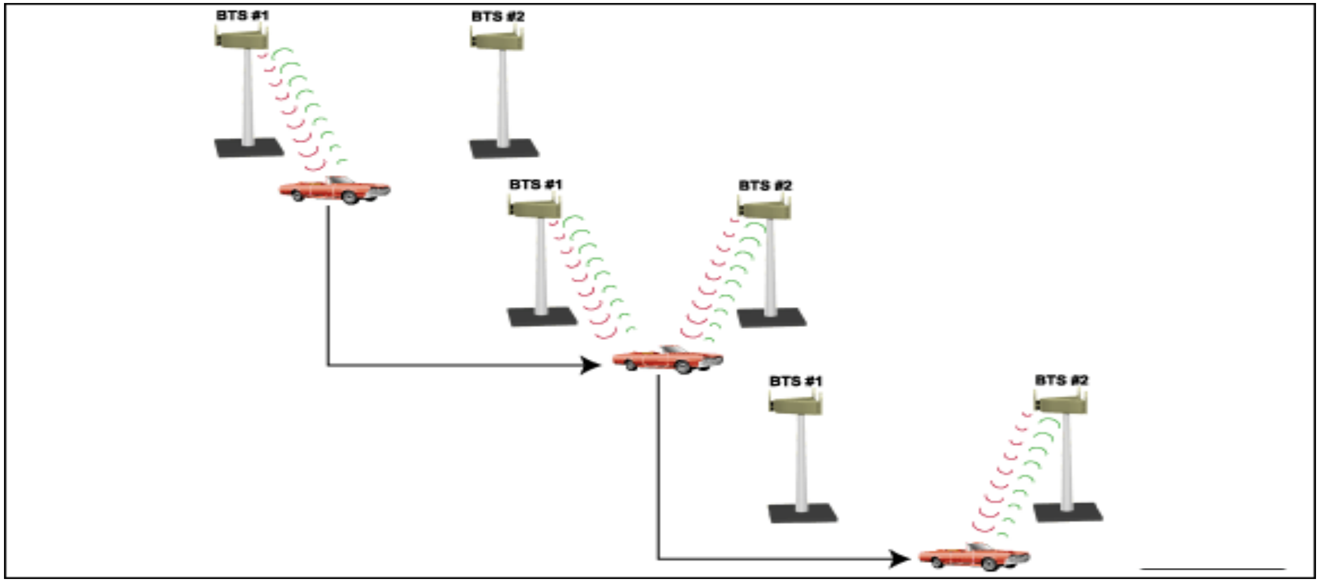
Courtesy: Harish Vishwanath

Why CDMA?

Mobile can transmit and receive from multiple base stations because all base stations use the same frequency

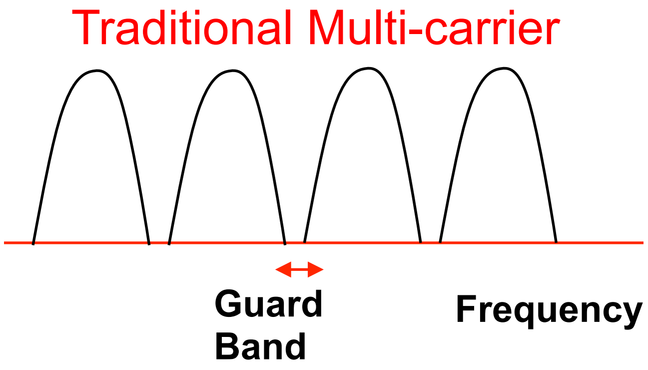
- Soft Handoff - Make-before-break handoff

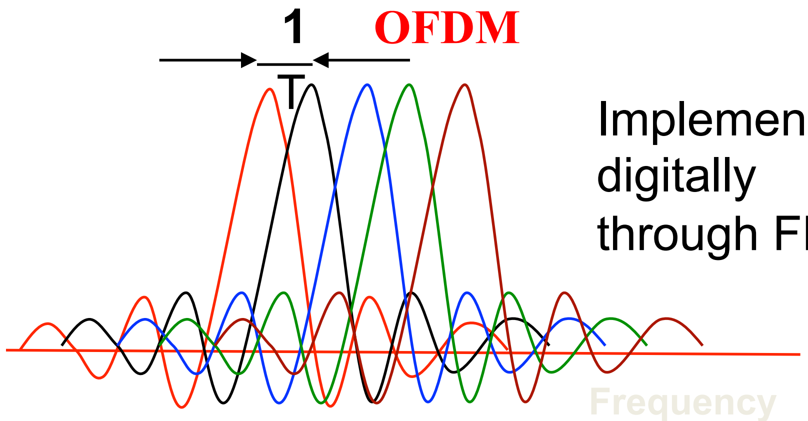
Signals from different bases can be received separately and then combined because each base uses a unique spreading code



What is OFDM ?

Orthogonal Frequency Division Multiplexing is block transmission of N symbols in parallel on N *orthogonal* sub-carriers



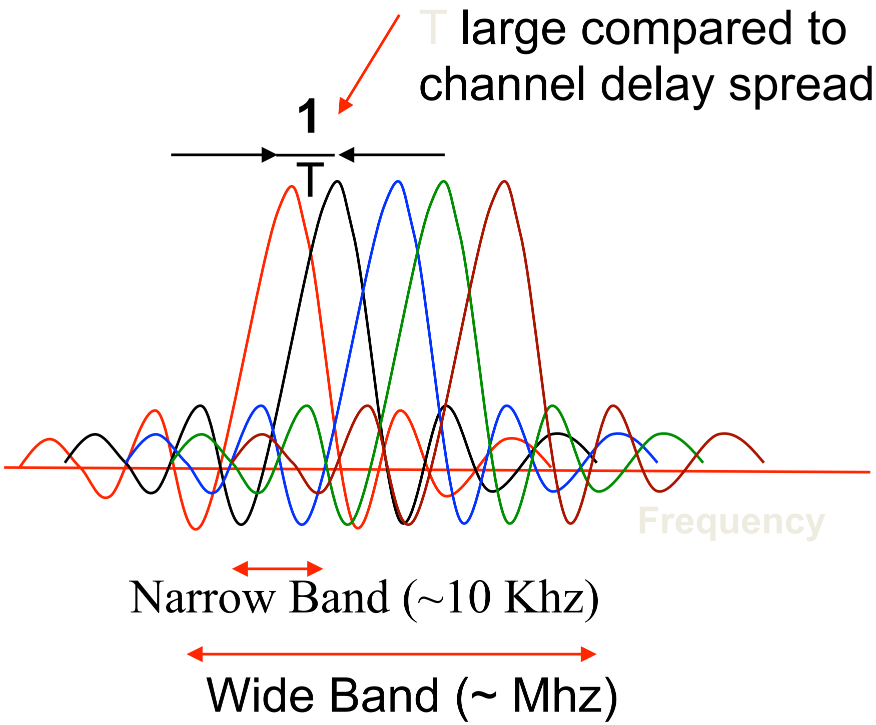


Implemented digitally through FFTs

OFDM invented in Bell Labs by R.W. Chang in ~1964 and patent awarded in 1970

Widely used: Digital audio and Video broadcasting, ADSL, HDSL, Wireless LANs

High Spectral Efficiency in Wideband Signaling



Sub-carriers remain orthogonal under multipath propagation

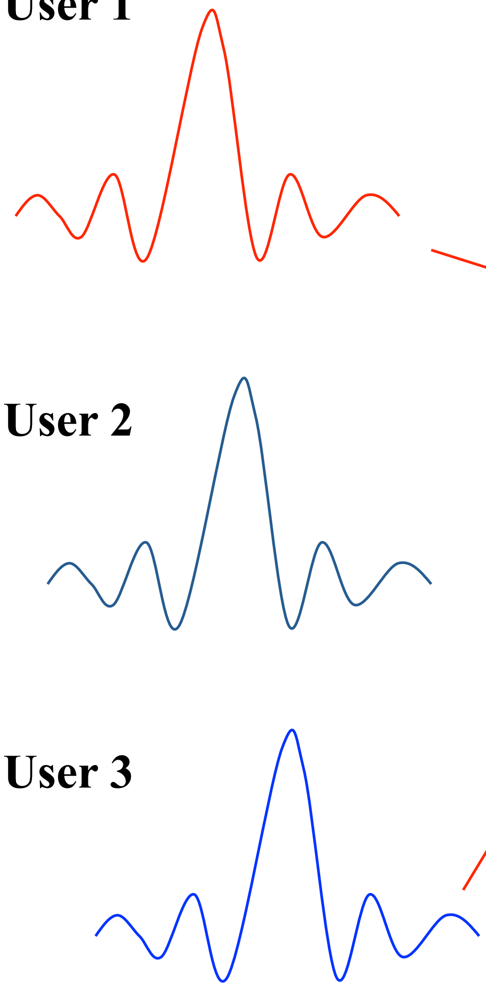
- Closely spaced sub-carriers without guard band
- Each sub-carrier undergoes (narrow band) flat fading
  - Simplified receiver processing
- Frequency or multi-user diversity through coding or scheduling across sub-carriers
- Dynamic power allocation across sub-carriers allows for interference mitigation across cells
- Orthogonal multiple access

Reverse link Orthogonal Frequency Division Multiple Access

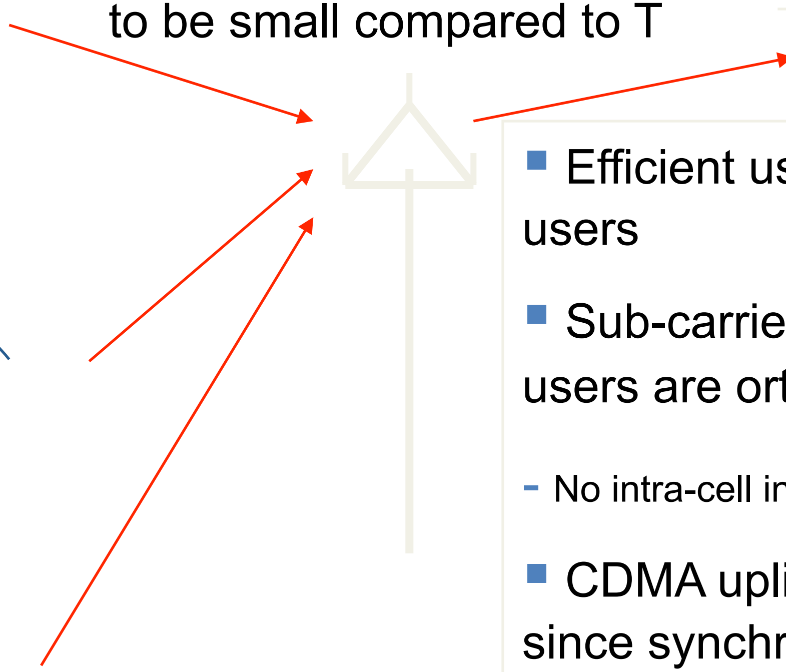
User 1

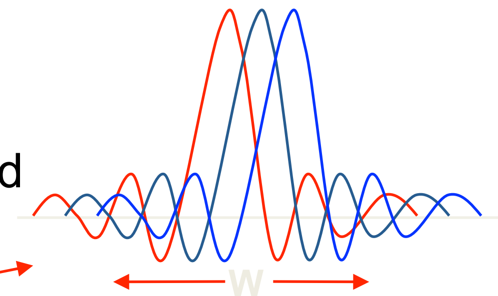
User 2

User 3



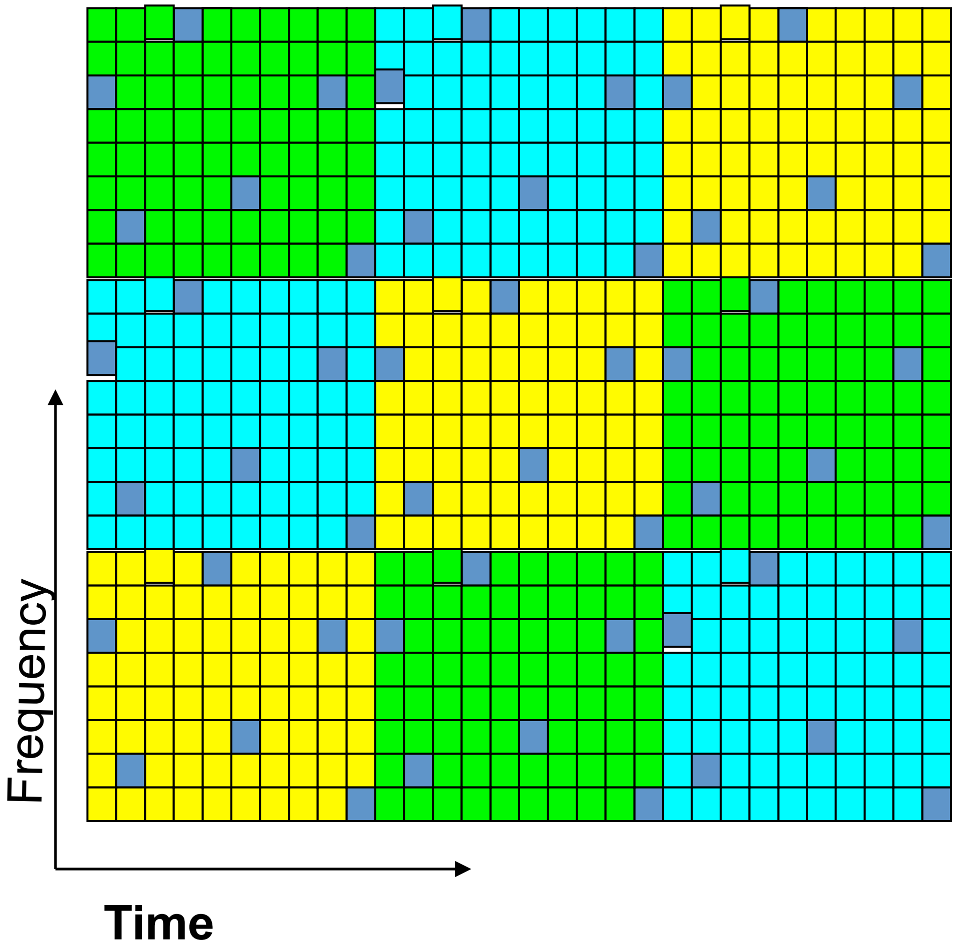
- Users are carrier synchronized to the base
- Differential delay between users' signals at the base need to be small compared to T





- Efficient use of spectrum by multiple users
- Sub-carriers transmitted by different users are orthogonal at the receiver
  - No intra-cell interference
- CDMA uplink is non-orthogonal since synchronization requirement is ~ 1/W and so difficult to achieve

Typical Multiplexing in OFDMA



Each color represents a user

Each user is assigned a frequency-time tile which consists of pilot sub-carriers and data sub-carriers

- Yellow color indicates pilot sub-carriers
- Channel is constant in each tile

Block hopping of each user's tile for frequency diversity

Typical pilot ratio: 4.8 % (1/21) for LTE for 1 Tx antenna and 9.5% for 2 Tx antennas

Courtesy: Harish Vishwanath

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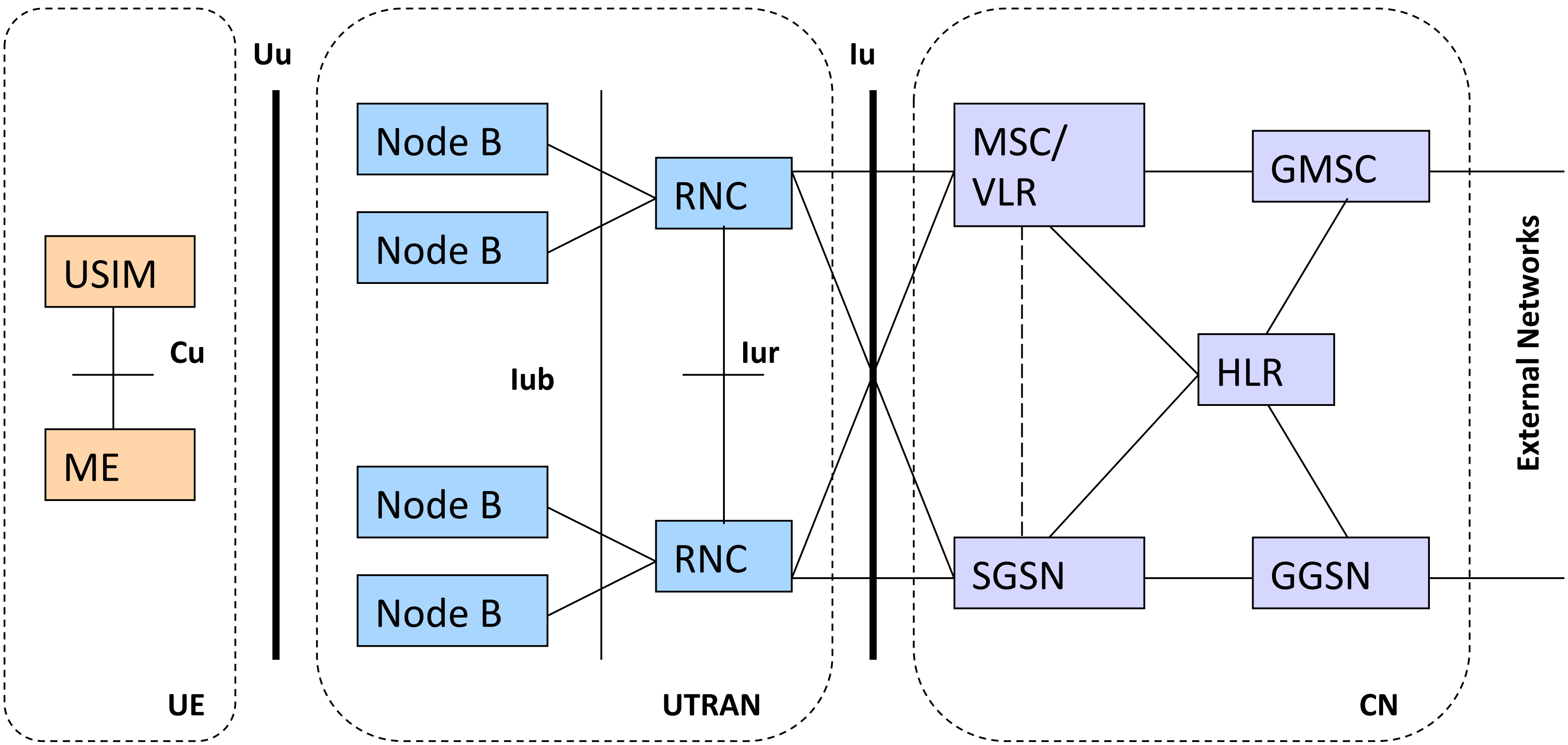
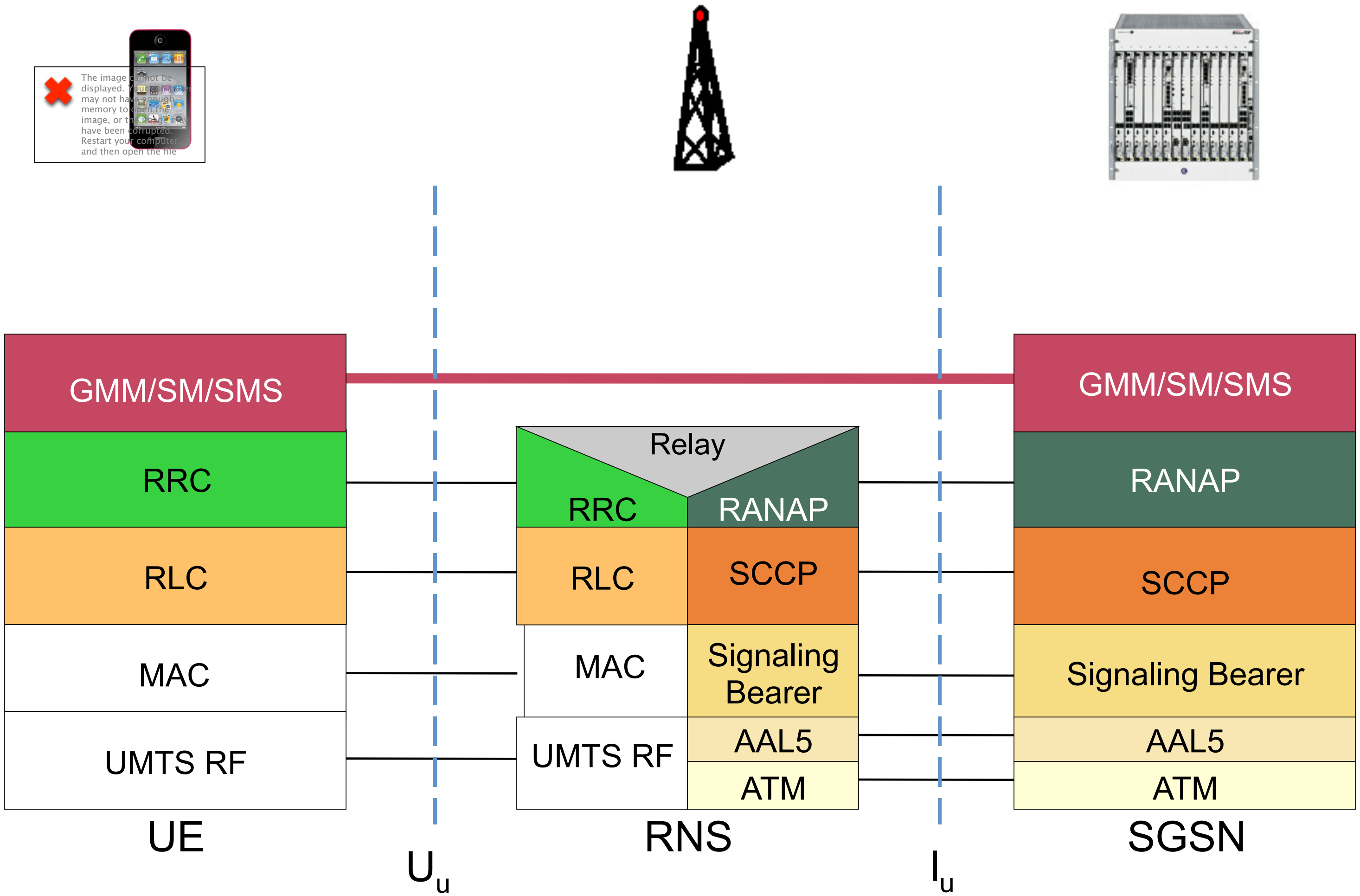
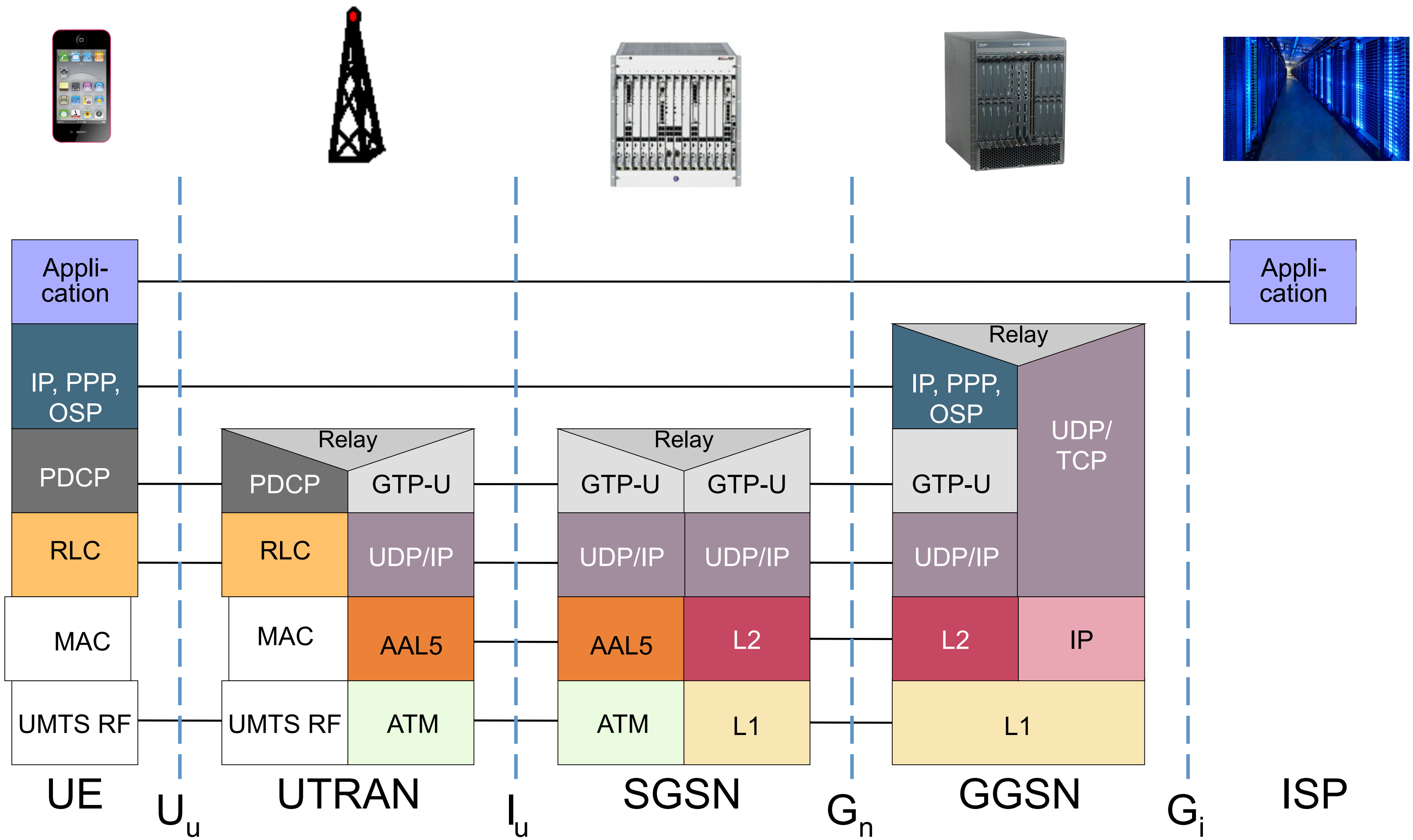
UMTS System Architecture



UMTS Control Plane Protocol Stacks



UMTS User Plane Protocol Stacks



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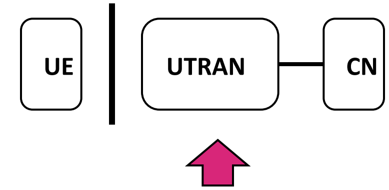


UMTS Terrestrial Radio Access Network Overview

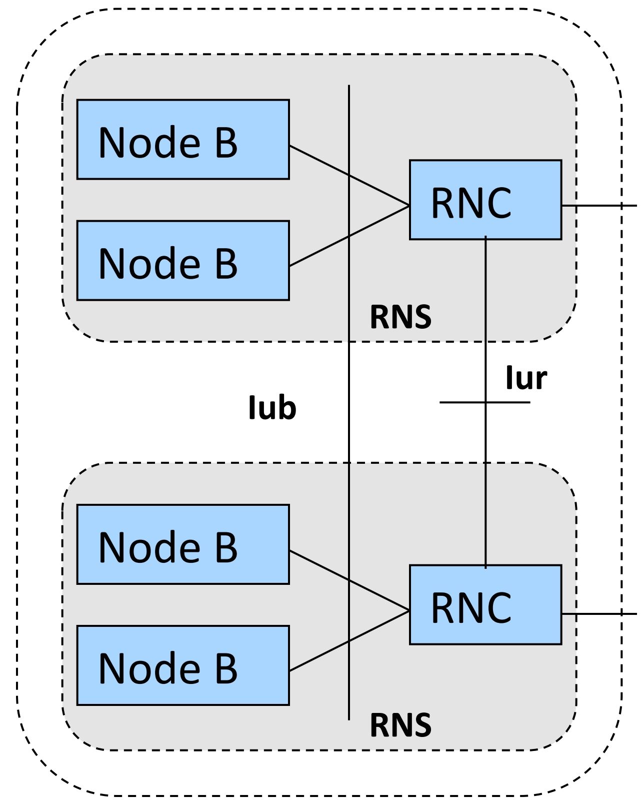
- Two Distinct Elements :

  Base Stations (Node B)
  Radio Network Controllers (RNC)

- 1 RNC and 1+ Node Bs are group together to form a Radio Network Sub-system (RNS)

- Handles all Radio-Related Functionality
  - Soft Handover
  - Radio Resources Management Algorithms

- Maximization of the commonalities of the PS and CS data handling



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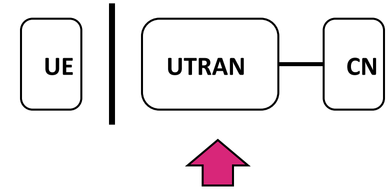
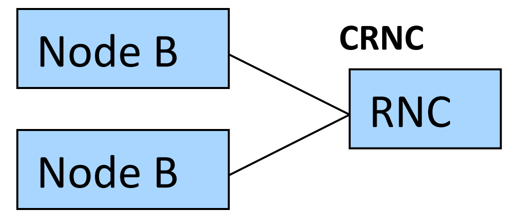


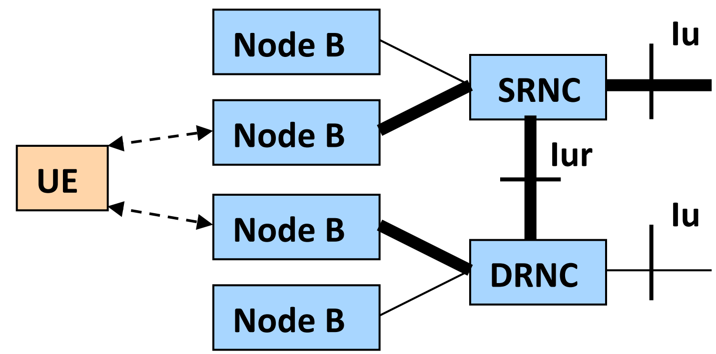
Logical Roles of the RNC

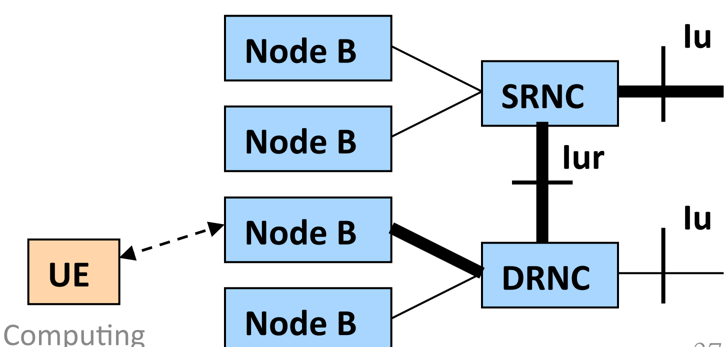
Controlling RNC (CRNC)
Responsible for the load and congestion control of its own cells



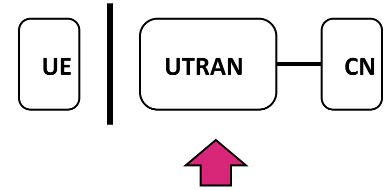
Serving RNC (SRNC)
Terminates : Iu link of user data, Radio Resource Control Signalling
Performs : L2 processing of data to/from the radio interface, RRM operations (Handover, Outer Loop Power Control)

Drift RNC (DRNC)
Performs : Macrodiversity Combining and splitting





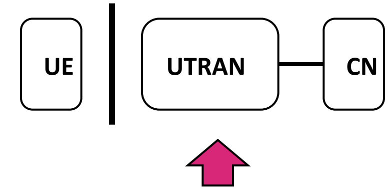
Radio Resources Management



- Network Based Functions
  - Admission Control (AC)
    - Handles all new incoming traffic. Check whether new connection can be admitted to the system and generates parameters for it.
  - Load Control (LC)
    - Manages situation when system load exceeds the threshold and some counter measures have to be taken to get system back to a feasible load.
  - Packet Scheduler (PS): at RNC and NodeB (only for HSDPA and HSUPA)
    - Handles all non real time traffic, (packet data users). It decides when a packet transmission is initiated and the bit rate to be used.

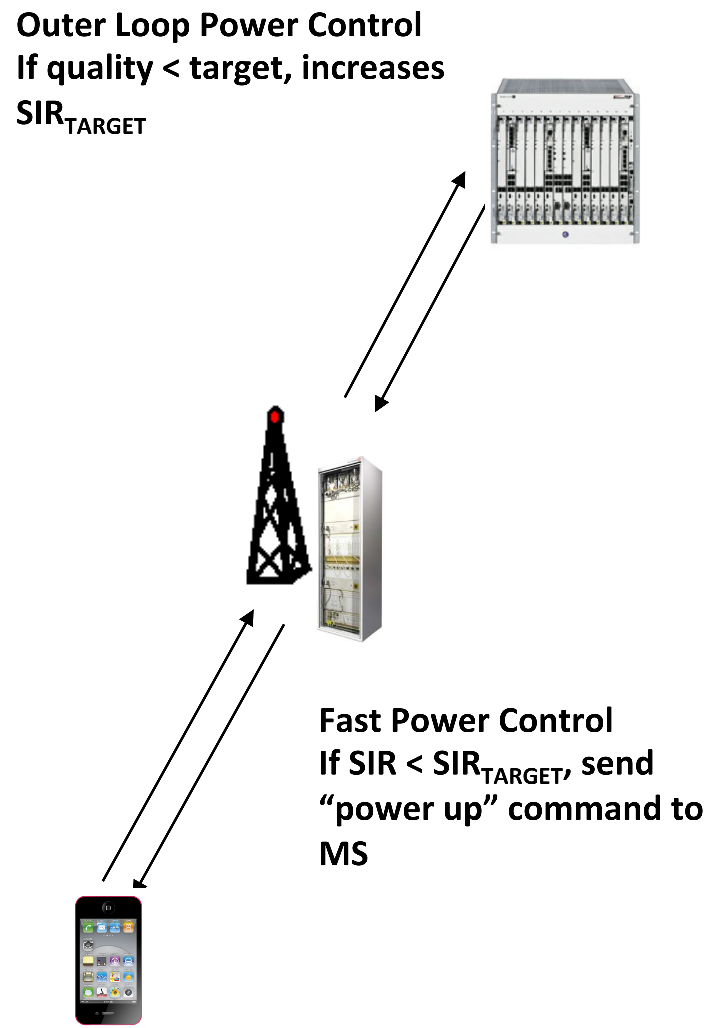
- Connection Based Functions
  - Handover Control (HC)
    - Handles and makes the handover decisions.
    - Controls the active set of Base Stations of MS.
  - Power Control (PC)
    - Maintains radio link quality.
    - Minimize and control the power used in radio interface, thus maximizing the call capacity.

Connection Based Function

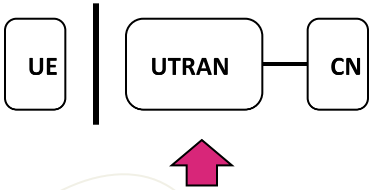


Power Control

- Prevent Excessive Interference and Near-far Effect
- Fast Close-Loop Power Control
  - Feedback loop with 1.5kHz cycle to adjust uplink / downlink power to its minimum
  - Even faster than the speed of Rayleigh fading for moderate mobile speeds
- Outer Loop Power Control
  - Adjust the target SIR setpoint in base station according to the target BER
  - Commanded by RNC

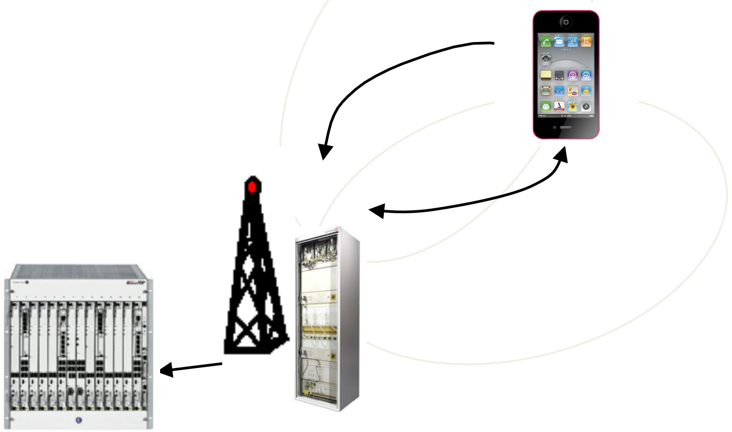


Connection Based Function

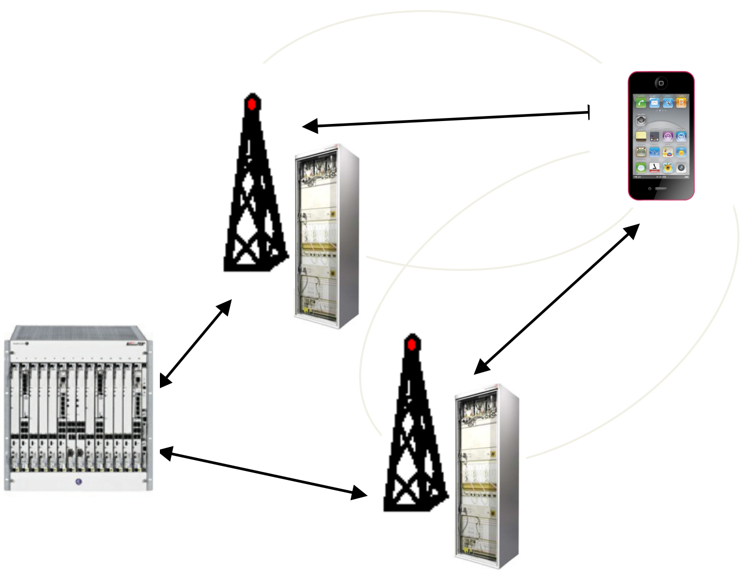


Handover

- Softer Handover
  - A MS is in the overlapping coverage of **2 sectors of a base station**
  - Concurrent communication via 2 air interface channels
  - 2 channels are maximally combined with rake receiver

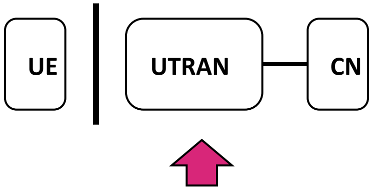


- Soft Handover
  - A MS is in the overlapping coverage of **2 different base stations**
  - Concurrent communication via 2 air interface channels
  - Downlink: Maximal combining with rake receiver
  - Uplink: Routed to RNC for selection combining, according to a frame reliability indicator by the base station



- Hard handover
  - HSDPA
  - Inter-system and inter-frequency

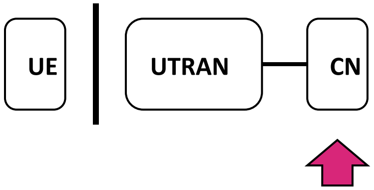
HSDPA



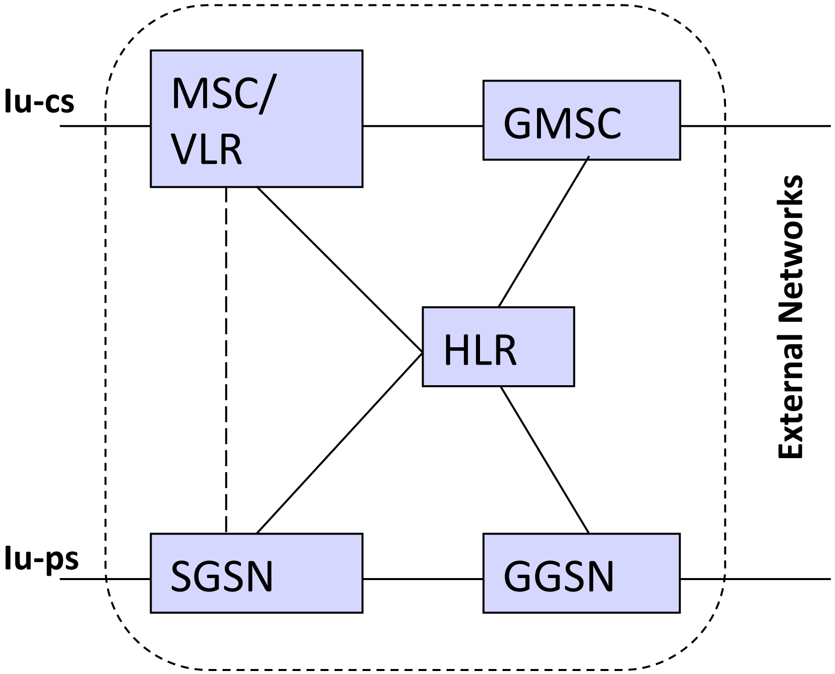
High Speed Downlink Packet Access

- Improves System Capacity and User Data Rates in the Downlink Direction to 10Mbps in a 5MHz Channel
- Adaptive Modulation and Coding (AMC)
  - Replaces Fast Power Control :
    User farer from Base Station utilizes a coding and modulation that requires lower Bit Energy to Interference Ratio, leading to a lower throughput
  - Replaces Variable Spreading Factor :
    Use of more robust coding and fast Hybrid Automatic Repeat Request (HARQ, retransmit occurs only between UE and BS)
- HARQ provides Fast Retransmission with Soft Combining and Incremental Redundancy
  - Soft Combining : Identical Retransmissions
  - Incremental Redundancy : Retransmits Parity Bits only
- Fast Scheduling Function
  - which is Controlled in the Base Station rather than by the RNC

Core Network

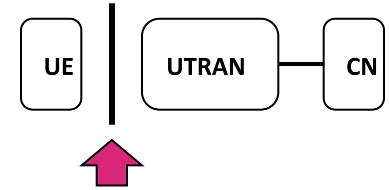


Core Network

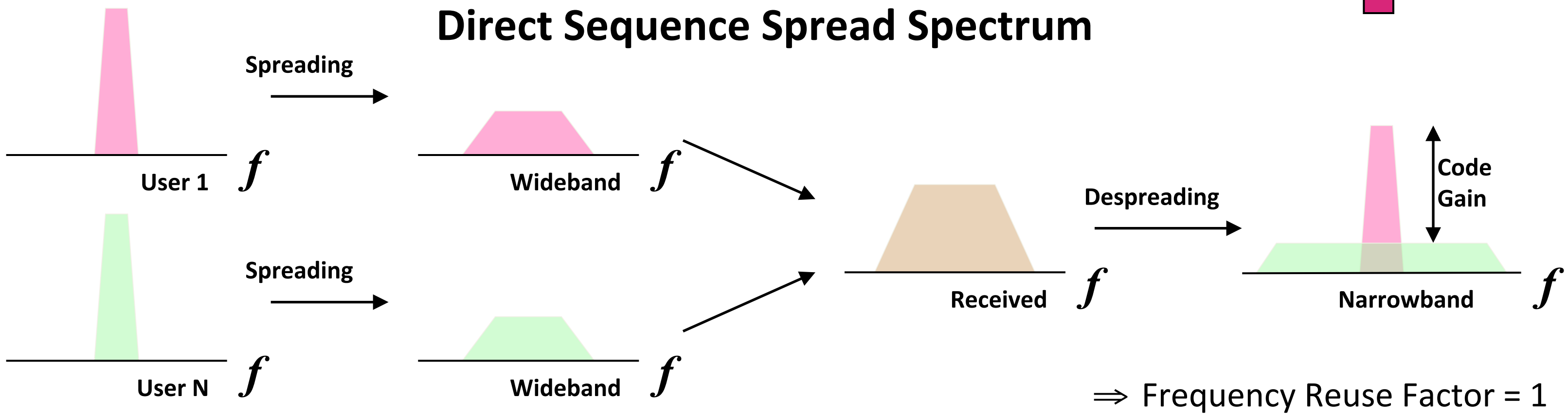


- CS Domain :
  - Mobile Switching Centre (MSC)
    - Switching CS transactions
  - Visitor Location Register (VLR)
    - Holds a copy of the visiting user's service profile, and the precise info of the UE's location
  - Gateway MSC (GMSC)
    - The switch that connects to external networks
- PS Domain :
  - Serving GPRS Support Node (SGSN)
    - Similar function as MSC/VLR
  - Gateway GPRS Support Node (GGSN)
    - Similar function as GMSC
- Register :
  - Home Location Register (HLR)
    - Stores master copies of users service profiles
    - Stores UE location on the level of MSC/VLR/SGSN

WCDMA Air Interface

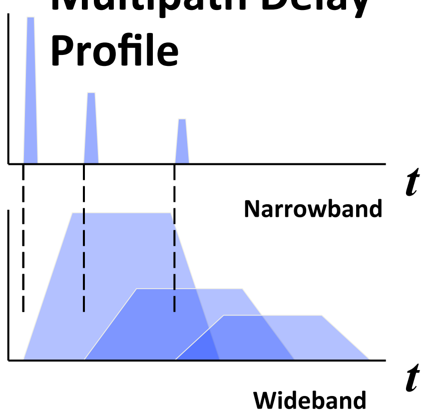


Direct Sequence Spread Spectrum



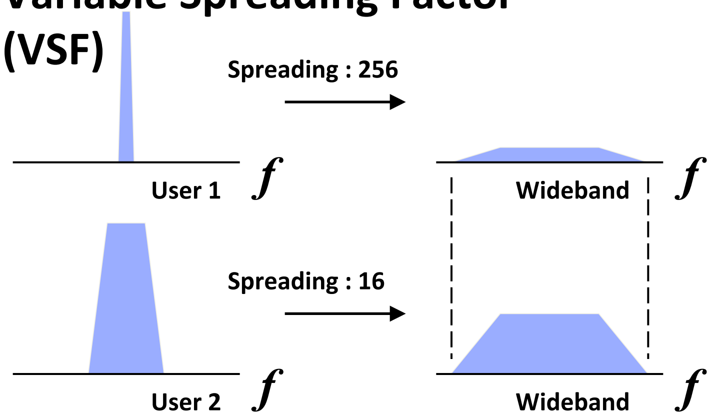
⇒ Frequency Reuse Factor = 1

Multipath Delay Profile



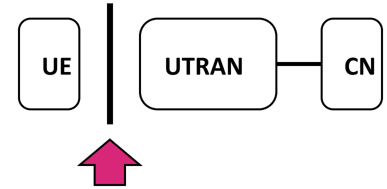
⇒ 5 MHz Wideband Signal Allows Multipath Diversity with Rake Receiver

Variable Spreading Factor (VSF)



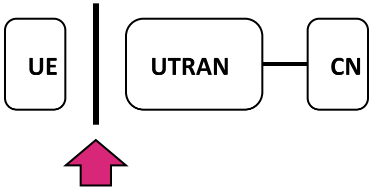
⇒ VSF Allows Bandwidth on Demand. Lower Spreading Factor requires Higher SNR, causing Higher Interference in exchange.

WCDMA Air Interface (Cont'd)

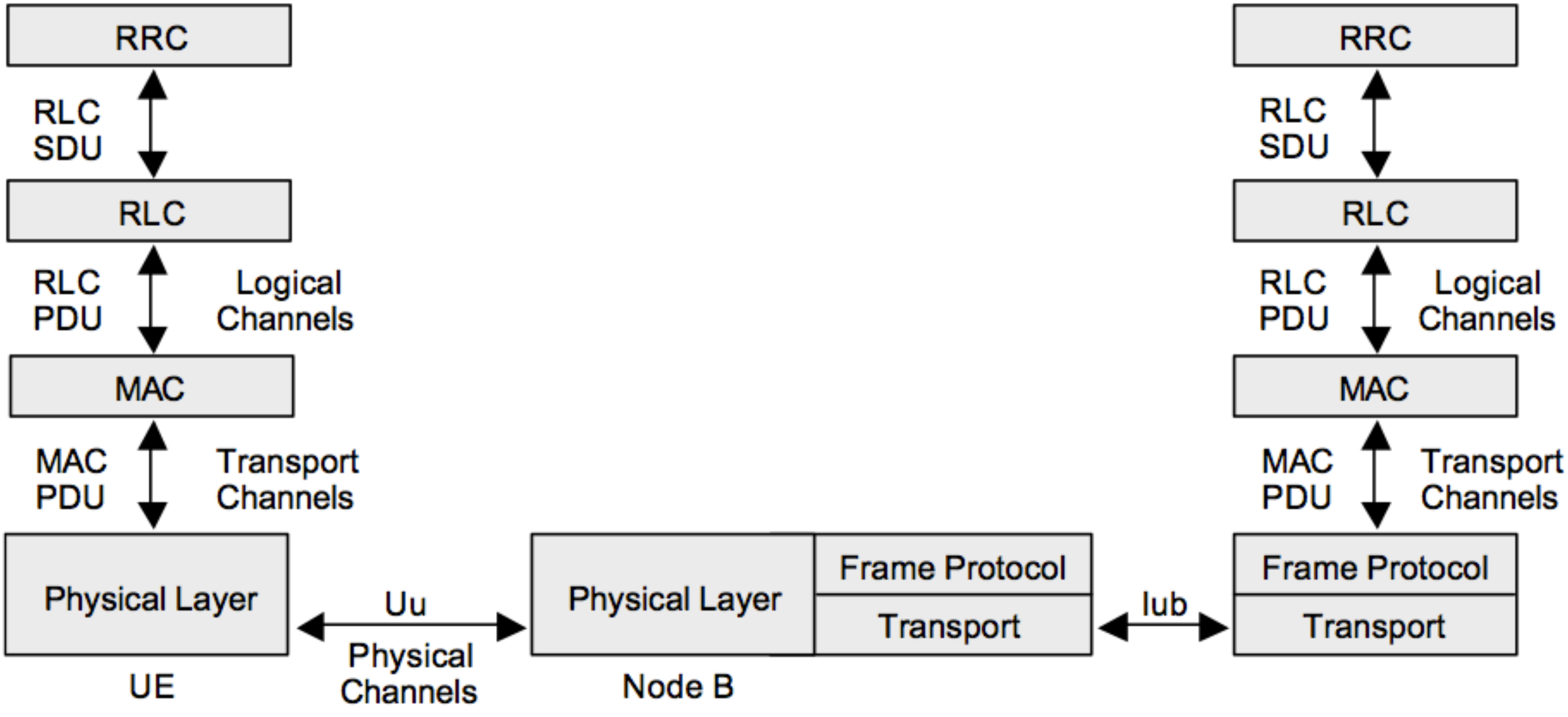


Multiple Access Method	DS-CDMA
Duplexing Method	FDD/TDD
Base Station Synchronization	Asychronous Operation
Channel bandwidth	5MHz
Chip Rate	3.84 Mcps
Frame Length	10 ms
Service Multiplexing	Multiple Services with different QoS Requirements Multiplexed on one Connection
Multirate Concept	Variable Spreading Factor and Multicode
Detection	Coherent, using Pilot Symbols or Common Pilot

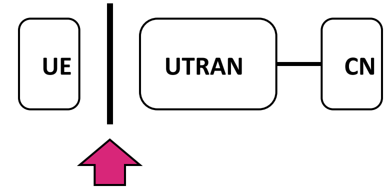
WCDMA Air Interface (Cont'd)



- Channel concepts



WCDMA Air Interface (Cont'd)

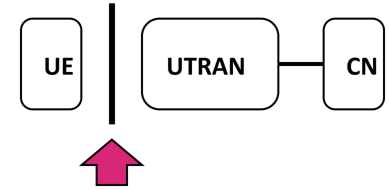


Mapping of Transport Channels and Physical Channels

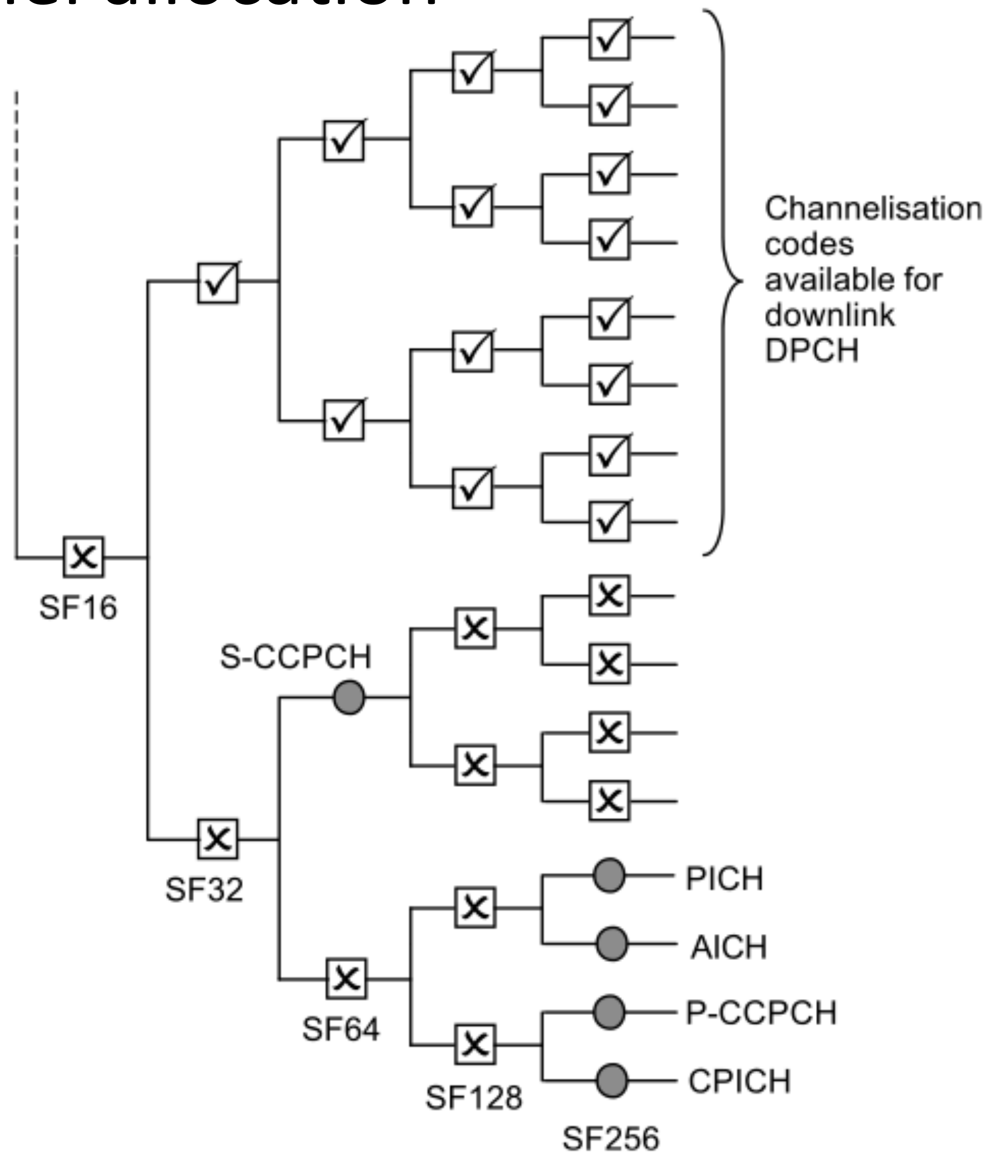
Transport Channel	Physical Channel
Broadcast Channel (BCH)	Primary Common Control Physical Channel (PCCPCH)
Forward Access Channel (FACH)	Secondary Common Control Physical Channel (SCCPCH)
Paging Channel (PCH)	Secondary Common Control Physical Channel (SCCPCH)
Random Access Channel (RACH)	Physical Random Access Channel (PRACH)
Dedicated Channel (DCH)	Dedicated Physical Data Channel (DPDCH)
Dedicated Channel (DCH)	Dedicated Physical Control Channel (DPCCH)
Downlink Shared Channel (DSCH)	Physical Downlink Shared Channel (PDSCH)
Common Packet Channel (CPCH)	Physical Common Packet Channel (PCPCH)
	Synchronization Channel (SCH)
	Common Pilot Channel (CPICH)
	Acquisition Indication Channel (AICH)
	Paging Indication Channel (PICH)
	CPCH Status Indication Channel (CSICH)
	Collision Detection/Channel Assignment Indicator Channel (CD/CA-ICH)

Highly Differentiated Types of Channels enable best combination of Interference Reduction, QoS and Energy Efficiency

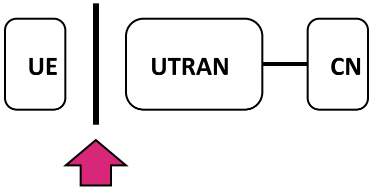
WCDMA Air Interface (Cont'd)



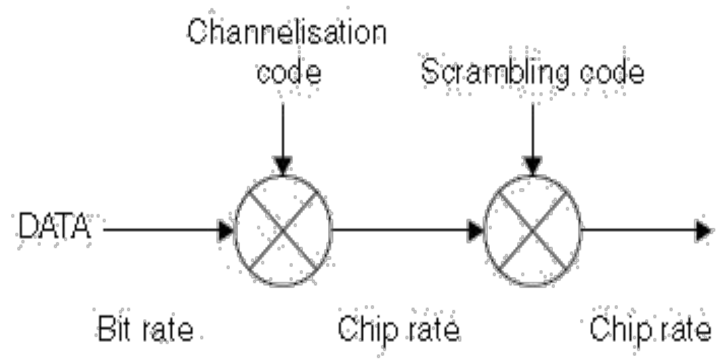
- Code to channel allocation



Codes in WCDMA

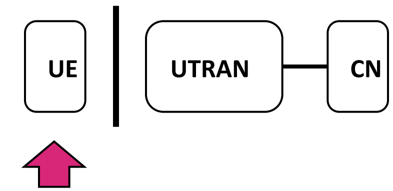


- Channelization Codes (=short code)
  - Used for
    - channel separation from the single source in downlink
    - separation of data and control channels from each other in the uplink
  - Same channelization codes in every cell / mobiles and therefore the additional scrambling code is needed



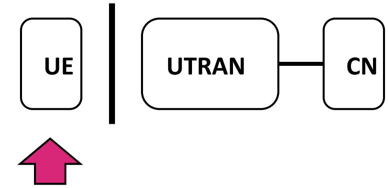
- Scrambling codes (=long code)
  - Very long (38400 chips = 10 ms =1 radio frame), many codes available
  - Does not spread the signal
  - Uplink: to separate different mobiles
  - Downlink: to separate different cells
  - The correlation between two codes (two mobiles/ Node Bs) is low
    - Not fully orthogonal

RRC State Machine



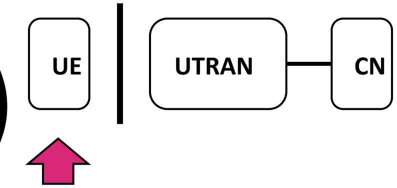
- IDLE: procedures based on reception rather than transmission
  - Reception of System Information messages
  - PLMN selection Cell selection Registration (requires RRC connection establishment)
  - Reception of paging Type 1 messages with a DRX cycle (may trigger RRC connection establishment) Cell reselection
  - Location and routing area updates (requires RRC connection establishment)

RRC State Machine (Cont'd)



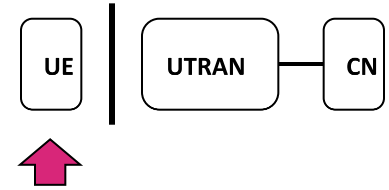
- CELL_FACH: need to continuously receive (search for UE identity in messages on FACH), data can be sent by RNC any time
  - Can transfer small PS data
  - UE and network resource required low
  - Cell re-selections when UE mobile
  - Inter-system and inter-frequency handoff possible
  - Can receive paging Type 2 messages without a DRX cycle

RRC State Machine (Cont'd)

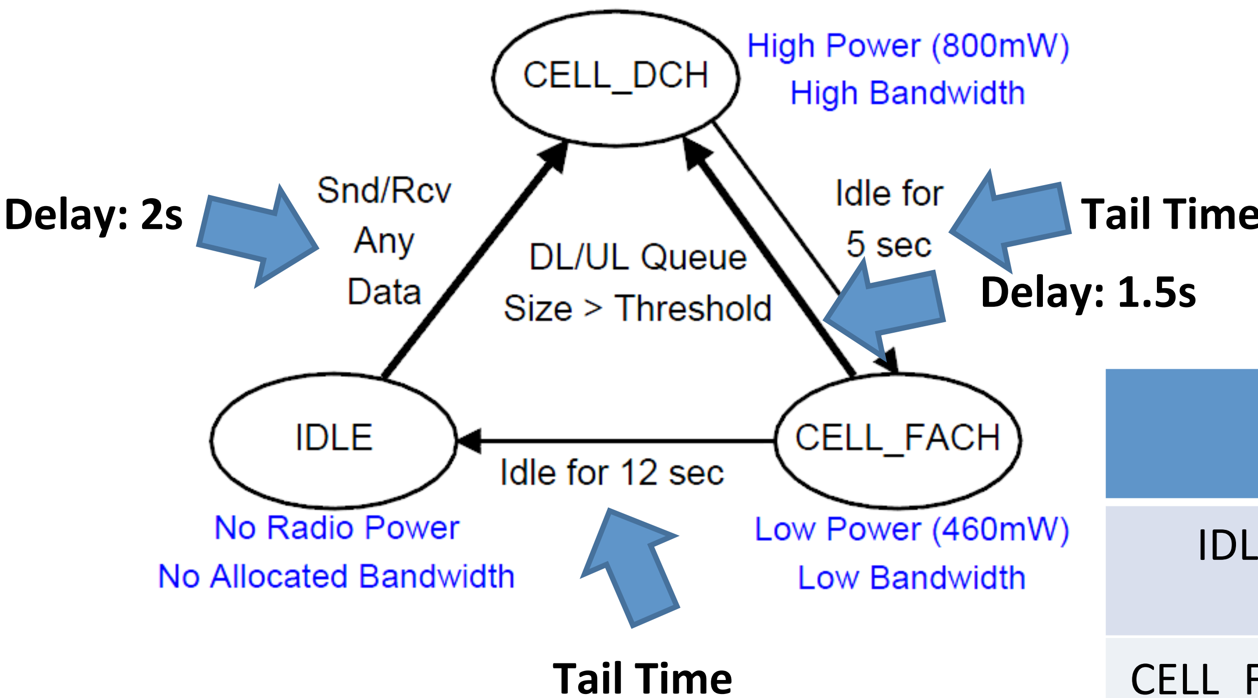


- CELL_DCH: need to continuously receive, and sent whenever there is data
  - Possible to transfer large quantities of uplink and downlink data
  - Dedicated channels can be used for both CS and PS connections
  - HSDPA and HSUPA can be used for PS connections
  - UE and network resource requirement is relatively high
  - Soft handover possible for dedicated channels and HSUPA Inter-system and inter-frequency handover possible
  - Paging Type 2 messages without a DRX cycle are used for paging purposes

RRC State Machine (Cont'd)



- State promotions have **promotion delay**
- State demotions incur **tail times**



Courtesy: Feng Qian

	Channel	Radio Power
IDLE	Not allocated	Almost zero
CELL_FACH	Shared, Low Speed	Low
CELL_DCH	Dedicated, High Speed	High

Outline

- Wireless communications basics
  - Signal propagation, fading, interference, cellular principle
- Multi-access techniques and cellular network air-interfaces
  - FDMA, TDMA, CDMA, OFDM
- 3G: UMTS
  - Architecture: entities and protocols
  - Physical layer
  - RRC state machine
- 4G: LTE
  - Architecture: entities and protocols
  - Physical layer
  - RRC state machine

LTE Technical Objectives and Architecture

- User throughput [/MHz]:
  - Downlink: 3 to 4 times Release 6 HSDPA
  - Uplink: 2 to 3 times Release 6 Enhanced Uplink
- Downlink Capacity: Peak data rate of 100 Mbps in 20 MHz maximum bandwidth
- Uplink capacity: Peak data rate of 50 Mbps in 20 MHz maximum bandwidth
- Latency: Transition time less than 5 ms in ideal conditions (user plane), 100 ms control plane (fast connection setup)
- Cell range: 5 km - optimal size, 30km sizes with reasonable performance, up to 100 km cell sizes supported with acceptable performance

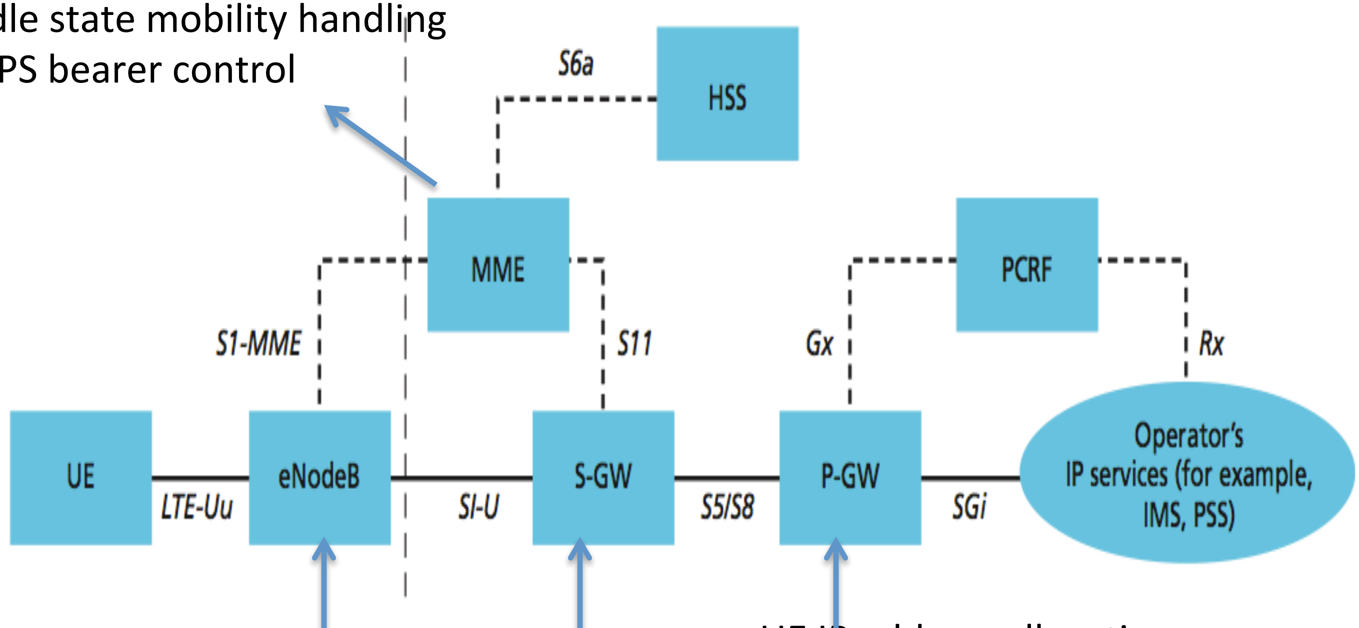
LTE Technical Objectives and Architecture (Cont'd)

- Mobility: Optimised for low speed but supporting 120 km/h
  - *Most data users are less mobile!*
- Simplified architecture: Simpler E-UTRAN architecture: no RNC, no CS domain, no DCH
- Scalable bandwidth: 1.25MHz to 20MHz: Deployment possible in GSM bands.

LTE Architecture

- Entities and functionalities

NAS security
Idle state mobility handling
EPS bearer control

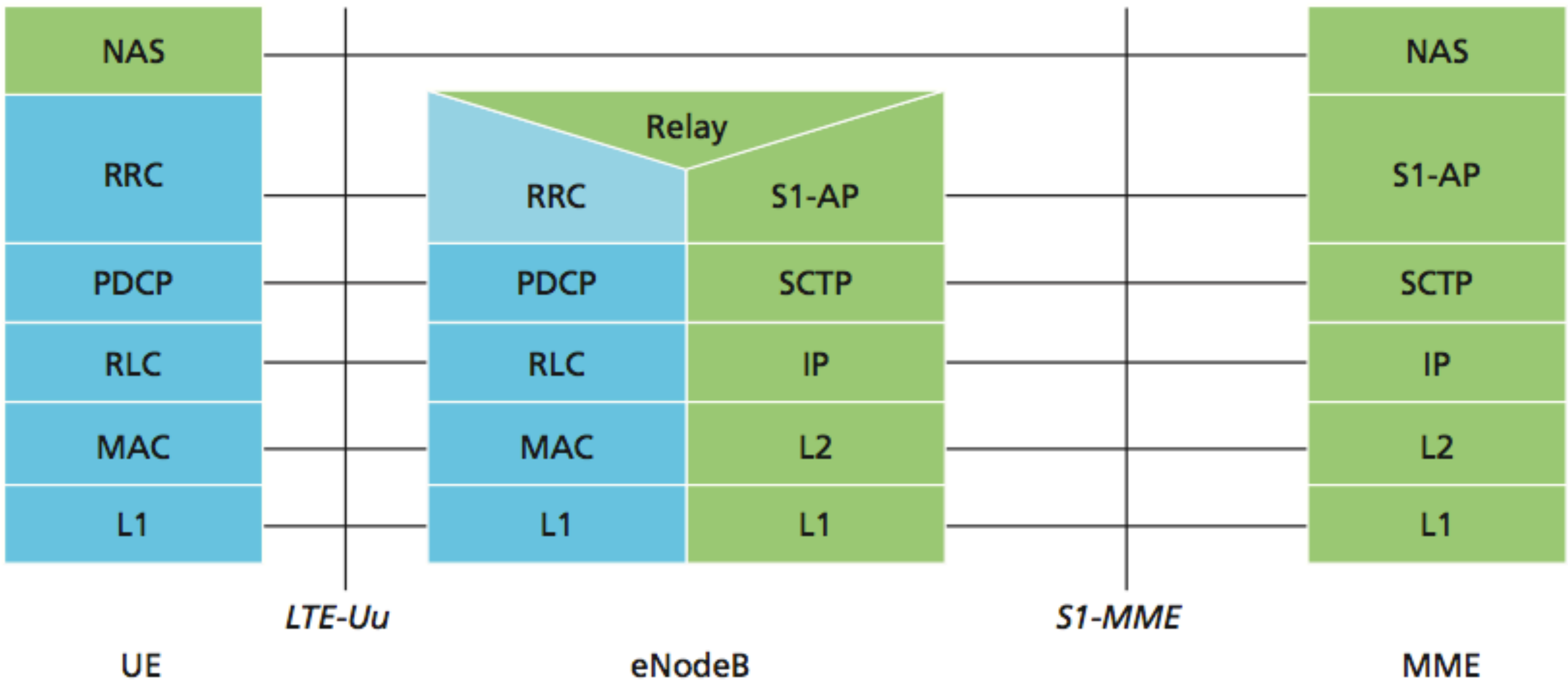


Radio bearer control
Inter-cell RRM
Connection mobility Control
Radio admission control

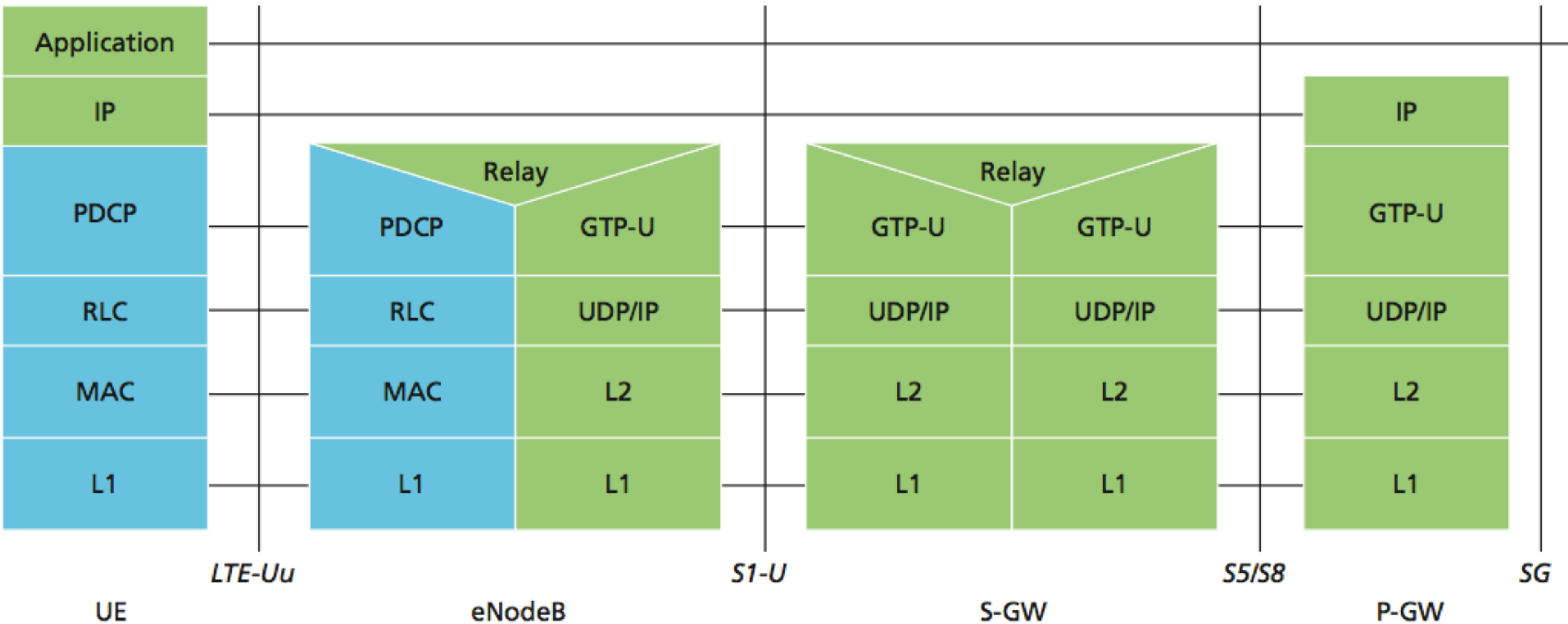
Mobility
anchoring

UE IP address allocation
Packet filtering

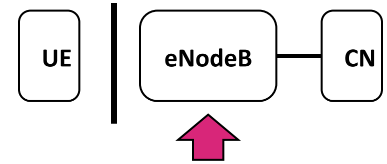
LTE Control Plane Protocol Stack



LTE Data Plane Protocol Stack

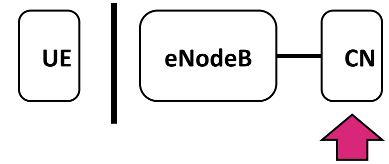


Functions of eNodeB



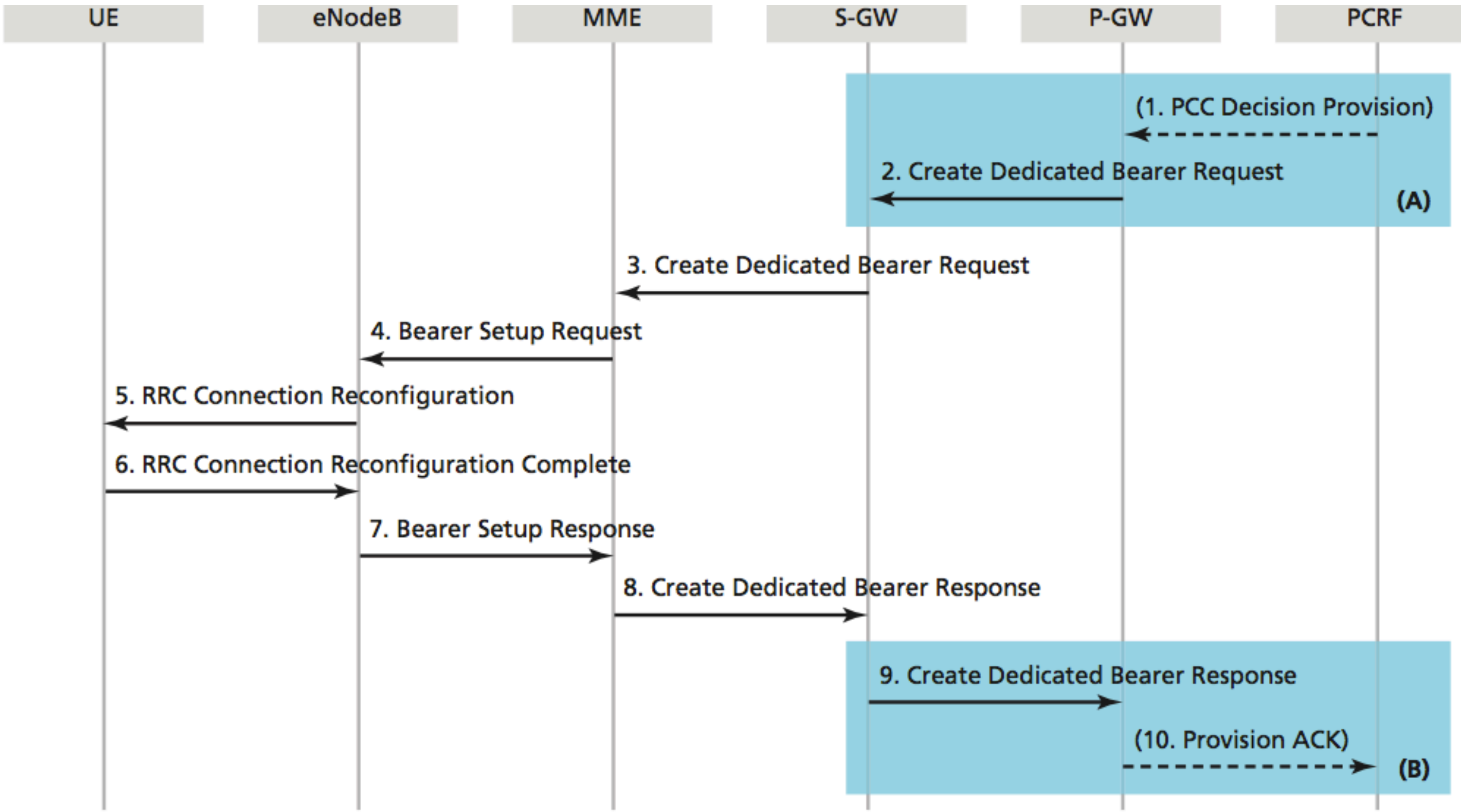
- Terminates RRC, RLC and MAC protocols and takes care of Radio Resource Management functions
  - Controls radio bearers
  - Controls radio admissions
  - Controls mobility connections
  - Allocates radio resources dynamically (scheduling)
  - Receives measurement reports from UE
- Selects MME at UE attachment
- Schedules and transmits paging messages coming from MME
- Schedules and transmits broadcast information coming from MME & O&M
- Decides measurement report configuration for mobility and scheduling
- Does IP header compression and encryption of user data streams

Functions of MME

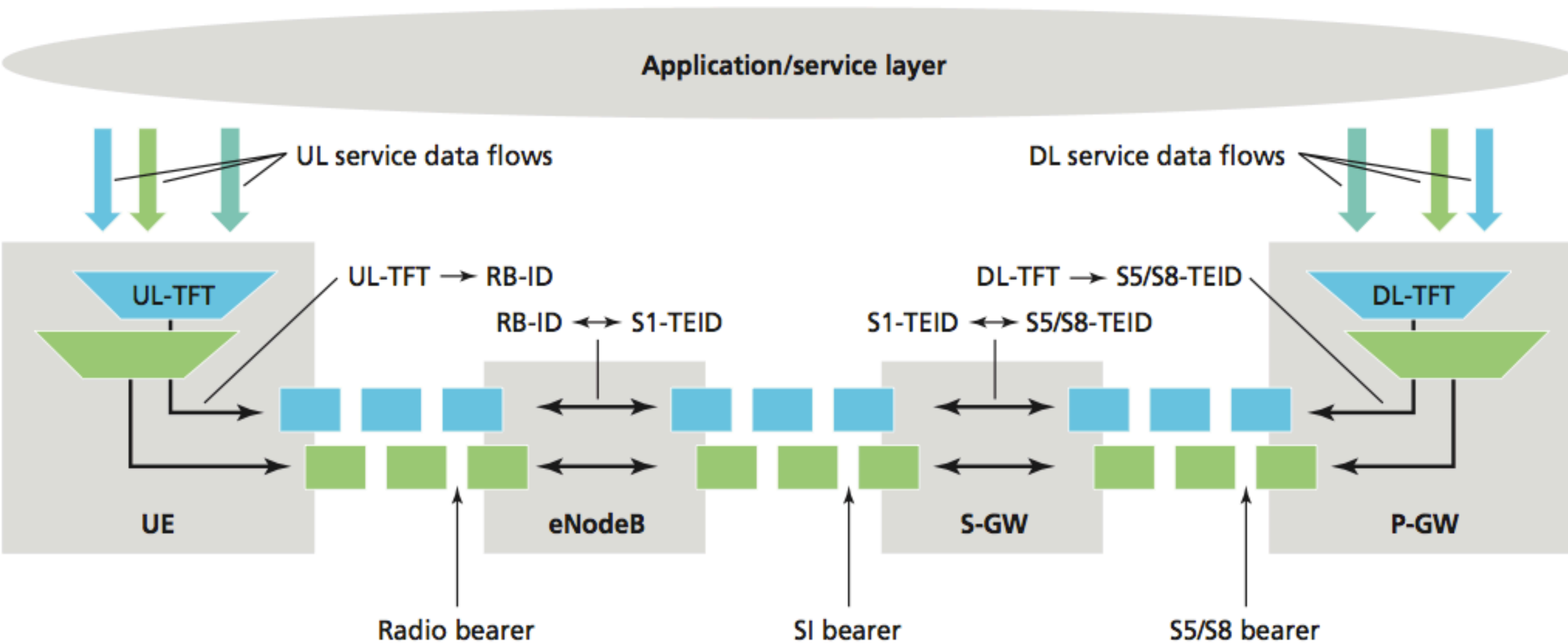


- Mobility Management Entity (MME) functions
  - Manages and stores UE context
  - Generates temporary identities and allocates them to UEs
  - Checks authorization
  - Distributes paging messages to eNBs
  - Takes care of security protocol
  - Controls idle state mobility
  - Ciphers & integrity protects NAS signaling

Session Establishment Message Flow

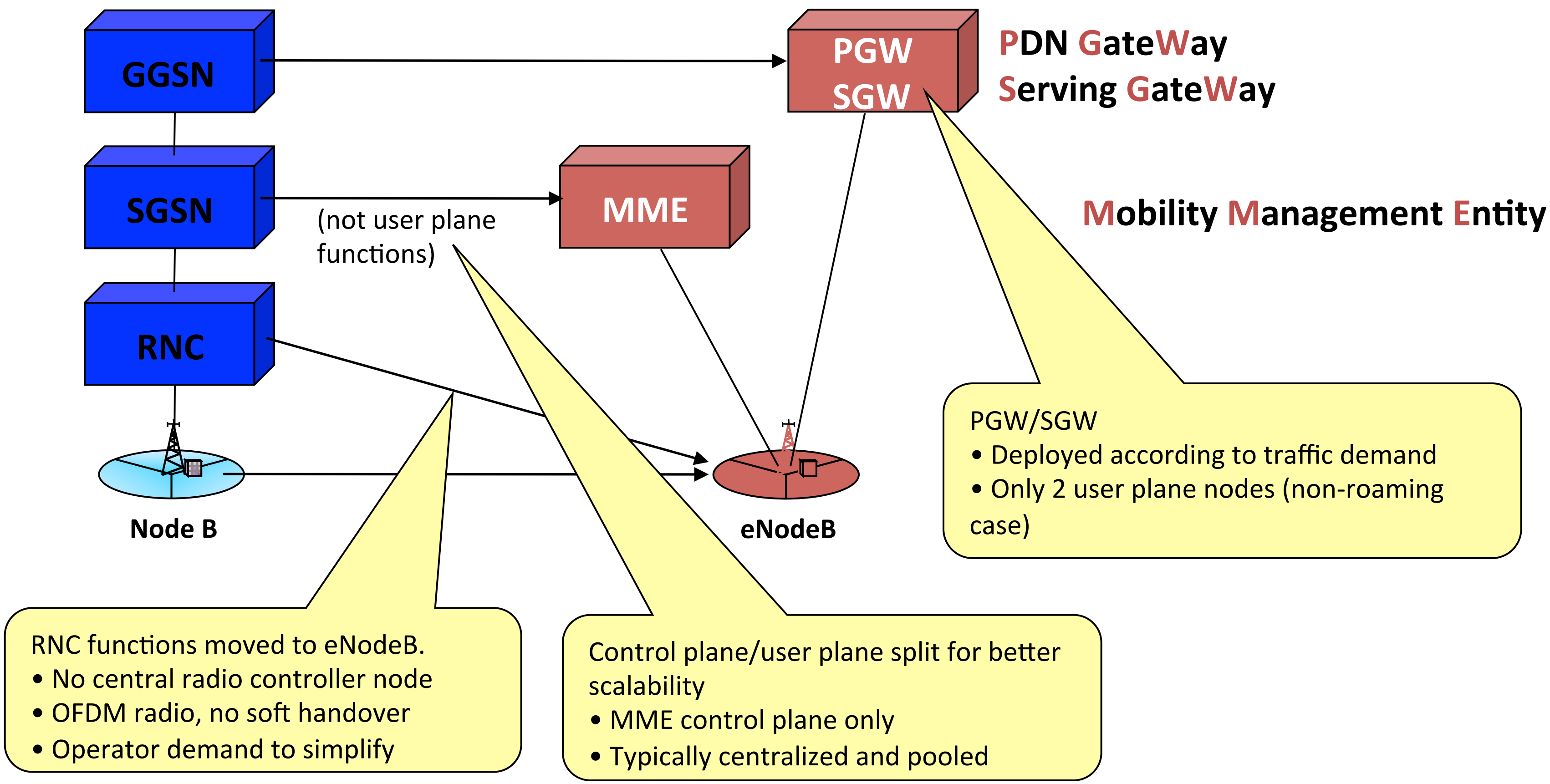


Session States

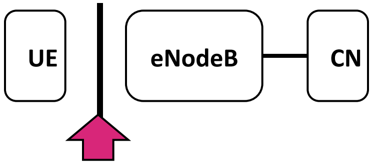


LTE vs UMTS

- Functional changes compared to the current UMTS Architecture

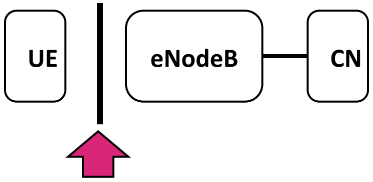


LTE PHY Basics

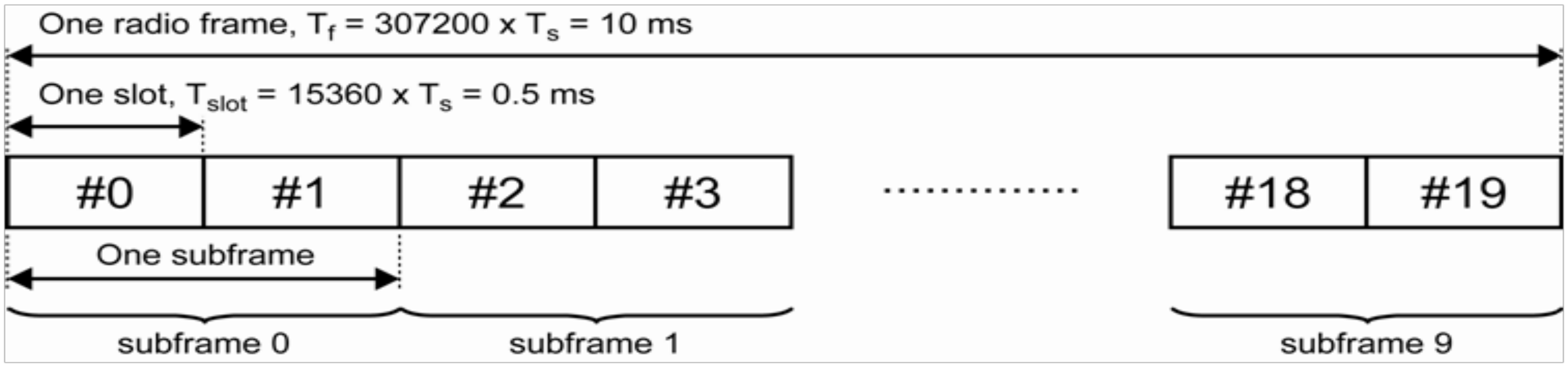


- Six bandwidths
  - 1.4, 3, 5, 10, 15, and 20 MHz
- Two modes
  - FDD and TDD
- 100 Mbps DL (SISO) and 50 Mbps UL
- Transmission technology
  - OFDM for multipath resistance
  - DL OFDMA for multiple access in frequency/time
  - UL SC-FDMA to deal with PAPR ratio problem

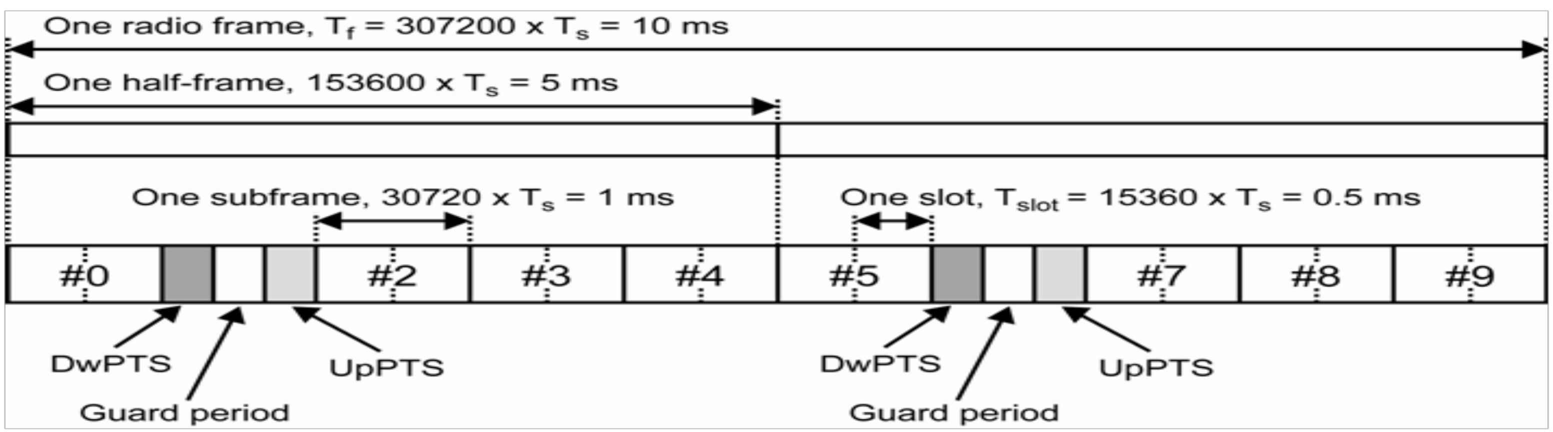
Frame Structure



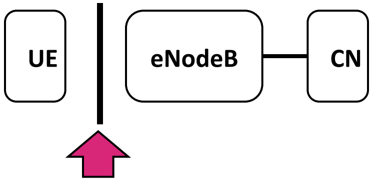
Frame Structure Type 1 (FDD)

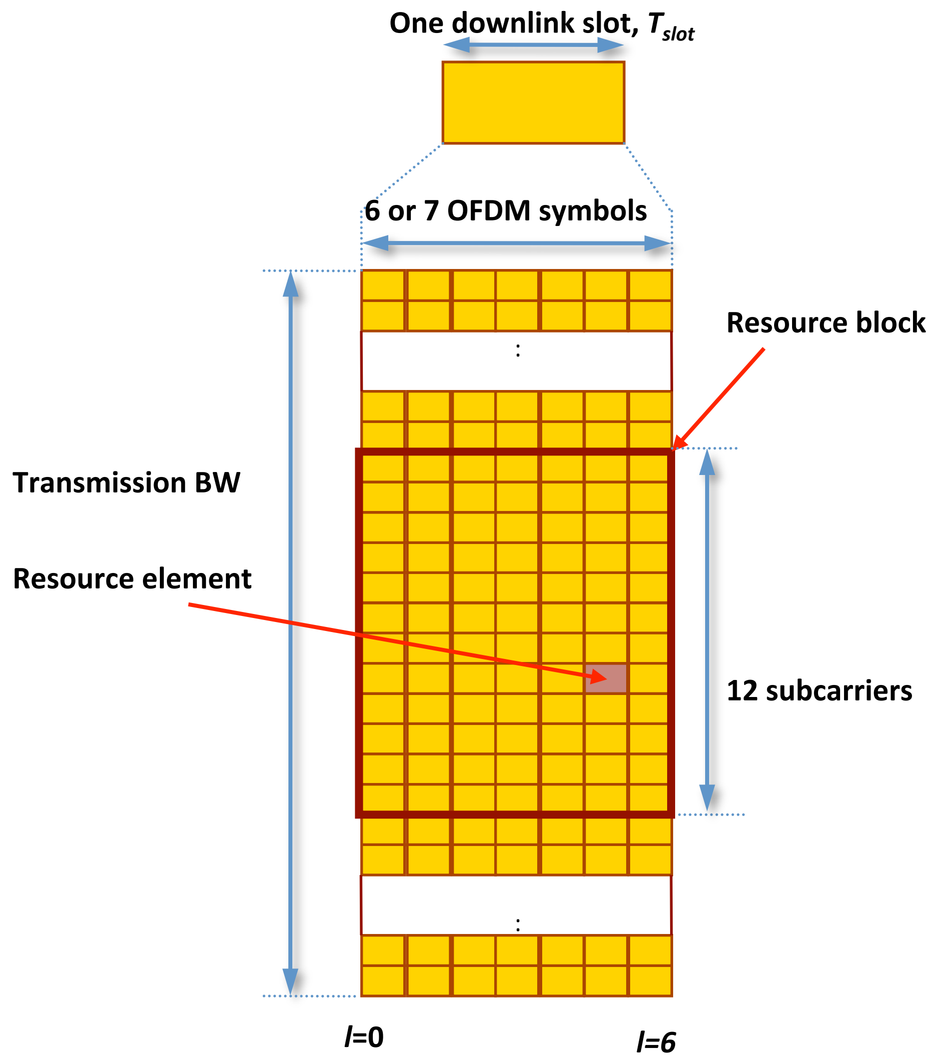


Frame Structure Type 2 (TDD)



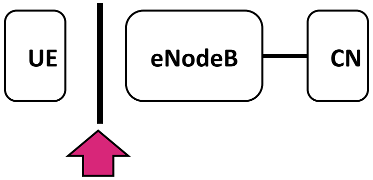
Resource Grid

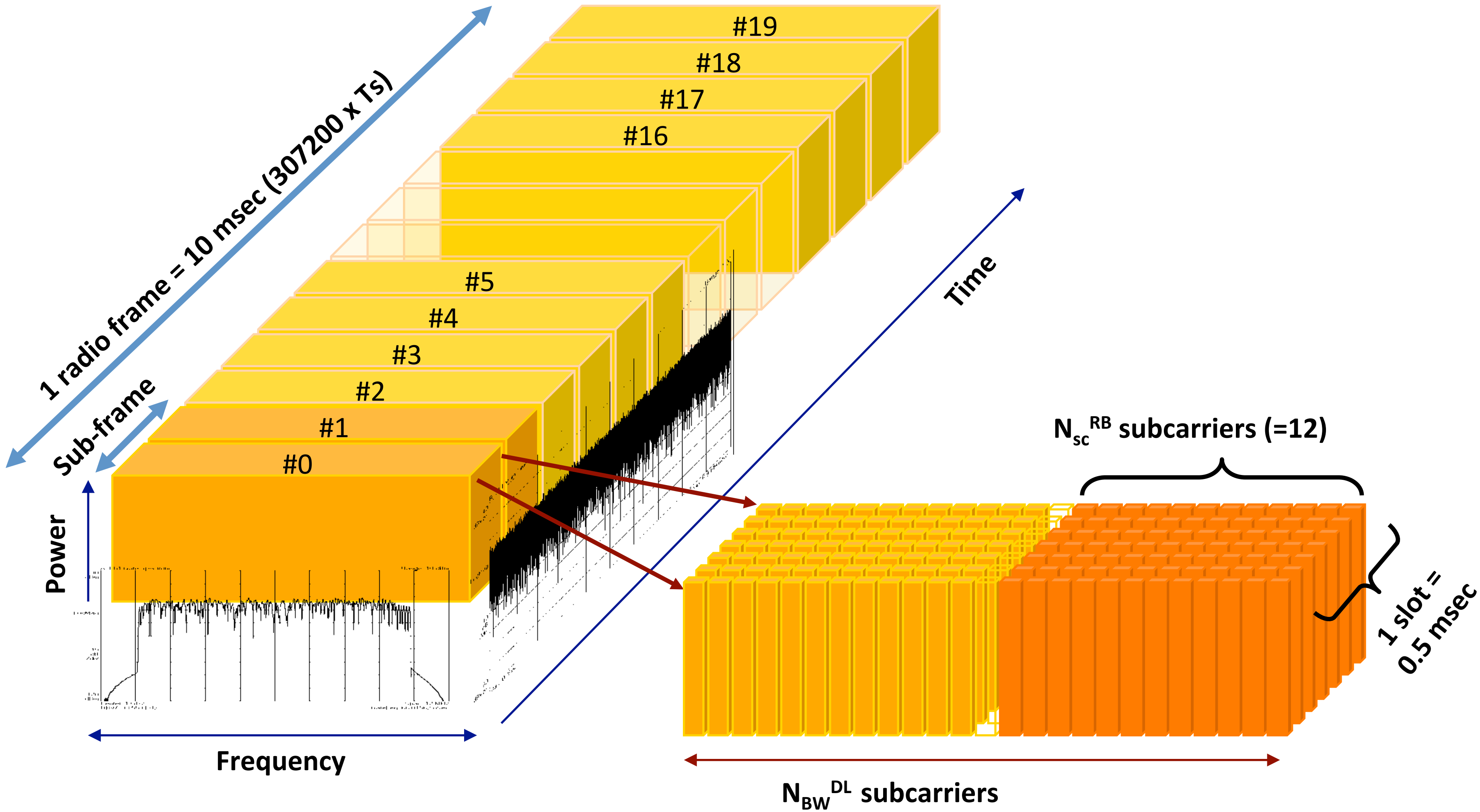




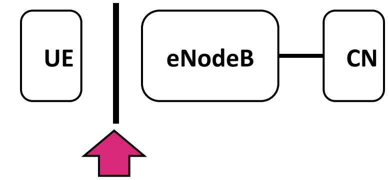
- 6 or 7 OFDM symbols in 1 slot
- Subcarrier spacing = 15 kHz
- Block of 12 SCs in 1 slot = 1 RB
  - *0.5 ms x 180 kHz*
  - Smallest unit of allocation

2-D time and Frequency Grid



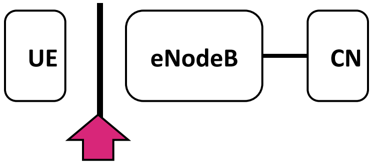


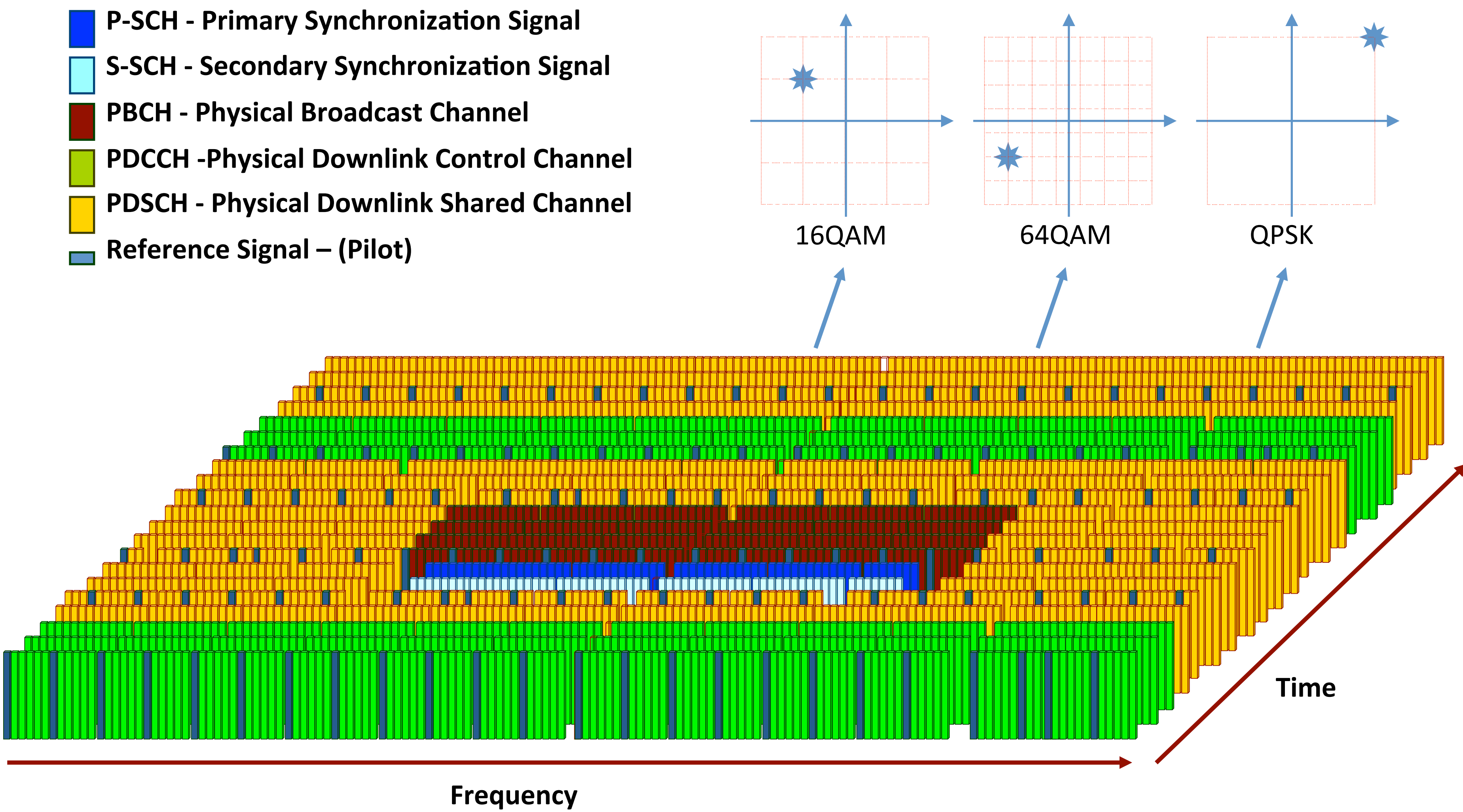
DL PHY Channels and Signals



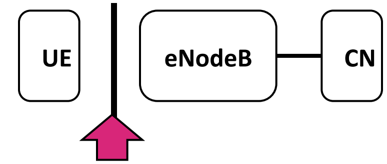
- Signals: generated in PHY layers
  - P-SS: used for initial sync
  - S-SS: frame boundary determination
  - RS: pilots for channel estimation and tracking
- Channels: carry data from higher layers
  - PBCH: broadcast cell-specific info
  - PDCCH: channel allocation and control info
  - PCFICH: info on size of PDCCH
  - PHICH: Ack/Nack for UL blocks
  - PDSCH: Dynamically allocated user data

DL Channel Mapping



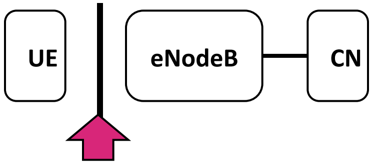


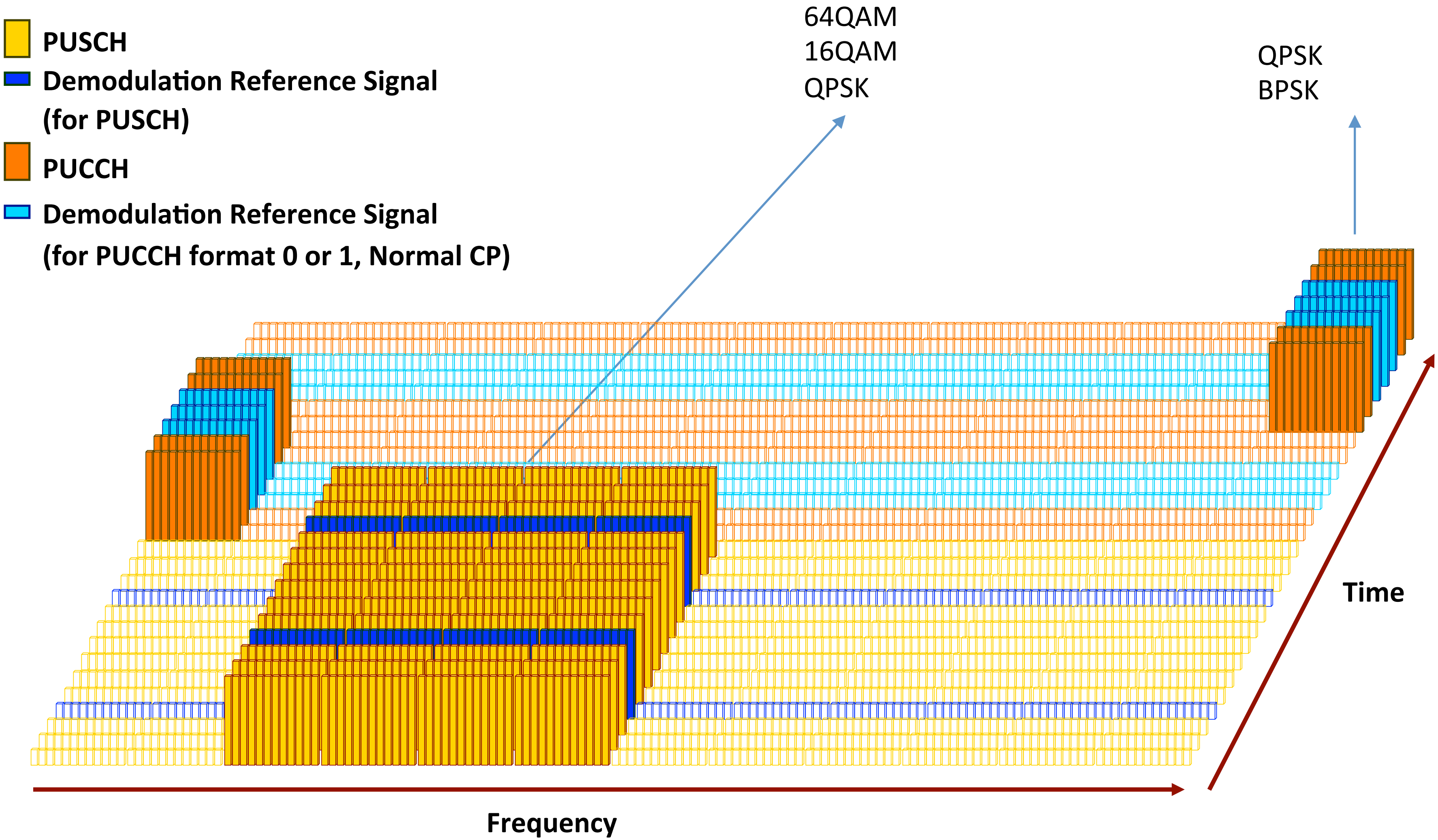
UL PHY Signals and Channels



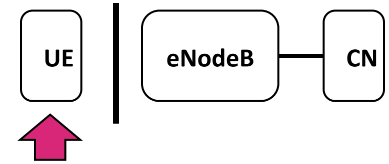
- Signals: generated in the PHY layer
  - Demodulation RS : sync and channel estimation
  - SRS: Channel quality estimation
- Channels: carry data from higher layers
  - PUSCH: Uplink data
  - PUCCH: UL control info
  - PRACH: Random access for connection establishment

UL Channel Mapping

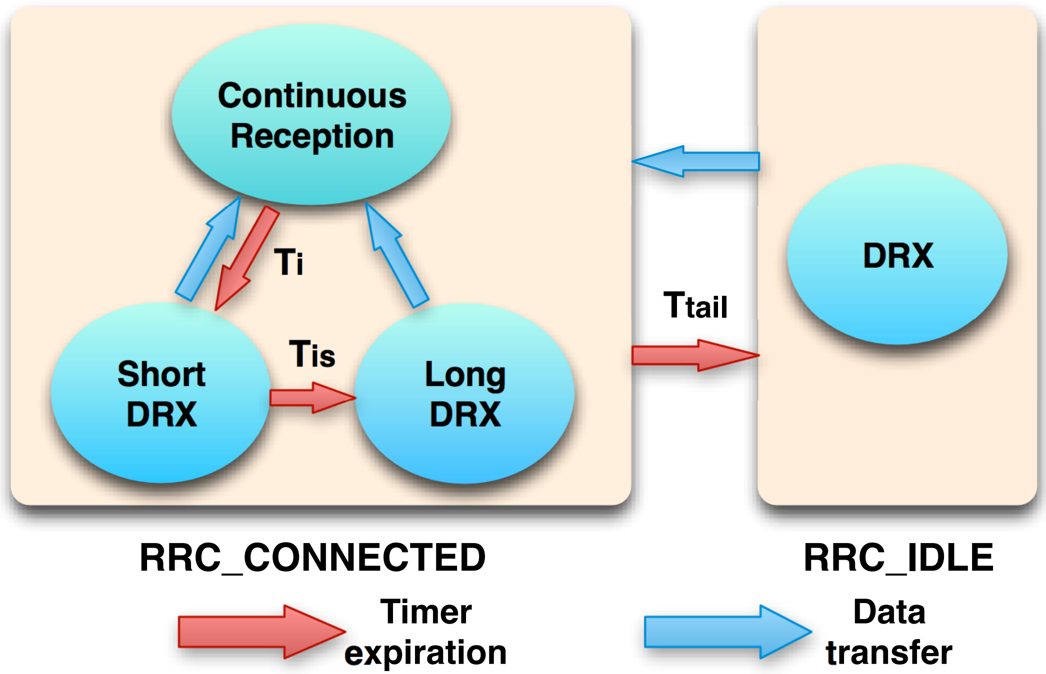


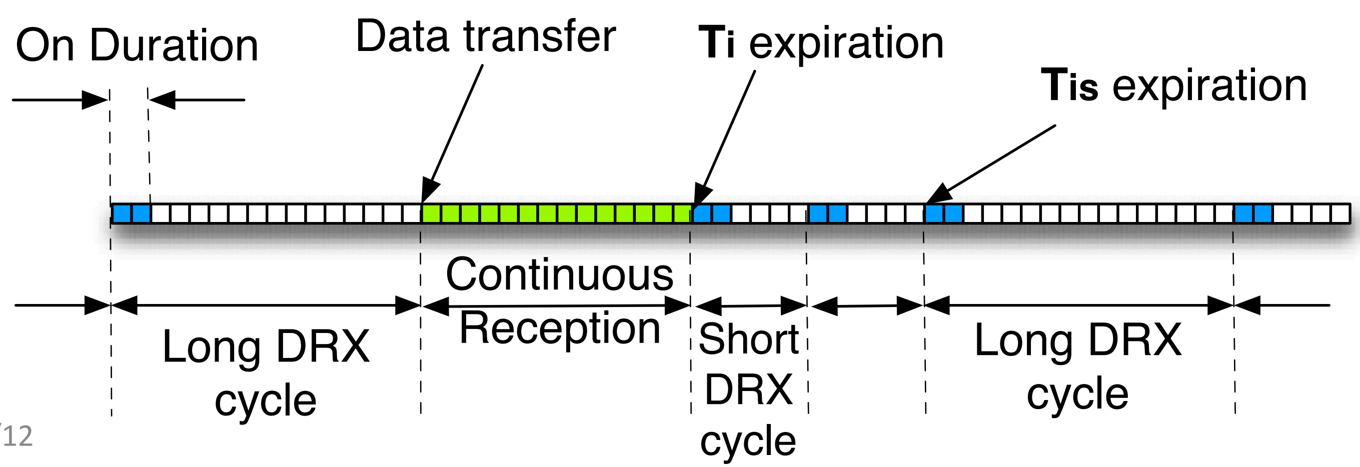


RRC State Machine



- Much simpler than UMTS





Summary

- Cellular networks are very different from WiFi
  - Cannot be based on carrier sensing due to large coverage area
  - Path must be setup dynamically due to mobility
  - Need to handle charging functions and QoS
- Different physical layer technologies have very different overhead during inactivity
  - Dedicated channels prevent others from using the channel
- Frequent RRC state transitions in UE can result in high network overhead and UE battery power consumption

Questions?