Introduction to LTE

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Audio/Video recordings of this class lecture are available at:

http://www.cse.wustl.edu/~jain/cse574-22/

Student Questions

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Q on 4b

Overview

1. LTE: Key Features
2. OFDMA and SC-FDMA
3. Evolved Packet Core (EPC)
4. LTE Frame Structure
5. Resource Allocation

Note: This is the 2nd lecture in a series of lectures on 1G to 5G. 4G, 4.5G, and 5G are covered in subsequent modules.

Student Questions

LTE: Key Features

Long-Term Evolution. 3GPP Release 8, 2009.

1. **3.9G** (Pre-4G) cellular technology
   Sold as 4G by some providers.
   4G=International Mobile Telecommunication (IMT) Advanced
   Requirements in ITU M.2134-2008

2. **Many different bands**: 700/1500/1700/**2100**/2600 MHz

3. **Flexible Bandwidth**: 1.4/3/5/10/15/20 MHz

4. Frequency Division Duplexing (FDD) and
   Time Division Duplexing (TDD)
   $\Rightarrow$ Both *paired* and *unpaired* spectrum

5. 4x4 MIMO, Multi-user collaborative MIMO

6. Beamforming in the downlink

Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.

Student Questions

❑ Can you explain downlink versus uplink?
Uplink: Mobile to the tower
Downlink: Tower to Mobile

LTE: Key Features (Cont)

8. Data Rate: 326 Mbps/down 86 Mbps up (4x4 MIMO 20 MHz)

9. Modulation: OFDM with QPSK, 16 QAM, 64 QAM

10. **OFDMA** downlinks,
    Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplinks

11. **Hybrid ARQ** Transmission

12. Short **Frame Sizes** of 10ms and 1ms $\Rightarrow$ faster feedback and better efficiency at high speed

13. **Persistent scheduling** to reduce control channel overhead for low-bit rate voice transmission.

14. **IP-based** flat network architecture

Student Questions

❑Why do we need Hybrid ARQ in LTE instead of regular ARQ?
It is better. It uses both Layer 1 and Layer 2. So the number of bits to be retransmitted is much smaller.
❑What's the purpose of having different access methods for downlink and uplink?
Tower has much more power and can implement many more features than mobiles. In the uplink, the mobile is the transmitter.

LTE: Key Features (Cont)

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Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplinks

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14. **IP-based** flat network architecture

Student Questions

❖ LTE: "Short Frame Sizes of 10ms and 1ms ⇒ faster feedback and better efficiency at high speed". How short can the frames be? What would be the trade-off?

DL and UL frames alternate. Short frames result in quicker opportunities to transmit.
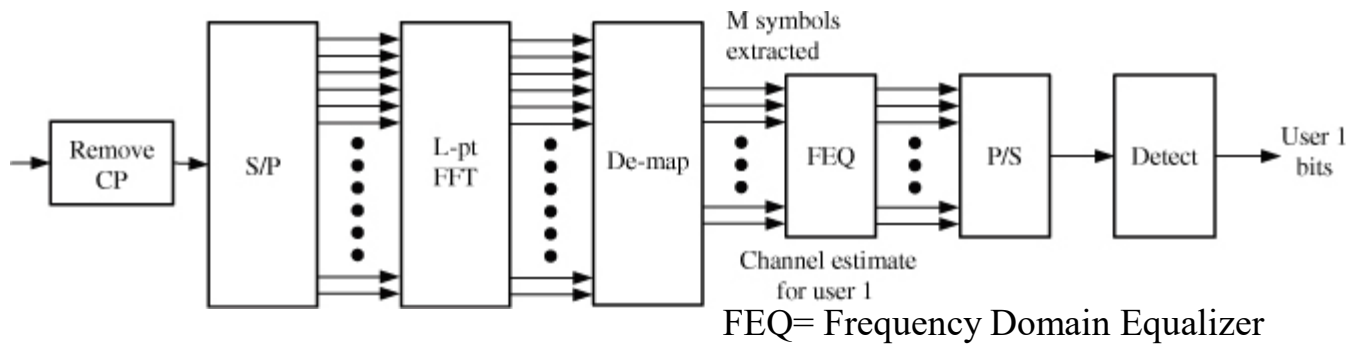
DL	UL	DL	UL	DL

OFDMA Downlink

❑ Transmitter at Base Station: IFFT converts frequency to time
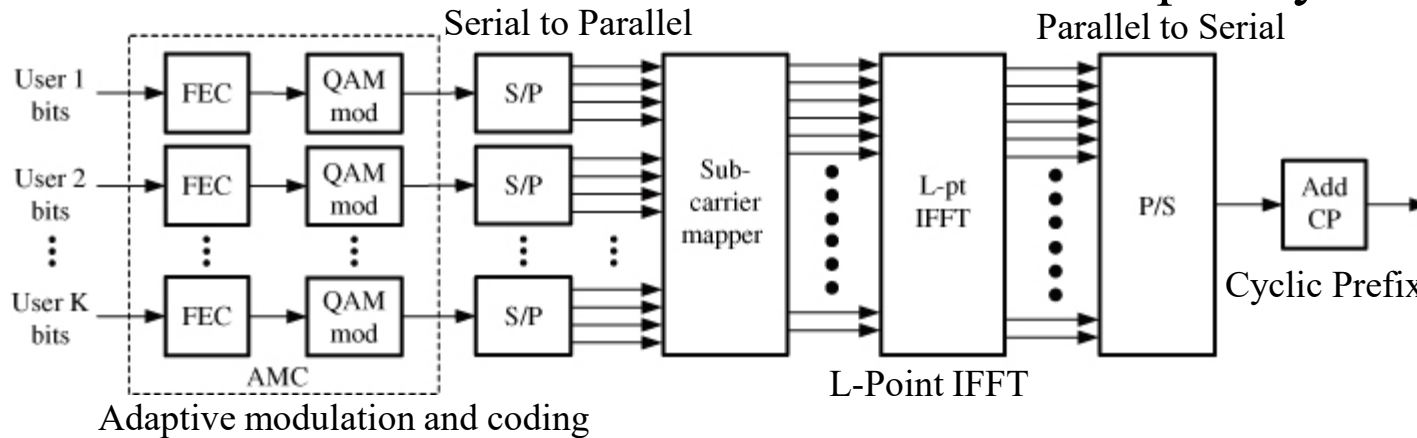
❑ Receiver at User Terminal: FFT converts time to frequency

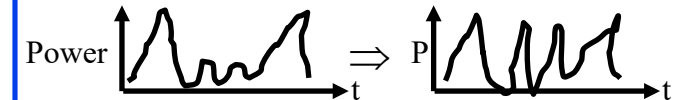FEQ= Frequency Domain Equalizer

Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.

Student Questions

❑Could you explain why we need the FEQ?

Time domain equalizers equalize the power peaks to a narrow range:

Frequency domain equalizers achieve a similar effect in the frequency domain and reduce round-off errors.

❑What is AMC in the first diagram?

Adaptive modulation and coding

❑Why is S/P after the QAM mod rather than before the QAM mod?

QAM produces a series of complex numbers.

❑What is L-pt? Cp?

L-Point, Cyclic prefix

Peak-to-Average Power Ratio (PAPR)

❑ OFDM

⇒ Each carrier is modulated according to the specific channel condition.
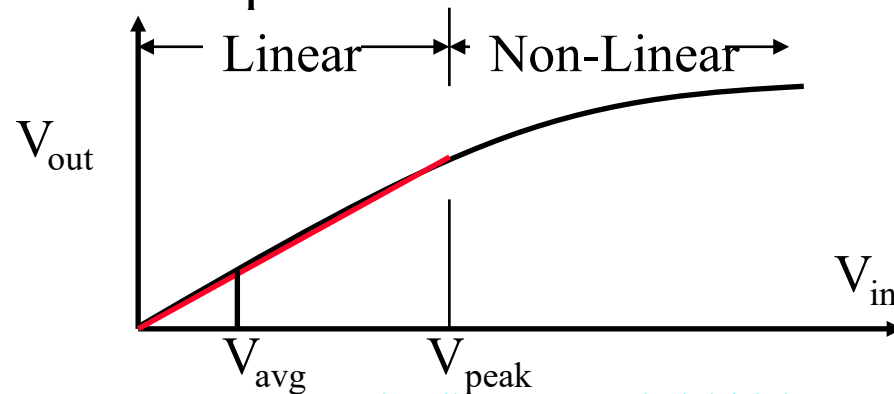
⇒ High variation of power levels

⇒ Higher Peak-to-Average Power Ratio (PAPR)

⇒ Higher cost of amplifiers

❑ Amplifiers are linear only over a restricted region

⇒ Costly amplifier or reduce average signal power significantly

⇒ Can afford such amplifiers in Base stations but not in mobiles.

SC-FDMA

❑ Single-Carrier Frequency Division Multiple Access

❑ Each user gets a contiguous part of the channel
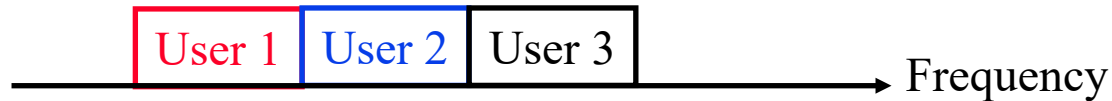
❑ Uses single carrier modulation and adds a cyclic prefix

❑ Single carrier $\Rightarrow$ Not much variation in amplitude
$\Rightarrow$ Lower PAPR

❑ Better for uplink because slight miss-synchronization among users does not affect the decoding significantly

❑ With OFDMA, each user's subcarriers are spread all over the band and may affect other users' subcarriers all over the band
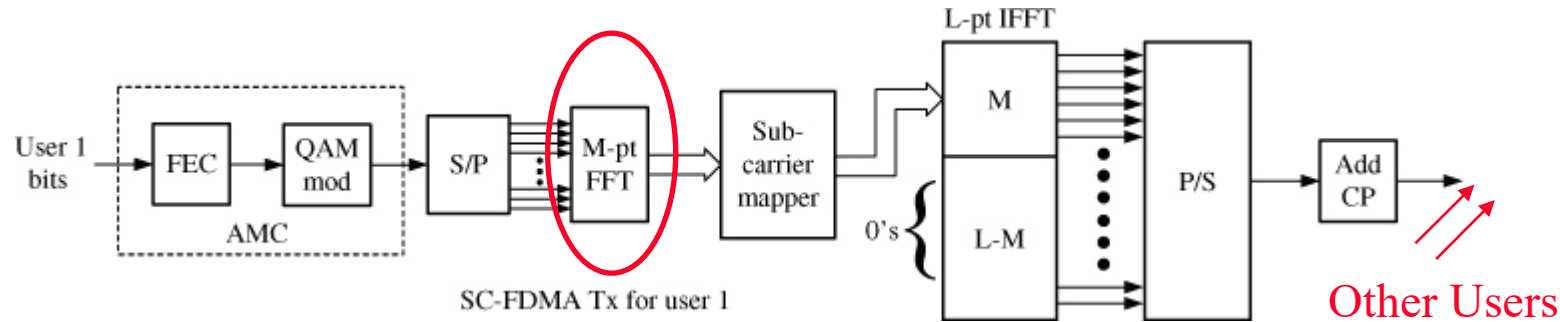
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❑ Could you run out of frequency for users in a particularly dense area? Or can you just add more base stations to counteract this?
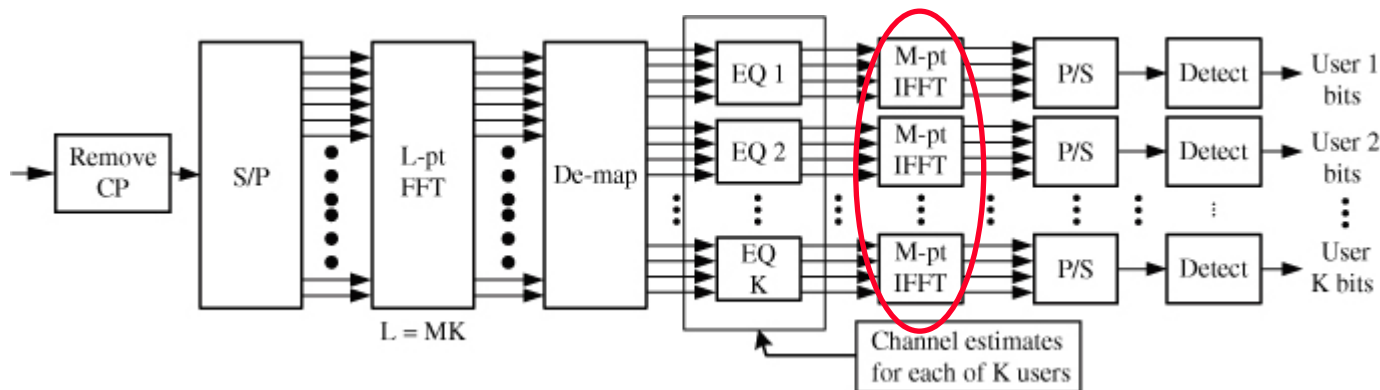
You can add more base station, update frequency reuse plan, and adjust power on existing base stations accordingly.

SC-FDMA (Cont)

❑ In practice, SC-FDMA is implemented as if the user is allocated a contiguous subset of subcarriers

❑ Transmitter at the User Terminal:

SC-FDMA Tx for user 1

Other Users

❑ Receiver at the Base Station:

❑ SC-FDMA = Discrete Fourier Transform *Pre-coded* OFDMA

Student Questions

❑ Can you explain where the multiple user bits are aggregated in the diagram?

After the right end of the upper diagram (i.e., in the air). The combined signal reaches the left end of the lower diagram.

❑ I don't understand why the base station is doing FFT and then IFFT in the later steps. Why is that?

FFT converts the signal from time domain to frequency domain. Some things are easier to do in time domain and others in frequency domain.
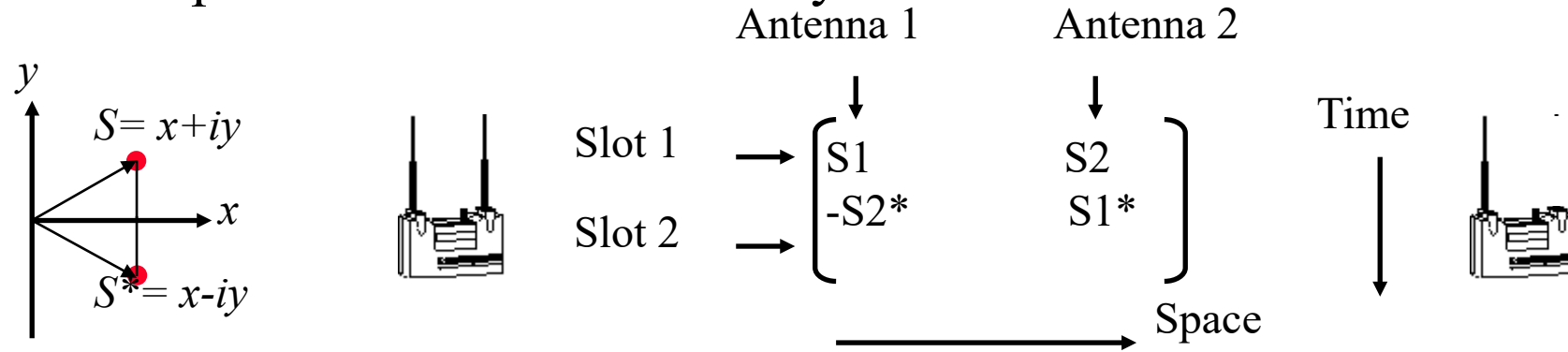
❑ What is M-pt? L-M?

M-point, L minus M.

❑ Can you explain again why SC-FDMA is pre-coded OFDMA?

They both use FFT.

Space Time Block Codes (STBC)

❑ Invented in 1998 by Vahid Tarokh.

❑ Transmit multiple redundant copies from multiple antennas

❑ Precisely coordinate the distribution of symbols in space and time.

❑ Receiver combines multiple versions of the received signals optimally to overcome multipath.

❑ Example: Two antennas: Two symbols in two slots ⇒ Rate 1

Antenna 1   Antenna 2

Slot 1 → $\begin{bmatrix} S1 & S2 \\ -S2^* & S1^* \end{bmatrix}$ ← Time
Slot 2 →

Space

$S = x+iy$
$S^* = x-iy$

S1* is complex conjugate of S1 ⇒ columns are orthogonal

Student Questions

❑Does the efficacy come from fewer symbols being sent, and there is much less interference, reducing the retransmission of duplicate symbols?

Yes. Less decoding errors.

❑The quiz showed that STBC requires transmitting multiple related signals that are not the same. But the slide shows that "transmit multiple copies." Do the copies mean the same signals?

Multiple versions. They are related but not identical.

Space-Frequency Block Codes

- STBC on OFDM (Multi-carrier): Two alternatives
- **STBC on each subcarrier**:
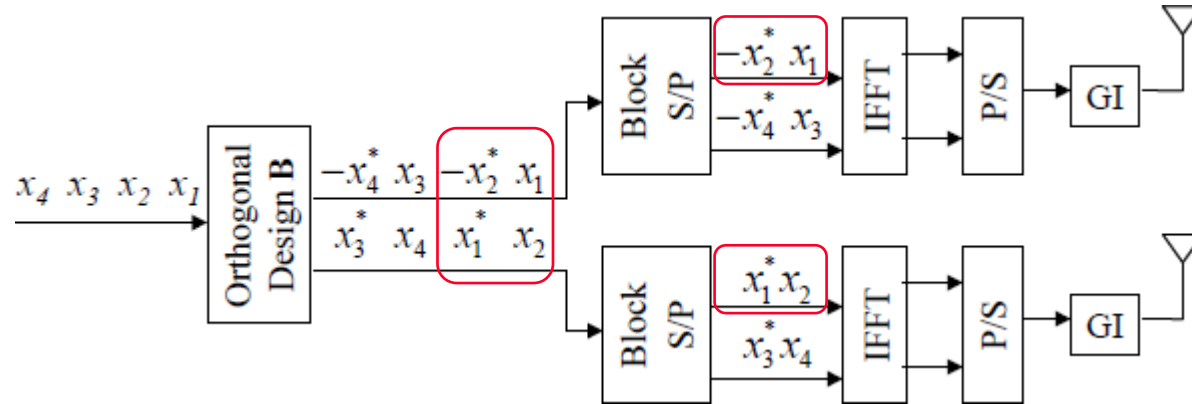
- **STBC on across subcarriers (SFBC)**: Helps if channel changes

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17-10

Puncturing

- Use a large number of error-correcting code (ECC) bits but send only some of them
- Example: 1/2 code = 1 ECC bit/Original bit
- Or 4 bits for each 2-bit symbol
- ¼ puncturing $\Rightarrow$ Drop every 4th bit
  $\Rightarrow$ send 3 bits for each 2-bit symbol = 2/3 code.
- Receiver puts random bits in the punctured positions and decodes $\Rightarrow$ high probability of correct decoding, particularly if the SINR is high
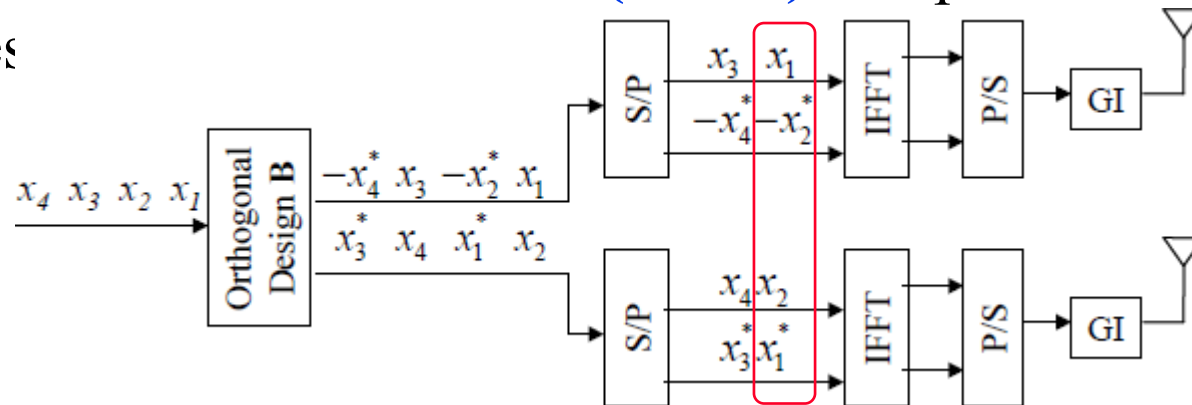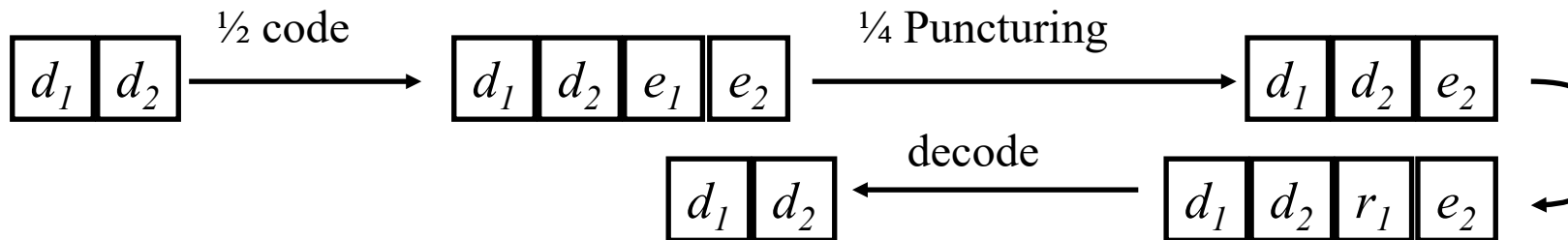- ½ code with 1/4th puncture is not as good as 2/3 code in general but puncturing helps in some situations, such as HARQ

½ code	¼ Puncturing

d_1 d_2 $\rightarrow$ d_1 d_2 e_1 e_2 $\rightarrow$ d_1 d_2 e_2

decode $\leftarrow$ d_1 d_2 $\leftarrow$ d_1 d_2 r_1 e_2

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Student Questions

- Should the 2nd bullet be 2 ECC bit/original bit or 1?
  1 ECC bit + 1 Original bit
  = 2 Total bits $\Rightarrow$ ½ code.
- Why is it called puncturing?
  Puncture = Cut-out
- Why do we need puncturing rather than designing a new ECC algorithm with shorter bits? In this way, it would avoid randomness.
  Puncturing was shown to be better than shorter ECC.

ARQ

- **A**utomatic **R**epeat re**Q**uest (ARQ)
- Retransmit a packet if it is received in error
- Previous (bad) bits are discarded.

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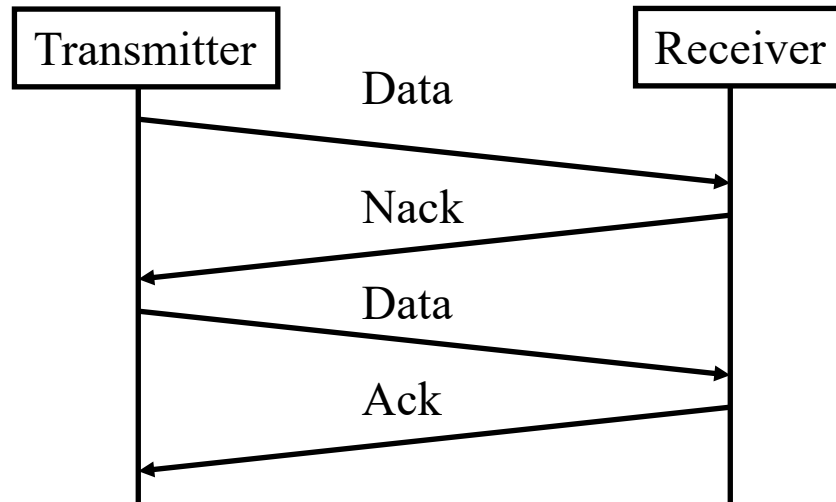
Hybrid ARQ

❑ PHY and MAC layers work together ⇒ Hybrid

❑ PHY layer sends some bits first (uses puncturing)

➢ Sends other bits only if necessary.

➢ Additional bits are sent until the decoding is successful. (**Incremental Redundancy** or **Type II** HARQ)

➢ Another alternative is to combine the good bits of multiple transmissions (**Chase Combining** or **Type I** HARQ)
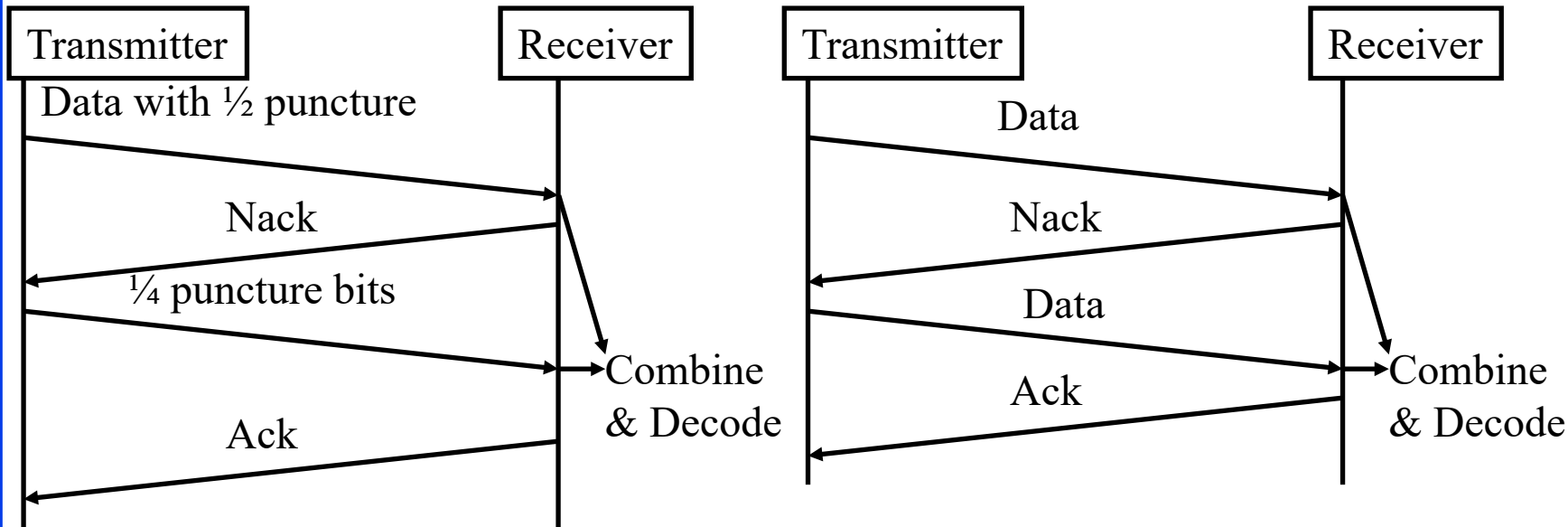
Transmitter   Receiver   Transmitter   Receiver

Data with ½ puncture   Data

Nack   Nack

¼ puncture bits   Data

Combine & Decode   Ack   Combine & Decode

Ack

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IP-Based Flat Network Architecture

❑ Flat $\Rightarrow$ Less hierarchical and fewer nodes

❑ All services (Voice/multimedia) over IP

❑ For backward compatibility, some non-IP protocols and services are still used in the LTE network
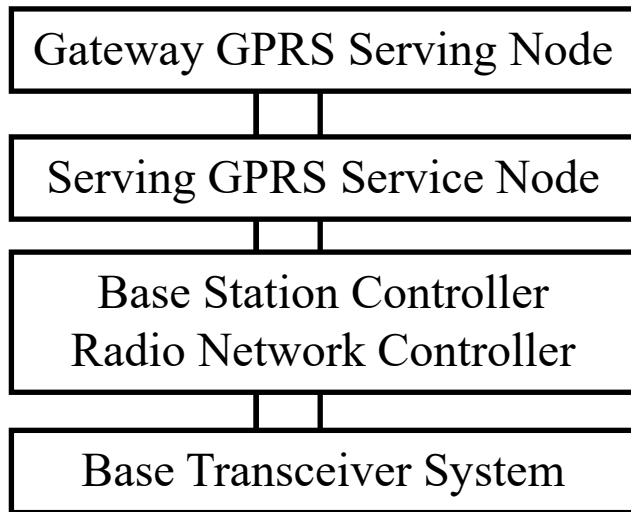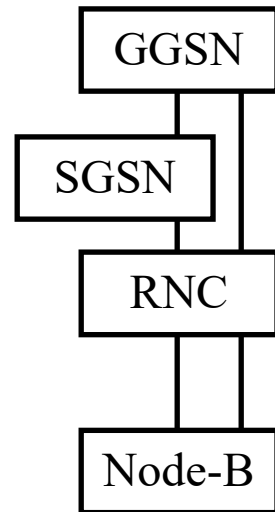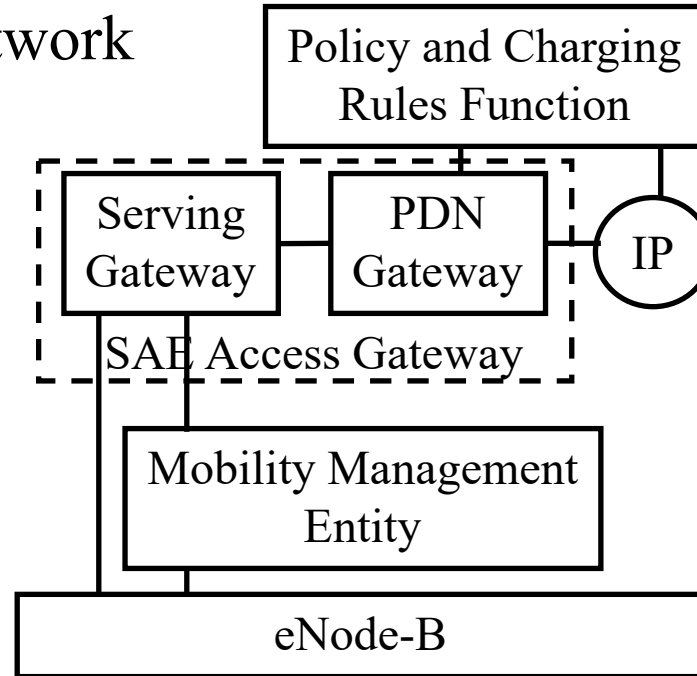
Gateway GPRS Serving Node	GGSN		Policy and Charging Rules Function
Serving GPRS Service Node	SGSN	Serving Gateway / PDN Gateway (SAE Access Gateway)	IP
Base Station Controller Radio Network Controller	RNC	Mobility Management Entity	
Base Transceiver System	Node-B	eNode-B	
2G	3G	LTE	

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17-14

Evolved Packet Core (EPC)

❑ Four new elements:

1. **Serving Gateway**: Demarcation point between RAN and Core. Serves as mobility anchor when terminals move

2. **Packet Data Network Gateway (PGW)**: Termination of EPC towards Internet or IMS network. IP services, address allocation, deep packet inspection, policy enforcement

3. **Mobility Management Entity (MME)**: Location tracking, paging, roaming, and handovers. All control plane functions related to subscriber and session management.

4. **Policy and Charging Rules Function (PCRF)**: Manages QoS using info from Home Subscriber Server (HSS)

Student Questions

Evolved Packet System (EPS)

Radio Access Network   Serving Network   Core Network

Student Questions

GSM Edge

MS GERAN BTS BSC | CS Core MSC MGW | SGW

WCDMA HSPA+ (UMTS)

UE UTRAN NodeB RNC | PS Core SGSN | SS7 GGSN

E-UTRAN

UE LTE eNB Control Data | EPC HSS MME PDN-GW S-GW | Internet

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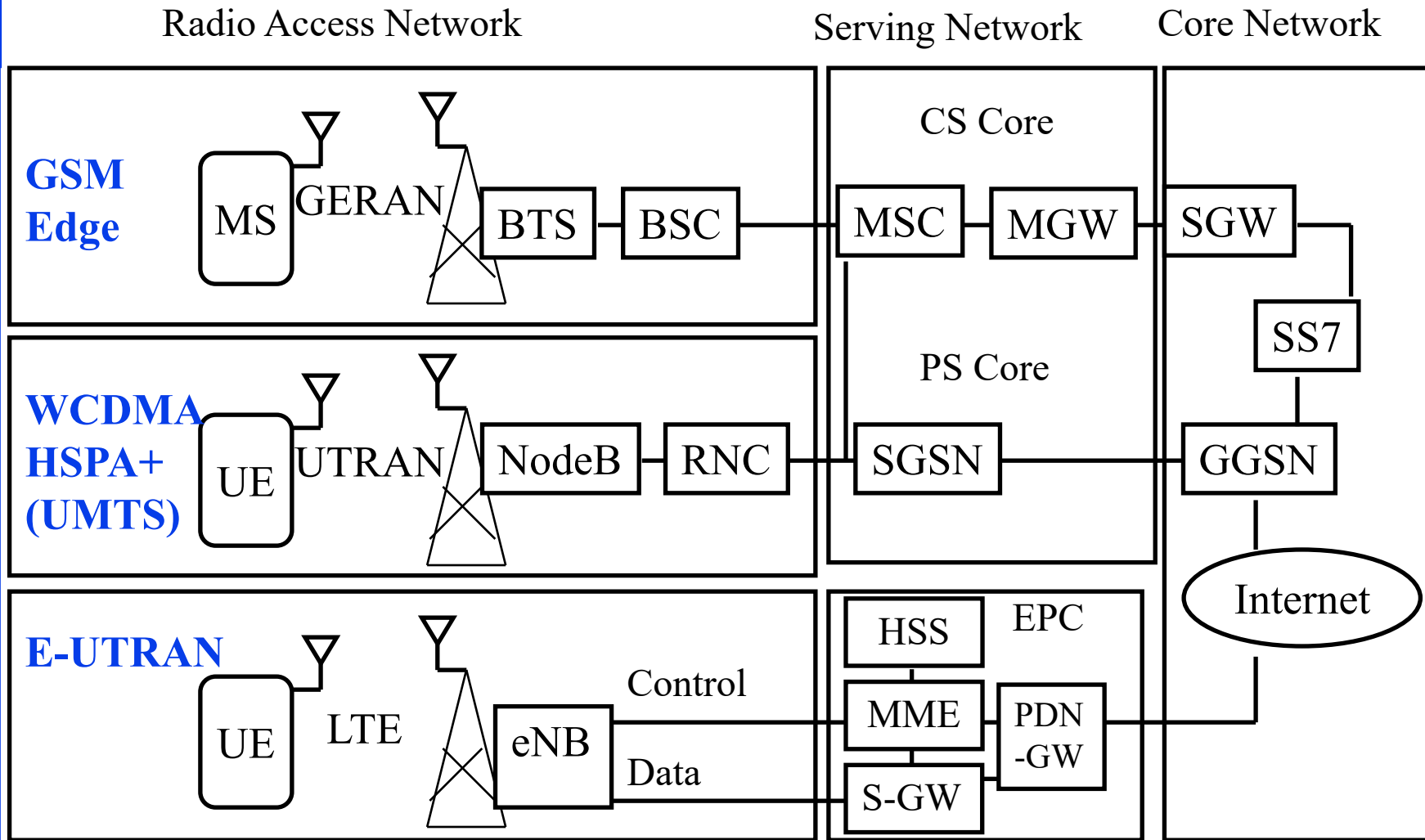
Evolved Packet System (Cont)

- CS = Circuit Switched
- EPC = Evolved Packet Core
- EPS = Evolved Packet System
- GERAN = GSM Enhanced Radio Access Network
- GGSN = Gateway GPRS Support Node
- HSS = Home Subscriber Server (similar to Home Location Register)
- LTE = Long-Term Evolution
- MME = Mobility Management Utility
- MSC = Mobile Switching Center
- PDN-GW = Public Data Network Gateway
- PS = Packet Switched
- RNC = Radio Network Control
- S-GW = Serving Gateway
- SGSN = Service GPRS Support Node
- SS7 = System 7
- eNB = Evolved NodeB

Student Questions

Evolved Packet Core (EPC)

❑ **Mobility Management Entity (MME):**
  ➢ Handles all control between base stations and core
  ➢ Only non-access spectrum (NAS) signaling, i.e., not involving air interface matters
  ➢ Authentication, Handovers, SMS, and voice

❑ **Serving Gateway (S-GW):**
  ➢ Separates S1 tunnel to eNB from S5 tunnel to Internet
  ➢ The two tunnels are independently changed as the user moves

❑ **PDN Gateway (PDN-GW):** Router to the Internet.
  ➢ Assigns IP addresses to mobile devices

❑ **Home Subscriber Server (HSS):** Like HLR in 3G
  ➢ Uses IP-based DIAMETER protocol
  ➢ Maintains Users International Mobile Subscriber Identity (IMSI), authentication information, telephone number, etc.

Student Questions

LTE Frame Structure
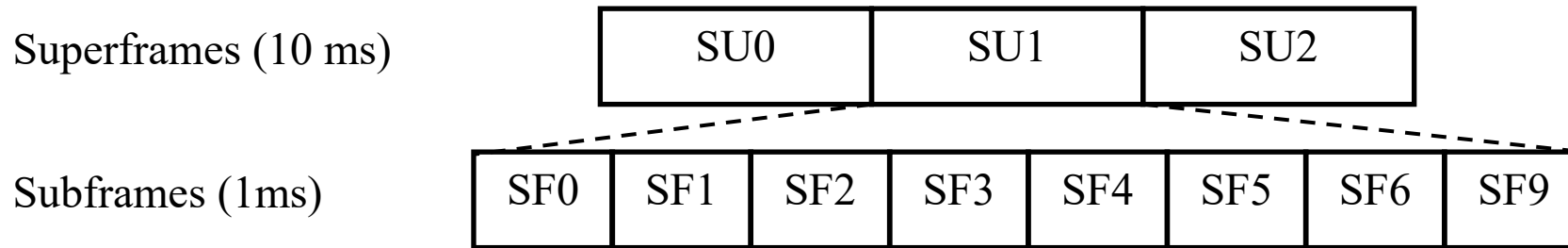
- ❑ Subframe = 2 slots of 0.5 ms each
- ❑ Slot = 6 or 7 symbols of 0.0667 ms each
- ❑ Normal Cyclic Prefix: 5.2 us for 1st symbol, 4.7 us for others

- ❑ Extended Cyclic Prefix: for larger networks. 16.7 us
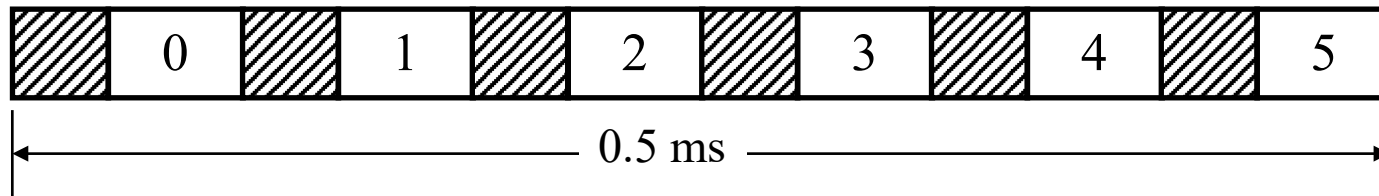
Ref: Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction,"
http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf

Student Questions

❑ If there are six symbols in a slot, how could a symbol take longer time than a slot? (0.667 ms vs. 0.5 ms)

Corrected.
The slot size is 0.0667 ms.

❑ Do we increase cyclic prefixes to ensure that the symbols don't overrun each other in a long-distance transmission? Example: give TX1 time to travel before sending TX2, so TX2 is not received before TX1.

Extended prefix gives more space for the symbols to expand. TX2 is not received before TX1 ends.

LTE Frame Structure

Superframes (10 ms)

SU0	SU1	SU2

Subframes (1ms)

| SF0	SF1	SF2	SF3	SF4	SF5	SF6	SF9

❑ Subframe = 2 slots of 0.5 ms each

❑ Slot = 6 or 7 symbols of 0.0667 ms each

❑ Normal Cyclic Prefix: 5.2 us for 1st symbol, 4.7 us for others

0	1	2	3	4	5	6

❑ Extended Cyclic Prefix: for larger networks. 16.7 us

0	1	2	3	4	5

⟵————————— 0.5 ms —————————⟶

Student Questions

❑ How could we detect the cyclic prefix's end and the symbol's start? We need an exact timer because there is no guard between them.

There could be an inter-symbol gap. Anyway, bit coding provides synchronization.

Resource Allocation

❑ **Time slot:** 0.5 ms
6 or 7 OFDM symbols

❑ **Subcarriers:** 15 kHz

❑ **Physical Resource Block:**
12 subcarriers (180 kHz)
over 1 time slot

❑ **Minimum Allocation**: 2 PRBs
per subframe

12 SC

12 SC

12 SC

PRBs for a
single UE

0.5ms 0.5ms

Subcarriers

Time

Slot

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WiMAX vs. LTE

❑ Similar with minor differences

❑ Net Head vs. Bell Head

❑ Enterprise Networking vs. Carrier Networking

❑ Academic vs. Telecom

❑ Intel/Google vs. Ericsson/QUALCOMM

❑ Both use OFDMA.
Both are incompatible with 2G and 3G (CDMA) radios.

❑ Quad-band ⇒ Penta-band

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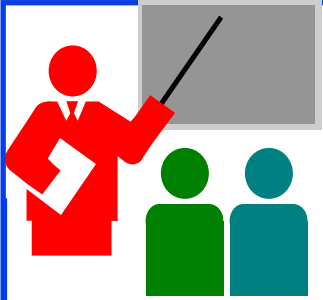
Summary

1. WiMAX and LTE are pre-4G technologies.

2. WiMAX and LTE have numerous **common features**: Many bands, flexible bandwidth, and FDD/TDD. MIMO/Beamforming HARQ, IP-Based, OFDMA. The key differentiator is SC-FDMA for uplink in LTE to reduce **PAPR**.

3. STBC requires transmitting redundant symbols from multiple antennae. **SFBC** requires that these redundant symbols be sent on different subcarriers.

4. **Puncturing** allows some ECC bits to be not transmitting. This is used in **HARQ** to send extra bits only if necessary.

5. LTE uses a **super-frame** of 10 subframes of 1 ms each. Each **subframe** has one **slot** for uplink and downlink each.

Student Questions

❑ Slides 17-15 (EPC), 17-22 (DASH), and 17-23 (VoLTE) are not covered by the video.
17-22 and 17-23 are misplaced. DASH is covered in CSE473, not here. VoLTE is covered in Module 18. EPC is explained in Slides 17-16 (EPS) and 17-17 (EPS Cont).

Reading List

❑ A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp., Safari Book.

❑ Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction," http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf
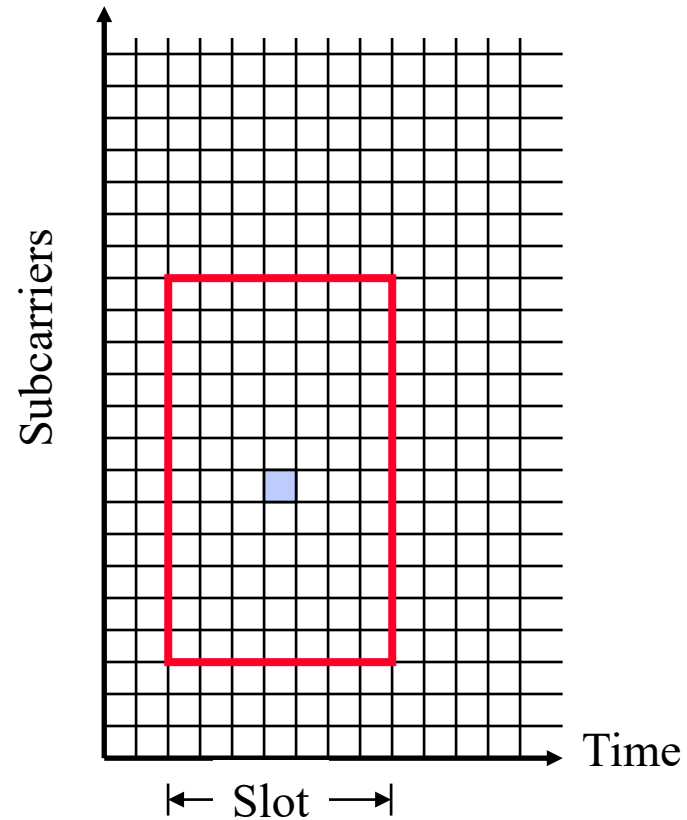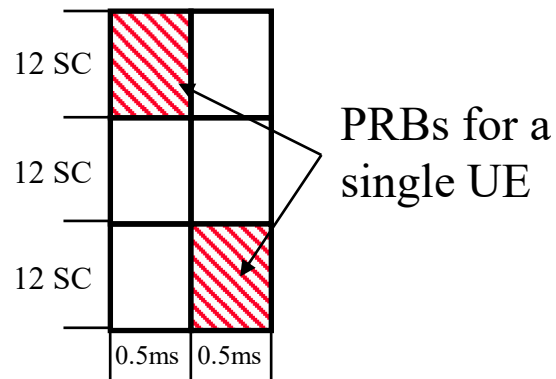
Student Questions

Wikipedia Links

- https://en.wikipedia.org/wiki/IMT-Advanced
- https://en.wikipedia.org/wiki/4G
- https://en.wikipedia.org/wiki/Radio_Resource_Control
- https://en.wikipedia.org/wiki/Radio_resource_management
- https://en.wikipedia.org/wiki/Single-carrier_FDMA
- https://en.wikipedia.org/wiki/Space%E2%80%93time_block_code
- https://en.wikipedia.org/wiki/Space-time_block_coding_based_transmit_diversity
- https://en.wikipedia.org/wiki/Space%E2%80%93time_code
- https://en.wikipedia.org/wiki/Spatial_multiplexing
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Transmit_diversity
- https://en.wikipedia.org/wiki/Mobility_management
- https://en.wikipedia.org/wiki/MIMO
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Precoding

Student Questions

Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Antenna_diversity
- https://en.wikipedia.org/wiki/Many_antennas
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Smart_antenna
- https://en.wikipedia.org/wiki/Beamforming
- https://en.wikipedia.org/wiki/Precoding
- https://en.wikipedia.org/wiki/Radio_Network_Controller
- https://en.wikipedia.org/wiki/Crest_factor
- https://en.wikipedia.org/wiki/PDCP
- https://en.wikipedia.org/wiki/Crest_factor
- https://en.wikipedia.org/wiki/E-UTRA
- https://en.wikipedia.org/wiki/Policy_and_charging_rules_function
- https://en.wikipedia.org/wiki/Puncturing
- https://en.wikipedia.org/wiki/Fading
- https://en.wikipedia.org/wiki/Single-frequency_network
- https://en.wikipedia.org/wiki/Evolved_Packet_System

Student Questions

Wikipedia Links (Cont)

❑ https://en.wikipedia.org/wiki/Channel_allocation_schemes
❑ https://en.wikipedia.org/wiki/Hybrid_automatic_repeat_request
❑ https://en.wikipedia.org/wiki/LTE_timeline
❑ https://en.wikipedia.org/wiki/Flat_IP
❑ https://en.wikipedia.org/wiki/E-UTRA
❑ https://en.wikipedia.org/wiki/Mobility_Management_Entity
❑ https://en.wikipedia.org/wiki/System_Architecture_Evolution
❑ https://en.wikipedia.org/wiki/EnodeB
❑ https://en.wikipedia.org/wiki/Signaling_gateway
❑ https://en.wikipedia.org/wiki/Packet_data_serving_node
❑ https://en.wikipedia.org/wiki/Automatic_repeat_request
❑ https://en.wikipedia.org/wiki/Hybrid_automatic_repeat_request
❑ https://en.wikipedia.org/wiki/Beamforming
❑ https://en.wikipedia.org/wiki/Multimedia_Broadcast_Multicast_Service
❑ https://en.wikipedia.org/wiki/Broadcast/Multicast_Control
❑ https://en.wikipedia.org/wiki/Multicast-broadcast_single-frequency_network

Student Questions

Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- https://en.wikipedia.org/wiki/Single-carrier_FDMA
- https://en.wikipedia.org/wiki/4G
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- https://en.wikipedia.org/wiki/E-UTRA
- https://en.wikipedia.org/wiki/Cooperative_MIMO
- https://en.wikipedia.org/wiki/Cyclic_prefix

Student Questions

LTE References

- Agilent Technologies, "LTE and the Evolution to 4G Wireless," Wiley, 2009, ISBN:0470682616
- E. Dahlman, et al, "3G Evolution:HSPA and LTE for Mobile Broadband," 2nd Edition, Academic Press, 2008, ISBN:0123745385
- 3GPP TS 36.104, "Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (Release 8) "
- 3GPP TR 25.913., "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)," v8.0.0, December 2008.
- ITU-R Report M.2134, "Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s)," November 2008.
- 3GPP TR 36.913, "Requirements for Further Advancements for E-UTRA," v8.0.1, March 2009.
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Acronyms

- 3GPP   3rd Generation Partnership Project
- ARQ   Automatic Repeat Request
- BPSK   Binary Phase Shift Keying
- BSC   Base Station Controller
- BTS   Base Transceiver Station
- CDMA   Code Division Multiple Access
- CS   Circuit Switched
- ECC   Error Correcting Code
- eNB   Enhanced Node B
- eNode-B   Enchanced Node B
- EPC   Evolved Packet Core
- EPS   Evolved Packet System
- FDD   Frequency Division Duplexing
- FDMA   Frequency Division Multiple Access
- FEQ   Frequency Domain Equalizer
- FFT   Fast Fourier Transform

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Acronyms (Cont)

- FSTD   Frequency-Shift Transmit Diversity
- GERAN   GSM/EDGE Radio Access Network
- GGSN   Gateway GPRS Support
- GPRS   General Packet Radio Service
- GSM   Global System for Mobile Communications
- GW   Gateway
- HSPA   High-Speed Packet Access
- IEEE   Institution of Electrical and Electronic Engineers
- IMS   Internet Multimedia System
- IMT-Advanced   International Mobile Telecommunications Advanced
- IP   Internet Protocol
- ITU   International Telecommunications Union
- kHz   Kilo Hertz
- LTE   Long Term Evolution
- MAC   Message Authentication Code
- MBMS   Multicast-Broadcast Mobile Services

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Acronyms (Cont)

- MGW — Media Gateway
- MHz — Mega Hertz
- MIMO — Multiple Input Multiple Output
- MME — Mobility Management Entity
- MS — Mobile Station
- MSC — Mobile Switching Center
- OFDM — Orthogonal Frequency Division Modulation
- OFDMA — Orthogonal Frequency Division Multiple Access
- PAPR — Peak-to-Average Power Ratio
- PCRF — Policy and Charging Rules Function
- PDFICH — Physical Control Format Indicator Channel
- PDN — Packet Data Network
- PGW — Packet Data network Gateway
- PHY — Physical Layer
- PS — Packet Switched
- QAM — Quadrature Amplitude Modulation

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Acronyms (Cont)

- QoS   Quality of Service
- QPSK   Quadrature Phase Shift Keying
- RAN   Radio Access Network
- RNC   Radio Network Control
- SAE   Service Access Gateway
- SC-FDMA   Single Carrier Frequency Division Multiple Access
- SC   Single Carrier
- SF   Subframe
- SFBC   Space Frequency Block Code
- SGSN   Service GPRS Support
- SGW   Serving Gateay
- SINR   Signal to Interference and Noise Ratio
- SN   Sequence Number
- SNR   Signal-to-noise ratio
- SOstart   Begining of Segment

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Acronyms (Cont)

- STBC   Space Time Block Code
- SU   Superframe
- TD-SCDMA   Time Division Synchronous Code Division Multiple Access
- TDD   Time Division Duplexing
- TDMA   Time Division Multiple Access
- UE   User Element
- UMTS   Universal Mobile Telecommunications System
- UTRAN   UMTS Terrestrial Radio Access Network
- VTC   Vehicular Technology Conference
- WCDMA   Wideband Code Division Multiple Access
- WiMAX   Worldwide Interoperability for Microwave Access

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https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

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CSE571S: Network Security (Fall 2011),
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