Introduction to LTE

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

http://www.cse.wustl.edu/~jain/cse574-20/

Student Questions

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)
   ⇒ 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

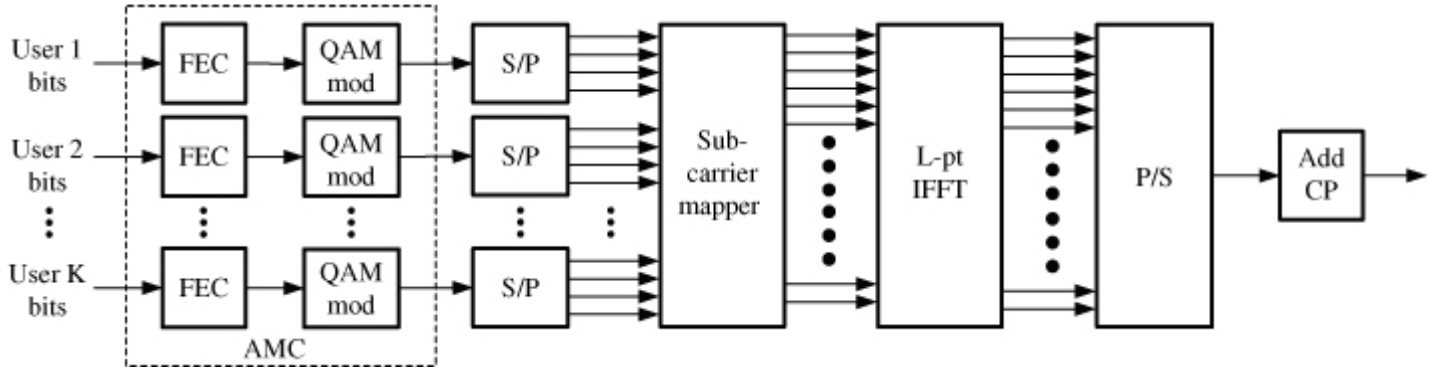
LTE: Key Features (Cont)

8. Data Rate: 326 Mbps/down 86 Mbps up (4x4 MIMO 20 MHz)
9. Modulation: OFDM with QPSK, 16 QAM, 64 QAM
10. **OFDMA** downlink,
    Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplink
11. **Hybrid ARQ** Transmission
12. Short **Frame Sizes** of 10ms and 1ms ⇒ 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

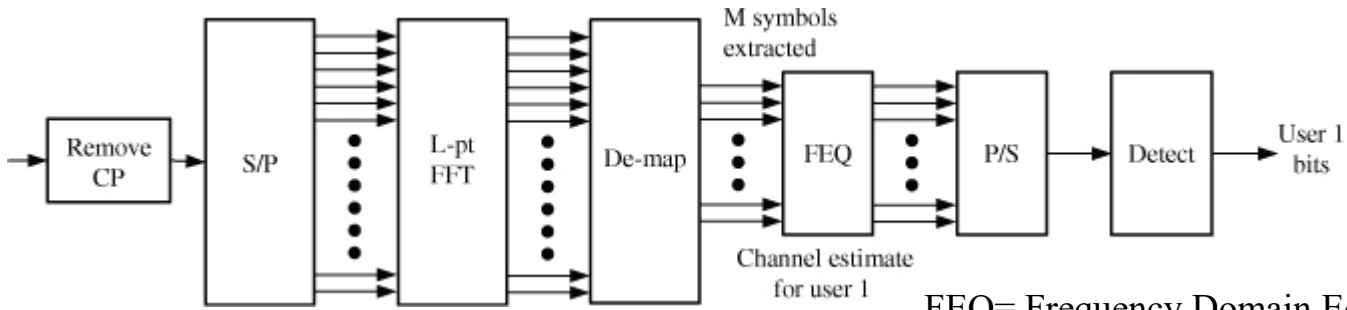
Student Questions

OFDMA Downlink

- Transmitter at Base Station: IFFT converts frequency to time



- Receiver at User Terminal: FFT converts time to frequency



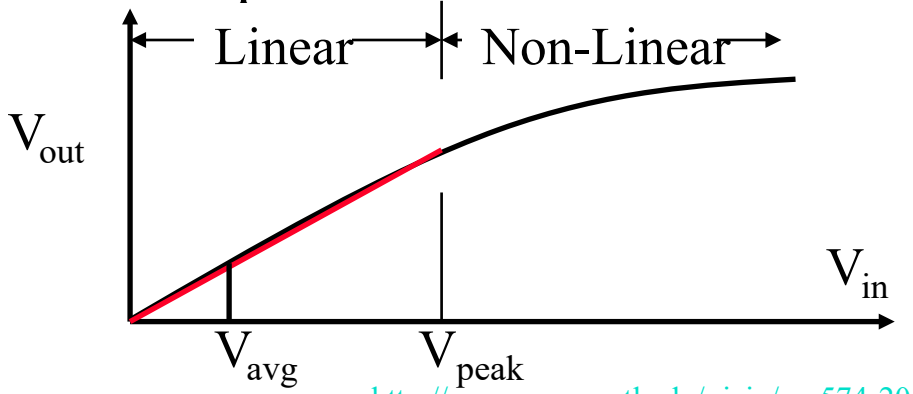
FEQ= Frequency Domain Equalizer

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

Student Questions

Peak-to-Average Power Ratio (PAPR)

- OFDM
  ⇒ Each carrier modulated according to 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



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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 ⇒ Not much variation in amplitude
  ⇒ Lower PAPR
- Better for uplink because slight mis-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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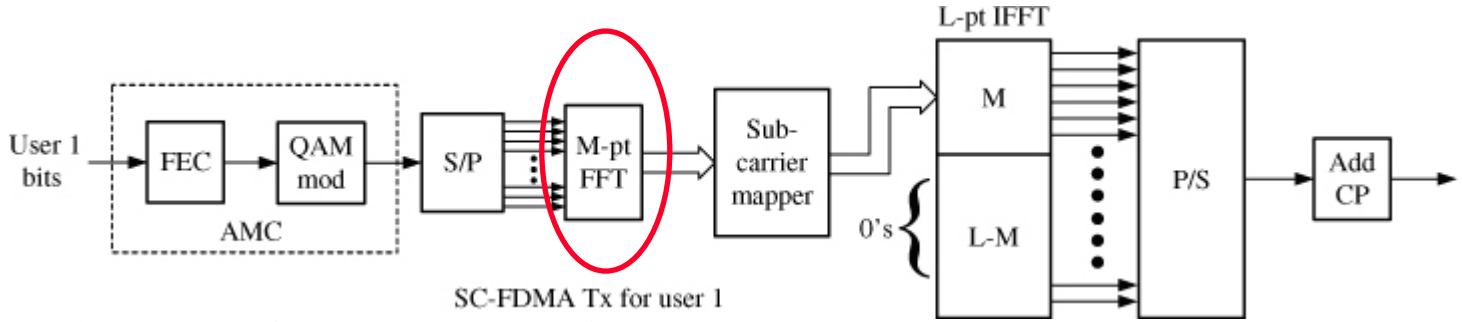
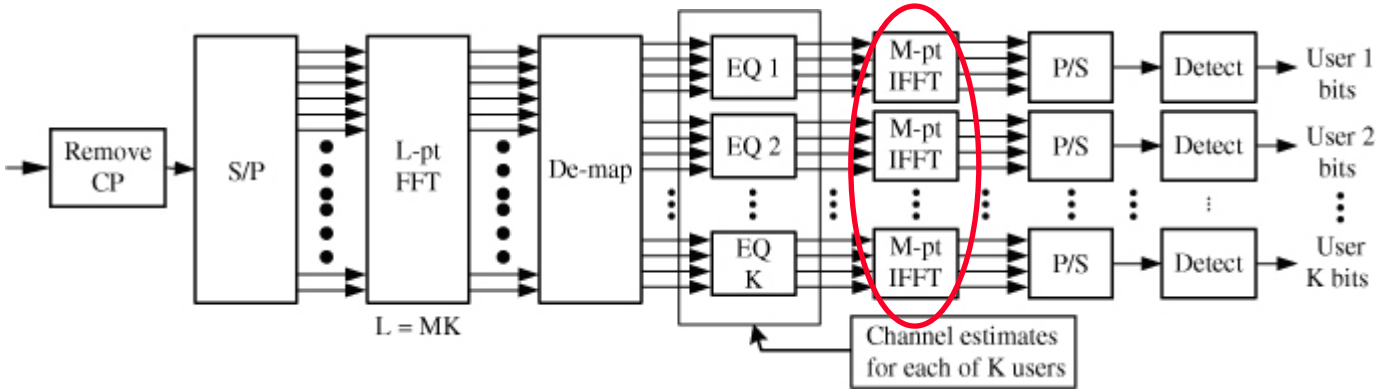
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

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:



- Receiver at the Base Station:



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

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

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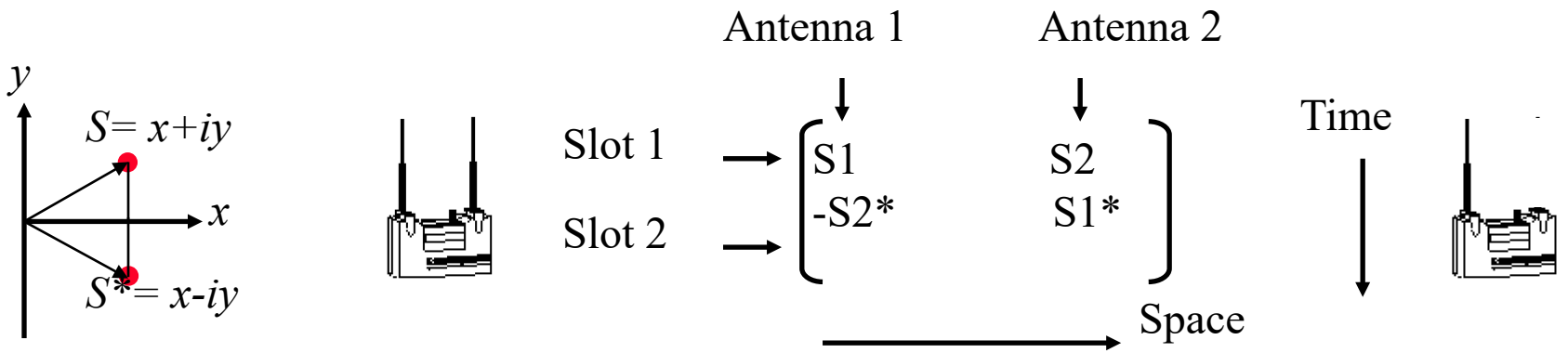
Space Time Block Codes (STBC)

- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas: Two symbols in two slots ⇒ Rate 1



S1* is complex conjugate of S1 ⇒ columns are orthogonal

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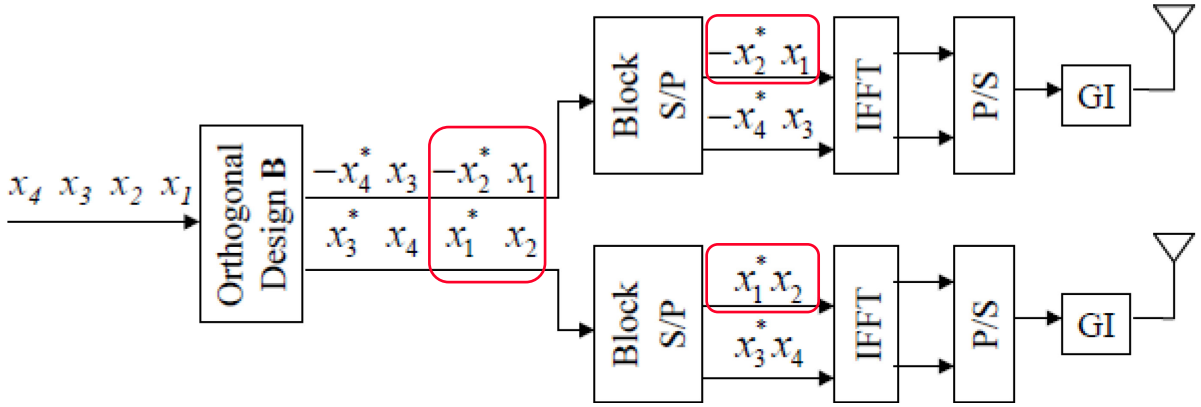
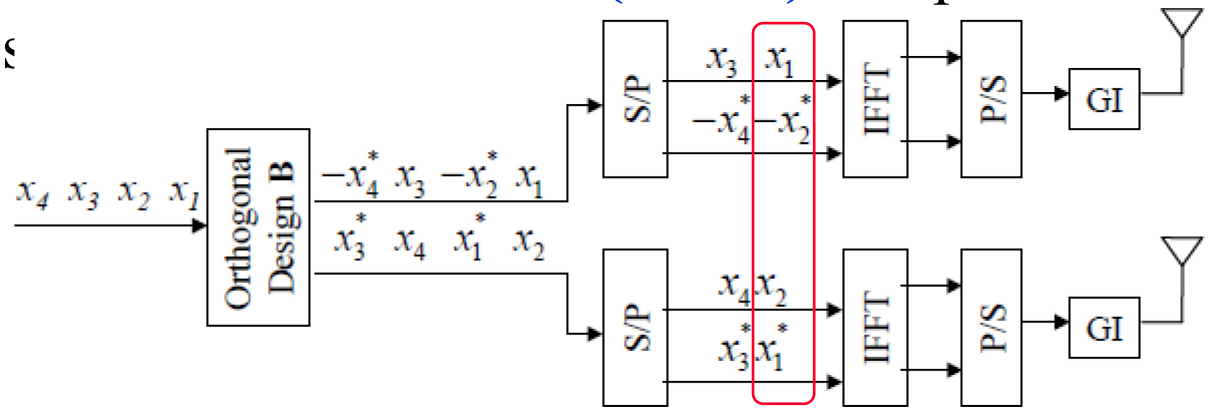
Space-Frequency Block Codes (SFBC)

- STBC on OFDM (Multi-carrier): Two alternatives
- **STBC on each subcarrier**:



- **STBC on across subcarriers (SFBC)**: Helps if channel changes

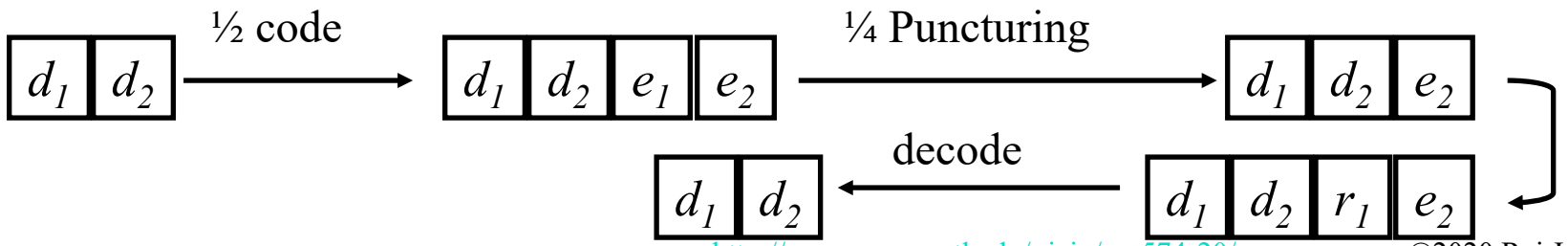


Ref: G. Bauch, "Space-Time Block Codes Versus Space-Frequency Block Codes," IEEE VTC, Apr 2003, https://pdfs.semanticscholar.org/105a/06314ba6718f3d698a7620b2e891d20c00de.pdf

Student Questions

Puncturing

- Use 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 ⇒ Drop every 4th bit
  ⇒ send 3 bits for each 2-bit symbol = 2/3 code
- Receiver puts random bits in the punctured positions and decodes ⇒ 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, H-ARQ



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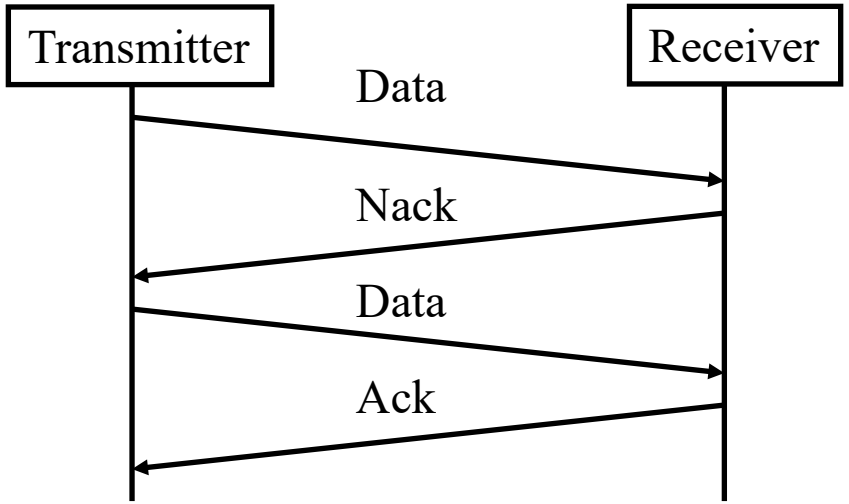
ARQ

- Automatic Repeat reQuest (ARQ)
- Retransmit a packet if it is received in error
- All bits of the previous (errored) packet are discarded.



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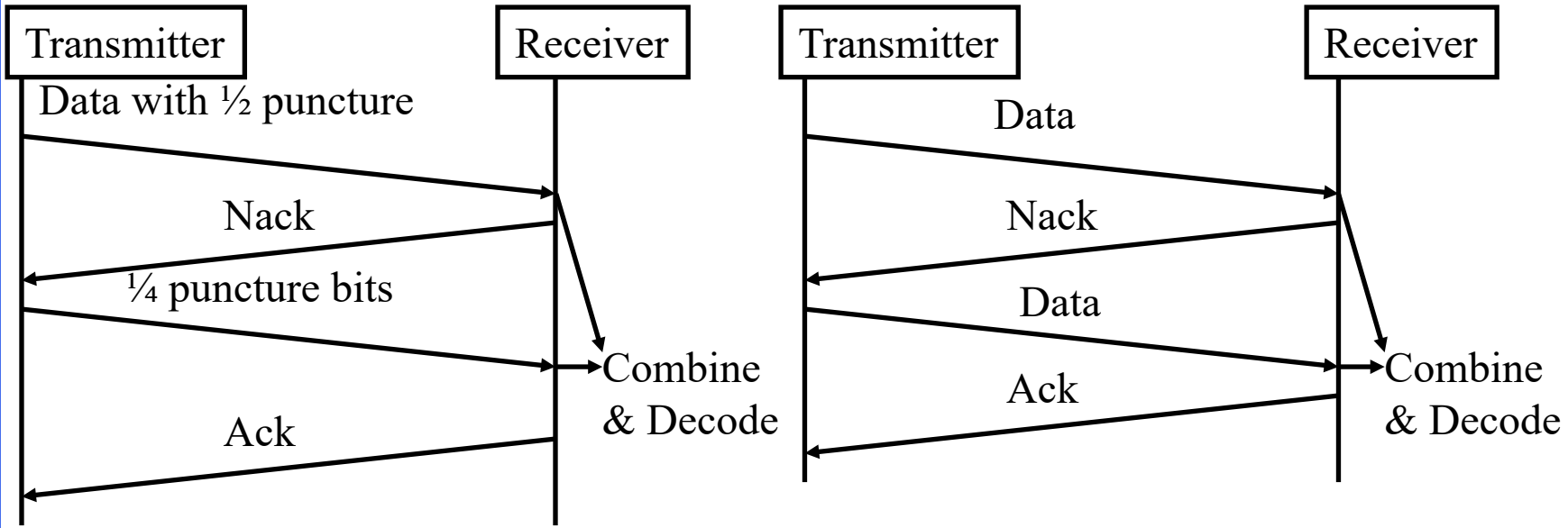
Hybrid ARQ

- PHY and MAC layers work together ⇒ Hybrid
- PHY layer sends some bits first (uses puncturing)
  - Sends additional bits only if necessary.
  - Additional bits are sent until the decoding is successful. (**Incremental Redundancy** or **Type II** H-ARQ)
  - Another alternative is to combine the good bits of multiple transmissions (**Chase Combining** or **Type I** H-ARQ)



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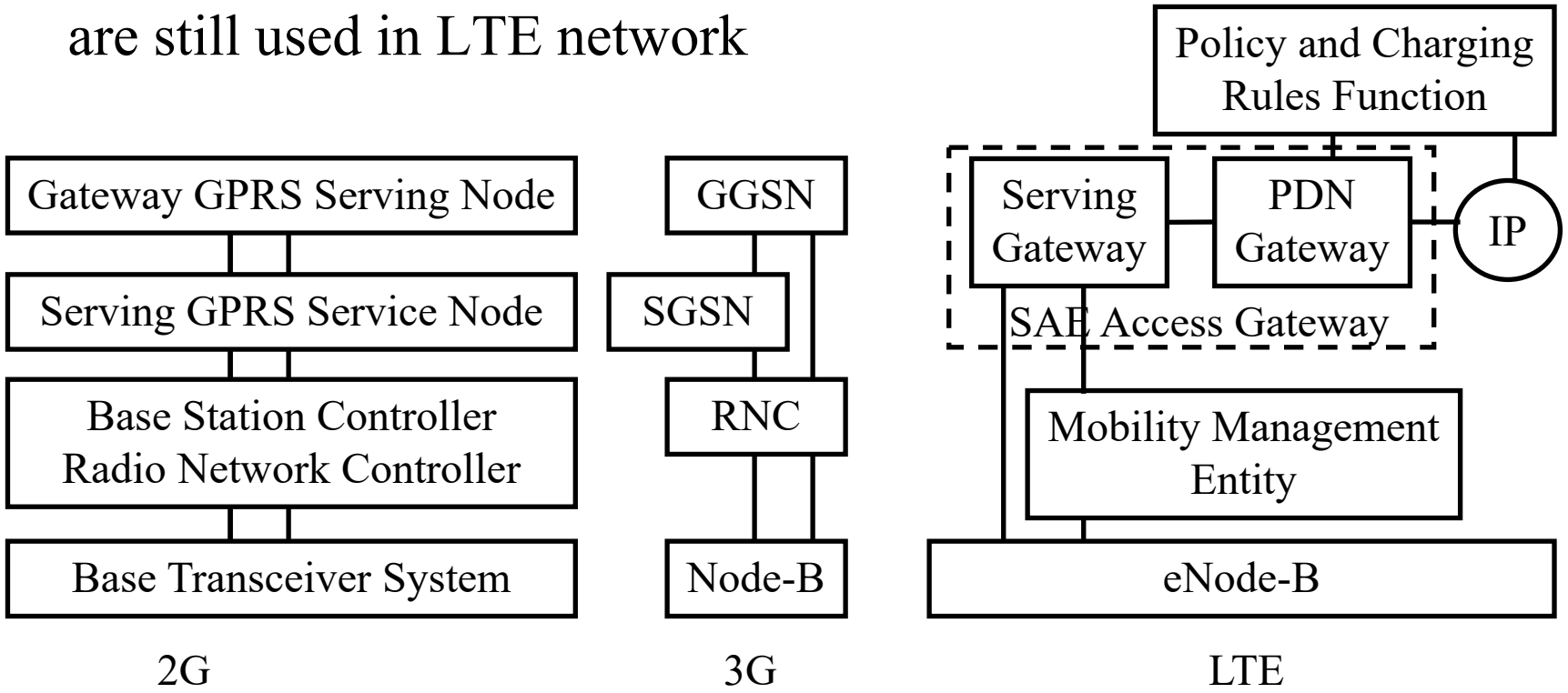
IP-Based Flat Network Architecture

- Flat ⇒ Less hierarchical and fewer nodes
- All services (Voice/multimedia) over IP
- For backward compatibility some non-IP protocols and services are still used in LTE network



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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

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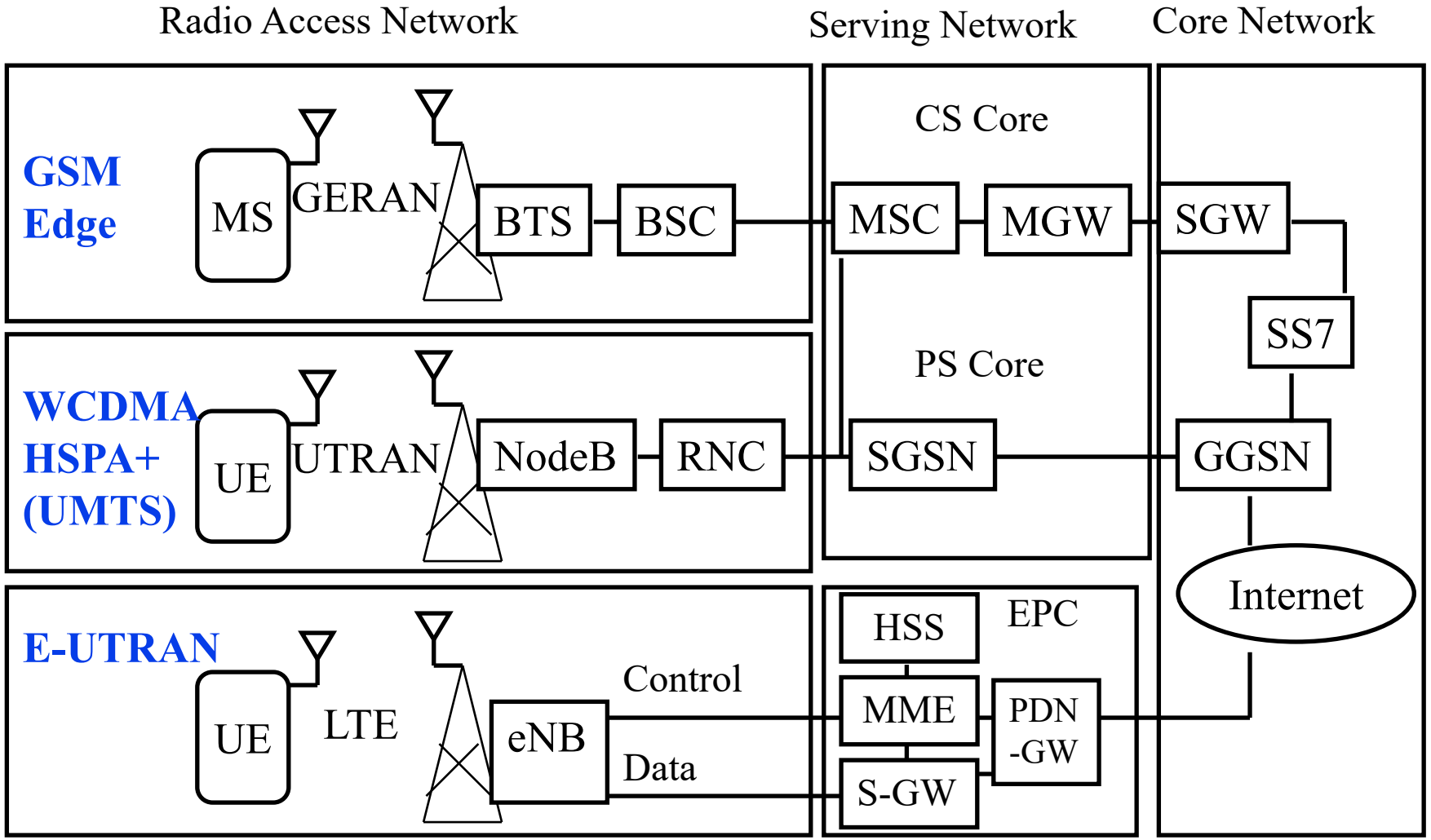
Evolved Packet System (EPS)



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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
- 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

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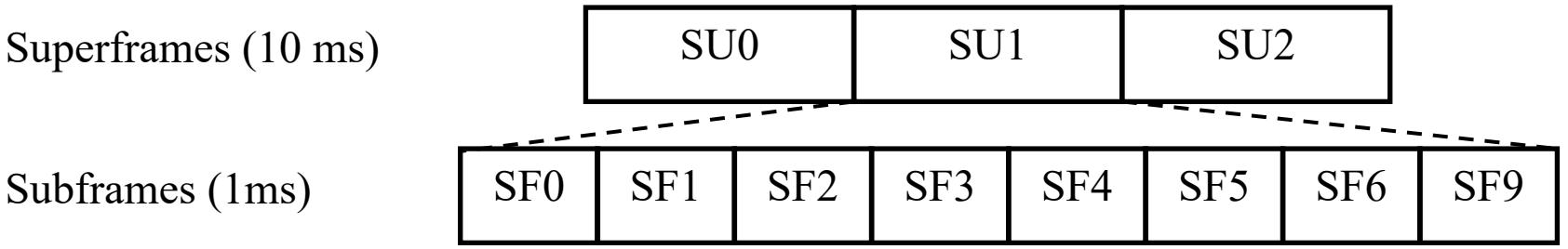
Evolved Packet Core (EPC)

- **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 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.

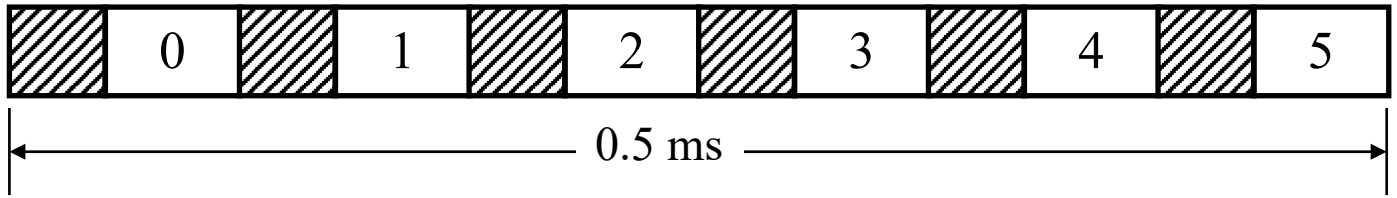
Student Questions

LTE Frame Structure



- Subframe = 2 slots of 0.5 ms each
- Slot = 6 or 7 symbols of 0.667 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

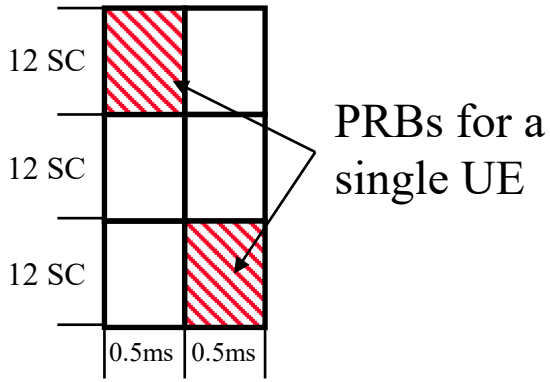


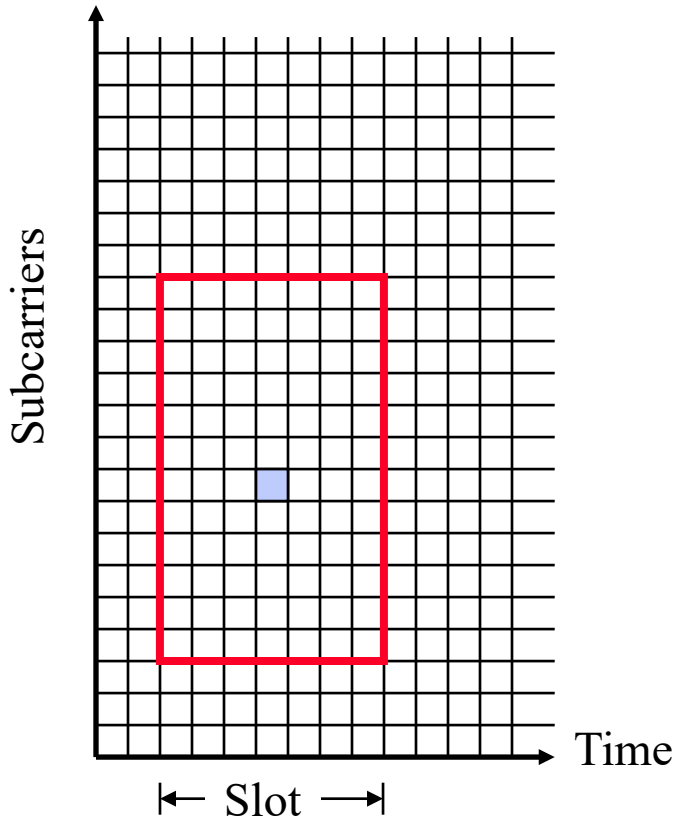
Ref: Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction,"
http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf

Student Questions

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





Student Questions

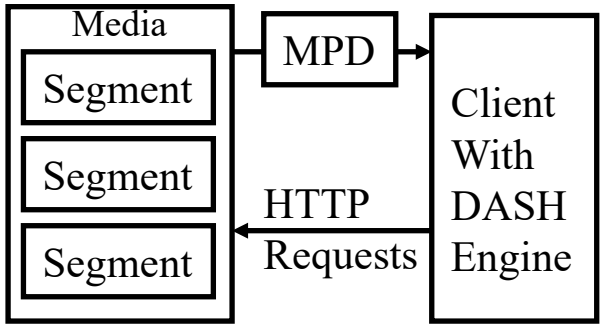
WiMAX vs. LTE

- Similar with very 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

Student Questions

Dynamic Adaptive Streaming over HTTP (DASH)

- Video is the major component of mobile traffic
  ⇒ DASH provides an efficient method for video streaming
- Standard developed jointly by 3GPP, ISO, Open IPTV Forum
- Standard Web Servers: No changes required to servers, Content Distribution Networks (CDN), or HTTP protocol. HTTP passes easily through firewalls
- Mobile client controls what is downloaded using a "media presentation description (MPD)" file defined by DASH
- MPD contains URLs for segments
- Client requests segments as needed. Allows fast forward, rewind, etc.

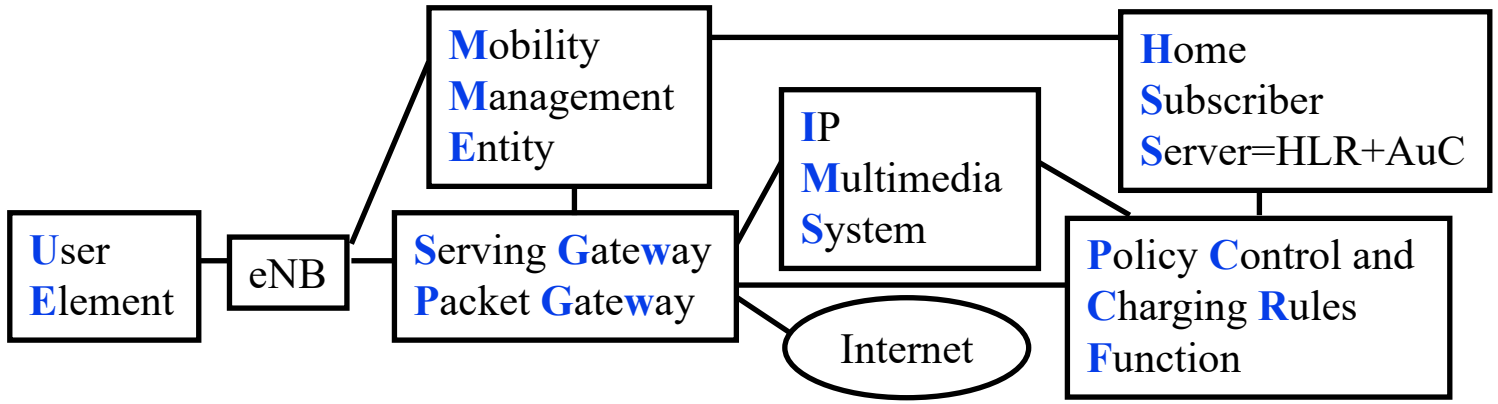


Ref: T. Stockhammer, "Dynamic Adaptive Streaming over HTTP – Standards and Design Principles," MMSys'11, Feb 2011, San Jose, CA, https://svn-itec.uni-klu.ac.at/trac2/dash/export/58/trunk/documentation/02%20mmt21da-stockhammer.pdf

Student Questions

Voice over LTE (VoLTE)

- Original LTE is not circuit switched
  ⇒ Voice needed to go through GSM or 3G circuits
  Called **C**ircuit **S**witch **F**all **B**ack (**CSFB**) ⇒ Need dual radios
- **IP Multimedia Services (IMS)** handles the call setup signaling
- **Transmission Time Interval (TTI) bundling** allows to repeat the uplink transmission in 4 consecutive subframes ⇒ 4x power ⇒ Improves link budget by 6 dB ⇒ reduces block error rate
- **Semi-persistent scheduling** saves scheduling overhead.
  Cannot adopt continuously to changing channel conditions
- **Packet Bundling**: Send only when two voice packets



Student Questions

Summary

1. WiMAX and LTE are pre-4G technologies.
2. WiMAX and LTE have numerous **common features**: Many bands, flexible bandwidth, FDD/TDD. MIMO/Beamforming H-ARQ, IP-Based, OFDMA. The key differentiator is SC-FDMA for uplink in LTE to reduce **PAPR**.
3. STBC requires transmitting redundant symbols from multiple antenna. **SFBC** require that these redundant symbols be sent on different subcarriers.
4. **Puncturing** allows some ECC bits to be not transmitted. This is used in **H-ARQ** 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

Reading List

- A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp., Safari Book.
- 3GPP, "LTE," http://www.3gpp.org/technologies/keywords-acronyms/98-lte
- 3GPP, "The Evolved Packet Core," http://www.3gpp.org/technologies/keywords-acronyms/100-the-evolved-packet-core
- 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.
- S. Sesia, I. Toufik, "LTE – The UMTS Long Term Evolution From Theory to Practice, Second Edition," Wiley , 2011, ISBN: 9780470660256, 792 pp. Safari book.

Student Questions

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

Student Questions

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

Student Questions

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

Student Questions

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

Student Questions

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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http://www.cse.wustl.edu/~jain/cse574-20/j_17lte.htm

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Student Questions

Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
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Student Questions