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

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

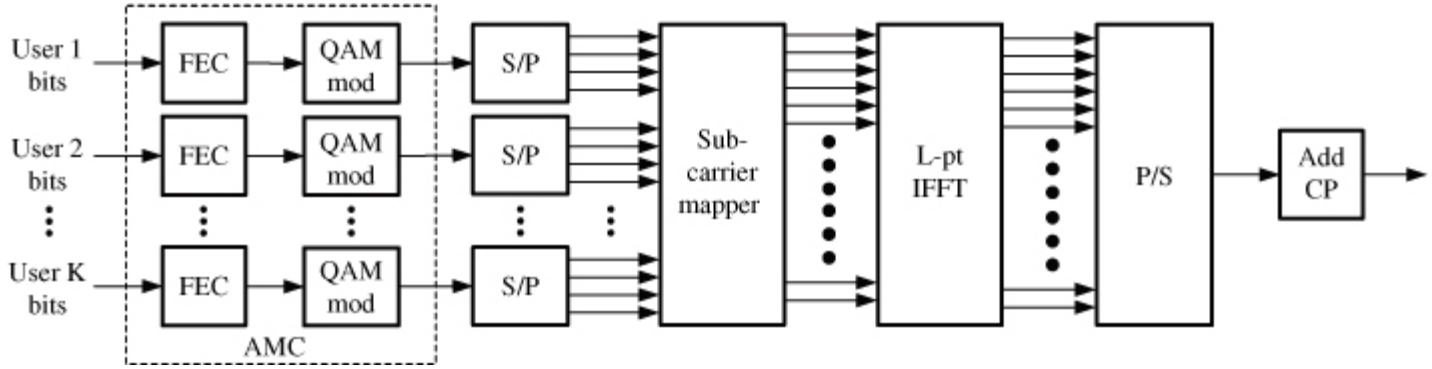
LTE: Key Features (Cont)

8. Data Rate: 326 Mbps/down 86 Mbps up (4x4 MIMO 20 MHz)
9. Modulation: OFDM with QPSK, 16 QAM, 64 QAM
10. **OFDMA** downlinks,
    Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplinks
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

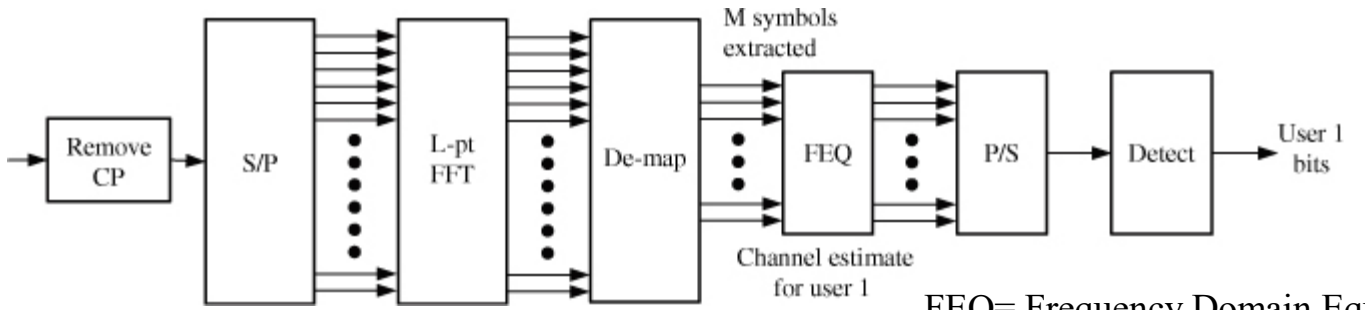
Student Questions

OFDMA Downlink

- Transmitter at Base Station: IFFT converts frequency to time



- Receiver at User Terminal: FFT converts time to frequency



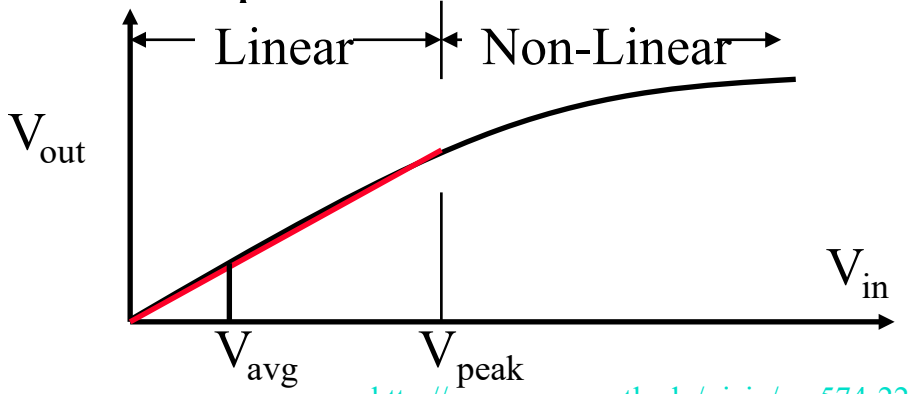
FEQ= Frequency Domain Equalizer

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 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.



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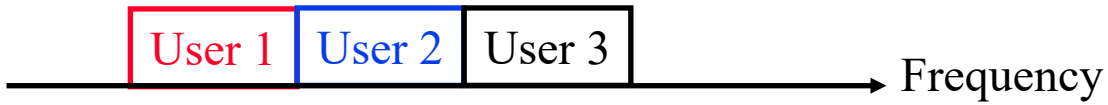
SC-FDMA

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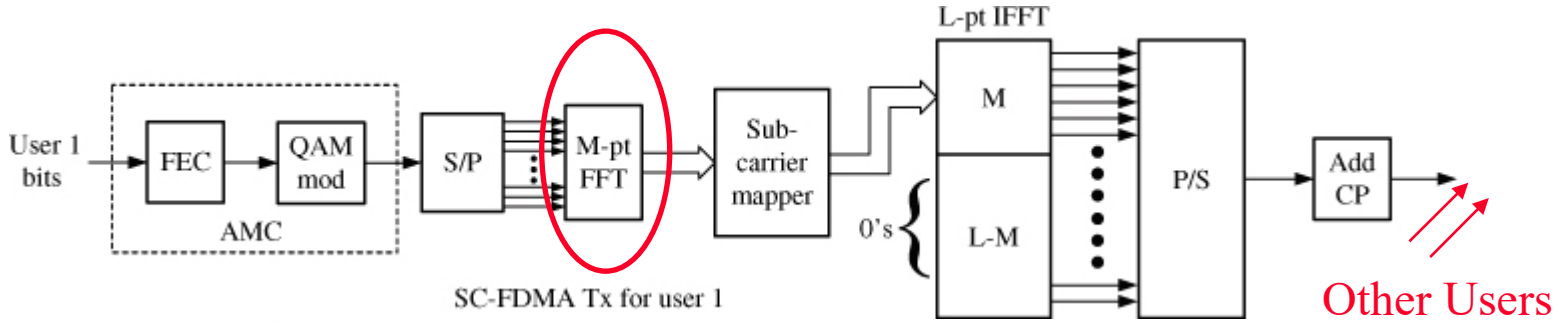
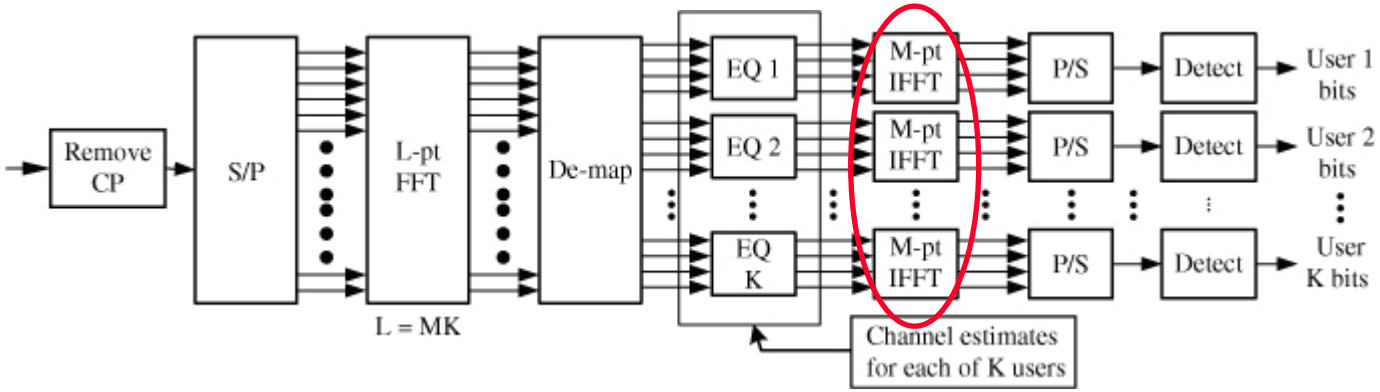
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

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:



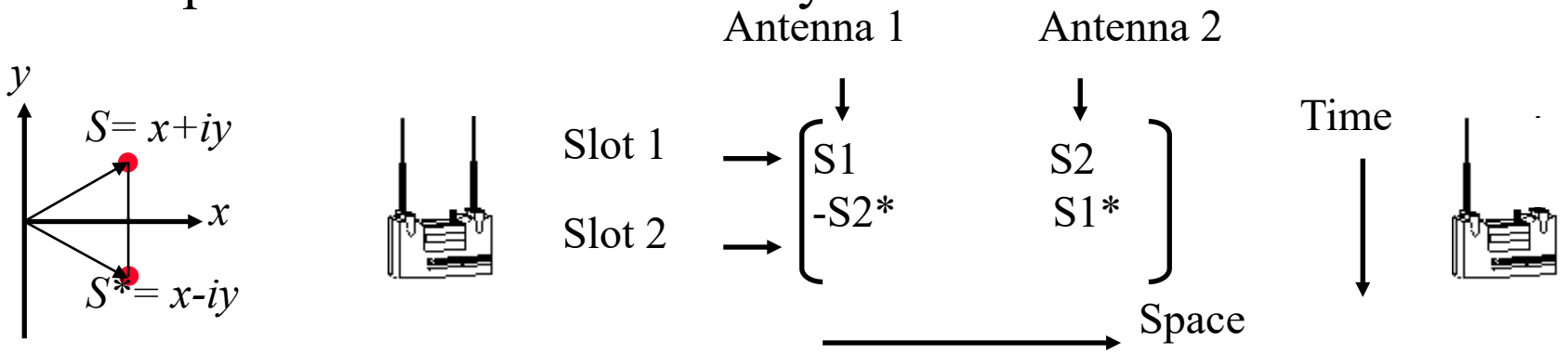
- SC-FDMA = Discrete Fourier Transform *Pre-coded* OFDMA

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

Student Questions

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 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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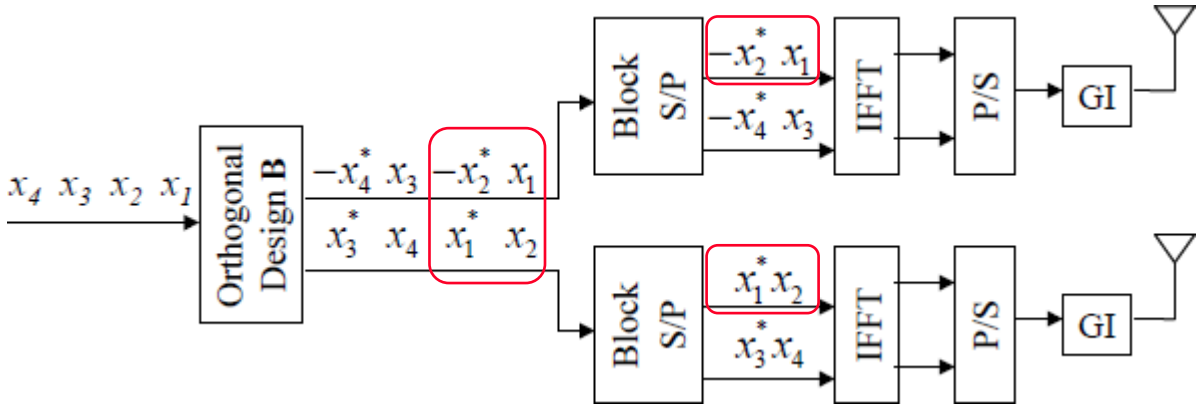
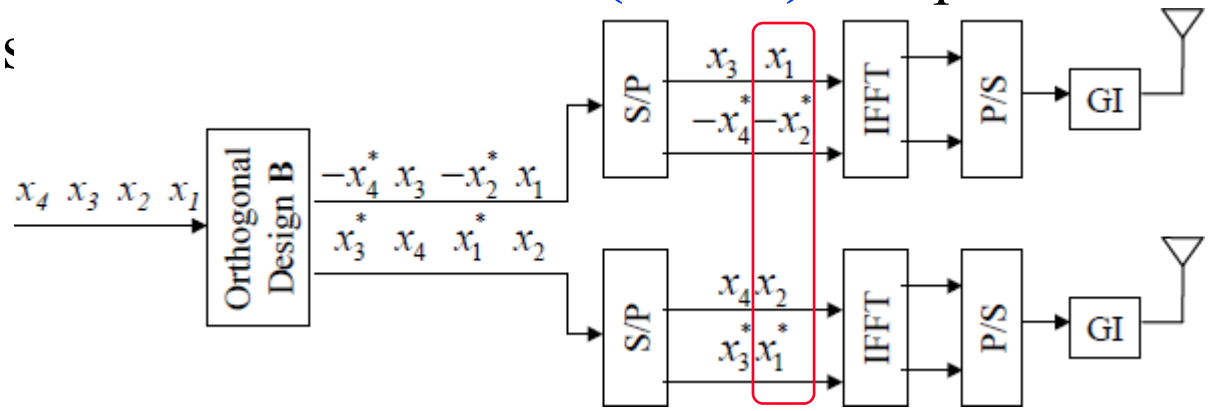
Space-Frequency Block Codes

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



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

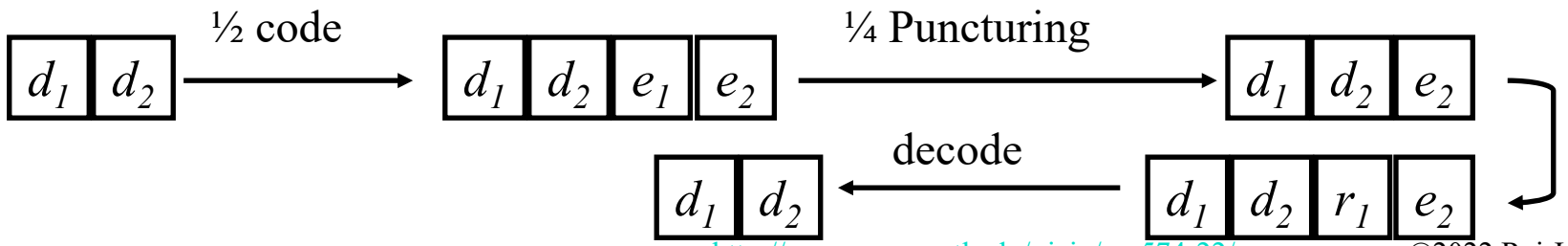


Ref: G. Bauch, "Space-Time Block Codes Versus Space-Frequency Block Codes," IEEE VTC, Apr 2003, https://pdfs.semanticscholar.org/105a/06314ba6718f3d698a7620b2e891d20c00de.pdf

Student Questions

Puncturing

- Use 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 ⇒ 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 HARQ



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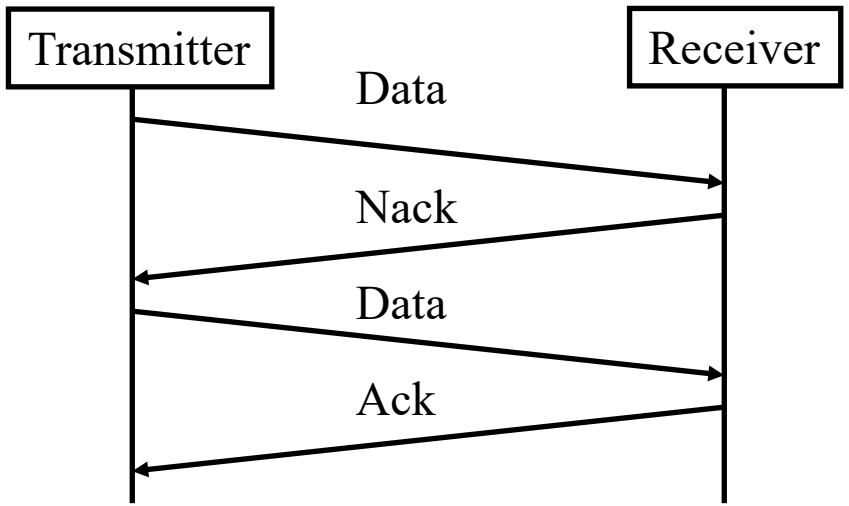
ARQ

- Automatic Repeat reQuest (ARQ)
- Retransmit a packet if it is received in error
- Previous (bad) bits are discarded.



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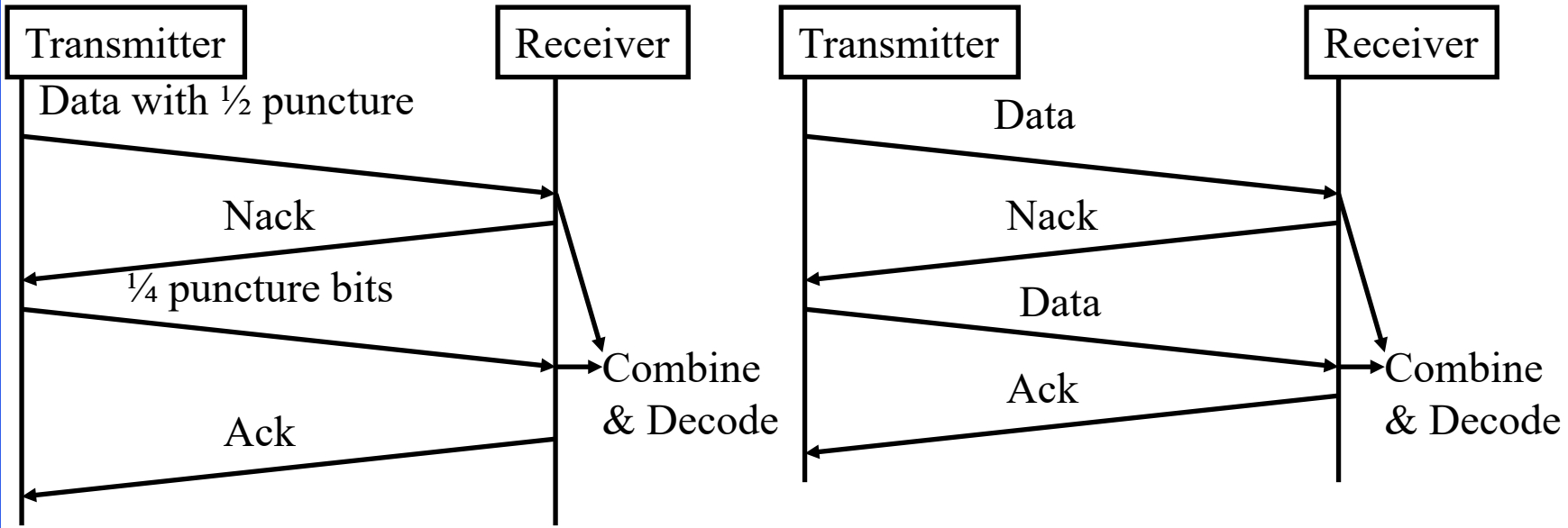
Hybrid ARQ

- 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)



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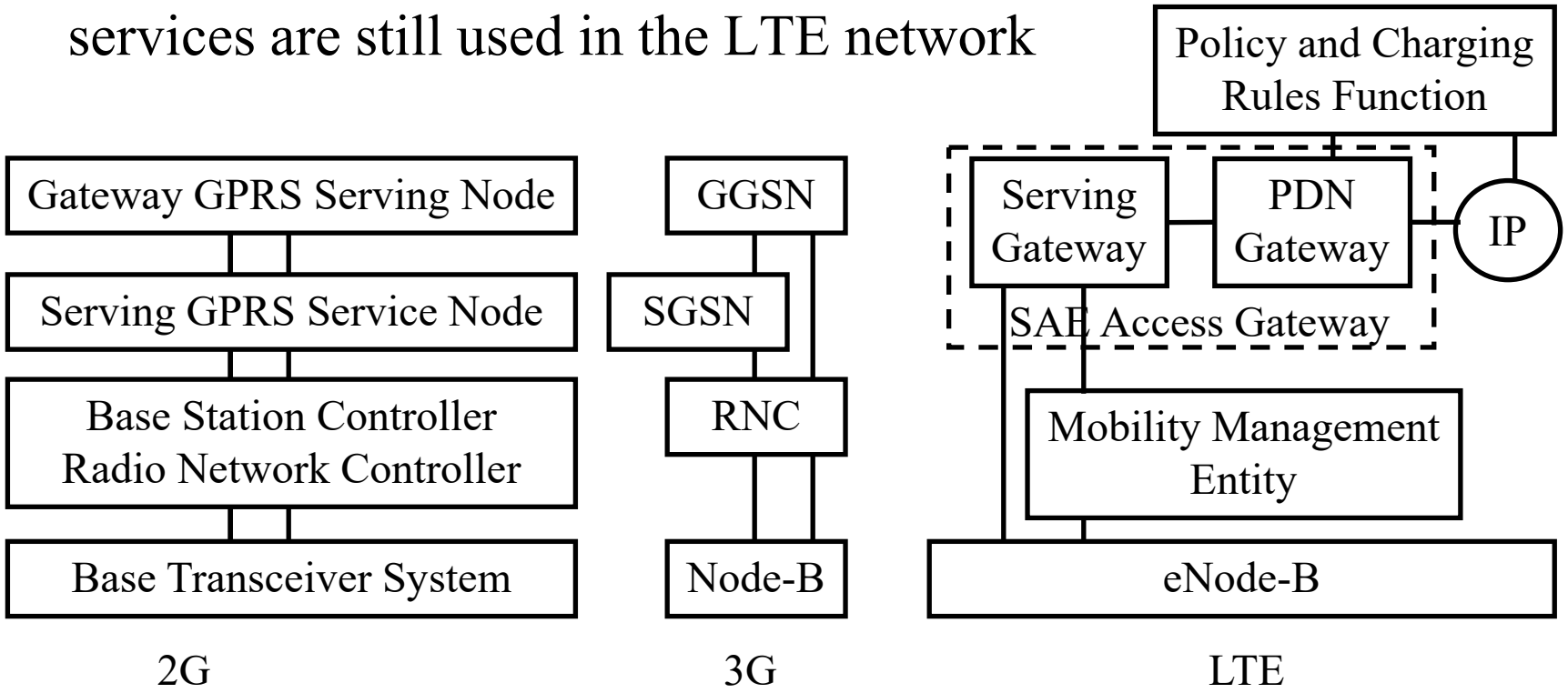
IP-Based Flat Network Architecture

- 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 the 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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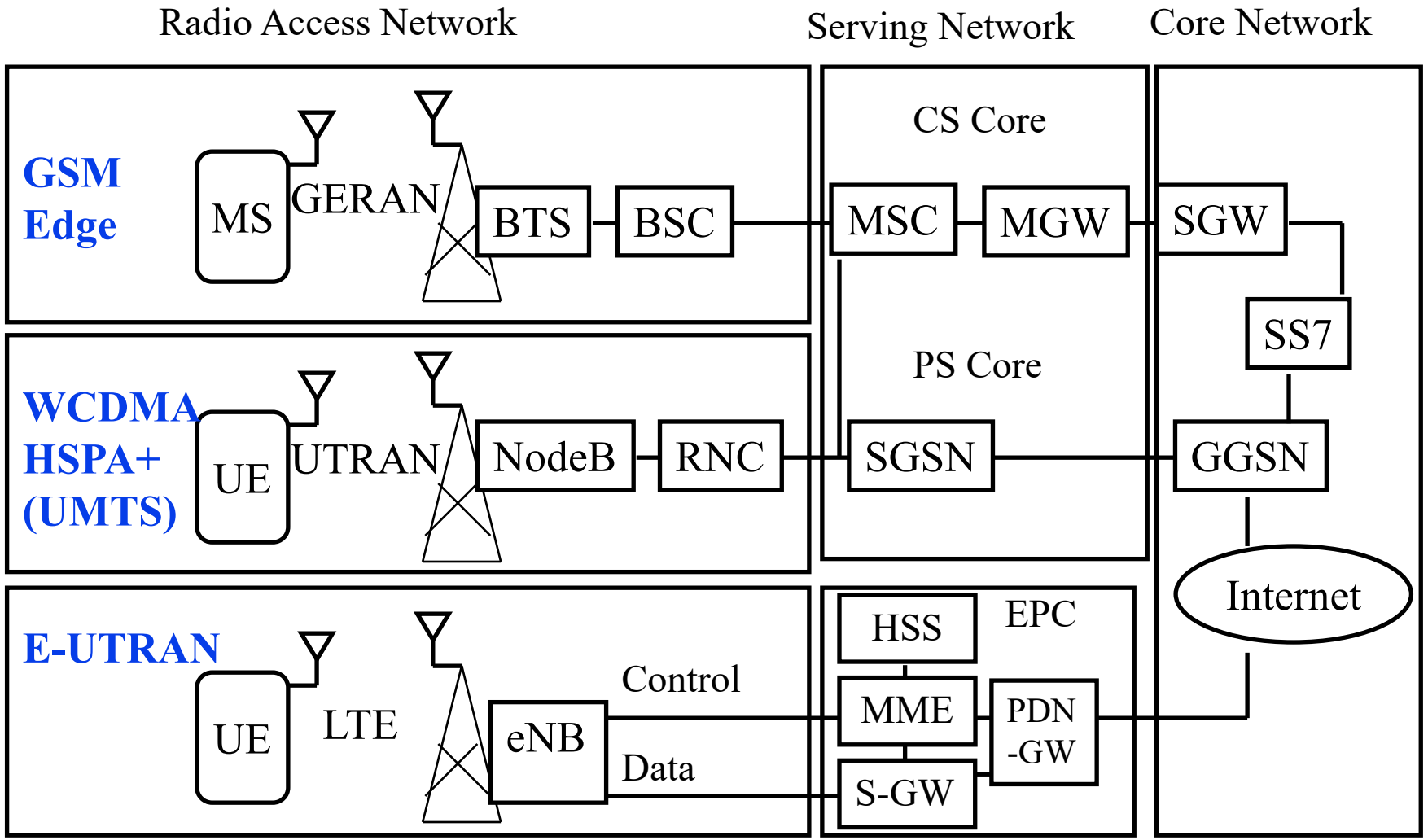
Evolved Packet System (EPS)



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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

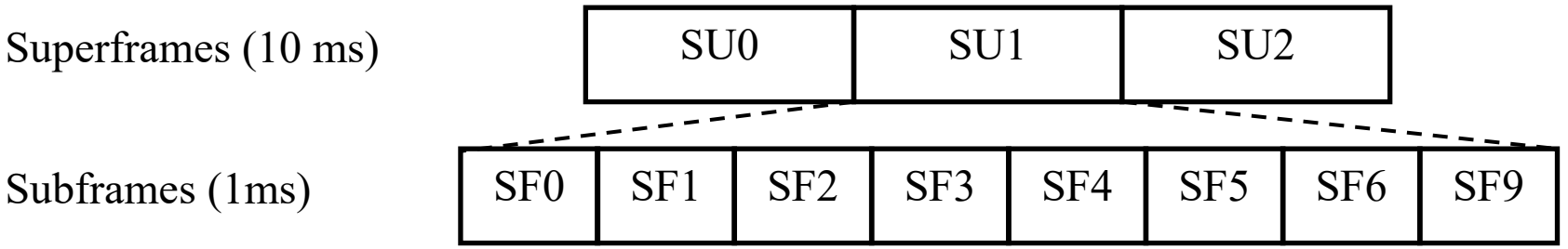
Student Questions

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.

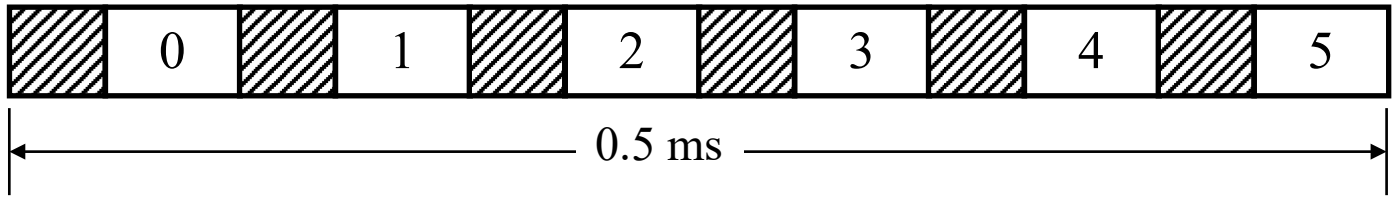
Student Questions

LTE Frame Structure



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

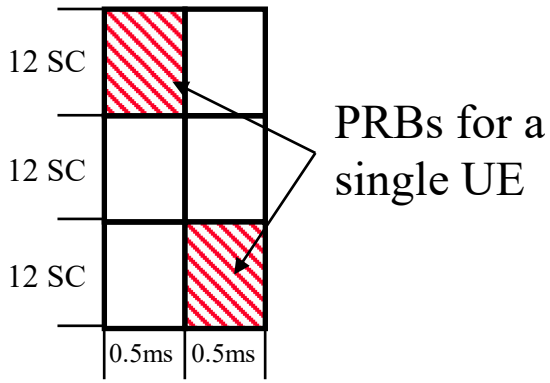


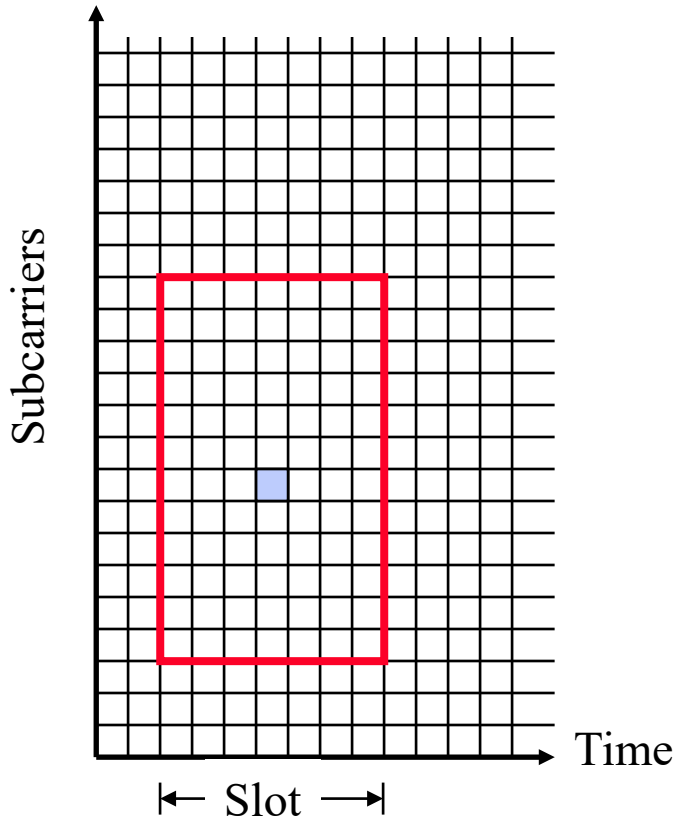
Ref: Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction,"
http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf

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

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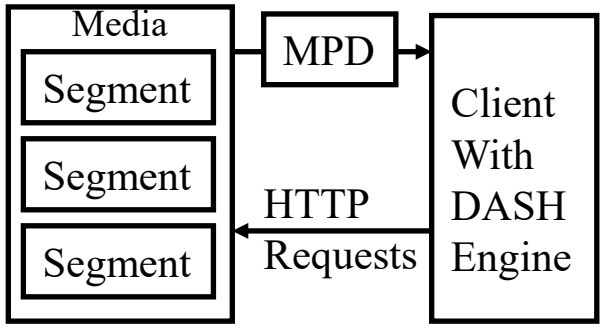
WiMAX vs. LTE

- 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

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 to servers, Content Distribution Networks (CDN), or HTTP protocol are required. 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.

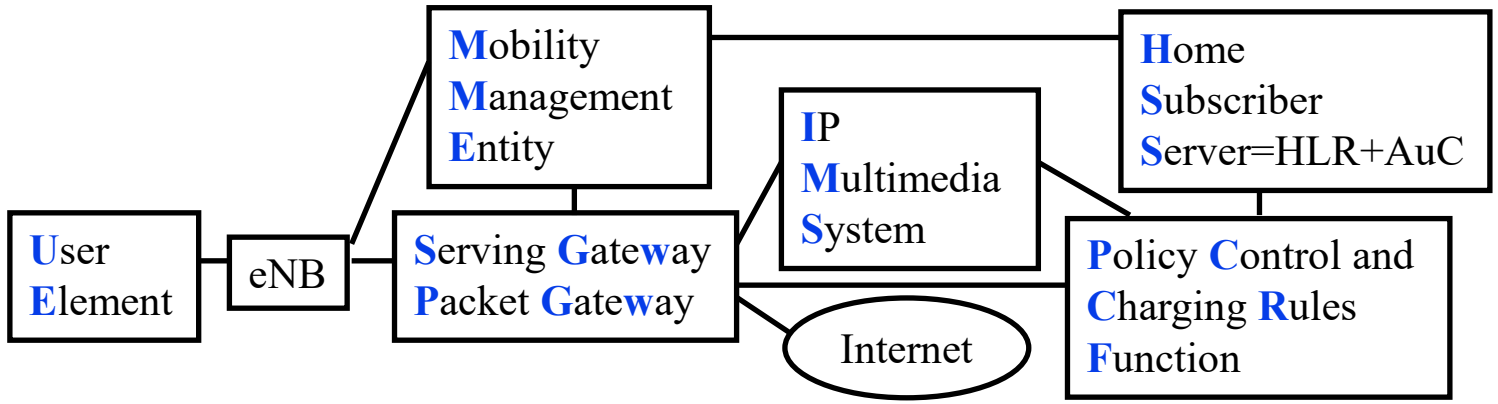


Ref: T. Stockhammer, "Dynamic Adaptive Streaming over HTTP – Standards and Design Principles," MMSys'11, Feb 2011, San Jose, CA, https://svn-itec.uni-klu.ac.at/trac2/dash/export/58/trunk/documentation/02%20mmt21da-stockhammer.pdf

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 of the uplink transmission in 4 consecutive subframes ⇒ 4x power ⇒ Improves the link budget by 6 dB ⇒ reduces the block error rate
- **Semi-persistent scheduling** saves scheduling overhead.
  Cannot adapt continuously to changing channel conditions
- **Packet Bundling**: Send only when two voice packets



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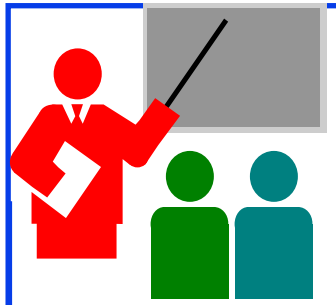

Summary

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

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.
- 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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Video Podcasts of Prof. Raj Jain's Lectures,
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