Introduction to LTE

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

http://www.cse.wustl.edu/~jain/cse574-14/

Overview

- 4G Definition
- LTE: Key Features
- OFDMA and SC-FDMA
- Resource Allocation
- Evolved Packet Core (EPC)
- LTE Frame Structure

What is 4G?

- International Mobile Telecommunication (IMT) Advanced
- Requirements in ITU M.2134-2008
- IP based packet switch network
- 1.0 Gbps peak rate for fixed services with 100 MHz
- 100 Mbps for mobile services. High mobility to 500 km/hr
- Seamless connectivity and global roaming with smooth handovers
- High-Quality Multimedia

Feature	Cell	Cell Edge	Peak
DL Spectral Efficiency (bps/Hz)	2.2	0.06	15
UL Spectral Efficiency (bps/Hz)	1.4	0.03	6.75
DL data rate w 40 MHz (Mbps)	88	2.4	600
UL data rate w 40 MHz (Mbps)	56	1.2	270

Ref: http://en.wikipedia.org/wiki/IMT-Advanced

4G Technologies

- ITU Approved two technologies as 4G (Oct 2010)
  - LTE-Advanced
  - WiMAX Release 2 (IEEE 802.16m-2011)
- LTE and WiMAX are near-4G (3.9G) and not 4G

LTE: Key Features

1. Long Term Evolution. 3GPP Release 8, 2009.
2. Initially developed as 3.9G (Pre-4G) cellular technology
   Now sold as 4G.
3. **Many different bands**: 700/1500/1700/**2100**/2600 MHz
4. **Flexible Bandwidth**: 1.4/3/5/10/15/20 MHz
5. Frequency Division Duplexing (FDD) and
   Time Division Duplexing (TDD)
   $\Rightarrow$ Both paired and unpaired spectrum
6. 4x4 MIMO, Multi-user collaborative MIMO
7. Beamforming in the downlink

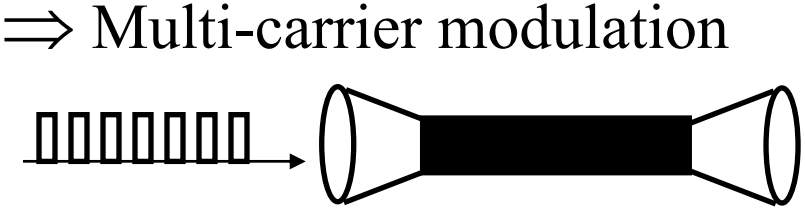
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.

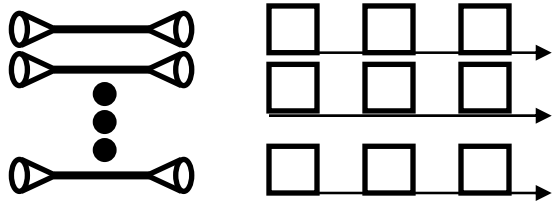
LTE: Key Features (Cont)

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

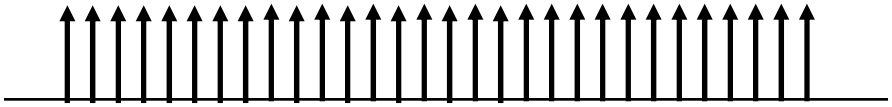
OFDM

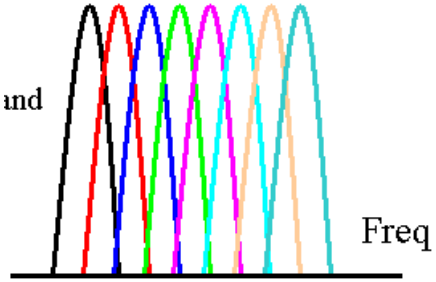
- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel
  ⇒ Multi-carrier modulation





- Frequency band is divided into 256 or more sub-bands.
  Orthogonal ⇒ Peak of one at null of others
- Each carrier is modulated with a BPSK, QPSK, 16-QAM, 64-QAM etc depending on the noise (Frequency selective fading)
- Used in 802.11a/g, 802.16,
  Digital Video Broadcast handheld (DVB-H)
- Easy to implement using FFT/IFFT





OFDM Advantages

1. Larger symbol sizes
   ⇒ **Reduced inter-symbol interference** due to multipath
   ⇒ Insensitivity to multipath ⇒ Allows better MIMO
2. **Low computational complexity**: Easily implemented with fast Fourier transforms (FFT) and Inverse FFT.
3. **Graceful performance degradation** under excessive delay spreads. Possible to fall back to lower coding schemes
   ⇒ Ideal for adaptive modulation and coding
4. **Frequency diversity**: Data is spread across subcarriers
   ⇒ robust against burst errors
5. Robust against **narrowband** interference

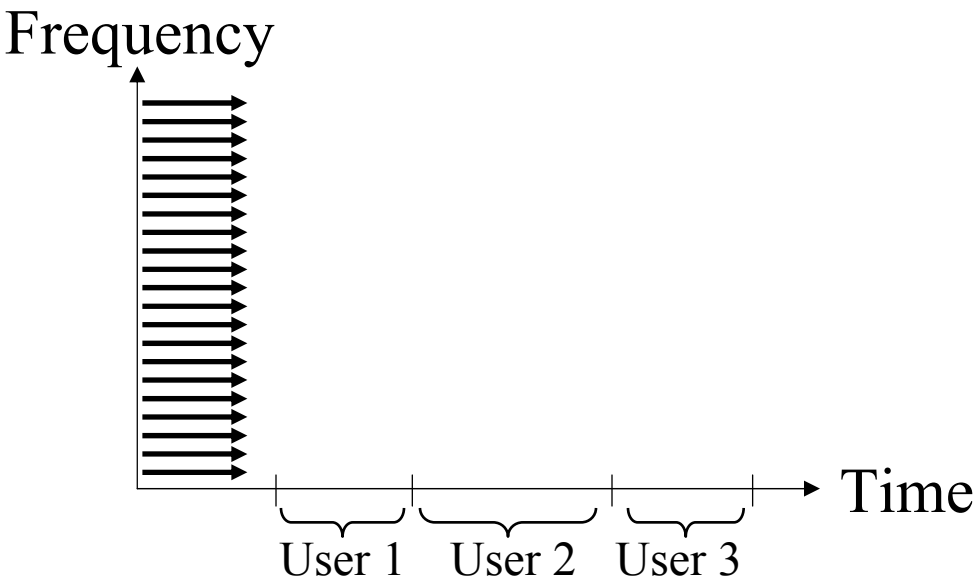
OFDM Advantages (Cont)

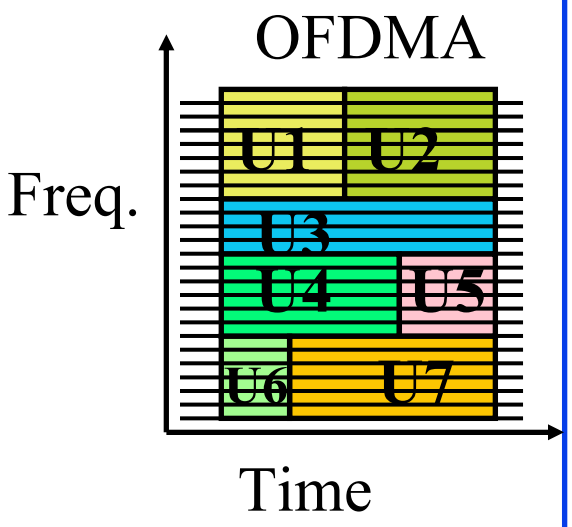
6. Allows pilot subcarriers for channel estimation
7. Efficient multiple access: OFDMA can be used for resource allocation
8. Efficient Broadcast: Multiple base stations can synchronize to combine their transmitted signals enabling higher broadcast data rates

- Disadvantage: High Peak-to-Average Ratio (PAPR)
  $\Rightarrow$ Expensive amplifiers

OFDMA

- Orthogonal Frequency Division Multiple Access
- Each user has a subset of subcarriers for a few slots
- OFDM systems use TDMA
- OFDMA allows Time+Freq DMA ⇒ 2D Scheduling





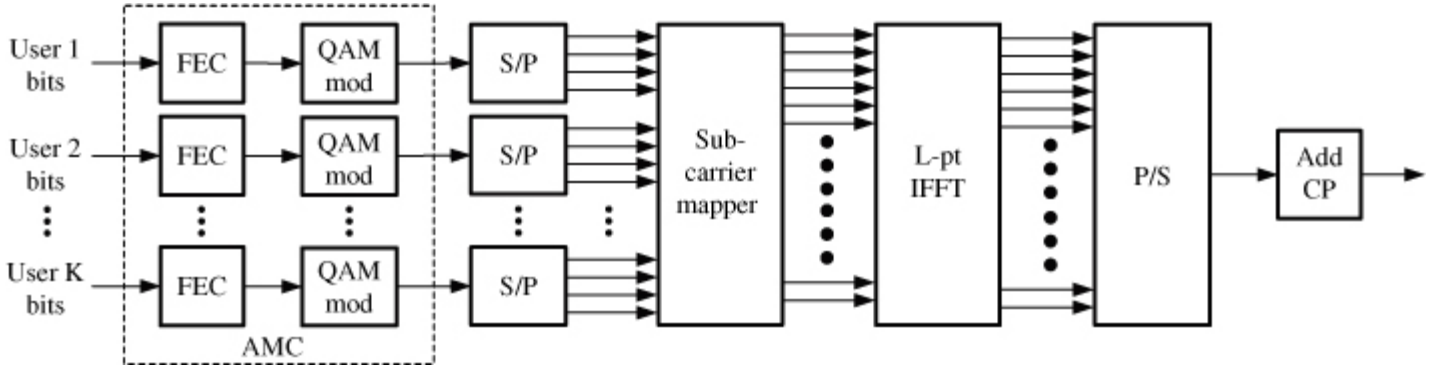
CDMA vs. OFDMA

- LTE uses OFDMA in the downlink

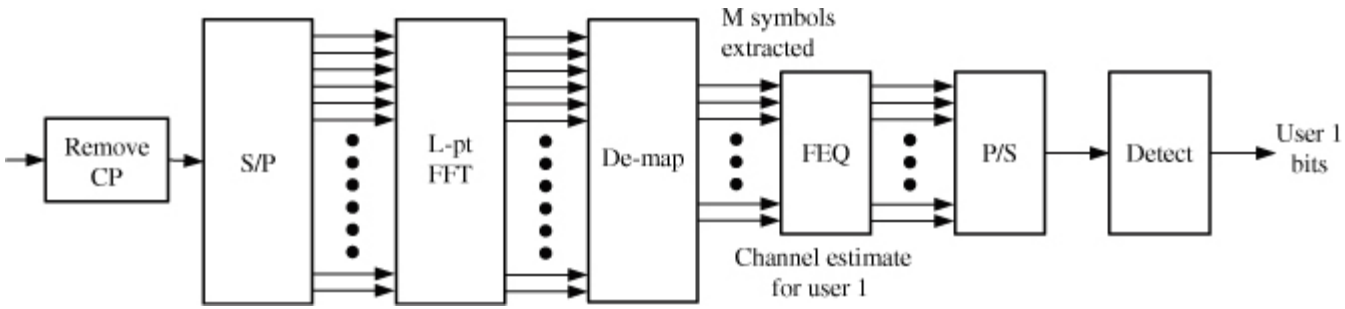
Feature	CDMA	OFDMA
Frequency Selective	No	Yes
Symbol period	Short	Long
Equalization	Easy up to 5 MHz	Easy for any bandwidth
Resistance to Multipath	Difficult above 5 MHz	East with proper cyclic prefix
MIMO	Difficult	Easy
Frequency Distortion	Averaged	Inter-carrier interference
User Multiplexing	Orthogonal codes	Frequency and Time

OFDMA Downlink

- Transmitter at Base Station: IFFT converts frequency to time



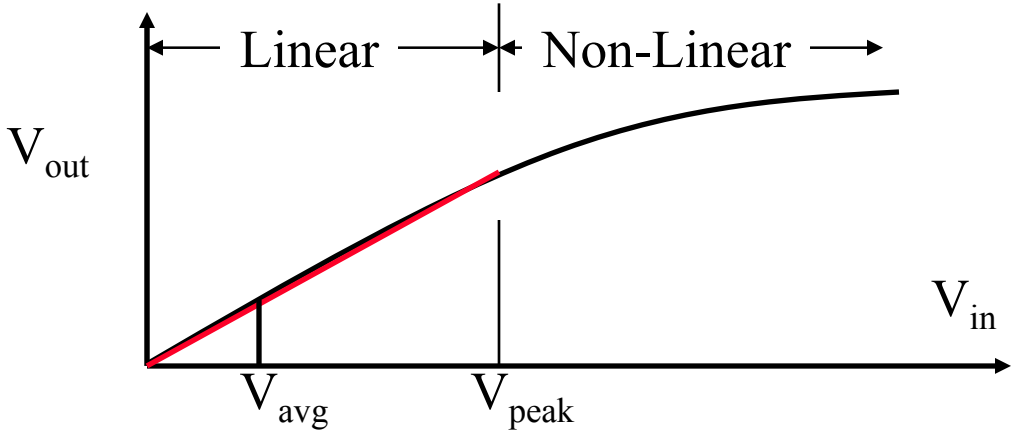
- Receiver at User Terminal: FFT converts time to frequency



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

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



SC-FDMA

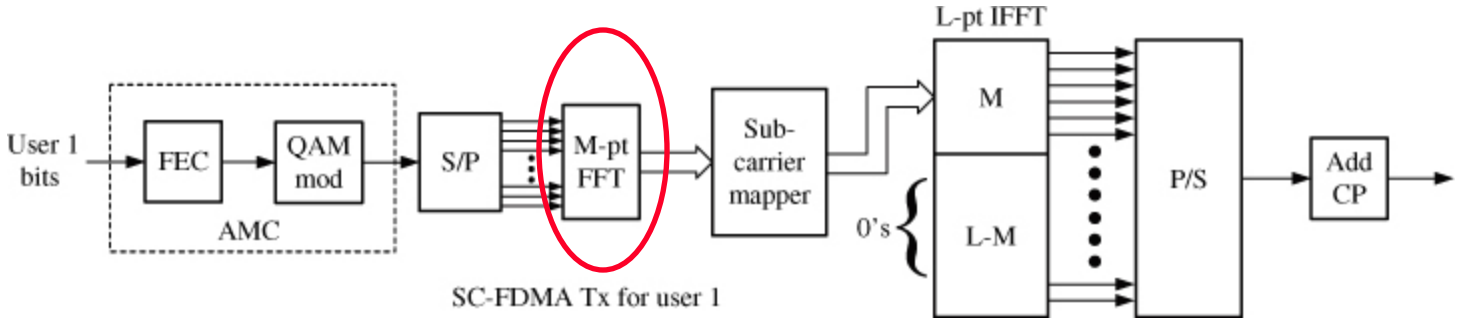
- Single-Carrier Frequency Division Multiple Access
- Each user gets a contiguous part of the channel

- 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

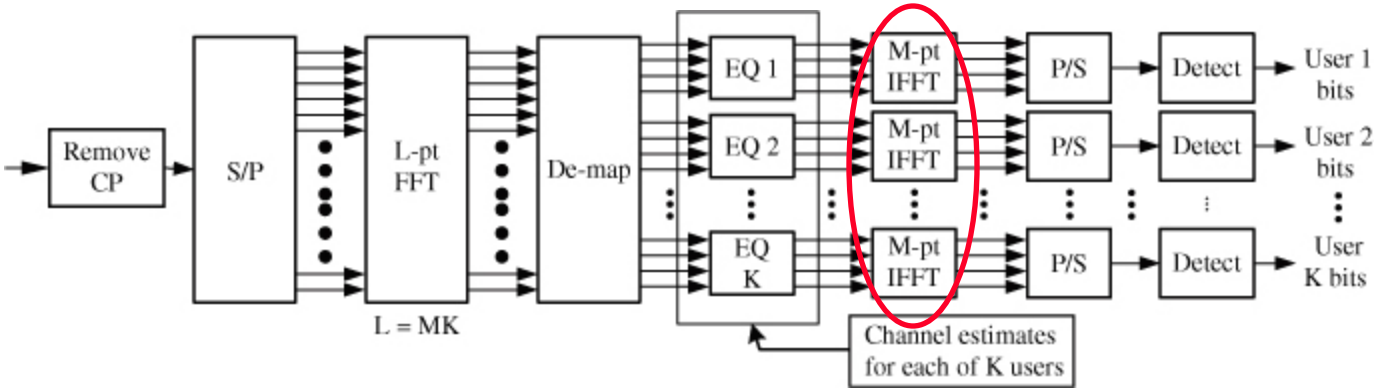
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

SC-FDMA

- 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:

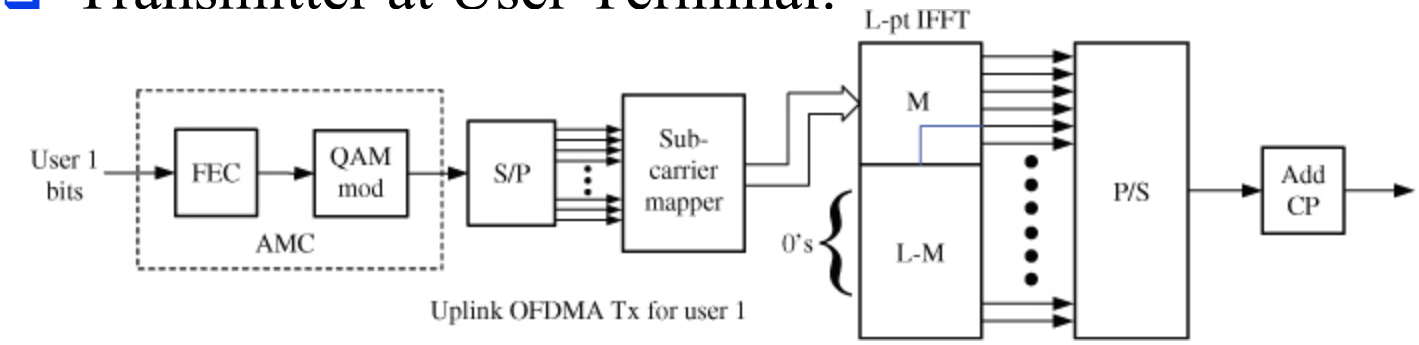


- SC-FDMA = Discrete Fourier Transform Pre-coded OFDMA

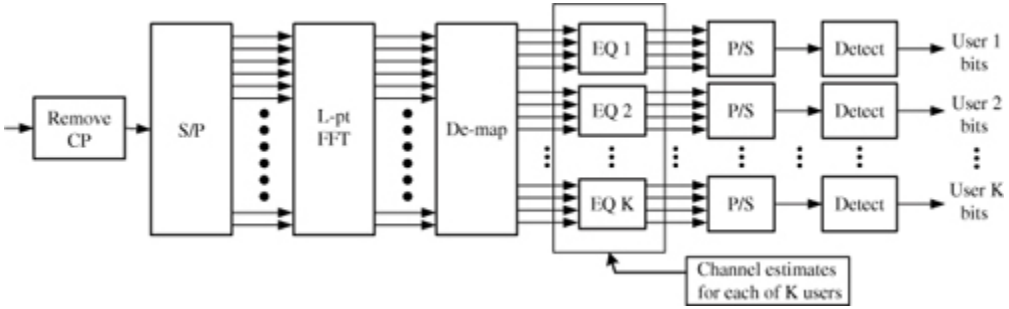
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

OFDMA Uplink

- LTE does not use OFDMA in uplink
  WiMAX uses OFDMA in uplink
- Transmitter at User Terminal:



- Receiver at the Base Station:



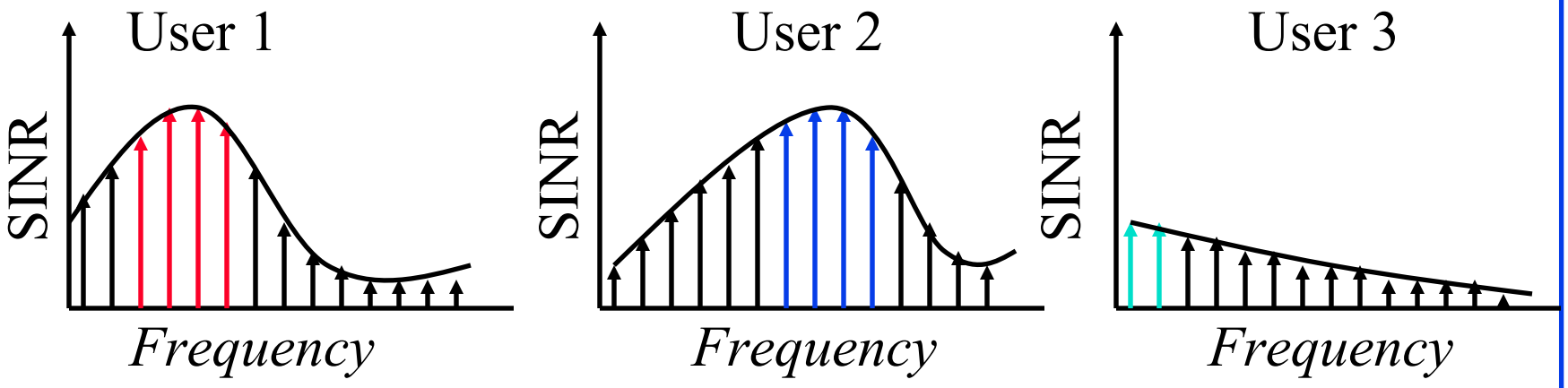
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

Channel Dependent Scheduling

- Schedule users at their best frequencies and times
  $\Rightarrow$ Optimize overall throughput
- Focus transmission power in the user's best channel portion
- Adaptive modulation and coding of each individual subcarrier depending upon the signal-to-interference and noise ratio (SINR) of that subcarrier
- By randomly distributing subcarriers over the entire band, the signal can be robust against frequency selective fading

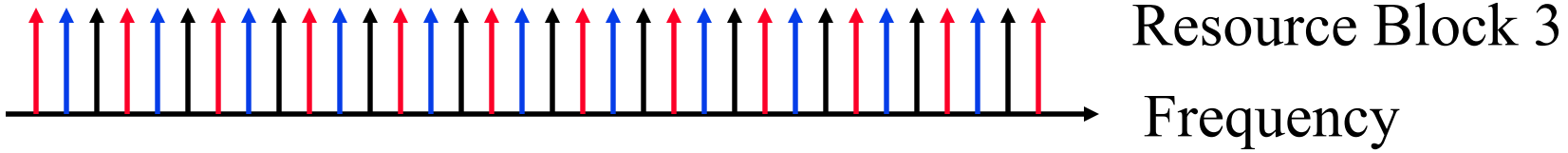
Multi-User Diversity

- Each user has a different signal to interference and noise ratio (**SINR**)
- Give each user their best frequency subcarriers to maximize their efficiency
- Select users that have high SINR to maximize total system efficiency
- Interesting scheduling with fairness and efficiency trade-offs

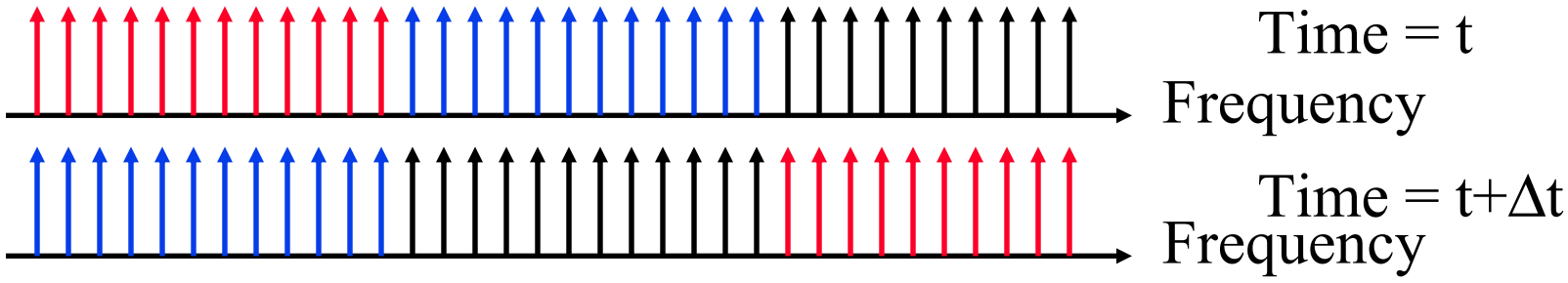


Resource Allocation (Cont)

- **Distributed** Subcarrier Allocation:

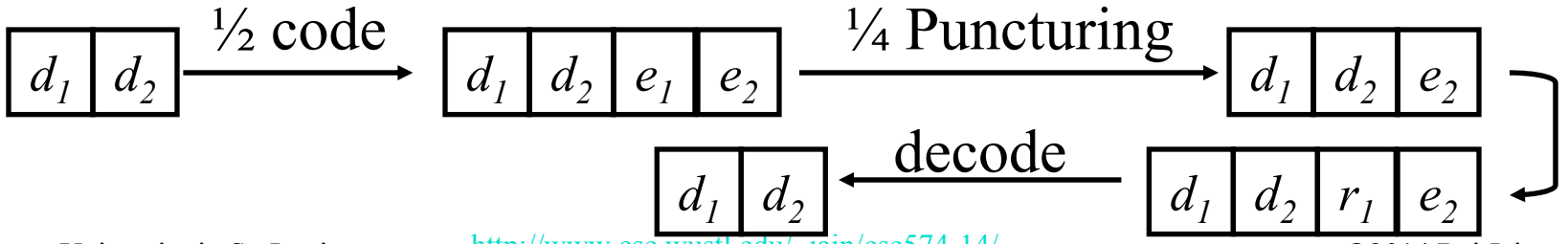


- **Contiguous** (Adjacent) Hopping Subcarrier Allocation: Uplink



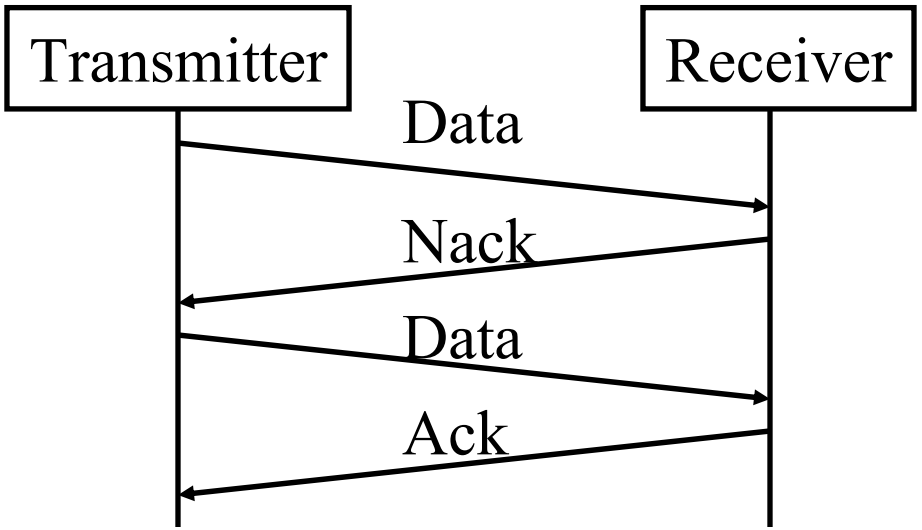
Puncturing

- 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



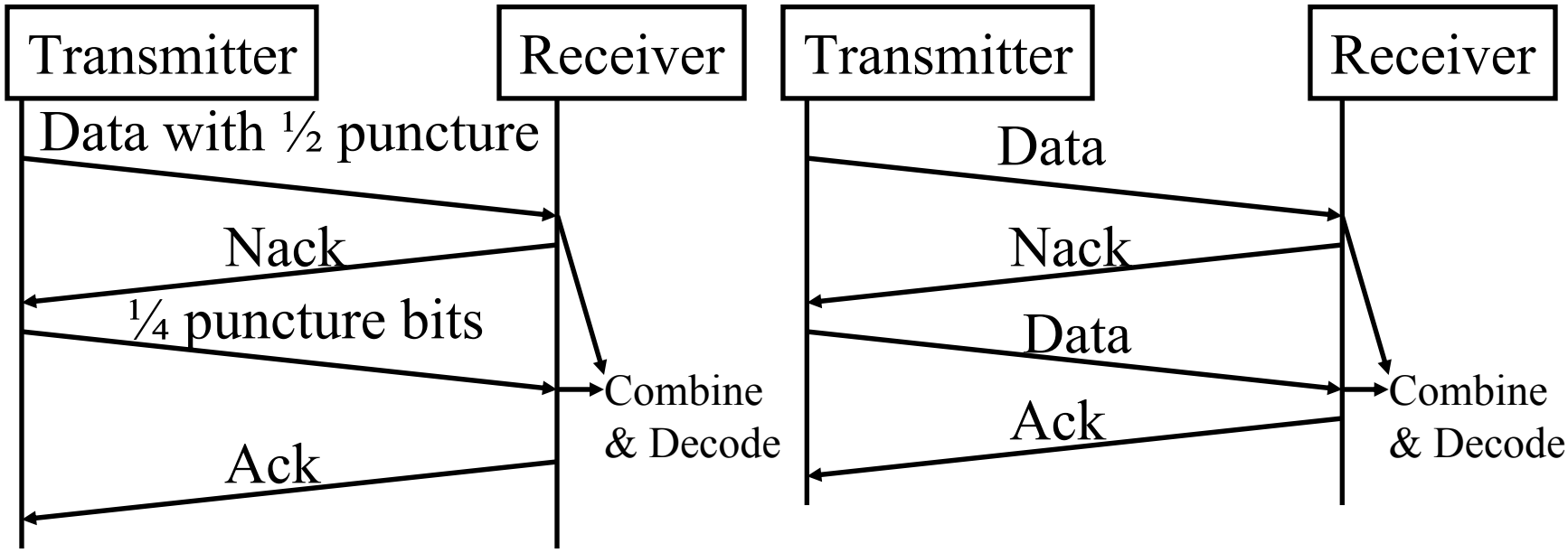
ARQ

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



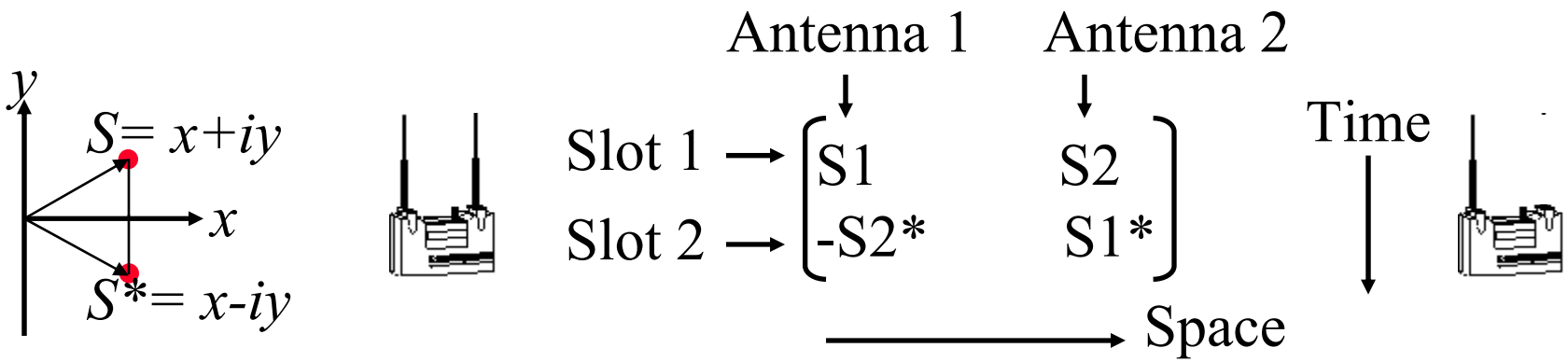
Hybrid ARQ

- 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)



Space Time Block Codes (STBC)

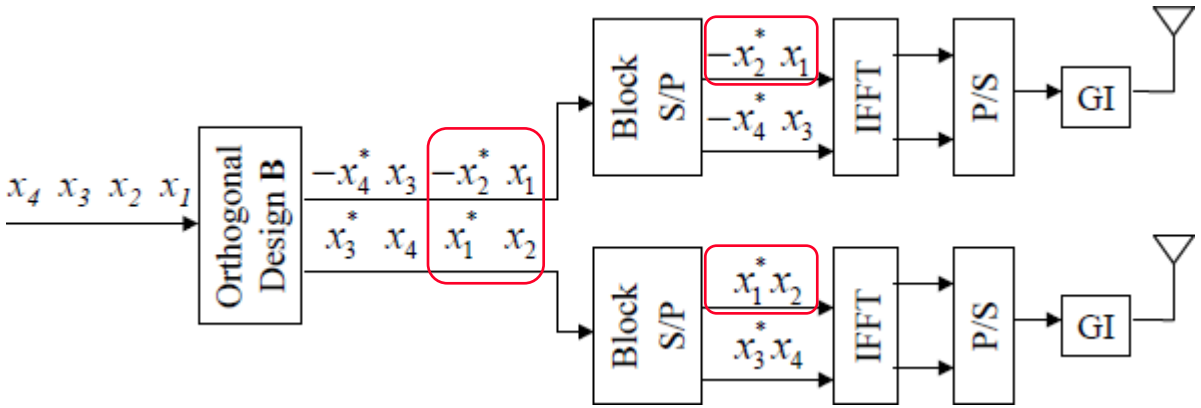
- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas: Two symbols in two slots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



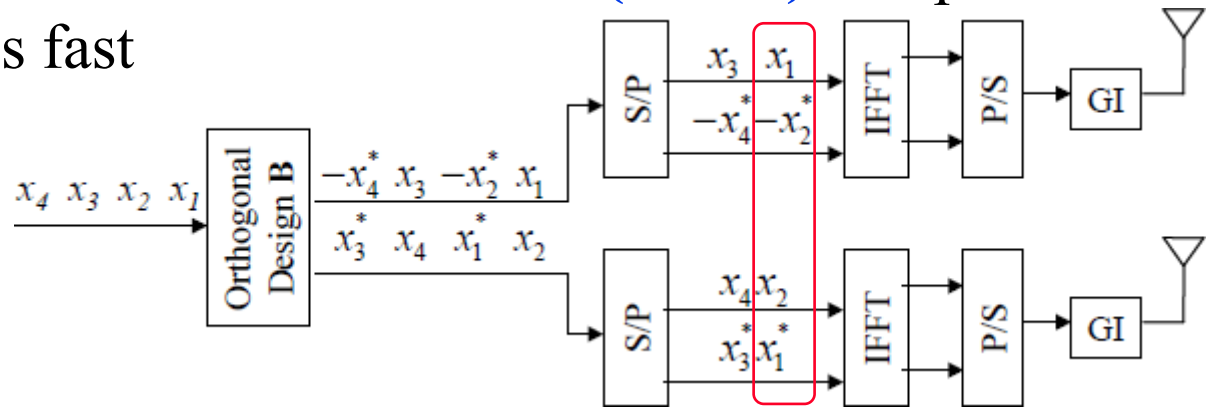
S1* is complex conjugate of S1 ⇒ columns are orthogonal

Space-Frequency Block Codes

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



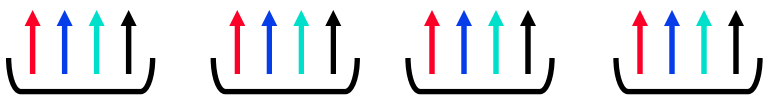
- **STBC on across subcarriers (SFBC)**: Helps if channel changes fast



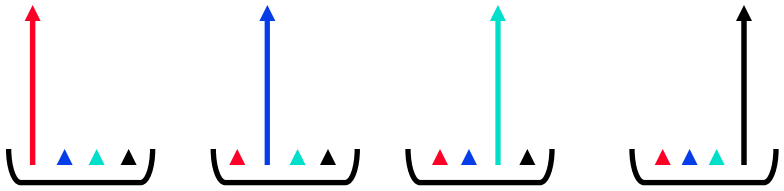
Ref: G. Bauch, "Space-Time Block Codes Versus Space-Frequency Block Codes," IEEE VTC, Apr 2003, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.2.1724&rep=rep1&type=pdf

Frequency-Shift Transmit Diversity

- Use fewer subcarriers in each slot and use higher power on those subcarriers
- 4 subcarriers with equal power in all time slots:



- FSTD:

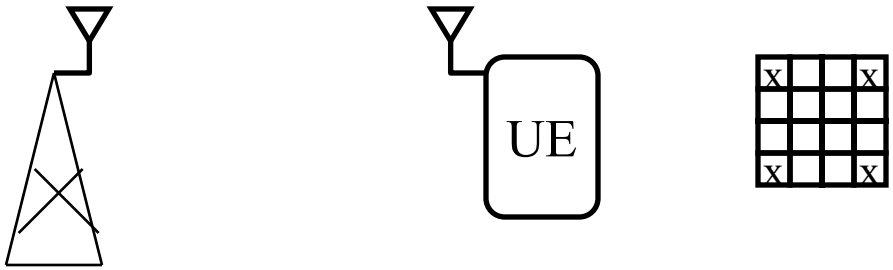


Multi-antenna Techniques

- **Transmit diversity**: Send multiple copies using space-frequency block coding (SFBC) plus Frequency-Shift Transmit Diversity (FSTD) using 4 antenna
- **Beamforming**: Focus in the direction of the receiver
- **Spatial Multiplexing**: 4×4 MIMO
- **Multi-User MIMO** for uplink

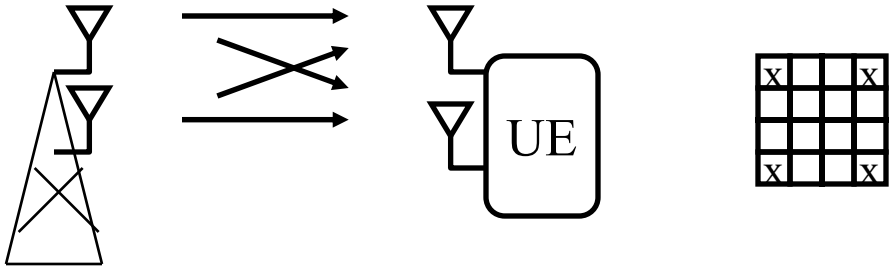
MIMO

- **SISO**



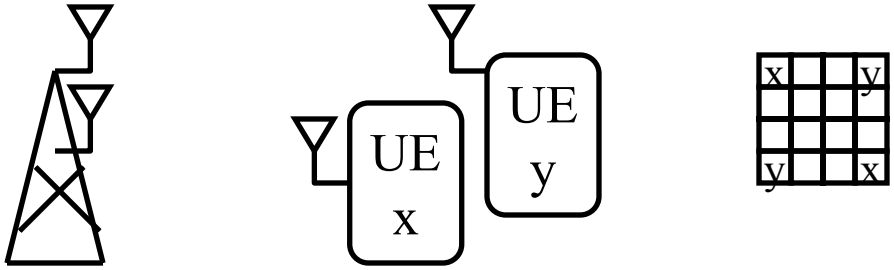
x=Pilot

- **Single User MIMO**



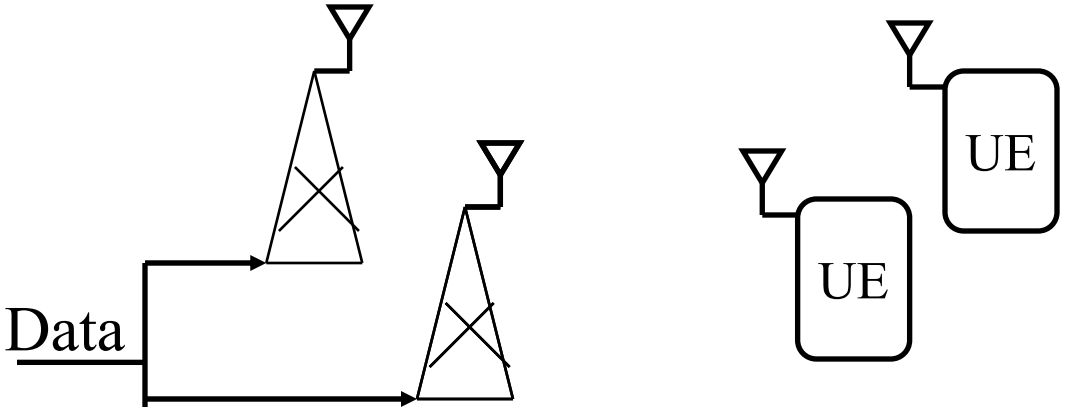
Pilots are used for channel estimation

- **Multi-User MIMO**



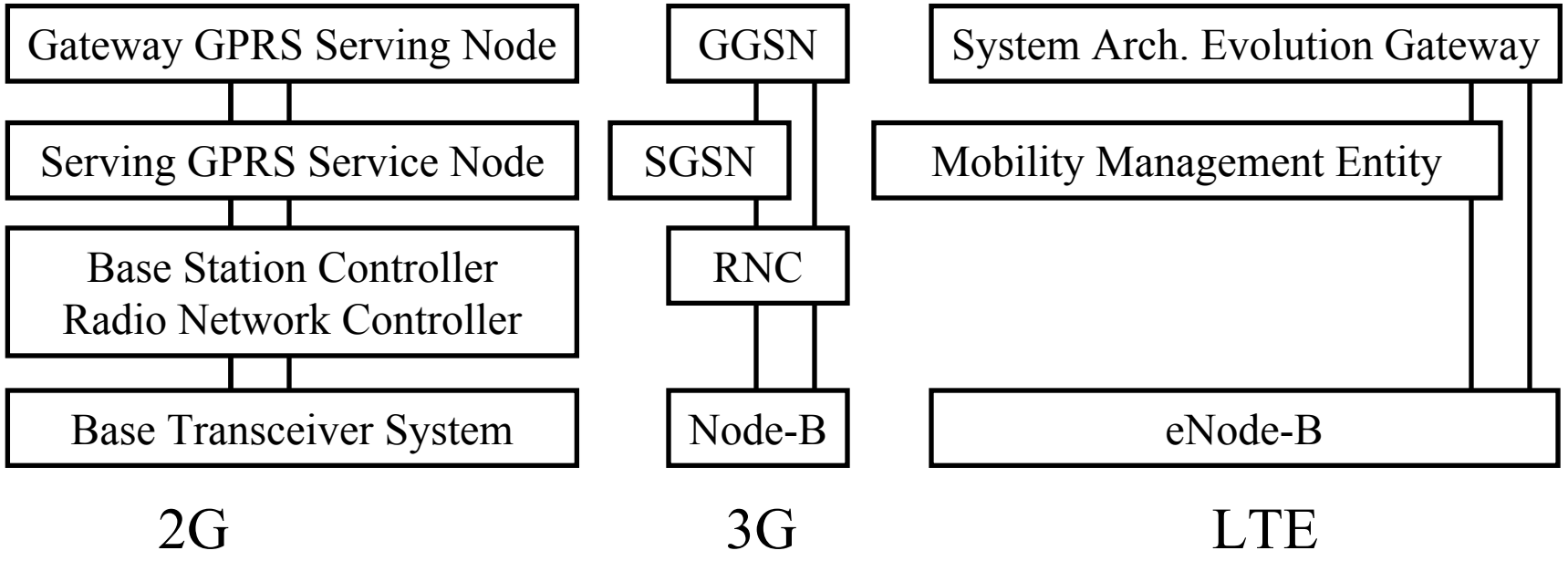
MIMO (Cont)

- **Cooperative MIMO**: Multiple towers coordinate the transmission of the data. A.k.a. networked MIMO



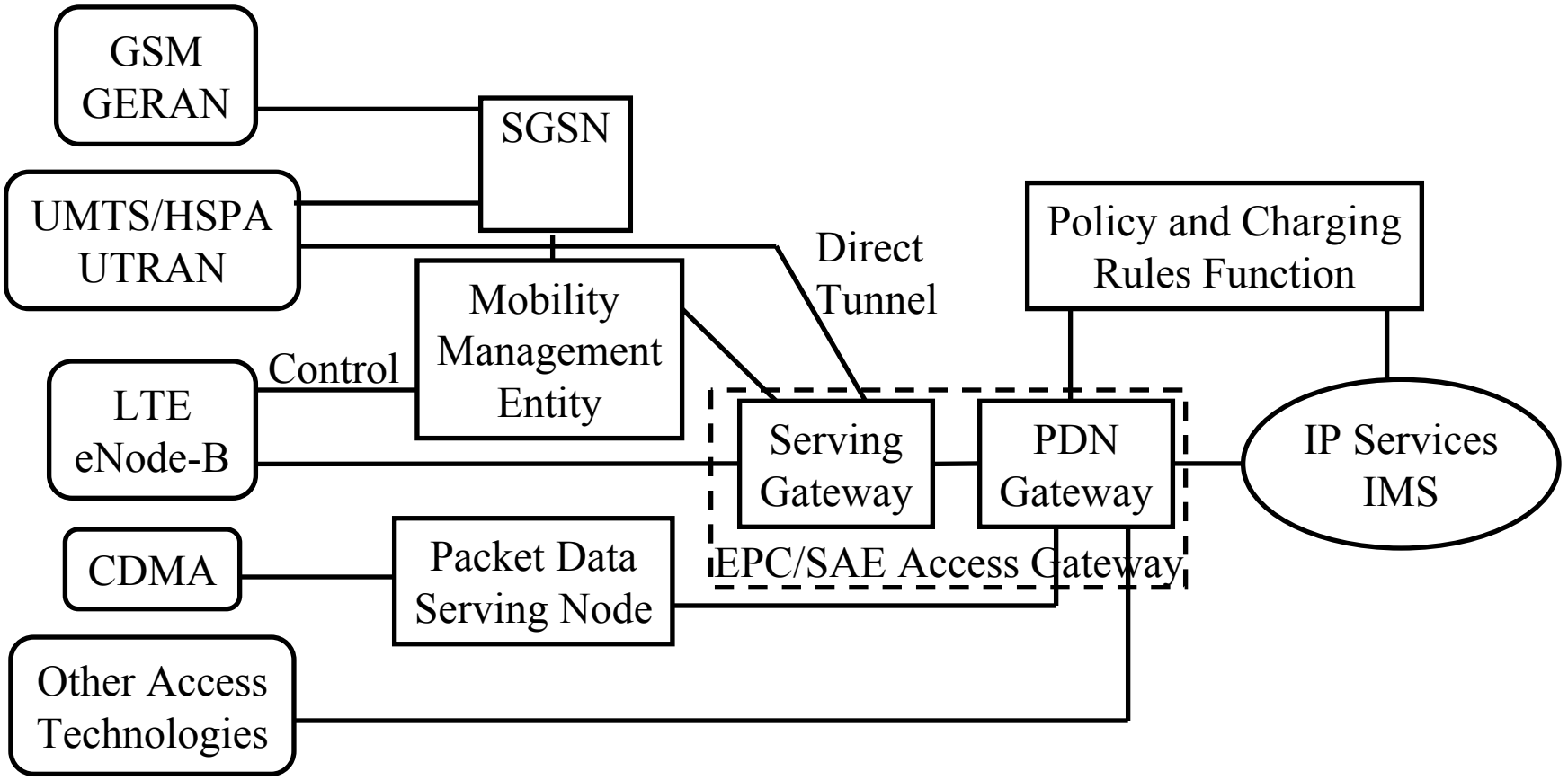
IP-Based Flat Network Architecture

- 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



Evolved Packet Core (EPC)

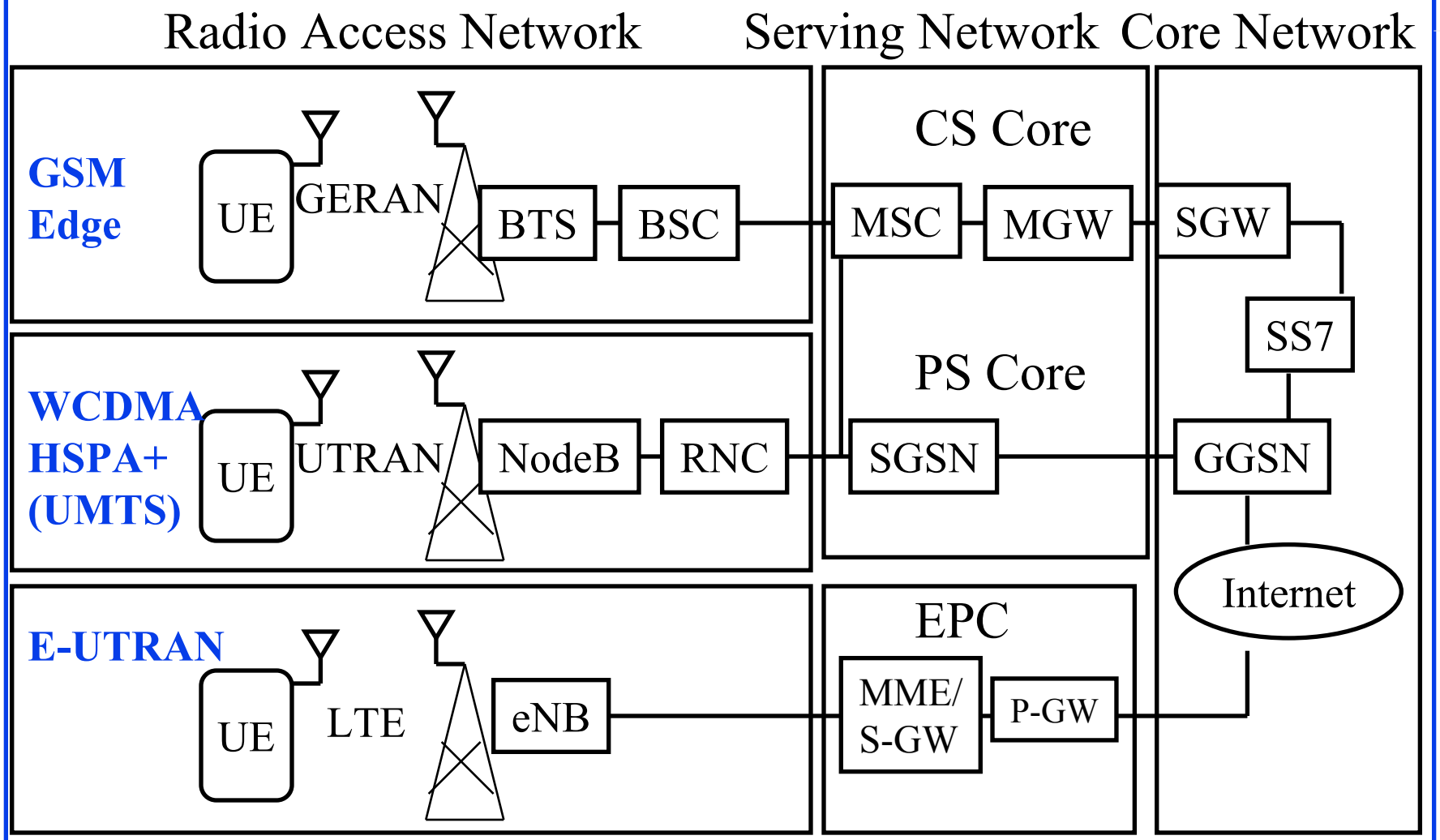
- Evolved Packet Core: IP based flat network



EPC (Cont)

- Supports new LTE and legacy 2G (GERAN) and 3G (UTRAN) networks
- 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

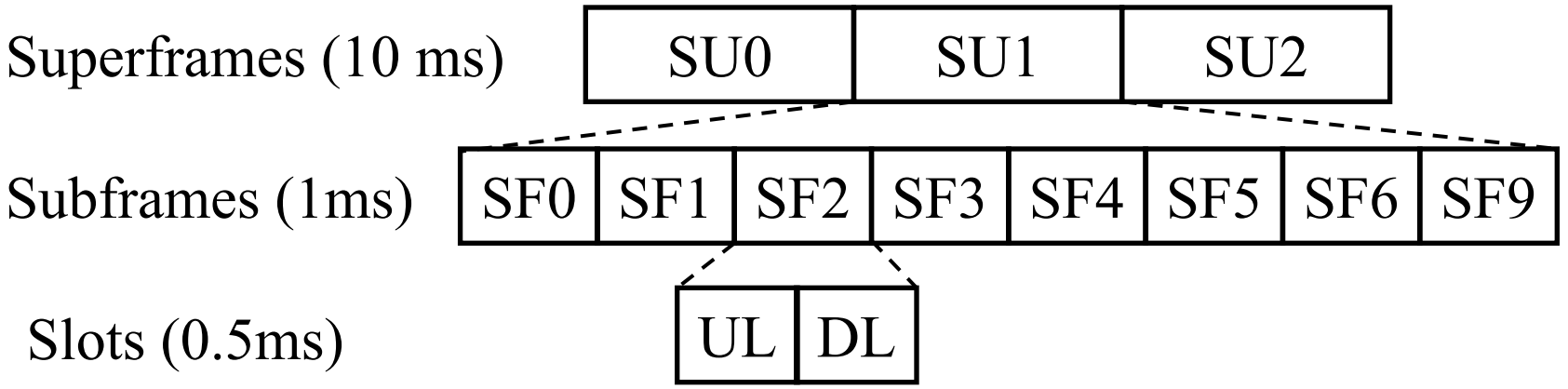
Evolved Packet System (EPS)



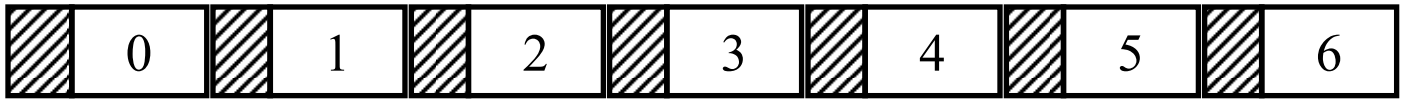
Evolved Packet System (Cont)

- CS = Circuit Switched
- EPC = Evolved Packet Core
- EPS = Evolved Packet System
- GERAN = GSM Enhanced Radio Access Network
- GGSN = Gateway GPRS Support Node
- LTE = Long Term Evolution
- MME = Mobility Management Utility
- MSC = Mobile Switching Center
- P-GW = Packet Gateway
- PS = Packet Switched
- RNC = Radio Network Control
- S-GW = Serving Gateway
- SGSN = Service GPRS Support Node
- SS7 = System 7
- eNB = Evolved NodeB

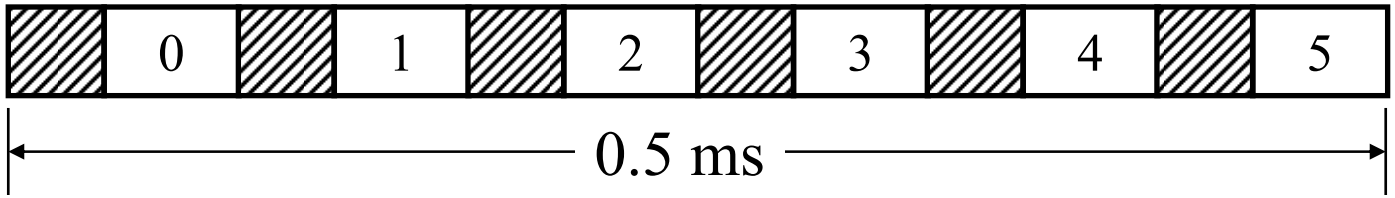
LTE Frame Structure



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



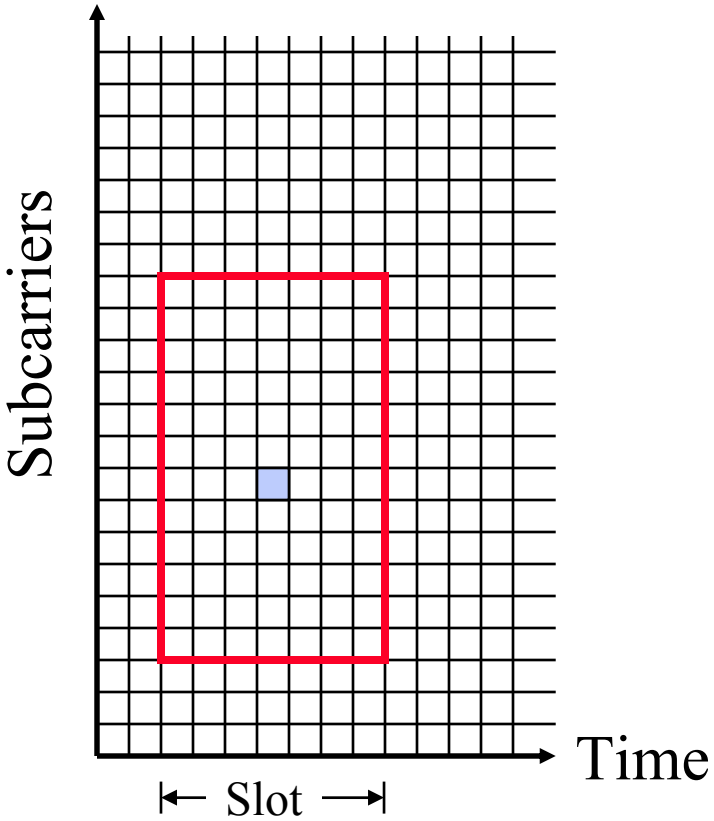
- Extended Cyclic Prefix: for larger networks. 16.7 us



Ref: Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction," http://www2.rohde-schwarz.com/file/1MA111_2E.pdf

Resource Allocation

- Time slot = 7 OFDM symbols = 0.5 ms
- Resource Block = 12 subcarriers over 1 time slot
- Subframe = 2 time slots = 1 ms



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Resource Allocation (Cont)

- Inter-carrier spacing = 15 kHz (Normal), 7.5 kHz (Multi-cell MBMS)

Cyclic Prefix	Subcarrier Spacing	Subcarriers /RB	Symbols /RB	Cyclic Prefix Time
Normal	15 kHz	12	7	5.2us for 1st symb 4.7 us for others
Extended	15 kHz	12	6	16.7 us
Extended	7.5 kHz	24	3	33.3 us

- Frame structure type II is for TDD systems compatible with Chinese TD-SCDMA systems. Not discussed here.

Ref: Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction," http://www2.rohde-schwarz.com/file/1MA111_2E.pdf

Control Channels

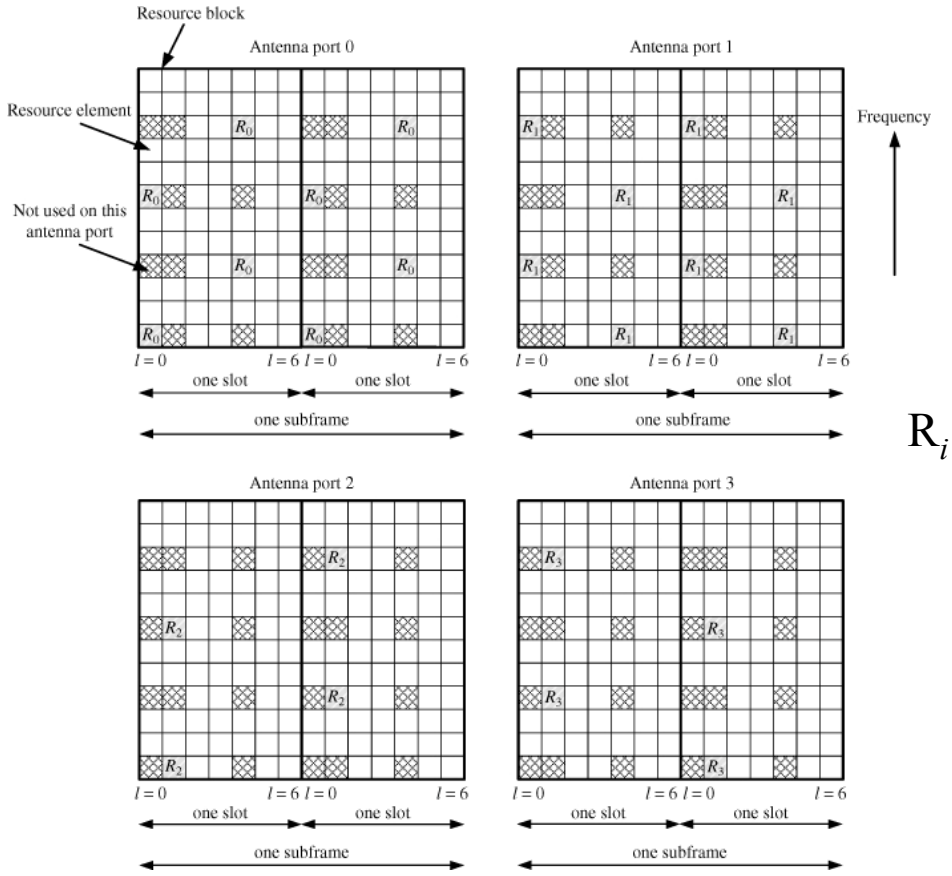
- **Downlink Control Information (DCI):** Carries downlink schedule, uplink schedule, power control, supported MIMO, etc. 10 Different DCI items.
- DCI is carried on **Physical Downlink Control Channel (PDCCH)**. Uses the first few symbols in each subframe
- **Physical Control Format Indicator Channel (PDFICH)**: First OFDM symbol of each subframe. Contains Control Format Indicator (CFI) which indicates the number of symbols for PDCCH.
- Data channels are called **transport channels**

Broadcast/Multicast Channels

- Broadcast Channels:
  - Contains all the information needed for users to join the system, e.g., bandwidth, antenna configuration, Pilot signal power, etc.
  - There is **no H-ARQ** on broadcast.
  - QPSK modulation
- Multicast Channels:
  - Mobile TV
  - Multi-cell transmission from multiple base stations
  - Uses **extended** Cyclic Prefix

Reference/Pilot Signals

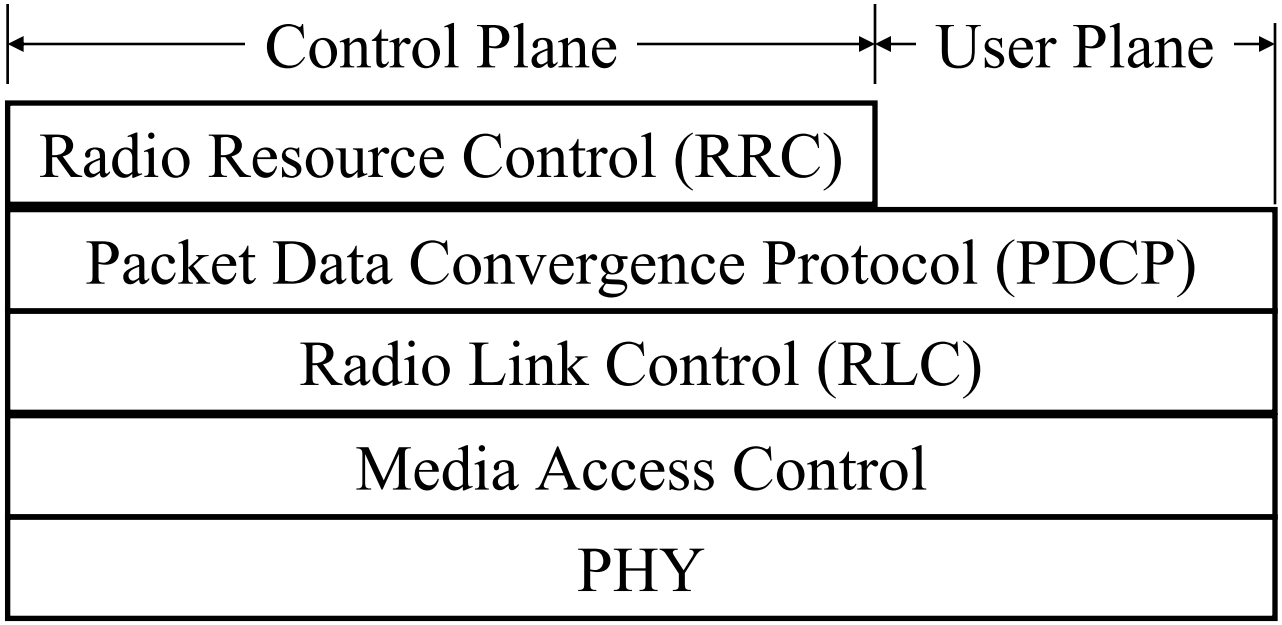
- Known symbols are inserted at predetermined pilot locations



R_i = Pilot from i^{th} antenna

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

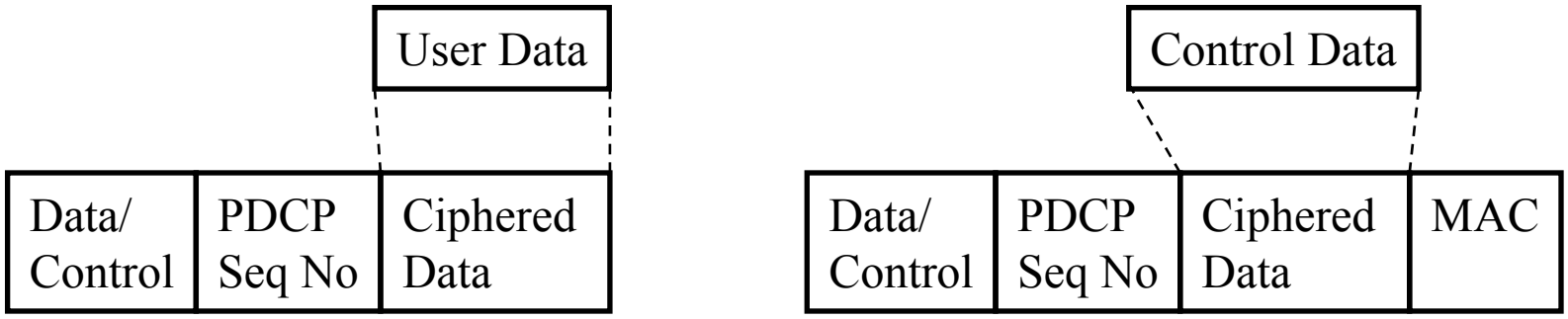
LTE Protocol Stack



- **Radio Resource Control (RRC):** Control plane functions of Paging, Connection, Disconnection, Mobility Management, QoS Management

Packet Data Convergence Protocol (PDCP)

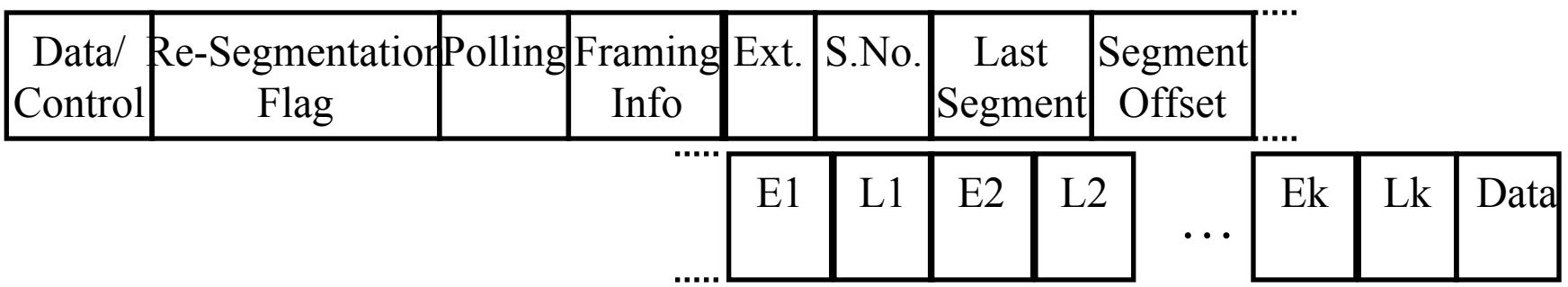
1. **Header compression** using IETF Robust Header Compression (ROHC)
2. **Integrity** Protection of control plane data using Message Authentication Code (MAC)
3. **Ciphering** (Encryption)
4. **In-sequence delivery** and duplicated elimination



Radio Link Control Layer

1. Segmentation and Reassembly
2. Aggregation (Concatenation)
3. Re-order out-of-order PDUs, ARQ.

- Three Modes:
  - **Transparent Mode**: No segmentation. No header.
  - **Unacknowledged Mode**: In-sequence delivery. No retransmission. Good for multimedia.
  - **Acknowledged Mode**

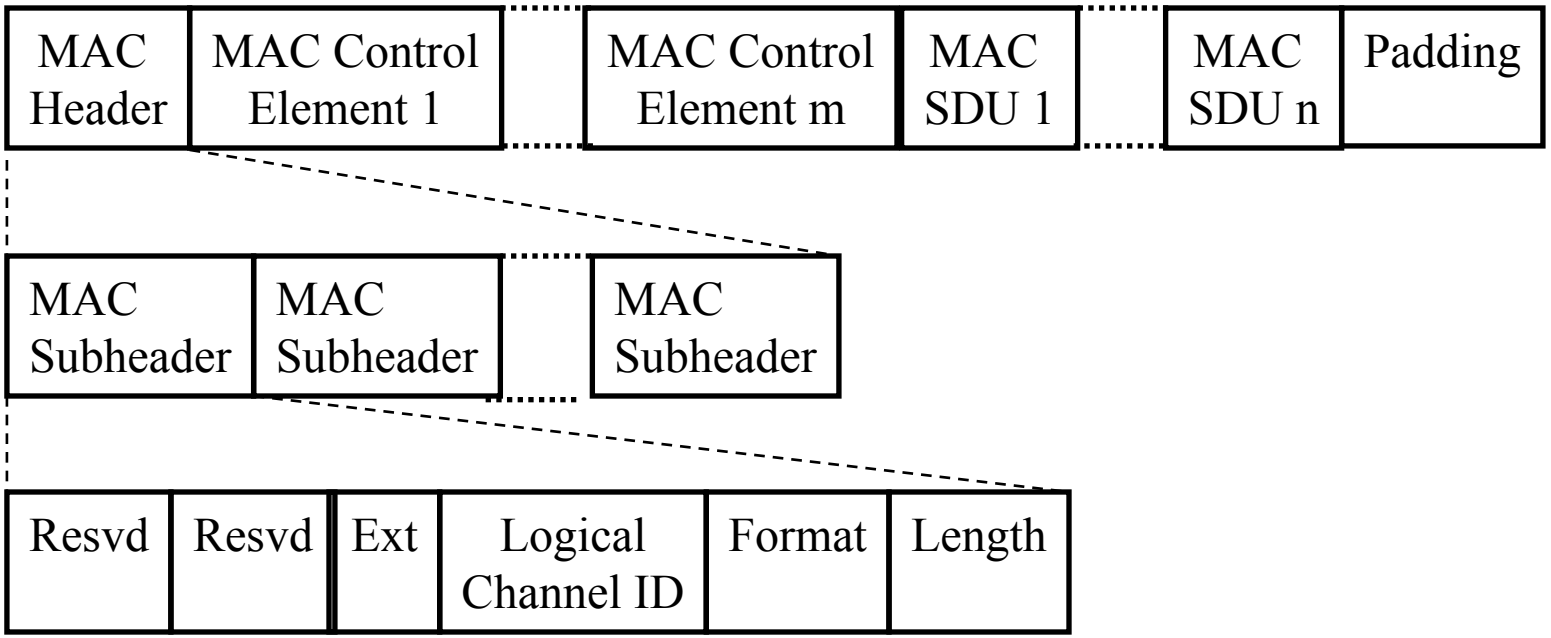


RLC (Cont)

- **Data/Control Flag**: This PDU is data or control PDU.
- **Re-Segmentation Flag**: Full or segmented PDU
- **Polling Bit**: Whether transmitter requests a status report
- **Framing Info**: SDU is segmented at the beginning and/or at the end of the data field
- **Extension Bit**: Whether Data field follows or a set of Extension field and Length Indicator fields follow
- **Sequence Number**: of the PDU
- **Last Segment Flag**: This is the last segment
- **Segment Offset**: Position of the segment in the PDU
- **Extension Bit 1**: Whether a set of NACK_SN, E, and E2 follows
- **Extension Bit 2**: Whether a set of SOstart and SOend follows
- **Negative Ack Seq No**: Sequence number of the lost PDU
- **SO Start and SO End**: Beginning and end offset of lost segment

Media Access Control (MAC)

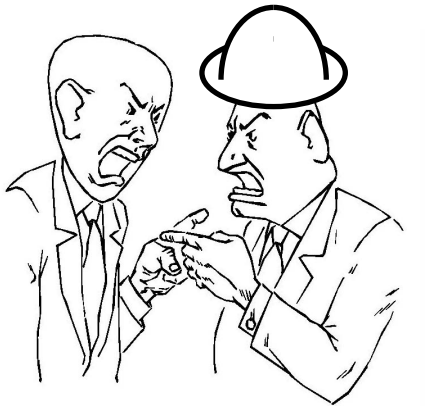
1. Multiplexing of various control and transport channels
2. Transmission scheduling
3. H-ARQ



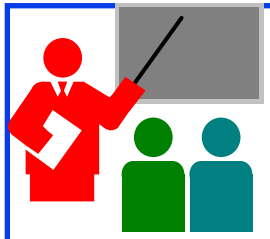
MAC (Cont)

- **Extension Flag**: More subheaders follow
- **Logical Channel ID**: Channel of the corresponding SDU
- **Format**: Indicates the size of the length field
  0 ⇒ Less than 128 byte SDU
- **Length**: Length of the SDU

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



Summary

1. 4G IMT-Advanced requires **1 Gbps** with 100 MHz for fixed services and 100 Mbps for mobile services.WiMAX and LTE are pre-4G technologies. Their next generations will be 4G.
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. **Puncturing** allows some ECC bits to be not transmitting. This is used in **H-ARQ** to send extra bits only if necessary.
4. STBC requires transmitting redundant symbols from multiple antenna. **SFBC** require that these redundant symbols be sent on different subcarriers.
5. LTE protocol stack consists of **RRC**, **PDCP** for header compression and encryption, **RLC** for segmentation and reassembly, and **MAC** for transmission scheduling.

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://www2.rohde-schwarz.com/file/1MA111_2E.pdf

Wikipedia Links

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

Wikipedia Links (Cont)

- http://en.wikipedia.org/wiki/Antenna_diversity
- http://en.wikipedia.org/wiki/Many_antennas
- http://en.wikipedia.org/wiki/Multi-user_MIMO
- http://en.wikipedia.org/wiki/Smart_antenna
- http://en.wikipedia.org/wiki/Beamforming
- http://en.wikipedia.org/wiki/Precoding
- http://en.wikipedia.org/wiki/Radio_Network_Controller
- http://en.wikipedia.org/wiki/Crest_factor
- http://en.wikipedia.org/wiki/PDCP
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- http://en.wikipedia.org/wiki/Evolved_Packet_System

Wikipedia Links (Cont)

- http://en.wikipedia.org/wiki/Channel_allocation_schemes
- http://en.wikipedia.org/wiki/Hybrid_automatic_repeat_request
- http://en.wikipedia.org/wiki/LTE_timeline
- http://en.wikipedia.org/wiki/Flat_IP
- http://en.wikipedia.org/wiki/E-UTRA
- http://en.wikipedia.org/wiki/Mobility_Management_Entity
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- http://en.wikipedia.org/wiki/Multicast-broadcast_single-frequency_network

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- http://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- http://en.wikipedia.org/wiki/Single-carrier_FDMA
- http://en.wikipedia.org/wiki/4G
- http://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing
- http://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- http://en.wikipedia.org/wiki/E-UTRA
- https://www.google.com/search?q=Cooperative+MIMO++%2Bsite%3Aen.wikipedia.org
- http://en.wikipedia.org/wiki/Cyclic_prefix

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- 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.

Acronyms

- 3GPP — 3rd Generation Partnership Project
- ARQ — Automatic Repeat Request
- BPSK — Binary Phase Shift Keying
- BS — Base Station
- BSC — Base Station Controller
- BTS — Base Transceiver Station
- CDMA — Code Division Multiple Access
- CFI — Control Format Indicator
- CS — Circuit Switched
- DCI — Downlink Control Information
- DL — Downlink
- DVB-H — Digital Video Broadcast handheld
- ECC — Error Correcting Code
- eNB — Enhanced Node B
- eNode-B — Enchanced Node B
- EPC — Evolved Packet Core

Acronyms (Cont)

- EPS Evolved Packet System
- FDD Frequency Division Duplexing
- FDMA Frequency Division Multiple Access
- FFT Fast Fourier Transform
- 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
- ID Identifier
- IEEE Institution of Electrical and Electronic Engineers
- IETF Internet Engineering Task Force
- IMS Internet Multimedia System
- IMT-Advanced International Mobile Telecommunications Advanced

Acronyms (Cont)

- IP Internet Protocol
- ITU International Telecommunications Union
- kHz Kilo Hertz
- LTE Long Term Evolution
- MAC Message Authentication Code
- MAC Media Access Control
- MBMS Multicast-Broadcast Mobile Services
- MGW Media Gateway
- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- MME Mobility Management Entity
- MSC Mobile Switching Center
- NACK Negative Acknowledgement
- OFDM Orthogonal Frequency Division Modulation
- OFDMA Orthogonal Frequency Division Multiple Access
- PAPR Peak-to-Average Power Ratio

Acronyms (Cont)

- PCRF Policy and Charging Rules Function
- PDCCH Packet Downlink Control Channel
- PDCP Packet Data Convergence Protocol
- PDFICH Physical Control Format Indicator Channel
- PDN Packet Data Network
- PDU Protocol Data Unit
- PGW Packet Data network Gateway
- PHY Physical Layer
- PS Packet Switched
- QAM Quadrature Amplitude Modulation
- QoS Quality of Service
- QPSK Quadrature Phase Shift Keying
- RAN Radio Access Network
- RLC Radio Link Control
- RNC Radio Network Control
- ROHC Robust Header Compression

Acronyms (Cont)

- RRC Radio Resource Control
- SAE Service Access Gateway
- SC-FDMA Single Carrier Frequency Division Multiple Access
- SC Single Carrier
- SDU Service Data Unit
- SFBC Space Frequency Block Code
- SGSN Service GPRS Support
- SGW Serving Gateay
- SINR Signal to Interference and Noise Ratio
- SISO Single Input Single Output
- SN Sequence Number
- SNR Signal-to-noise ratio
- SO Segment Offset
- SOstart Begining of Segment
- STBC Space Time Block Code
- TD-SCDMA Time Division Synchronous Code Division Multiple Access

Acronyms (Cont)

- TDD Time Division Duplexing
- TDMA Time Division Multiple Access
- UE User Element
- UL Uplink
- UMTS Universal Mobile Telecommunications System
- UTRA UMTS Terrestrial Radio Access
- UTRAN UMTS Terrestrial Radio Access Network
- VTC Vehicular Technology Conference
- WCDMA Wideband Code Division Multiple Access
- WiMAX Worldwide Interoperability for Microwave Access