Introduction to LTE Advanced Pro (4.5G)

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

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

http://www.cse.wustl.edu/~jain/cse574-18/

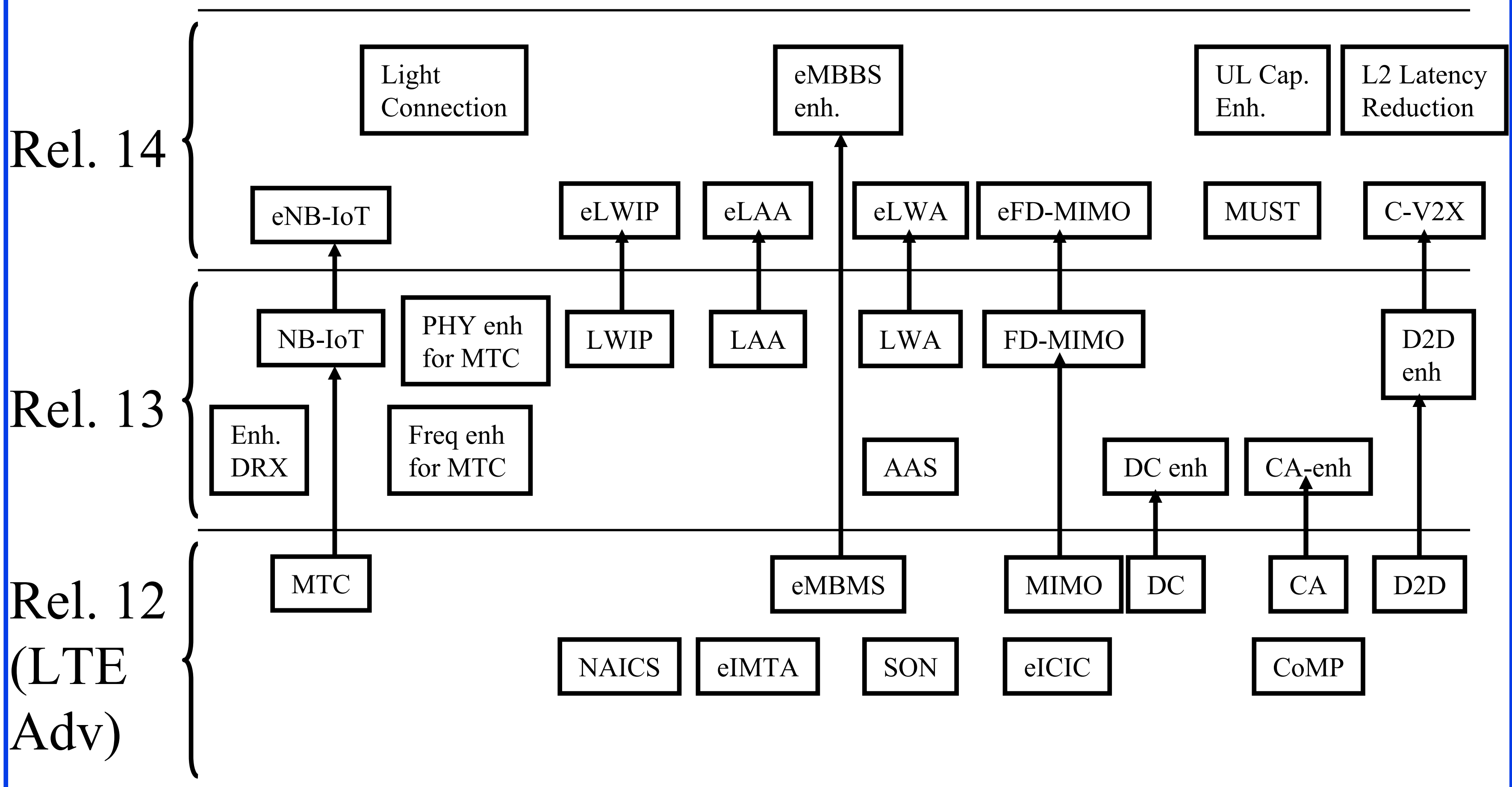
1. What is LTE Advanced Pro?
2. LTE Advanced Pro Features in 3GPP Release 13
3. LTE Advanced Pro Features in 3GPP Release 14

Note: This is the 4th module in a series of lectures on 1G to 5G. 5G is covered in the next module.

3GPP Releases

- **Rel. 8-9**: LTE
- **Rel. 10-12**: LTE-Advanced (4G)
- **Rel. 13-14**: LTE Advanced-Pro (**4.5G**)
- **Rel. 15-16**: LTE NR (5G)

LTE Advanced Pro



Ref: Rohde & Schwarz, "LTE-Advanced Pro Introduction eMBB Technology Components in 3GPP Release 13/14," White paper, 50 pp., https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/LTE-Advanced-Pro_Introduction_White_paper_en_5215-8258-52_v0100.pdf

Release 13 Features

1. Active Antenna Systems (AAS)
2. Self-Organizing Networks (SON)
3. Elevation Beamforming
4. Inter-eNB CoMP
5. Indoor Positioning
6. Carrier Aggregation Enhancements
7. License Assisted Access (LAA)
8. LTE-WLAN Aggregation Enhancements
9. Wi-Fi with IP Flow Mobility
10. RAN Sharing
11. Enhanced D2D Proximity Services (PROSE)
12. Dual Connectivity Enhancements
13. MTC Enhancements
14. Single-Cell Point-to-Multipoint (SC-PTM)

Release 14 Features

1. Enhance Narrowband IoT (eNB-IoT)
2. Enhanced Machine Type Communications (eMTC)
3. Enhanced LWIP (eLWIP)
4. Enhanced LTE-WLAN Aggregation (eLWA)
5. Enhanced License Assisted Access (eLAA)
6. Enhanced Full-Dimension (eFD) MIMO
7. Enhanced Multimedia Broadcast Multicast Service (eMBMS)
8. **Multiuser Superposition Transmission (MUST)**
9. **Layer 2 (L2) Latency Reduction**
10. **Vehicle to Vehicle (V2X) Based on Sidelink**
11. Uplink (UL) Capacity Enhancements
12. Light Connection

Active Antenna Systems (AAS)

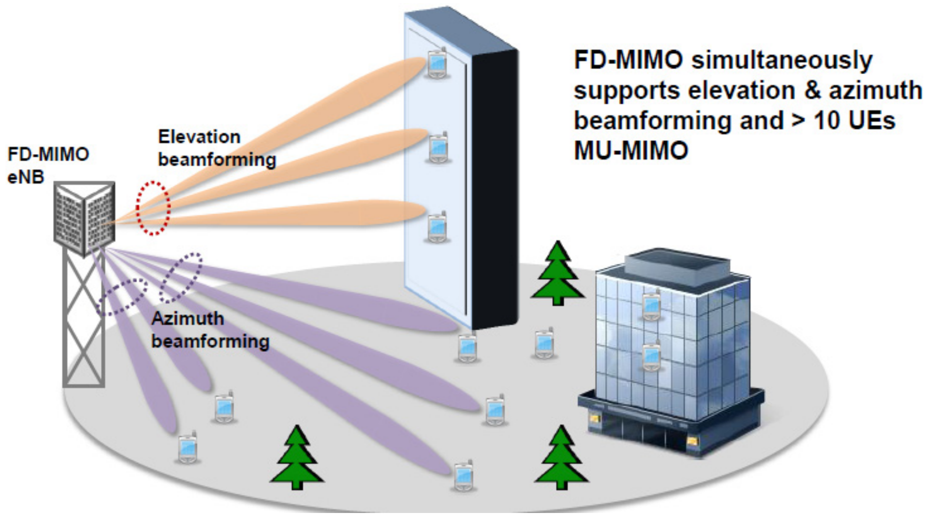
- Antenna + Transceiver combined $\Rightarrow$ Active Antenna
- Allows Active antenna arrays
  - Produce dynamically adjustable radiation patterns depending upon the current traffic
  - Beam footprint can be adjusted (beamforming)
  - Cell edge can be adapted to load demand
  - Dynamic Cell Splitting: Vertical or horizontal sectors and/or Smaller footprints $\Rightarrow$ Reduced real-estate costs
  - Software reconfigurations allow easy evolution
- Allows multi radio access technologies
- Allows combining local and wide area technologies

Self-Organizing Networks (SON)

- For AAS based deployments
- Parameters are now dynamically computed and applied
- Previous releases had static optimization.
  Release 13 extended to dynamic optimization
- eNB can now signal to neighboring cells any changes in configuration
- Planned changes are notified in advance to avoid failures

Elevation Beamforming

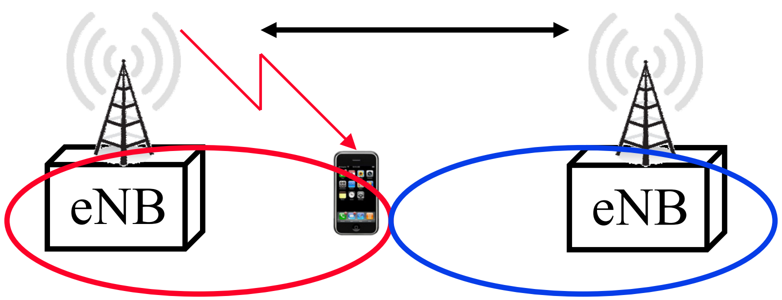
- Aka 3D-MIMO or Full-dimension MIMO (**FD-MIMO**)
- Infinite Antennas = **Massive MIMO**
- Require appropriately coded Channel State Information Reference signals (CSI-RS) and Sounding Reference Signals (SRS), and demodulation reference signals (DMRS)
- 16 Antennas in R13, 32 in R14



Ref: G. Xu, et al, "Full-Dimension MIMO: Status and Challenges in Design and Implementation," May 2014, http://www.ieee-ctw.org/2014/slides/session3/CTW_2014_Samsung_FD-MIMO.pdf

Inter-eNB CoMP

- Coordinated Multipoint Operation (CoMP) in Release 11 was restricted to eNBs connected via ideal backhaul
  ⇒ No need for network interfaces
- In Release 12, a signaling interface has been added which allows eNBs to interchange measurement and resource allocation information
- In Release 13, new signaling elements were added



Indoor Positioning

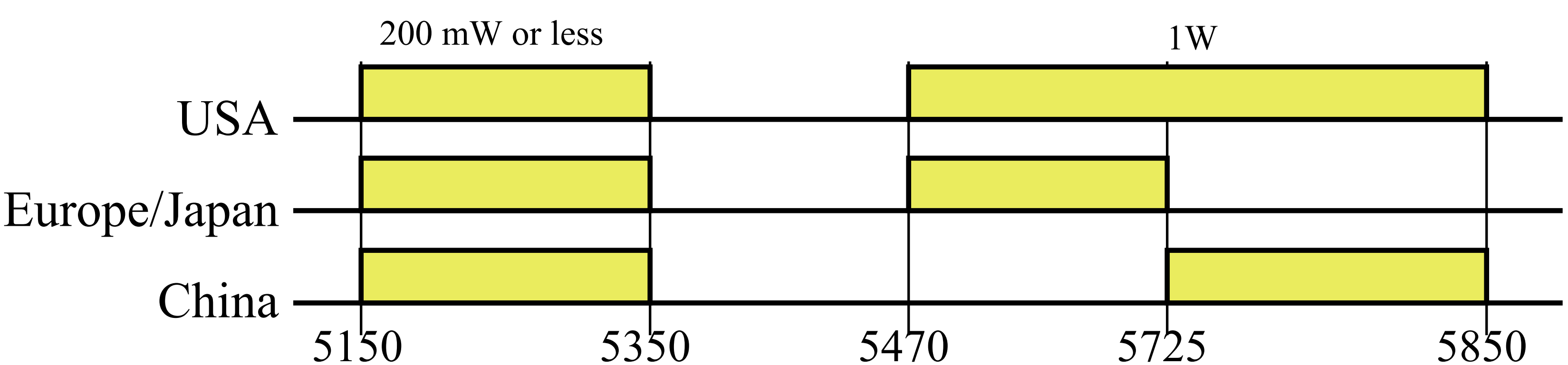
- FCC requires indoor positioning for E911
  - x/y location within 50 m by 2021
  - Provide z location by 2023
- Position can be determined by:
  - Barometric sensors
  - Wireless LANs
  - Bluetooth beacons
  - Terrestrial beacon system broadcasting signals for positioning, e.g., Metropolitan Beacon Systems (MBS)
- R13 supports only standalone mode and UE assisted mode without network assistance are supported. Only MBS is supported.
- R14 introduced advanced techniques using Enhanced Cell-ID and Observed Time Difference of Arrival.

Carrier Aggregation Enhancements

- CA was introduced in R10
- R12 limited to 5 carriers ⇒ 100 MHz
- R13 extended to 32 carriers ⇒ 640 MHz
  - Both FDD and TDD
  - Inter-band and Intra-band
  - Licensed and Unlicensed
- 64-QAM can be used with carrier aggregation

License Assisted Access (LAA)

- 5 GHz band for public hot-spots and in-building
- Different rules and bands in different countries, e.g.,
  - Avoid if a radar is operating
  - Can't block 20 MHz if using only 180 kHz
  - Transmit only if free. Recheck after maximum occupancy time $\Rightarrow$ Can not transmit continuously as in standard LTE
- Carrier aggregation with unlicensed band and licensed band when possible. DL enhancement in R13. UL enhancements in R14.



LAA (Cont)

- End-to-End LTE ⇒ Better integration than with Wi-Fi
- Before R13, several different solutions called LTE-U were used.
- R13 introduced a global standard to include 5 GHz unlicensed band using several 20 MHz channels
- To coexist with Wi-Fi, LAA uses
  - Listen before talk
  - Discontinuous transmission on a carrier with limited maximum transmission duration
  - Dynamic frequency selection to avoid interference with radar systems in some regions
  - Multicarrier transmission across multiple unlicensed channels

LTE-WLAN Aggregation Enhancements

- LTE-WLAN aggregation (LWA) was introduced in R12
- In R13:
  - LTE_WLAN Radio Level Integration with IPSec tunnel (LWIP) allows both uplink and downlink traffic to be sent over WLAN
  - RAN Controlled LTE-WLAN interworking (RCLWL) allows eNB to send traffic steering commands to UE based on UE measurements

Wi-Fi with IP Flow Mobility

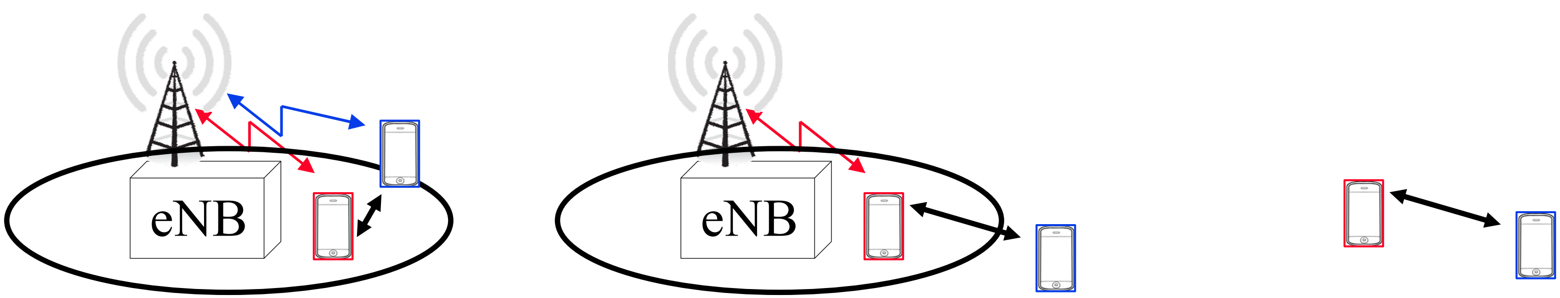
- Network Based Internet Protocol Flow Mobility (NBIFOM)
- IP flows can be steered towards PDN or Wi-Fi
- Trusted and untrusted WLAN interfaces have been defined.
- Similar to but different from LTE-WLAN aggregation (LWA)
- Even Voice and Video traffic can be sent over Wi-Fi
  $\Rightarrow$ Allows increased coverage area

RAN Sharing

- Multiple operators can share a radio access network (RAN)
- Each operator runs a "Public Land Mobile Network (PLMN)"
- Owner operator can put limits on total UL/DL load of sharing PLMNs
- QoS profile can also be limited as agreed

Enhanced D2D Proximity Services (PROSE)

- Device-to-Device (D2D) was introduced in R12
- In R13:
  - UEs can search multiple PLMNs for “side-link”
  - Out-of-coverage D2D discovery
  - Support for relaying using D2D. L3 relay was defined. Public safety personnel can connect to network through other mobiles.



(a) (b) (c) First Responders only

Dual Connectivity Enhancements

- Dual connectivity was introduced in R12
  Allowed only downlink throughput enhancement
- In R13:
  - Uplink bearer split
  - UE splits the traffic only if the queue is over a threshold
  - Timing differences between two bears is handled
    ⇒ Allows dual connectivity to different operators
  - Traffic steering is supported.
    Local traffic and Selective IP traffic can be directed towards small cell to avoid overloading core network

LTE Cat-M1

- For machine type communication in Release 13.
- 1 Mbps using 1.4 MHz = 6 Physical Resource Blocks (PRB)
- Signaling inside 1.4 MHz ⇒ Do not need to listen to 20 MHz
- All power on fewer subcarriers
  ⇒ **P**ower **S**pectral **D**ensity (**PSD**) Boosting
  ⇒ 15 dB reduction in link budget by PSD and repetition
  ⇒ Allows UEs in basements and indoors
- Reduced Tx power to 20 dBm
  ⇒ integrated amplifier
- Popular in North America

Cat-0 vs. Cat-M1

	Cat-0	Cat-M1
Downlink	64-QAM	16-QAM
Uplink	16-QAM	16-QAM
Bandwidth	Full	1.08 MHz
Peak Rate	1Mbps (DL/UL)	FD: 1 Mbps (DL/UL) HD: 300 kbps DL, 375 kbps/UL
Power Classes	23 dBm	12 dBm, 20 dBm
Path loss	140.7 dB	155.7 dB

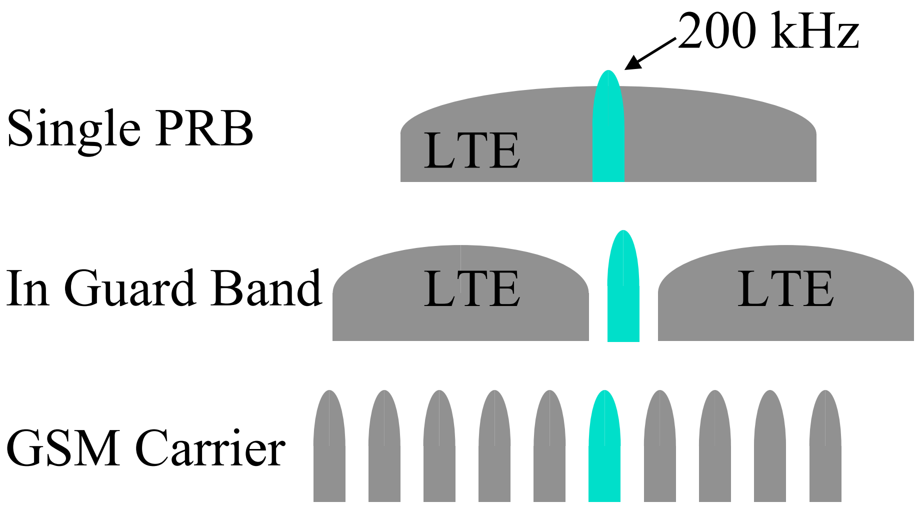
Narrow Band IoT (NB-IoT)

- **LTE Cat-NB1** or Category -2 UE also in Release 13.
- Designed for ultra-low cost (<$5), low data rate, high power efficiency, deep in house coverage
  - No handovers while active
  - No channel measurements
  - No MIMO
  - QPSK or BPSK
  - Single RF Chain ⇒ Half-duplex
  - Data repetition to enable deep in-house coverage
- 15 uW in idle state, 500 mW in transmitting.
  A 5 W-hr battery will last 10 years
- Most promising IoT protocol. Already in use in China. Popular in Europe.

Ref: Hossam Fattah, "5G LTE Narrowband Internet of Things (NB-IoT)," CRC Press, Boca Raton, 3 September 2018, 262 pp., ISBN 9780429847585

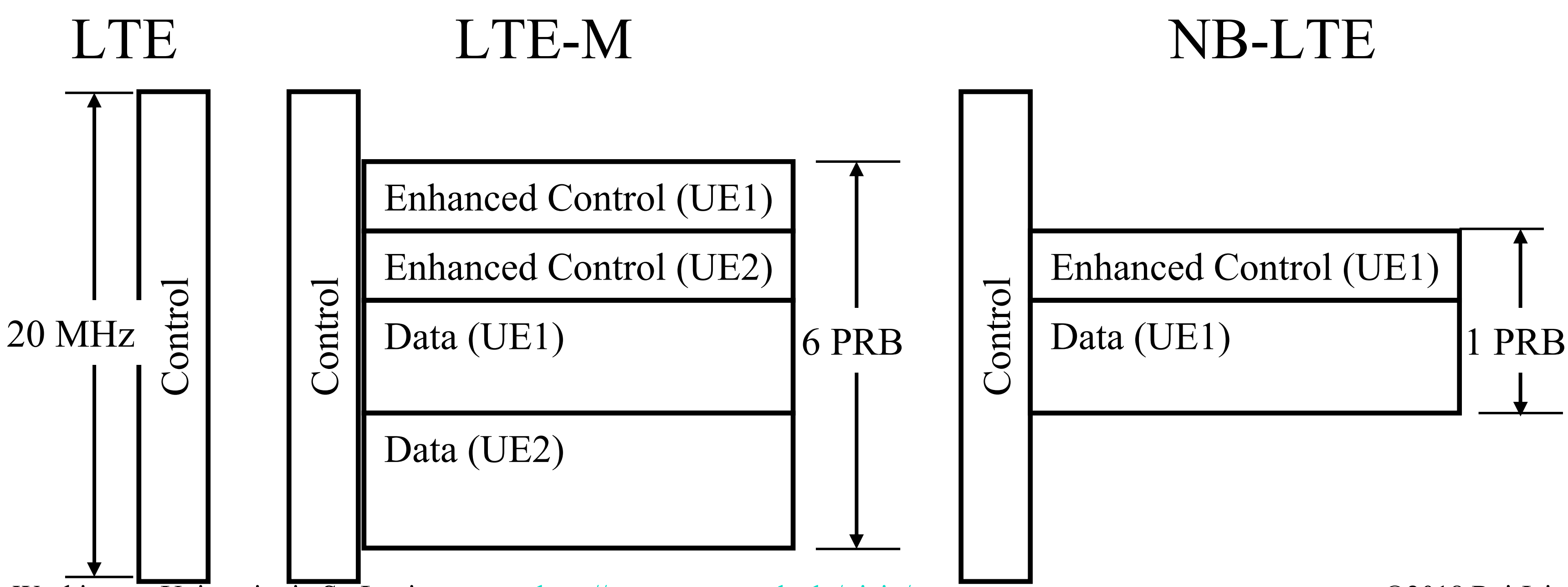
Band for NB-IoT

- 128 kbps using 180 kHz band = Single PRB of 12 subcarriers (12 tones)
- Can be in-band, in guard-band, or out-of-band using 200 kHz GSM carrier
- All 3 deployments invisible to non-NB-IoT devices
- Optionally concentrate power in 3.75 kHz tone to allow longer distance transmissions.
- All 12 tones in DL.
  1, 3, 6, or 12 tones in UL.



Signaling Enhancements for MTC

- **E**nhanced **P**hysical **D**ownlink **C**ontrol **Ch**annel (EPDCCH)
- LTE Cat 0 UE receive signaling in the entire 20 MHz band
- LTE-M UEs receive signaling in their 1.4 MHz band
- For NB-LTE UEs, signaling is part of the assigned PRB



Carriers for NB-IoT

- Several NB-IoT channels/carriers per sector. One anchor carrier used to broadcast system information, control, and shared channels.
- All devices in idle state camp on this anchor carrier. Can be scheduled to receive/transmit on non-anchor carriers.
- Can serve up to 50,000 devices per sector
- In R13, paging and random access only on anchor carriers
  In R14, this can be done on non-anchor carriers also.
- In R13, two UE power classes: 20 dBm and 23 dBm
  In R14, one more UE power class with 14 dBm

NB1 Energy Saving Mechanisms

- **Extended Idle Mode Discontinuous Reception (eDRX):**
  - Normal LTE devices listen to paging every 1.28s in idle state.
  - NB1 devices can request to extend this to 5.12s to 43.69 minutes. If the network accepts, the device can power off for that long without loosing its state including IP address.
- **Power Save Mode**: LTE devices have to perform periodic tracking area updates. NB1 devices can extend this update timer to several days.
- **Control Plane CIoT EPS Optimization**:
  NB1 user data can be sent/received in control channels
  ⇒ No need to schedule user data bearer
- **Non-IP Data Delivery (NIDD):** A Service Capability Exposure Function (SCEF) encapsulates/decapsulates IP packets and sends/receives data without IP headers to/from NB1 device

MTC Enhancements in R14

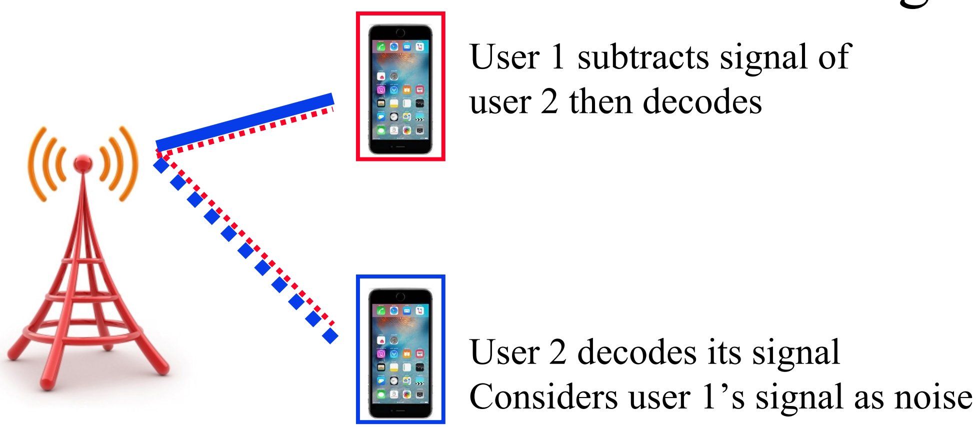
- More accurate positioning
- Multicast to several UEs
- Improvement to VoLTE speech with enhanced coverage
  Packet bundling at application and MAC layers
- Higher data rates: Cat NB2
  - 2536 bits per transmission in UL and DL
    compared to 1000 bits in UL and 680 bits in DL for NB1
  - Two HARQ processes in stead of one
  - 127 kbps in DL and 159 kbps in UL

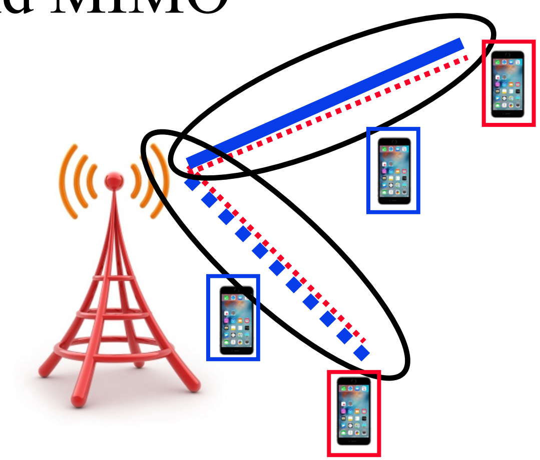
Single-Cell Point-to-Multipoint (SC-PTM)

- Enhancement of enhanced Multimedia Multicast Broadcast (eMBMS)
- eMBMS allows multi-cell broadcasts but requires synchronization among eNBs.
- SC-PTM does not require synchronized networks as in eMBMS
- Each cell handles it's own broadcasts.
- A physical downlink shared channel (PDSCH) is used
- Control information is broadcast on a "single-cell multicast control channel (SC-MCCH). Indicates active MBMS sessions and information about each session
- Data is broadcast on a "Single Cell multicast transport channel (SC-MTCH).
- In R14, SC-PTM was extended to NB-IoT devices

Multi-User Superposition Transmission (MUST)

- Users are distinguished by power levels
  Non-Orthogonal Multiple Access (NOMA)
- Users with poor channel condition get higher power
- Users with higher power decode their signal treating others as noise
- Users with lower power subtract the higher powered signals before decoding.
- Can also be used with beamforming and MIMO





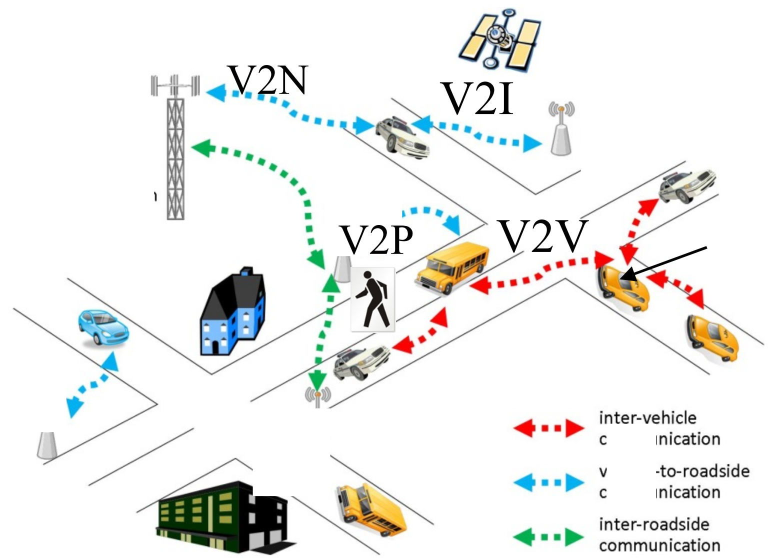
Ref: G. Ding, et al, "Application of Non-orthogonal Multiple Access in LTE and 5G Networks," https://pdfs.semanticscholar.org/a404/21a9762db528bfe848166765fee43e740c94.pdf

L2 Latency Reduction

- Instant Uplink Access (IUA): A.k.a Fast up link
  - A long-lasting grant with recurring resources is provided to the device
  - Extension of Semi-Persistent Scheduling (SPS) with shorter recurring periods of up to 1 ms
  - Device transmits only if there is data
    Does not need to transmit padding if there is no data
    $\Rightarrow$ Saves power
  - eNB sends Nack if no data is received during a scheduled grant
- Short Transmit-time Travel Interval (TTI):
  - Time to switchover from receive to transmit
  - 2 symbols for FDD, 7 symbols for TDD

Cellular Vehicle-to-X (C-V2X)

- Vehicle-to-Vehicle (V2V): Collision avoidance
- Vehicle-to-Infrastructure (V2I): Traffic lights
- Vehicle-to-Pedestrians (V2P): Safety alerts
- Vehicle-to-Network (V2N): Maps, routing
- Use 5.9 GHz VANET spectrum direct PC5 interface for V2I, V2P, V2V
- Use licensed spectrum for V2N
- Direct communication using enhanced LTE D2D sidelink w PC5 Interface
- Another alternative is to use UE to eNB Uu interface for upload and retransmission/broadcast from eNB



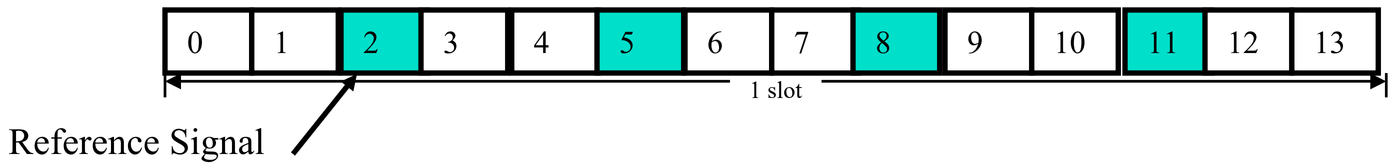
Ref: Qualcomm, "Expanding the 5G NR ecosystem and roadmap in 3GPP Release 16 and beyond," Sep 2018, 35 pp., https://www.qualcomm.com/media/documents/files/expanding-the-5g-nr-ecosystem-and-roadmap-in-3gpp-rel-16-beyond.pdf

D2D vs. V2V

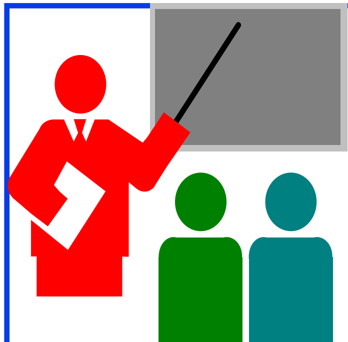
	D2D	V2V
Application	Voice	M2M
Packet Size	Small	Large
Latency	Not Critical	Critical 20-100 ms
UE Density	Low # of safety personnel	High number of vehicles
Dynamics	Pedestrian speeds	250 km/h

V2V Extensions

- Higher Doppler due to high speed: Doubled the number of demodulation reference symbols (DMRS) to 4



- Lower Latency: Scheduling and data in the same subframe
- Collision Avoidance: UEs can sense load on the channel and request resources in advance to avoid collisions
- Global Navigation Satellite Systems (GNSS) based Synchronization: V2V almost always have GPS. It can be used in addition to eNB timing.
- Enhanced sidelink configuration and signaling



Summary

1. LTE Advanced Pro is 4.5G technology developed by 3GPP as Release 13 and 14
2. Release 13 introduced several new features:
    1. AAS and FD-MIMO
    2. Spectrum Aggregation enhancements: LAA, LWA, LWIP
    3. IoT/MTC
    4. D2D for Safety personnel
3. Release 14 mostly further enhanced these features and added:
    1. MUST
    2. V2X

Reading List

1. Rohde & Schwarz, "LTE-Advanced Pro Introduction eMBB Technology Components in 3GPP Release 13/14," White paper, 50 pp., https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/LTE-Advanced-Pro_Introduction_White_paper_en_5215-8258-52_v0100.pdf
2. G. Pfeifer, "5G Technology Introduction, Market Status Overview and Worldwide Trials," 5G and IoT Seminar, Italy, May 2017, https://cdn.rohde-schwarz.com/it/seminario/5G_Seminar_Part1_Standardization_Market_PHY_170509_Italy.pdf

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Wikipedia Links

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- https://en.wikipedia.org/wiki/Laa
- https://en.wikipedia.org/wiki/LTE-WLAN_Aggregation
- https://en.wikipedia.org/wiki/LTE_(telecommunication)
- https://en.wikipedia.org/wiki/LTE_Advanced
- https://en.wikipedia.org/wiki/LTE_Advanced_Pro
- https://en.wikipedia.org/wiki/LTE_in_unlicensed_spectrum
- https://en.wikipedia.org/wiki/MIMO
- https://en.wikipedia.org/wiki/Multi-Operator_Radio_Access_Network
- https://en.wikipedia.org/wiki/Multimedia_Broadcast_Multicast_Service
- https://en.wikipedia.org/wiki/Narrowband_IoT
- https://en.wikipedia.org/wiki/Radio_access_network
- https://en.wikipedia.org/wiki/Telecom_infrastructure_sharing
- https://en.wikipedia.org/wiki/Vehicle-to-everything
- https://en.wikipedia.org/wiki/Vehicular_ad_hoc_network

Acronyms

- 3GPP Third Generation Partnership Project
- AAS Active Antenna System
- BPSK Binary Phase Shift Keying
- CA Carrier Aggregation
- CDN Content Distribution Networks
- cDRX Continuous Mode DRX
- CoMP Coordinated Multi-Point Operation
- dB deciBel
- DC Dual Connectivity
- DL Downlink
- DMRS Demodulation Reference Signal
- DRX Discontinuous Reception
- eICIC Enhanced Inter-Cell Interference Cancellation
- eIMTA Enhanced Interference Mitigation and Traffic Adaptation
- eLAA Enhanced License Assisted Access
- eLWA Enhanced LTE/WLAN Aggregation

Acronyms (Cont)

eLWIP	Enhanced LTE/WLAN over IP Tunnel
eMBB	Enhanced Mobile Broadband
eMBMS	Enhanced Multicast Broadcast Multimedia Service
eMTC	Enchanded Machine Type Communication
eNB	Evolved Node-B
EPDCCH	Enhanced Phyiscal Downlink Control Channel
EPS	
FCC	Federal Communications Commission
FD	Full Dimension
GHz	Giga Hertz
GNSS	Global Navigation Satellite Systems
HARQ	Hybrid Automatic Repeat Request
HTTP	Hyper-text Transfer Protocol
ICS	IMS Centralized Services
ID	Identifier
IMS	Internet Multimedia System

Acronyms (Cont)

- IoT Internet of Thins
- IP Internet Protocol
- ISBN International Standard Book Number
- IUA ICS User Agent
- kHz Kilo Hertz
- LAA License Assisted Access
- LAN Local Area Network
- LTE Long-Term Evolution
- LWA LTE/WLAN Aggregation
- LWIP LTE/WLAN over IPSec Tunnel
- MBMS Multimedia Broadcast Multicast Service
- MBS Metropolitan Beacon System
- MCCH Multicast Control Channel
- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- MPD Media Presentation Description

Acronyms (Cont)

- MTC Machine Type Communication
- MUST Multi-User Superposition Transmission
- mW milliWatt
- NAICS Network Assisted Interference Cancellation and Supression
- NB Narrow-Band
- NOMA Non-Orthogonal Multiple Access
- NR New Radio
- PC5 One of LTE V2X Interfaces
- PDN Public Data Network
- PDSCH Physical Downlink Shared channel
- PHY Physical
- PLMN Public Land Mobile Network
- PRB Physical Resource Block
- PROSE Proximity Services
- PSD Power Spectral Density
- PSM Power save mode

Acronyms (Cont)

- PTM Point-to-Multipoint
- QAM Quadrature Amplitude Modulation
- QoS Quality of Service
- QPSK Quadrature Phase Shift Keying
- RAN Radio Access Network
- RF Radio Frequency
- RS Reference Signal
- SC-PTM Single-Cell Point-to-Multipoint
- SON Self-Organizing Network
- SRS Sounding Reference Signals
- TDD Time-Division Duplex
- TTI Transmit Transition Interval
- UE User Element
- UL Uplink
- URL Uniform Resource Locator
- VANET Vehicular Area Network

Acronyms (Cont)

- WAN   Wide-Area Network
- WLAN   Wireless Local Area Network

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http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-18/j_19lap.htm

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),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw