Introduction to 4G LTE-Advanced

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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-16/

Overview

1. LTE-Advanced: Requirements and New Technologies
2. Carrier Aggregation
3. Coordinated Multipoint Operation
4. Small Cells
5. Inter-Cell Interference Coordination

Note: This is the 2nd lecture in a series of lectures on LTE and LTE-Advanced

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

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

- Seamless connectivity and global roaming with smooth handovers
- High-Quality Multimedia
- ITU has approved two technologies as 4G (Oct 2010)
  - LTE-Advanced
  - WiMAX Release 2 (IEEE 802.16m-2011)

LTE-Advanced Requirements

- UMTS Rel. 10, 2011H1
- **Goal**: To meet and exceed IMT-advanced requirements
- **Data Rate**: 3 Gbps downlink, 1.500 Mbps uplink (low mobility) using 100 MHz
- **Spectral Efficiency**: 30 bps/Hz using 8x8 MIMO downlink, 15 bps/Hz assuming 4x4 MIMO uplink
- **Cell Spectral Efficiency**: DL 3.7 bps/Hz/cell assuming 4x4 MIMO, 2.4 bps/Hz/cell assuming 2x2 MIMO (IMT-Adv requires 2.6 bps/Hz/cell)
- **Downlink Cell-Edge Spectral Efficiency**: 0.12 bps/Hz/User assuming 4x4 MIMO, 0.07 bps/Hz/user assuming 2x2 MIMO (IMT-Adv requires 0.075 bps/Hz/user)

Ref: 3GPP, "Requirements for Further Advancements for E-UTRA (LTE-Advanced),," 3GPP TR 36.913 v8.0.1 (03/2009), http://www.3gpp.org/ftp/specs/archive/36_series/36.913/

LTE-Advanced Requirements (Cont)

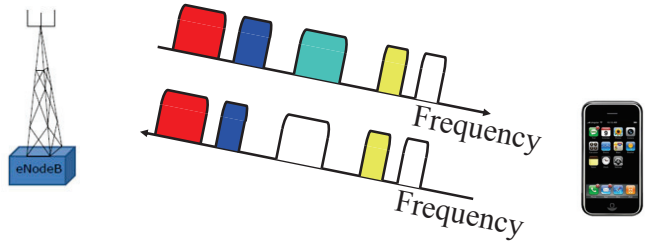
- **Latency**: Less than 10 ms from dormant to active; Less than 50 ms from camped to active
- **Mobility**: up to 500 kmph
- **Spectrum Flexibility**: FDD and TDD, Wider channels up to 100 MHz

LTE Advanced Techniques

- **Three Key Factors**: Spectrum (Band, Bandwidth), Spectral Efficiency, and Cell sizes
- **Bandwidth**: 100 MHz using carrier aggregation
  5 carriers allowed now. 32 in future.
  Higher UE power ⇒ Used if high throughput needed
- **Spectral Efficiency**:
  - Frequency Reuse Factor of 1
  - Higher order MIMO (8x8 DL, 4x4 UL)
  - New MIMO Techniques: Single-user uplink MIMO
  - Inter-Cell Interference Co-ordination and cancellation
- **Cell Sizes**:
  - Relays
  - Home eNB

Carrier Aggregation

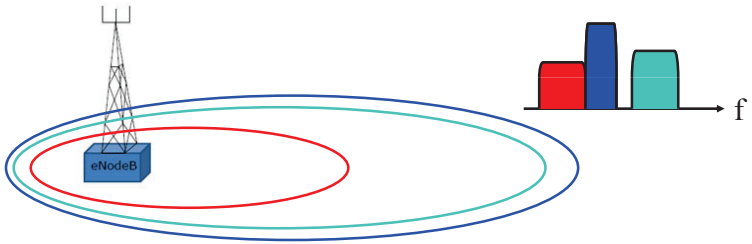
- Aggregation = Combine multiple bands (Component Carriers)



- Backward compatible with LTE (Single carrier)
  ⇒ Each band can be 1.4, 3, 5, 10, or 20 MHz
- Maximum 5 component carriers ⇒ 100 MHz max
- Each component can be different width
- Number of components in DL and UL can be different, but Number of components in DL ≥ Number of components in UL

Carrier Aggregation (Cont)

- Components can be contiguous (adjacent) or non-contiguous (inter-band or intra-band)
- Each component carrier has a serving cell.
  Size of different component carrier cells may differ
- PHY, MAC, RLC are all extended to handle varying number of components
  e.g., Larger buffers in RLC to accommodate larger data rate



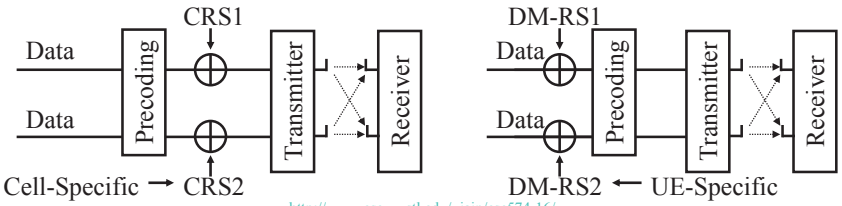
Ref: http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced

MIMO

- 8x8 MIMO in DL and 4x4 in UL
- MIMO used only when SINR is high ⇒ Good Channel
- If SINR is low, other spectral efficiency techniques, such as, transmit diversity, are used.
- Many different transmission modes defined.
  UE is informed about the mode to use via signaling
- Modes differ in number of antennas, antenna port, precoding type, type of reference signal
- Three new categories of UE: Category 6, 7, 8
  Category 8 supports maximum features

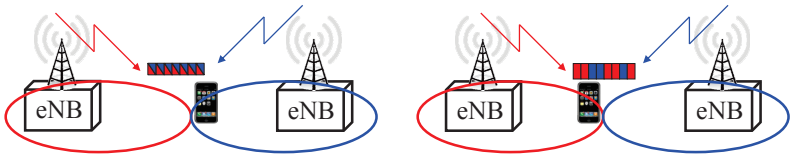
Precoding

- Used to map the modulation symbols to different antennas
  Depends upon the number of antennas and number of layers
- Reference (Pilot) signals are transmitted with the data
- **Code-Book based precoding**: Cell Reference Signals (CRS)
- **Non-Code book based precoding**: Demodulation Reference Signals (DM-RS) are added before precoding.
  Receiver can infer precoding from the pilots.



Coordinated Multipoint Operation (CoMP)

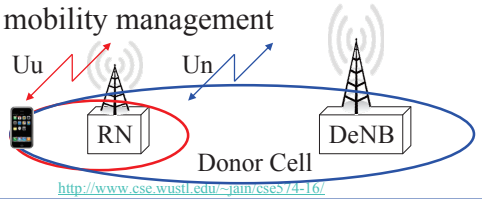
- To improve performance at cell edge
- Base stations coordinate transmissions and reception
- Joint Transmission: Multiple transmitters in the same subframe
- Dynamic Point Selection: Transmission scheduled from one BS
- Joint Reception: Multiple BS receive the signal from one UE and combine
- UE is informed about different UL/DL decisions



(a) Joint Transmission (b) Dynamic Point Selection

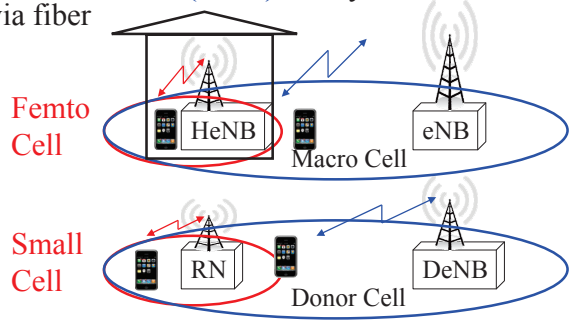
Relay Nodes

- **Relay Nodes**: Low-power base stations
  Used to enhance performance at cell edges, hot-spot areas, indoor coverage
- **Donor eNB (DeNB)**: Primary base station
- A modified version of E-UTRAN air interface Uu is defined: Un
- Both Donor and Relays may use the same/different frequencies
- Self-Interference: Relay transmission may interfere with its reception on the same frequency
  ⇒ Avoided using time sharing
- Donor does the mobility management



HetNet/Small Cells

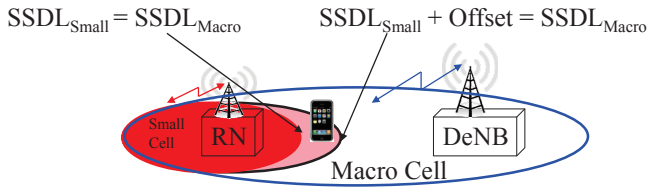
- **Macro eNB**: Normal Base Station
- **Relay Node (RN)**: Micro or Pico Cell.
- **HeNB**: Home eNB for indoor coverage in homes, offices, malls. Privately owned and operated. Femto Cell.
- **Remote Radio Heads (RRH)**: Relay nodes connected to DeNB via fiber



Ref: 3GPP, "HetNet/Small Cells," http://www.3gpp.org/hetnet

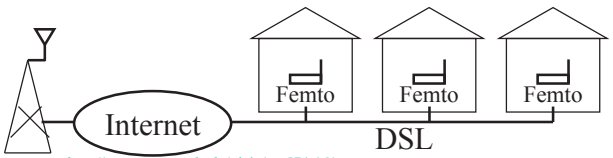
HetNet/Small Cells (Cont)

- UE selects the BS with the strongest Signal in DL (SSDL) ⇒ Both BS have same SSDL at the edge
- **Cell Range Extension (CRE)**: Allow small cell to serve more users by requiring UE to join small cell even if the power is slightly below the macro cell ⇒ Interference from macro is mitigated by coordination



Types of Cells

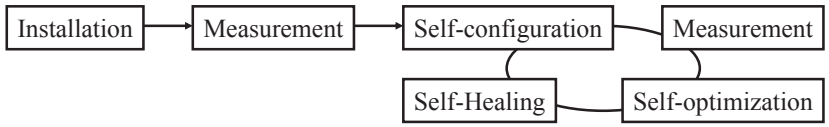
- **Cell** (**MacroCell**): Cover a few miles. Public Access. Open Area.
- **MicroCell** (10^{-6}): Less than a mile wide. Public Access. Malls, Hotels, Train Stations
- **PicoCell** (10^{-12}): in-Building with public access
- **FemtoCell** (10^{-15}): In-Building with restricted access
- **AttoCell** (10^{-18}): In-room
- **ZeptoCell** (10^{-21}): On-Desk
- No milli, nano cells.



FemtoCells: Key Features

- 50-100 m cell radius
- Indoor
- Residential, Small office/home office (SOHO)
- Backhaul over DSL
- Plug and Play: *Self-Organizing*, Self optimizing
- Omni-directional antenna. No sectorization
- 10-50 users, 10-40 Mbps, Low cost
- Defined User group
- Continuation of Macro network: Handover of calls
- Regular mobile equipment work in femtocells
- Multiple FemtoCells should coexist
- New Applications: HD video streaming, LAN services

Self-Organizing Network (SON)



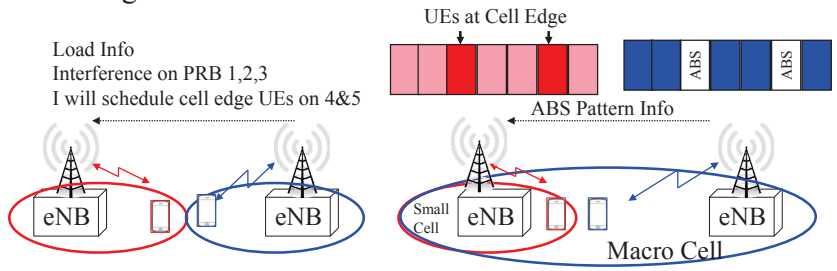
- User installable. 70M UMTS femtocells expected in 2012
- Not-physically accessible to the carrier
- Operator provides femtocell ID. Customer registers location
- Self-Configures:
  - Transmission Frequencies
  - Transmission Power
  - Preamble: Identifies the segment (IDcell). Some IDs for reserved for femtocells. Helps differentiate from macrocell.
  - Neighbor Cell list: Helps in handover
- Turned on/off by the consumer ⇒ Dynamic topology

Management and Configuration

- Self-Configuration
- Remote configuration by service provider
- Femtocell senses the channel to detect neighboring cells
- May broadcast messages for neighbors

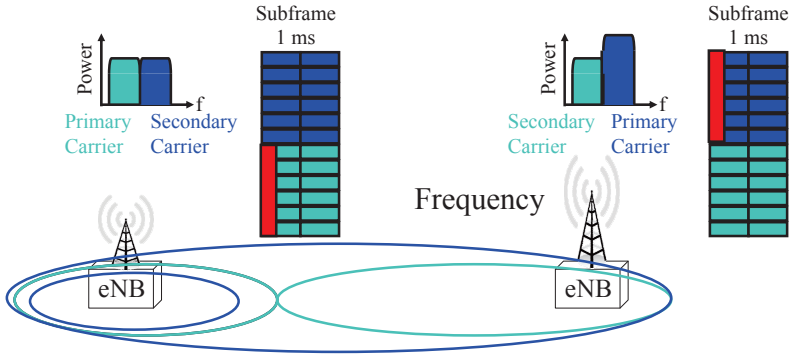
Enhanced Inter-Cell Interference Coordination (eICIC)

- **ICIC**: A eNB sends a "load information" message to the neighbor eNB about interference level per physical resource block. The neighbor adjusts DL power levels at those blocks
- **Almost Blank Subframes (ABS)**: Only control channels and cell-specific pilots, no user data ⇒ Allows UEs in CRE region to mitigate macro-cell interference = eICIC



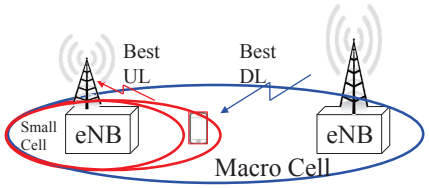
Carrier Aggregation with Cross-Carrier Scheduling

- **Physical DL Control channel (PDCCH)** in macro cell and small cell is sent on different carriers and may be at a higher power than traffic channels
- A UE can talk to both BS's using control channels on different carriers



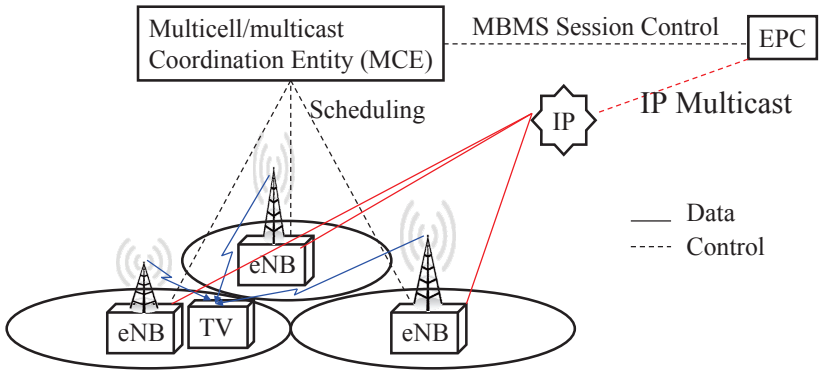
CoMP with Small Cells

- A UE can get service from multiple BSs (eNB, RN, HeNB, RRH)
  - Can get data through multiple BSs
  - Can send data through multiple BSs
  - Can send data to one BS and receive from another



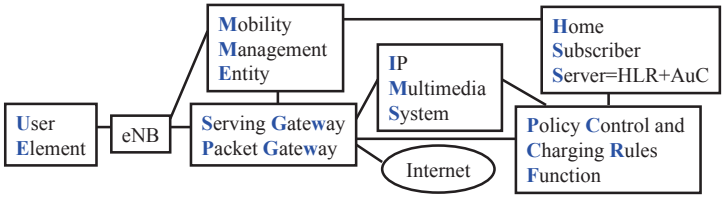
Multimedia Broadcast Multicast Service (MBMS)

- MBMS Single Frequency Network (MBSFN)
- MCE handles synchronized data delivery



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



Summary

1. LTE-A meets and exceeds all requirements for 4G as specified in IMT-Advanced.
2. Three key factors that affect data rate are: spectrum, spectral efficiency, and cell size
3. LTE-A can aggregate up to 5 carriers to make up to 100 MHz
4. LTE-A has frequency reuse factor of 1 since spectrum is expensive, uses high-order MIMO.
5. LTE-A uses relay nodes to cover remote areas and hot-spots. Also allowes Home eNB (Femto cells).
6. Code-book and non-code book precoding improves MIMO
7. Coordinated Multipoint operation (CoMP) allows mitigation of interference at cell edge. CoMP can also be used with cross-carrier scheduling.

Reading List

- 3GPP, "LTE-Advanced," http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced
- 3GPP, "HetNet/Small Cells," http://www.3gpp.org/hetnet
- 3GPP, "Heterogeneous Networks in LTE," http://www.3gpp.org/technologies/keywords-acronyms/1576-hetnet
- 3GPP, "Carrier Aggregation Explained," http://www.3gpp.org/technologies/keywords-acronyms/101-carrier-aggregation-explained

Wikipedia Links

- https://en.wikipedia.org/wiki/LTE_Advanced
- https://en.wikipedia.org/wiki/Femtocell
- https://en.wikipedia.org/wiki/Home_Node_B
- https://en.wikipedia.org/wiki/Self-organizing_network
- https://en.wikipedia.org/wiki/Voice_over_LTE

LTE-Advanced Books

- S. Ahmadi, "LTE-Advanced," Academic Press, 2013, ISBN: 9780124051621, 1152 pp. Safari book.
- E. Dahlman, S. Parkvall, J. Skold, "4G: LTE/LTE-Advanced for Mobile Broadband, 2nd Edition," Academic Press, 2013, ISBN: 9780124199859, 544 pp. Safari book.
- C. Cox, "An Introduction to LTE: LTE, LTE-Advanced, SAE and 4G Mobile Communications, 2nd Edition" Wiley, 2014, ISBN: 9781118818039, 486 pp. Safari book.
- A. Ghosh, R. Ratasuk, "Essentials of LTE and LTE-A," Cambridge University Press, 2011, ISBN: 9780521768702, 264 pp. Safari book.
- A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.
- H. Holma, A. Toskala, "LTE Advanced: 3GPP Solution for IMT-Advanced," Wiley, 2012, ISBN: 9781119974055, 248 pp. Safari book.
- X. Zhang, X. Zhou, "LTE-Advanced Air Interface Technology," CRC Press, 2012, ISBN: 9781466501522, 528 pp. Safari book.
- A. Taha, H. Hassanein, N. Ali, "LTE, LTE-ADVANCED AND WiMAX: TOWARDS IMT-ADVANCED NETWORKS," Wiley, 2012, ISBN: 9780470745687, 303 pp. Safari book.

Small Cells - Books

- J. Zhang and G Roche, "Femtocells: Technologies and Deployment," Wiley, 2010, ISBN:0470742983

LTE-Advanced Specifications

- TR 36.806 E-UTRA Relay architectures for E-UTRA (LTE-Advanced)
- TR 36.808 E-UTRA Carrier Aggregation; Base Station (BS) radio transmission and reception
- TR 36.814 E-UTRA Further advancements for E-UTRA physical layer aspects
- TR 36.815 Further Advancements for E-UTRA; LTE-Advanced feasibility studies in RAN WG4
- TR 36.817 E-UTRA Uplink multiple antenna transmission; Base Station (BS) radio transmission and reception
- TR 36.819 Coordinated multi-point operation for LTE physical layer aspects
- TR 36.823 E-UTRA Carrier Aggregation Enhancements; UE and BS radio transmission and reception
- TR 36.826 E-UTRA Relay radio transmission and reception
- TR 36.871 E-UTRA Downlink Multiple Input Multiple Output (MIMO) enhancement for LTE-Advanced
- TR 36.912 Feasibility study for Further Advancements for E-UTRA (LTE-Advanced)

LTE-Advanced Specifications (Cont)

- TR 36.913 Requirements for further advancements for E-UTRA (LTE-Advanced)
- TR 36.932 Scenarios and requirements for Small Cell Enhancements for E-UTRA and E-UTRAN
- TS 36.101 E-UTRA User Equipment (UE) radio transmission and reception
- TS 36.211 E-UTRA Physical channels and modulation
- TS 36.212 E-UTRA Multiplexing and channel coding
- TS 36.213 E-UTRA Physical layer procedures
- TS 36.216 E-UTRA Physical layer for relaying operation
- TS 36.221 E-UTRA Medium Access Control (MAC) protocol specification
- TS 36.300 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2
- TS 36.306 E-UTRA User Equipment (UE) radio access capabilities
- TS 36.331 E-UTRA Radio resource Control (RRC) protocol specification
- TS 36.423 Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 Application Protocol (X2AP)

All available at http://www.3gpp.org/

Femtocell Specifications

- 3GPP Rel 8 specifies HNB (Home Node B) and HeNB (22.*)
- Rel 9 includes an IMS (IP Multimedia Subsystem) capable HNB (23.*)
- TS 22.220: Service Requirements for HNB and HeNB
- TR 23.830: Architecture aspects of HNB and H3NB
- TR 23.832: IMS aspects of architecture for HNB
- TR 25.820: 3G HNB study item
- TR 25.967: FDD HNB RF Requirements
- TR 32.821: Study of self-organizing networks related OAM interfaces for HNB TR33.820: Security of HNB/HeNB
- TS 25.467: Mobility procedures for HNB
- TS 25.468: UTRAN Iuh Interface RANAP (Radio Access Network Application Part) User adaptation signaling
- TS 25.469: UTRAN Iuh Interface HNB application part signaling
- TS 32.581: HNB OAM&P (Operation, Administration, Management and Provisioning) concepts and requirements for Type 1 interface HNT to HNT Management system

Femtocell Specifications (Cont)

- TS 32.582: HNB OAM&P information model for Type 1 interface HNT to HNT Management system
- TS 32.583: HNB OAM&P procedure flows for Type 1 interface HNT to HNT Management system
- Broadband Forum TR-069 management protocol has been adopted to include femtocells.

LTE-Advanced References

- ITU-R Report M.2134, "Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s)," November 2008.
- 4G LTE News, 4G LTE Forum, LTE-Advanced and more, http://www.lteportal.com/MediaChannel/Articles/
- Rohde & Schwarz, "1MA232: LTE-Advanced (3GPP Rel. 11) Technology Introduction," https://www.rohde-schwarz.com/en/applications/lte-advanced-3gpp-rel.11-technology-introduction-application-note_56280-42753.html

Acronyms

3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframes
BS	Base Station
CoMP	Coordinated Multipoint Operation
CRE	Cell Range Extension
CRS	Cell Reference Signals
CSFB	Circuit Switch Fall Back
dBm	deciBel miliwatt
DeNB	Donor eNB
DFT	Discrete Fourier Transform
DL	Down Link
DM-RS	Demodulation Reference Signal
DSL	Digital Subscriber Line
eNB	eNode B
EPC	Evolved Packet Core
FDD	Frequency Division Duplexing

Acronyms (Cont)

FDMA	Frequency Division Multiple Access
GPS	Global Positioning System
HD	High Definition
HeNB	Home eNB
HetNet	Heterogeneous Network
HSS	Home Subscriber System
ID	Identifier
IDFT	Inverse Discrete Fourier Transform
IEEE	Institution of Electrical and Electronic Engineers
IMS	Internet Multimedia System
IMT-Advanced	International Mobile Telecommunications Advanced
IP	Internet Protocol
ITU	International Telecommunications Union
LAN	Local Area Network
LTE-Advanced	Long-Term Evolution Advanced
LTE	Long-Term Evolution

Acronyms (Cont)

MAC	Media Access Control
MBMS	Multimedia Broadcast Multicast Service
MBSFN	MBMS Single Frequency Network
MCE	Multicast Coordination Entity
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi-User MIMO
NTP	Network Time Protocol
OAM	Operation, Administration, and Management
PDCCH	Packet Data Control Channel
PHY	Physical Layer
PRB	Physical Resource Block
RAN	Radio Access Network
RANAP	Radio Access Network Application
RF	Radio Frequency

Acronyms (Cont)

- RLC Radio Link Control
- RN Relay Node
- RRC Radio Resource Control
- RRH Remote Radio Heads
- RS Reference Signal
- SAE Service Access Gateway
- SC-FDMA Single Carrier Frequency Division Multiple Access
- SFBC Space-Frequency Block Code
- SINR Signal to Interference and Noise Ratio
- SOHO Small Office Home Office
- SON Self-Organizing Network
- SSDL Strongest Signal in Downlink
- SU-MIMO Single User MIMO
- TDD Time Division Duplexing
- TV Television

Acronyms (Cont)

- UE User Element
- UL Uplink
- UMTS Universal Mobile Telecommunications System
- UTRA UMTS Terrestrial Radio Access
- UTRAN UMTS Terrestrial Radio Access Network
- VoLTE Voice over LTE
- WG Working Group
- WiMAX Worldwide Interoperability for Microwave Access

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Related Modules

Internet of Things,
http://www.cse.wustl.edu/~jain/cse574-16/j_10iot.htm

Introduction to LTE,
http://www.cse.wustl.edu/~jain/cse574-16/j_16lte.htm

Introduction to 5G,
http://www.cse.wustl.edu/~jain/cse574-16/j_195g.htm

Low Power WAN Protocols for IoT,
http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm

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