無線網路概論
Intro. to Wireless Internet

Lecture 13 – 4G/LTE
5G Overview

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YZU CSE

Credit: Partial slides are from Prof. Peter Steenkiste

Lecture Material

- "Wireless Communication Networks and Systems", Corry Beard and William Stallings, 2016.
  - Ch. 14 - 4th Generation Systems and Long Term Evolution
- Wireless Networks and Applications
  - Prof. Peter Steenkiste, Carnegie Mellon University
  - http://www.cs.cmu.edu/~prs/

Outline

- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
- LTE advanced
- 5G overview

Purpose, motivation, and approach to 4G

- Defined by ITU directives for International Mobile Telecommunications Advanced (IMT-Advanced)
- All-IP packet switched network.
- Ultra-mobile broadband access
- Peak data rates
  - Up to 100 Mbps for high-mobility mobile access
  - Up to 1 Gbps for low-mobility access
- Dynamically share and use network resources
- Smooth handovers across heterogeneous networks
  - 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs
- High quality of service for multimedia applications

High Level Features

- No support for circuit-switched voice
  - Instead providing Voice over LTE (VoLTE)
- Replace spread spectrum/CDMA with OFDM

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

4G

- Two candidates for 4G
  - IEEE 802.16 WiMax
    - Enhancement of previous fixed wireless standard for mobility
  - Long Term Evolution
    - Third Generation Partnership Project (3GPP)
    - Consortium of Asian, European, and North American telecommunications standards organizations
- Both are similar in use of OFDM and OFDMA
- LTE has become the universal standard for 4G

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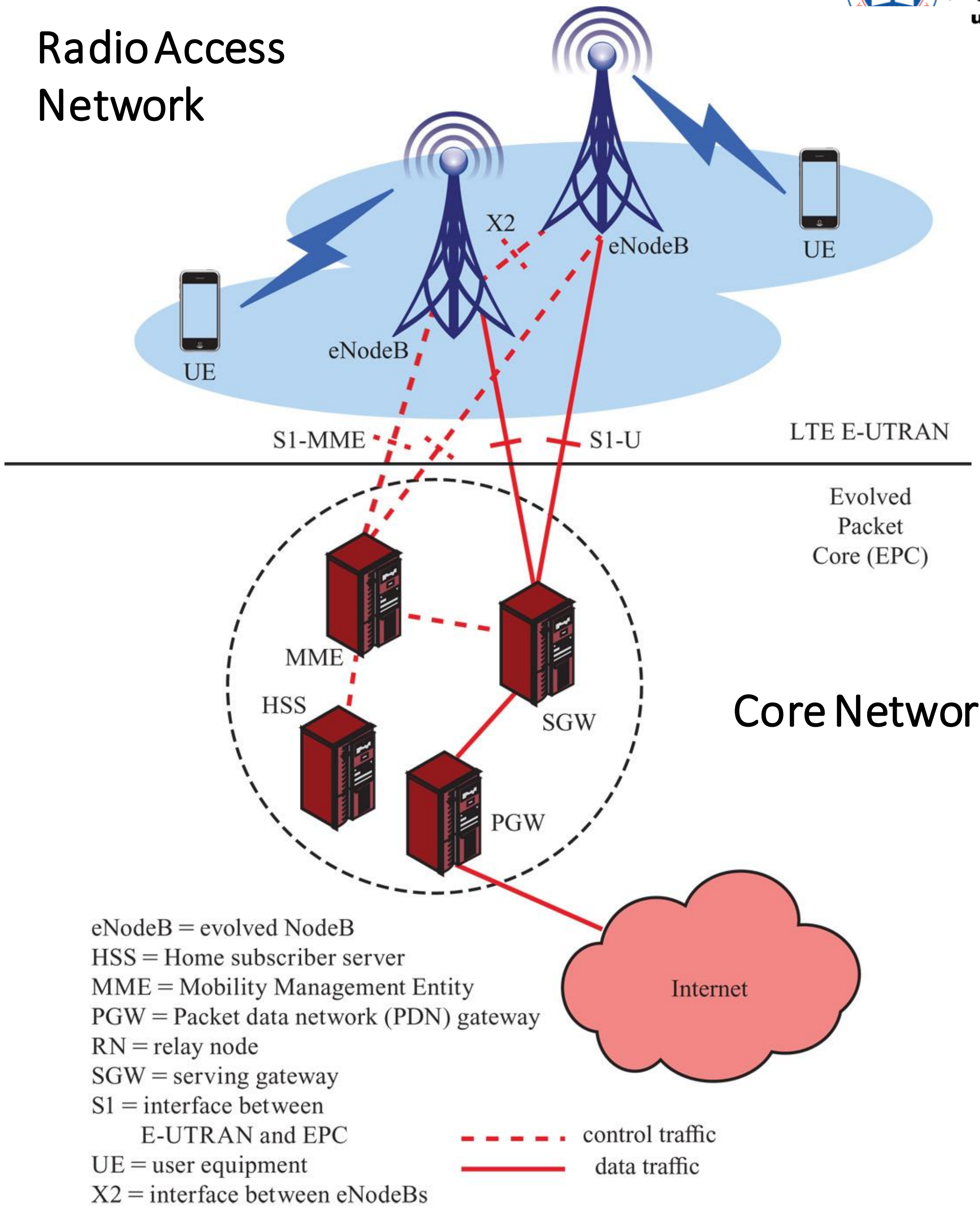
Architecture

- evolved NodeB (eNodeB)
  - Most devices connect into the network through the eNodeB
- Evolution of the previous 3GPP NodeB (~2G BTS)
  - Now based on OFDMA instead of CDMA
- Has its own control functionality, rather than using the Radio Network Controller (RNC - ~2G BSC)
  - eNodeB supports radio resource control, admission control, and mobility management
  - Originally the responsibility of the RNC

Radio Access Network



Core Network

Evolved Packet System

- Overall architecture is called the Evolved Packet System (EPS)
- 3GPP standards divide the network into
  - Radio access network (RAN): cell towers and connectives to mobile devices
  - Core network (CN): management and connectivity to other networks
- Each evolve independently.
- Long Term Evolution (LTE) is the RAN
  - Called Evolved UMTS Terrestrial Radio Access (E-UTRA)
  - Enhancement of 3GPP's 3G RAN
    - Called the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
  - eNodeB is the only logical node in the E-UTRAN
  - No RNC

Evolved Packet System

- Evolved Packet Core (EPC)
  - Operator or carrier core network
  - It is important to understand the EPC to know the full functionality of the architecture
- Traditionally circuit switched but now entirely packet switched
  - Based on IP - Voice supported using voice over IP (VoIP)

Design Principles of the EPS

- Packet-switched transport for traffic belonging to all QoS classes
  - Voice, streaming, real-time, non-real-time, background
- Comprehensive radio resource management
  - End-to-end QoS, transport for higher layers
  - Load sharing/balancing
  - Policy management across different radio access technologies
- Integration with existing 3GPP 2G and 3G networks
- Scalable bandwidth from 1.4 MHz to 20 MHz
- Carrier aggregation for overall bandwidths up to 100 MHz

Evolved Packet Core Components

- Mobility Management Entity (MME)
  - Supports user equipment context, identity, authentication, and authorization
- Serving Gateway (SGW)
  - Receives and sends packets between the eNodeB and the core network
- Packet Data Network Gateway (PGW)
  - Connects the EPC with external networks
- Home Subscriber Server (HSS)
  - Database of user-related and subscriber-related information
- Interfaces
  - S1 interface between the E-UTRAN and the EPC
    - For both control purposes and for user plane data traffic
  - X2 interface for eNodeBs to interact with each other
    - Again for both control purposes and for user plane data traffic

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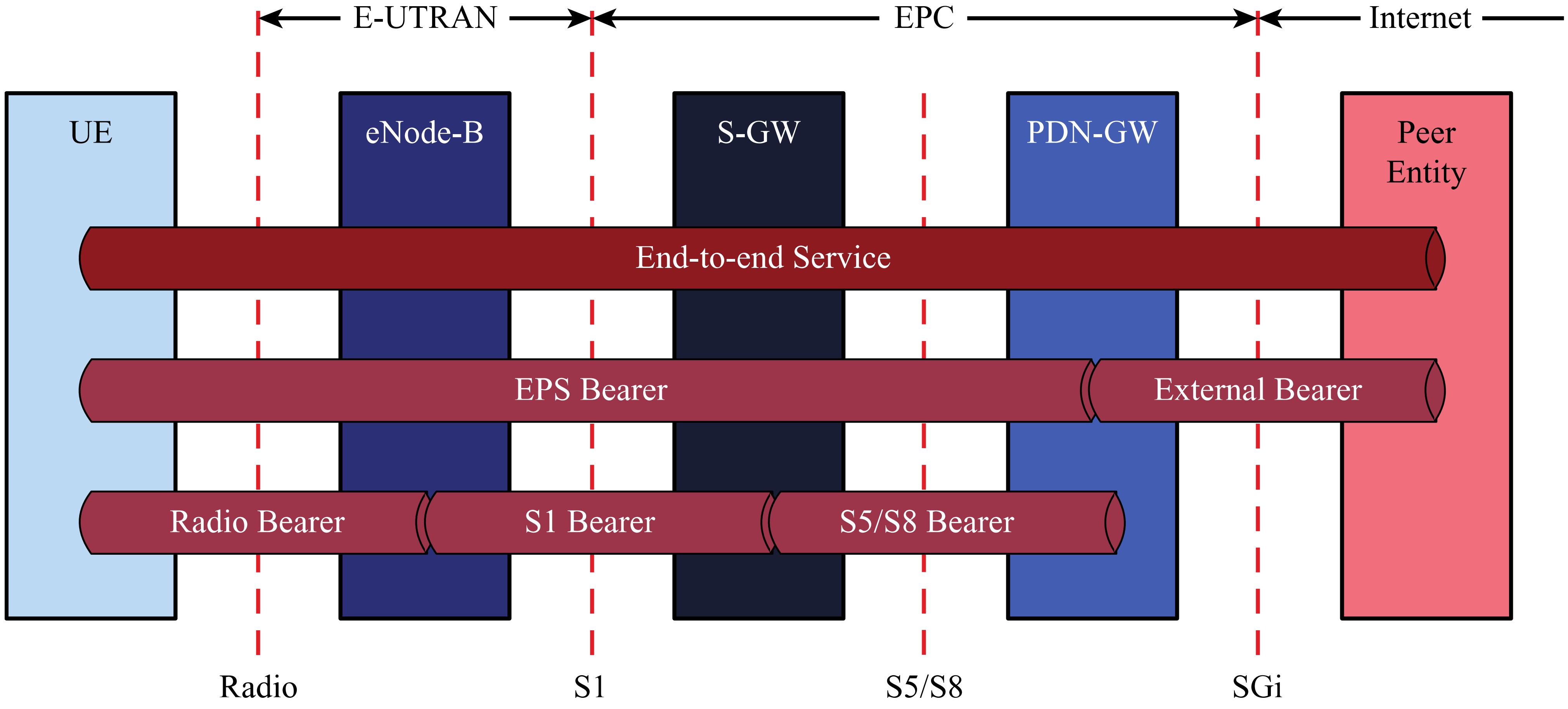
LTE Resource Management

- LTE uses bearers for quality of service (QoS) control instead of circuits
- EPS bearers
  - Between entire path between PGW and UE
  - Maps to specific QoS parameters such as data rate, delay, and packet error rate
- Service Data Flows (SDFs) differentiate traffic flowing between applications on a client and a service
  - SDFs must be mapped to EPS bearers for QoS treatment
  - SDFs allow traffic types to be given different treatment
- End-to-end service is not completely controlled by LTE

LTE QoS Bearer



Bearer Management based on QoS Class Identifier (QCI)

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video (live streaming)
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (live streaming) Interactive Gaming
8		8	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9*		9			

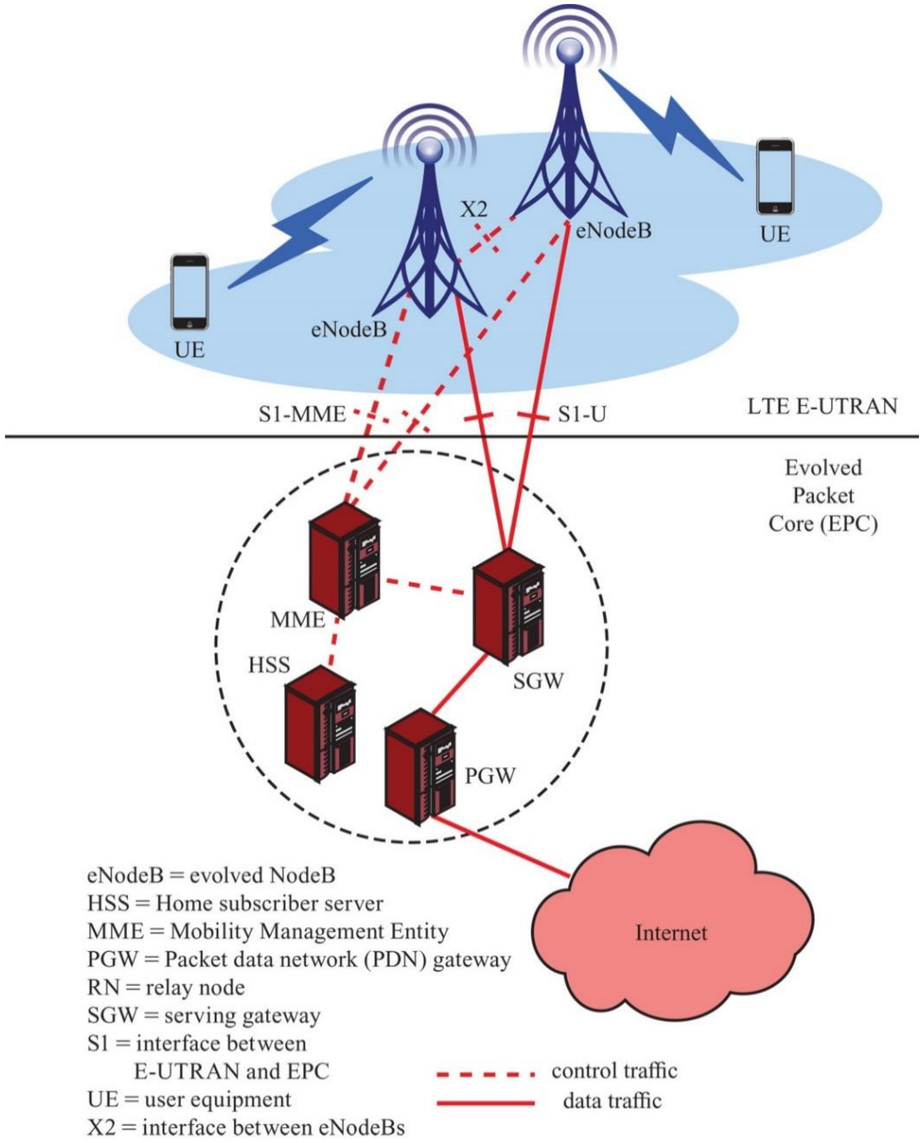
* QCI value typicaly used for the default bearer

Guaranteed (minimum) Bit Rate (QCI 1–4)

No Guarantees (QCI 5–9)

EPC: Mobility Management

- X2 interface used when moving within a RAN coordinated under the same Mobility Management Entity (MME)
- S1 interface used to move to another MME
- Hard handovers are used: A UE is connected to only one eNodeB at a time



EPC: Inter-cell Interference Coordination (ICIC)

- Reduces interference when the same frequency is used in a neighboring cell
- Goal is universal frequency reuse
  - N = 1 in “Cellular principles” lecture
  - Must avoid interference when mobile devices are near each other at cell edges
  - Interference randomization, cancellation, coordination, and avoidance are used
- eNodeBs send indicators
  - Relative Narrowband Transmit Power, High Interference, and Overload indicators
- Later releases of LTE have improved interference control
  - “Cloud RAN”: use a cloud to manage interference, spectrum

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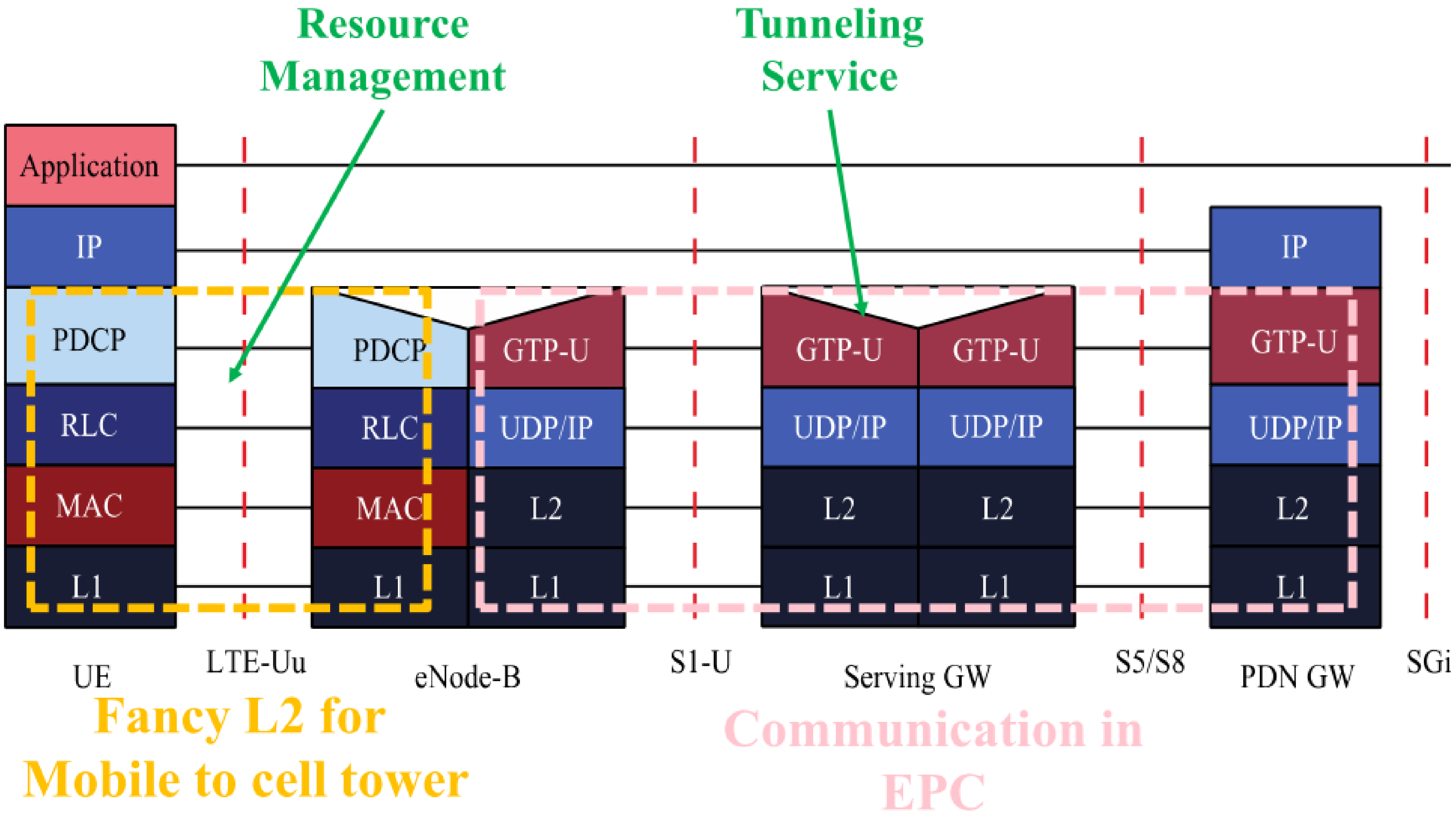
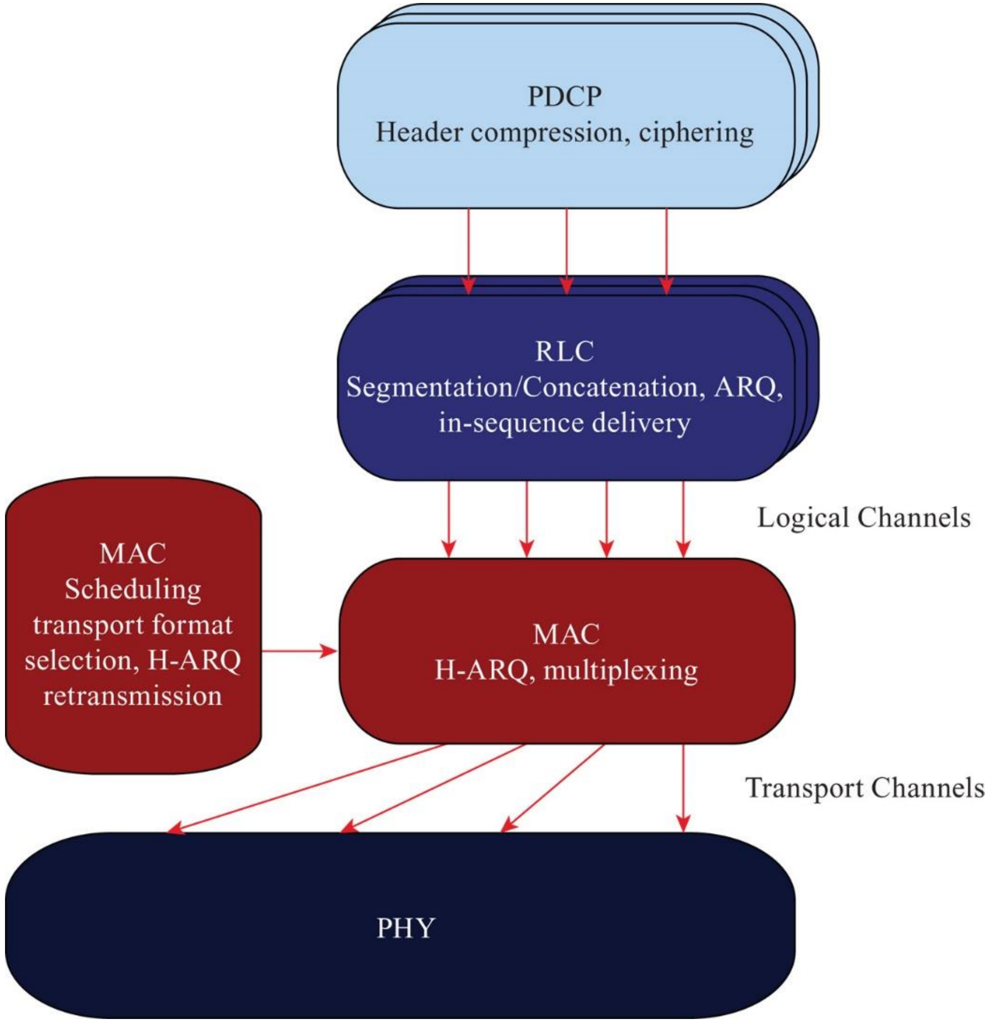
Protocol Layers End-to-End

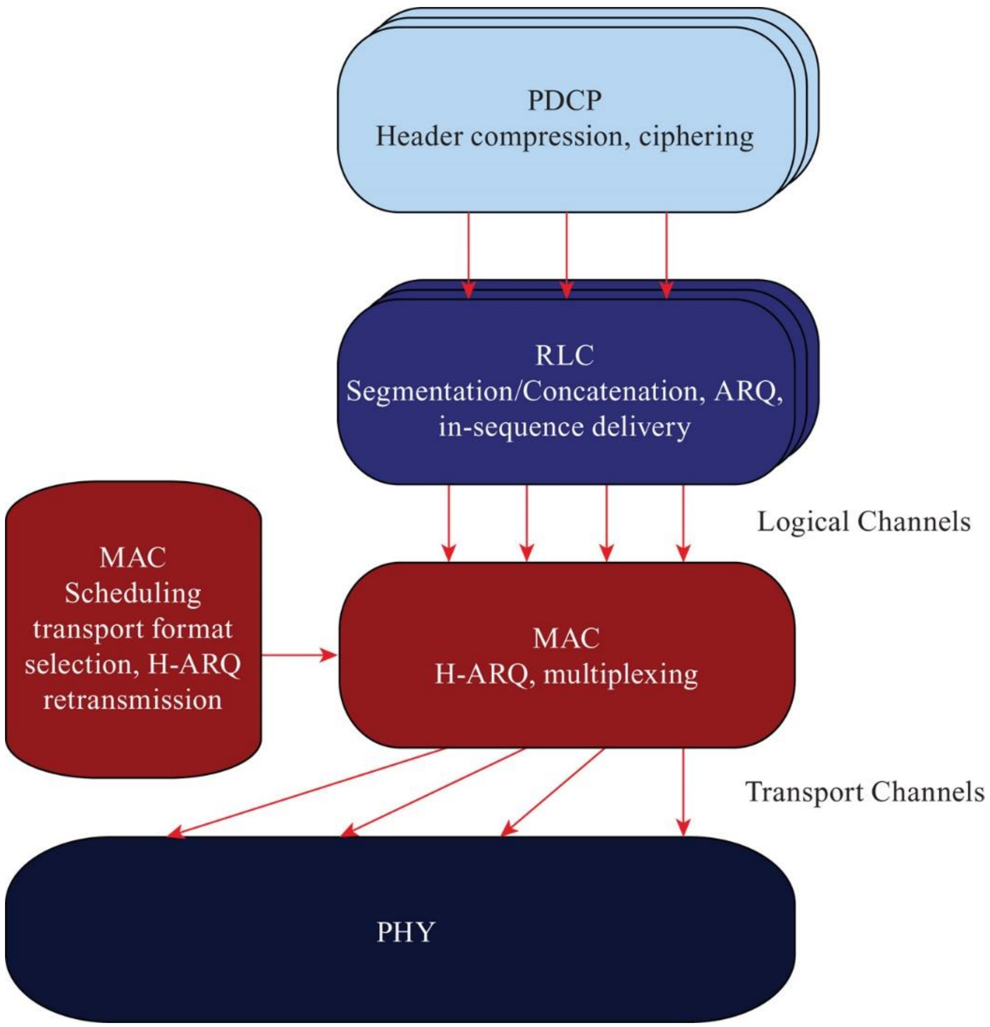


PDCP and RLC



- Packet Data Convergence Protocol (PDCP)
  - Delivers packets from UE to eNodeB
  - Involves header compression, ciphering, integrity protection, in-sequence delivery, buffering and forwarding of packets during handover
- Radio Link Control (RLC)
  - Segments or concatenates data units
  - Performs ARQ
    - Recover from MAC layer H-ARQ failures
    - ARQ: Automatic Repeat Request (retransmission)
    - H-ARQ: Hybrid ARQ – combines FEC and ARQ

MAC and PHY

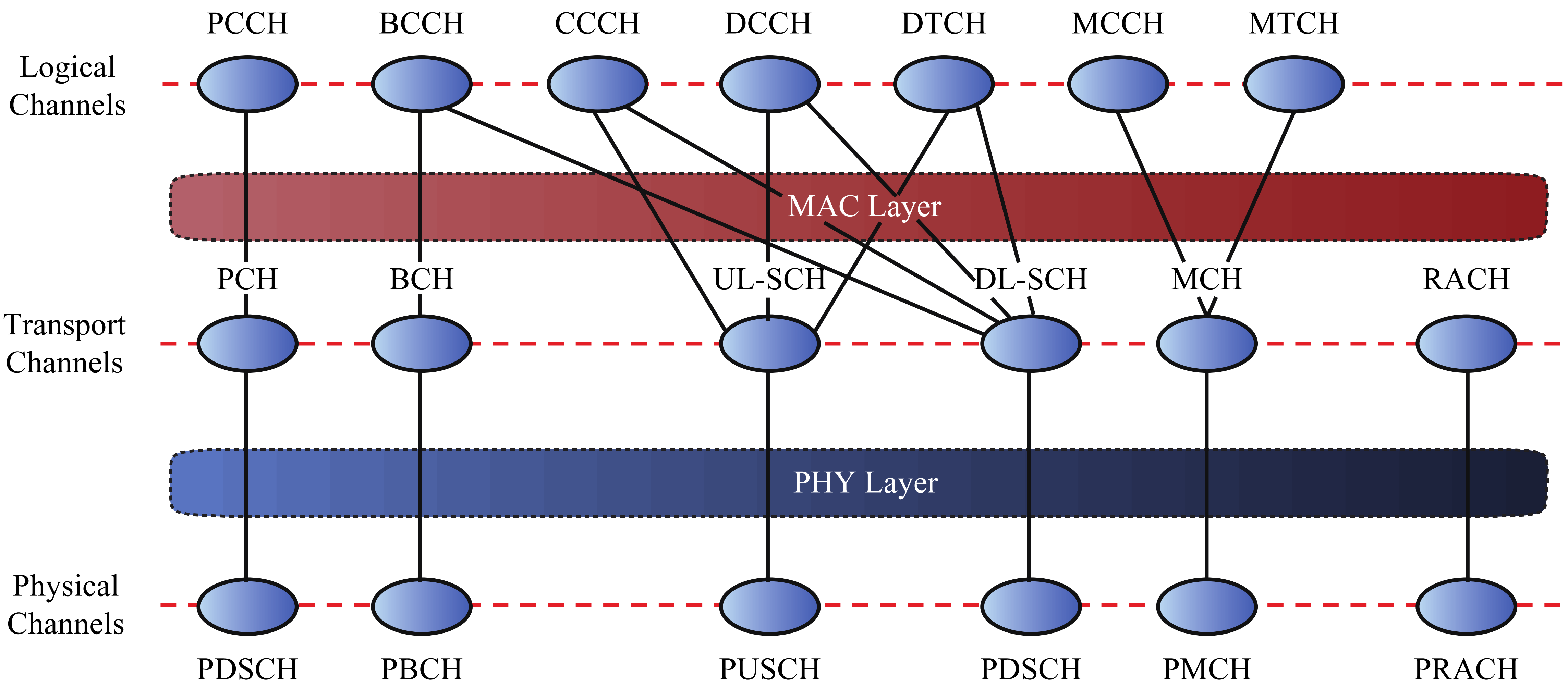


- Medium Access Control (MAC)
  - Performs H-ARQ: combines FEC and retransmission (ARQ)
  - Prioritizes and decides which UEs and radio bearers will send or receive data on which shared physical resources
  - Decides the transmission format, i.e., the modulation format, code rate, MIMO rank, and power level
- Physical layer actually
  - transmits the data

LTE Channel Structure

- Three types of channels
  - Channels provide services to the layers above
- Logical channels
  - Provide services from the MAC layer to the RLC
  - Provide a logical connection for control and traffic
- Transport channels
  - Provide PHY layer services to the MAC layer
  - Define modulation, coding, and antenna configurations
- Physical channels
  - Define time and frequency resources use to carry information to the upper layers
- Different types of broadcast, multicast, paging, and shared channels

Mapping of Channels



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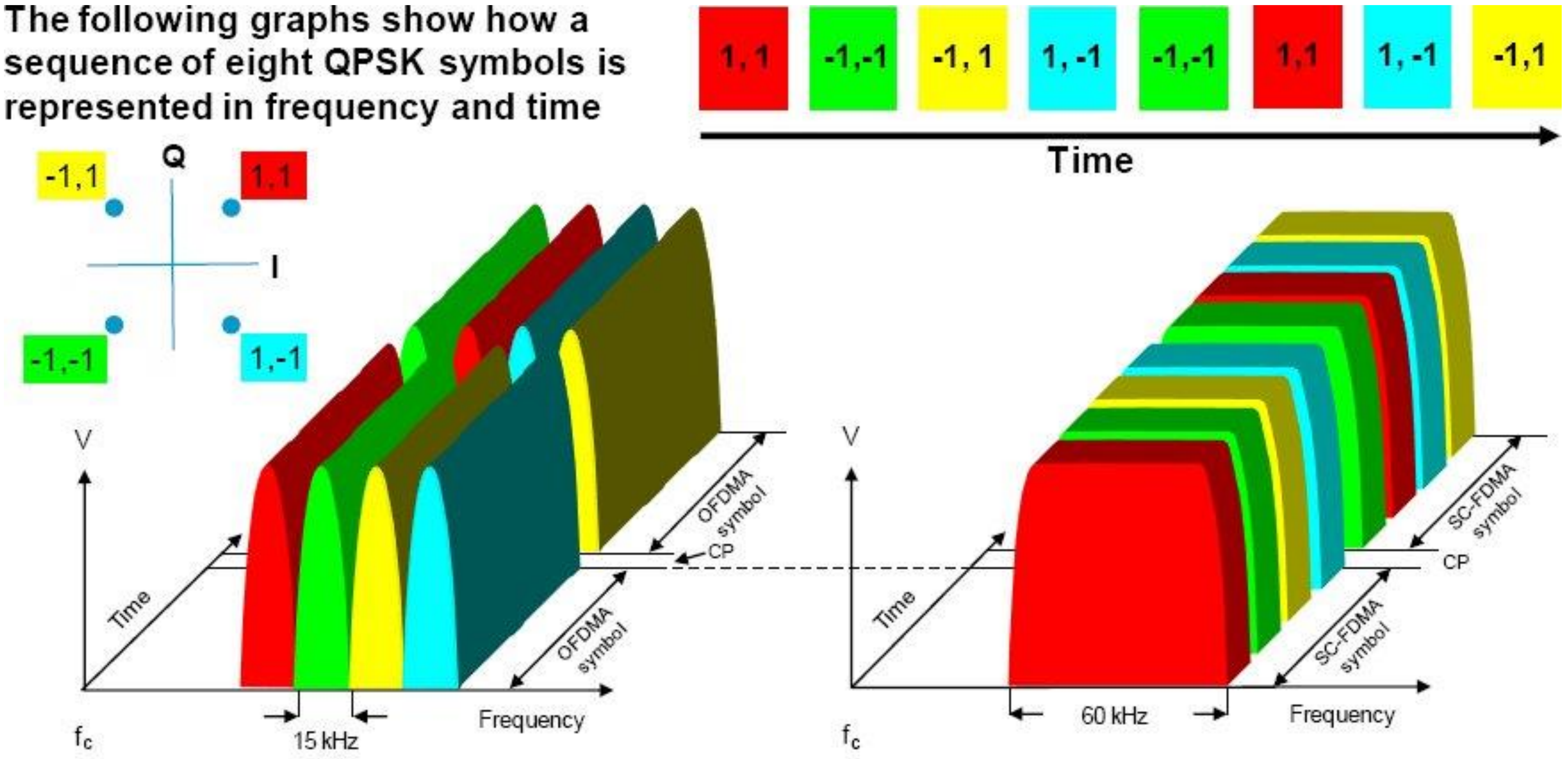
LTE Radio Access Network

- LTE uses OFDM and MIMO
- OFDM offers benefits similar to those of CDMA
  - Good immunity to fading as only a small portion of the energy for any one link is typically lost due to a fade
  - Fast power control to keep the noise floor as low as possible
- Additional advantages
  - Highly resistant to fading and inter-symbol interference
  - Low modulation rates on each of the many sub-carriers
  - Sophisticated error correction
  - Scales rates easier than CDMA
  - Allows more advanced antenna technologies, like MIMO
- Breaks information into pieces and assigns each one to a specific set of sub-carriers

Different Solution for Up and Downlink

- LTE downlink uses OFDM with Multiple Access (OFDMA)
  - Multiplexes multiple mobiles on the same subcarrier
  - Improved flexibility in bandwidth management, e.g., multiple low bandwidth users can share subcarriers
  - Enables per-user frequency hopping to mitigate effects of narrowband fading
- As the number of sub-carriers increases, the composite time-domain signal starts to look like Gaussian noise
- This translates into a high peak-to-Average Power ratio (PAPR)
- The uplink uses Single Carrier FDMA (SC-FDMA)
  - OFDM but using a single carrier
  - Provides better energy and cost efficiency for battery-operated mobiles

The following graphs show how a sequence of eight QPSK symbols is represented in frequency and time



OFDMA

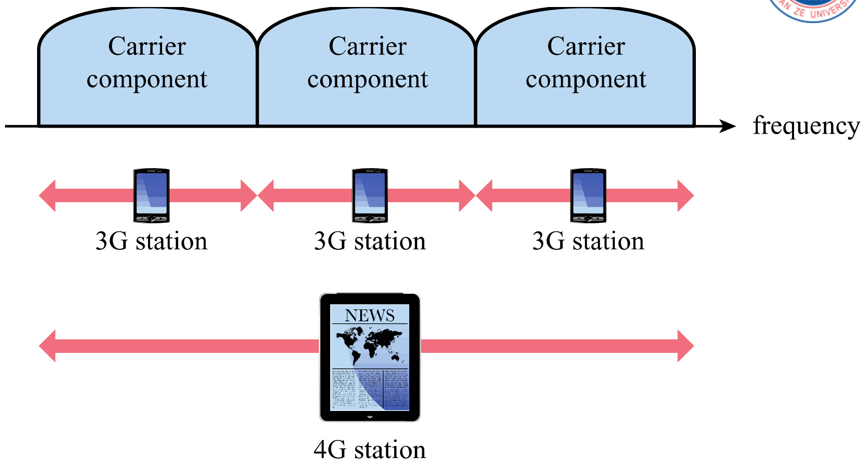
Data symbols occupy 15 kHz for one OFDMA symbol period

SC-FDMA

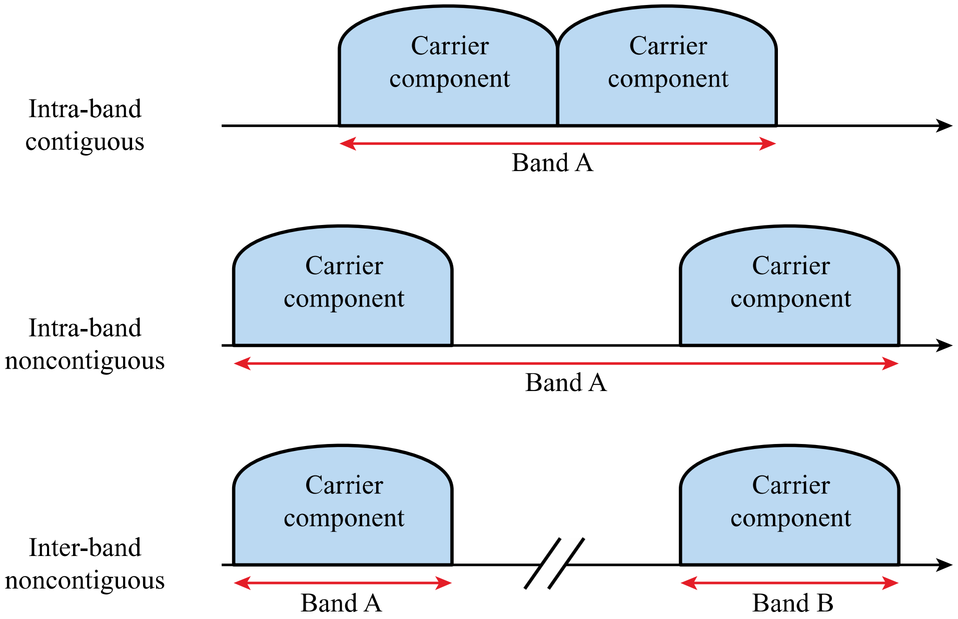
Data symbols occupy M*15 kHz for 1/M SC-FDMA symbol periods

Carrier Aggregation

- Ultimate goal of LTE-Advanced is 100 MHz bandwidth
  - Combine up to 5 component carriers (CCs)
  - Each CC can be 1.4, 3, 5, 10, 15, or 20 MHz
  - Up to 100 MHz
- Three approaches to combine CCs
  - Intra-band Contiguous: carriers adjacent to each other
  - Intra-band noncontiguous: Multiple CCs belonging to the same band are used in a noncontiguous manner
  - Inter-band noncontiguous: Use different bands



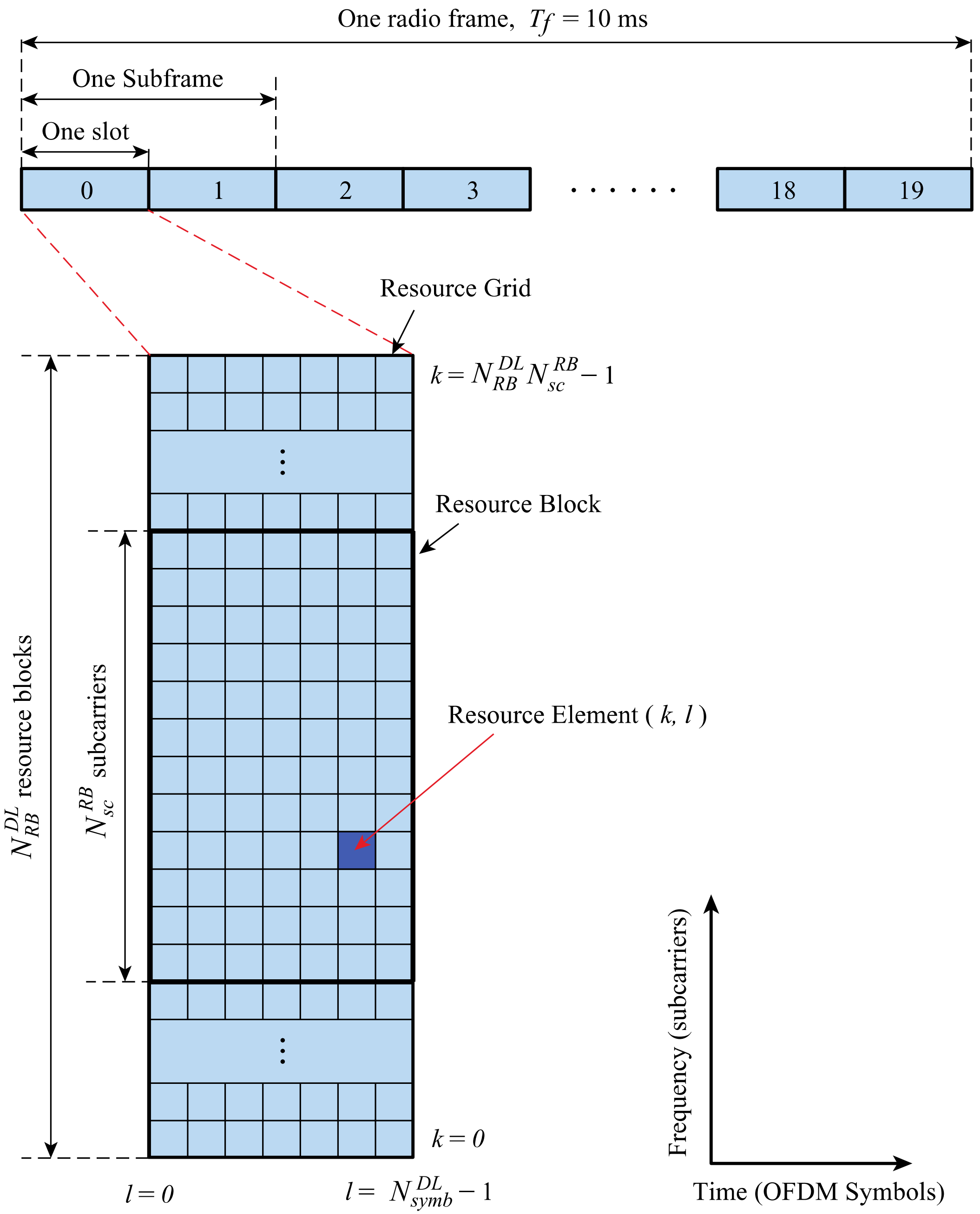
(a) Logical view of carrier aggregation



(b) Types of carrier aggregation

Resource Blocks

- A time-frequency grid is used to illustrate allocation of physical resources
- Each column is 6 or 7 OFDM symbols per slot
- Each row corresponds to a subcarrier of 15 kHz
  - Some subcarriers are used for guard bands
  - 10% of bandwidth is used for guard bands for channel bandwidths of 3 MHz and above

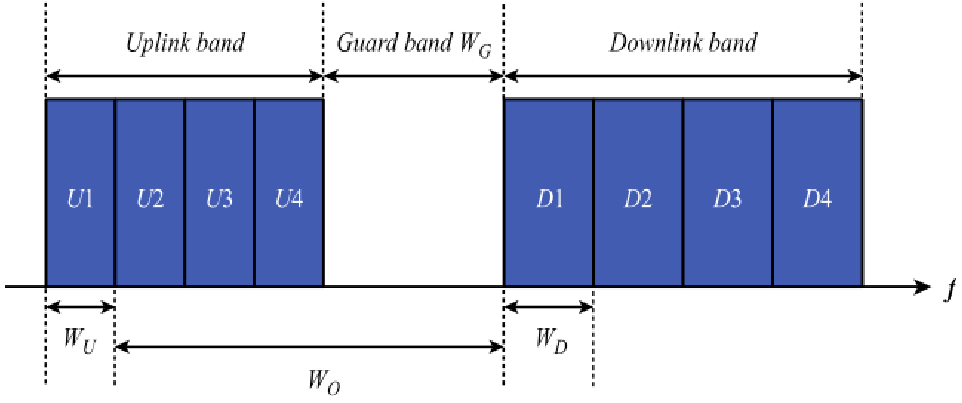


Resource Blocks

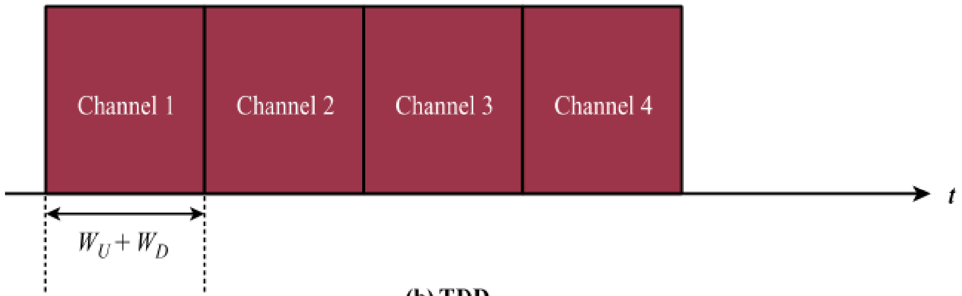
- Resource Block
  - 12 subcarriers, 6 or 7 OFDM symbols
  - Results in 72 or 84 resource elements in a resource block
- MIMO: 4×4 in LTE, 8×8 in LTE-Advanced
  - Separate resource grids per antenna port
- eNodeB assigns RBs with channel-dependent scheduling
- Multiuser diversity can be exploited
  - To increase bandwidth usage efficiency
  - Assign resource blocks for UEs with favorable qualities on certain time slots and subcarriers
  - Can also consider fairness, QoS priorities, typical channel conditions, ..

Managing Uplink and Downlink

- LTE uses both TDD and FDD
  - Both have been widely deployed
- Time Division Duplexing (TDD)
  - Uplink and downlink transmit in the same frequency band, but alternating in the time domain
- Frequency Division Duplexing (FDD)
  - Different frequency bands for uplink and downlink
- LTE uses two cyclic prefixes (CPs)
  - Extended CP is for worse environments



(a) FDD



(b) TDD

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LTE-Advanced

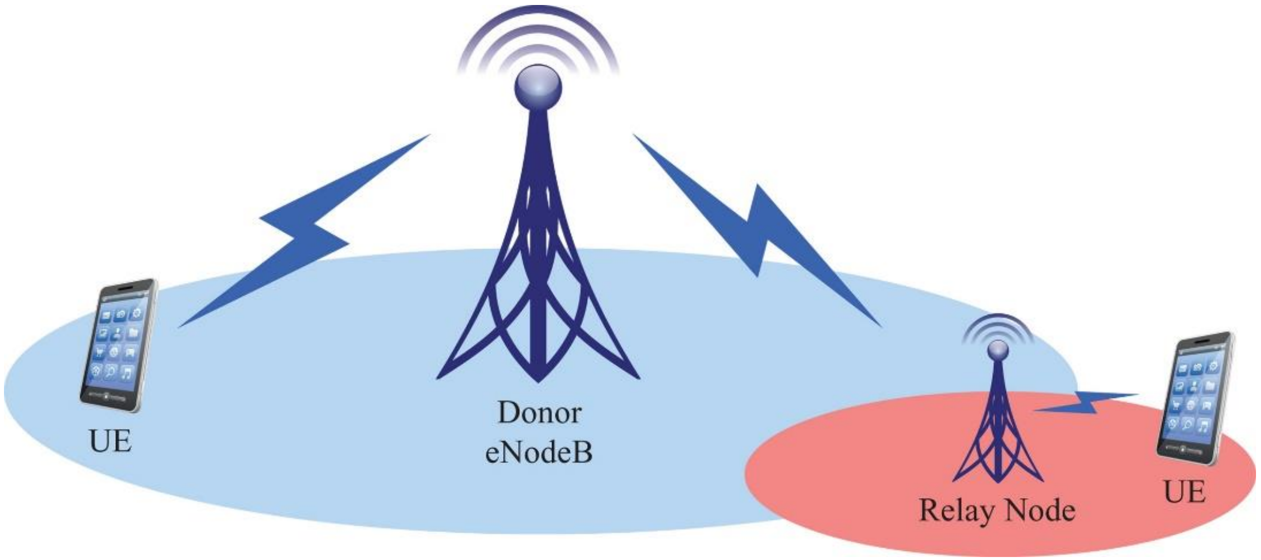
- Carrier aggregation – up to 100 MHz
- MIMO enhancements to support higher dimensional MIMO – up to 8 x 8
- Relay nodes
- Heterogeneous networks involving small cells such as femtocells, picocells, and relays
- Cooperative multipoint transmission and enhanced intercell interference coordination
- Voice over LTE

Comparison
LTE and LTE-Advanced

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	$<$100 ms	$<$50 ms
	Dormant to active	$<$50 ms	$<$10 ms
User plane delay		$<$5 ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2 $\times$ 2	30 bps/Hz @8 $\times$ 8
	Uplink	2.5 bps/Hz @1 $\times$ 2	15 bps/Hz @4 $\times$ 4
Mobility		Up to 350 km/hr	Up to 350–500 km/hr

Relaying

- Relay nodes (RNs) extend the coverage area of an eNodeB
  - Receive, demodulate and decode the data from a UE
  - Apply error correction as needed
  - Then transmit a new signal to the base station
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies

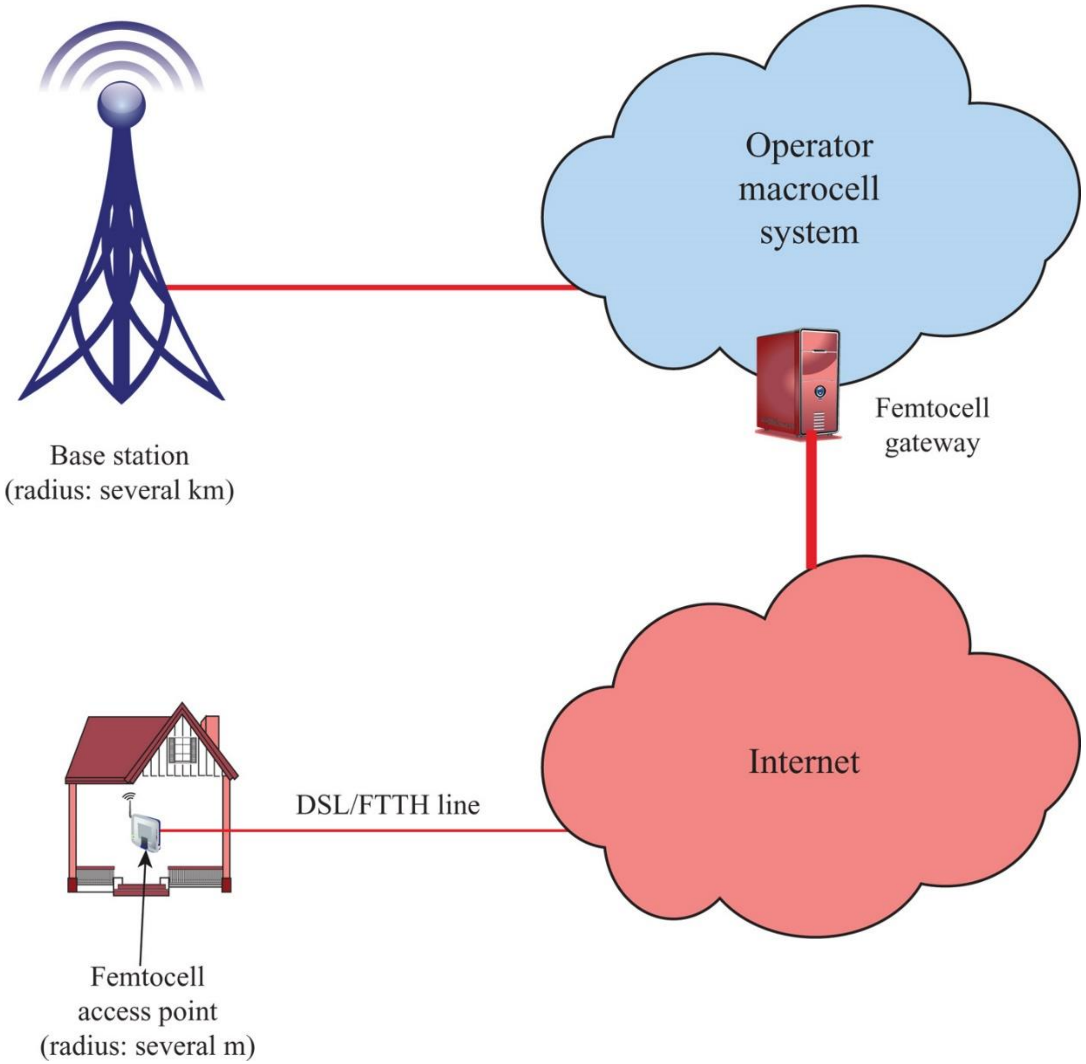


Heterogeneous Networks

- It is increasingly difficult to meet data transmission demands in densely populated areas
- Small cells provide low-powered access nodes
  - Operate in licensed or unlicensed spectrum
  - Range of 10 m to several hundred meters indoors or outdoors
  - Best for low speed or stationary users
- Macro cells provide typical cellular coverage
  - Range of several kilometers
  - Best for highly mobile users

Heterogeneous Networks

- Femtocell
  - Low-power, short-range self-contained base station
  - In residential homes, easily deployed and use the home's broadband for backhaul
  - Also in enterprise or metropolitan locations
- *Network densification* is the process of using small cells
  - Issues: Handovers, frequency reuse, QoS, security
- A network of large and small cells is called a *heterogeneous network (HetNet)*



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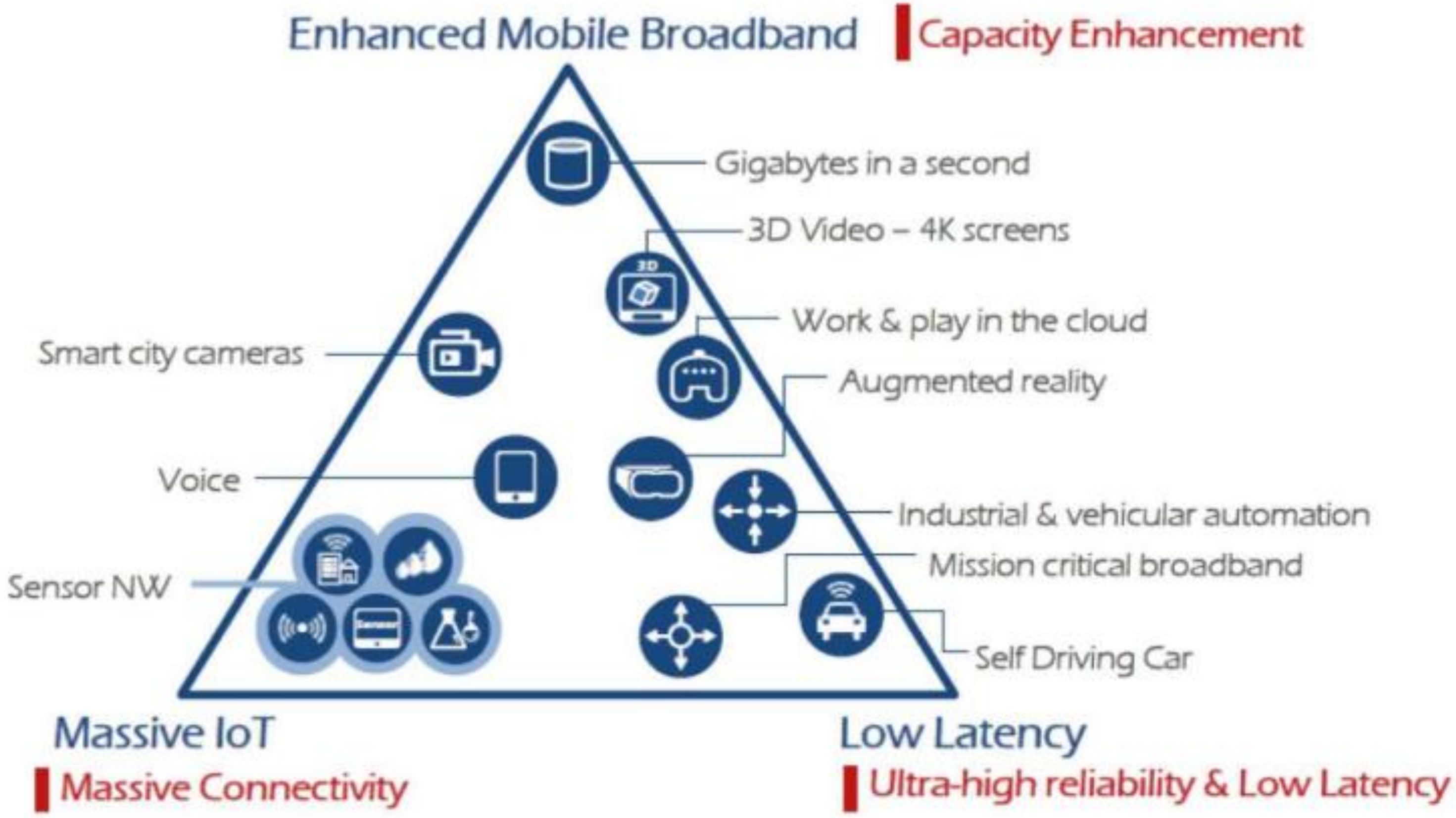
Overview 5G

- Goals and Motivation
- Architecture
- Managing heterogeneity
- Virtualization and cloud technology
- Cloud-RAN
- 5G campus networks

5G Vision ITU

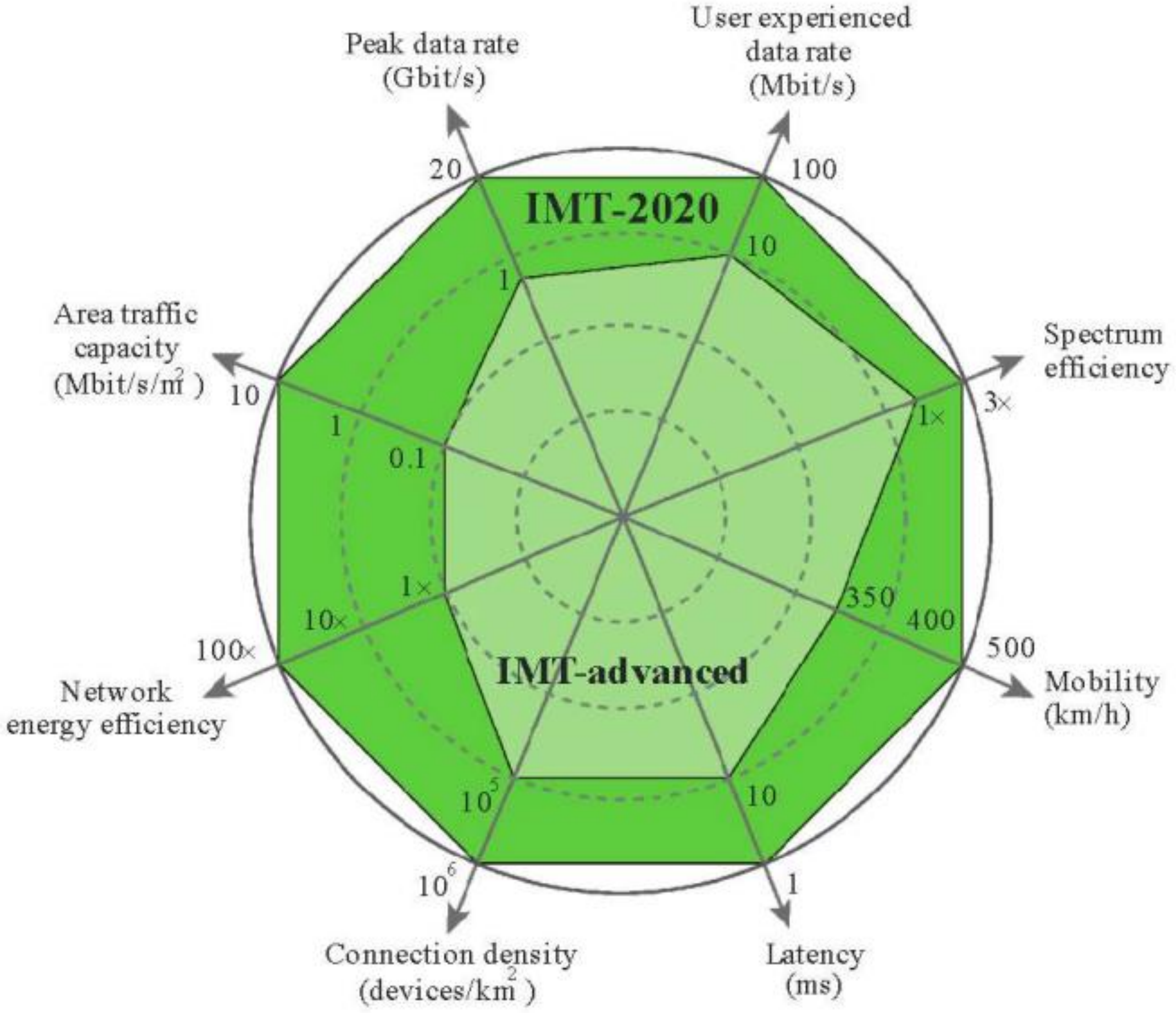


(Source: ETRI graphic, from ITU-R IMT 2020 requirements)

Faster 4G

Growing application domains

Performance Goals ITU



5G technology
More of the same?

- Goal is 10+ fold increase in bandwidth over 4G
  - Combination of more spectrum and more aggressive use of 4G technologies
- Very aggressive use of MIMO
  - Tens to hundred antennas
  - Very fine grain beamforming and MU-MIMO
- More spectrum: use of millimeter bands
  - Low band: below 2 GHz, e.g., 660-850 MHz
  - Mid band: below 6 GHz, new bands, e.g., 2.5-3.7 GHz
  - High band: mmWave, over 26 GHz, e.g., 25-39 GHz
    - New bands - challenging but a lot of spectrum available

Is That Enough?

- Scaling up existing solutions attacks bandwidth challenges, but what about …
- Dealing with heterogeneity
  - Widely different traffic loads
  - Use of very different parts of the spectrum
- Dealing with increased complexity
  - Multiple traffic classes, signaling protocols
  - Diverse types of PHY processing
- Managing multiple deployment models and controlling costs
  - Mobile users vs IoT vs low latency/high bandwidth
  - Private cellular – 5G campus networks

5G Key Technologies

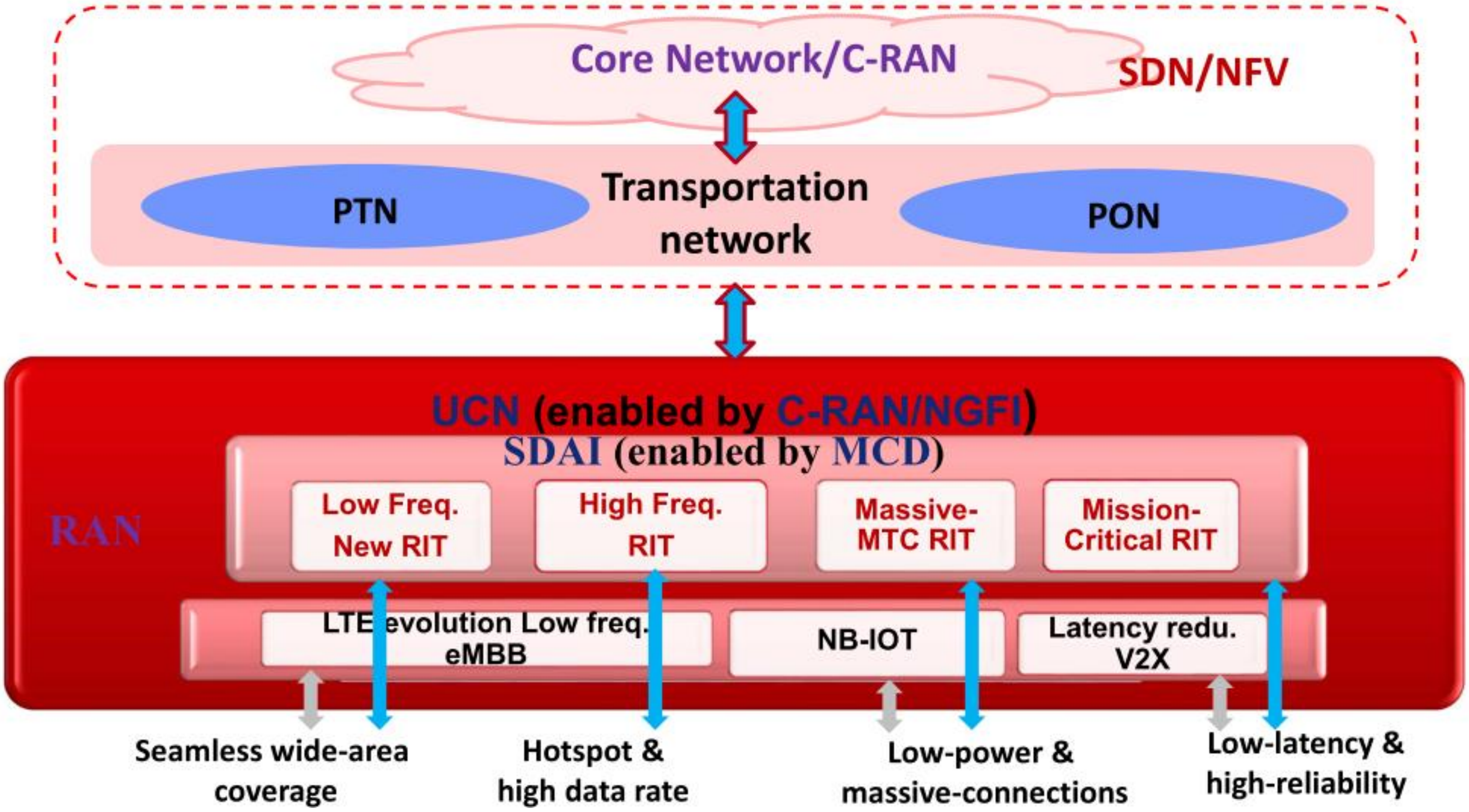


Figure based on: https://www.itu.int/en/ITU-T/gsc/Documents/GSC-20/Session-6/GSC20_Session6_5G_Chih_IEEE.ppt

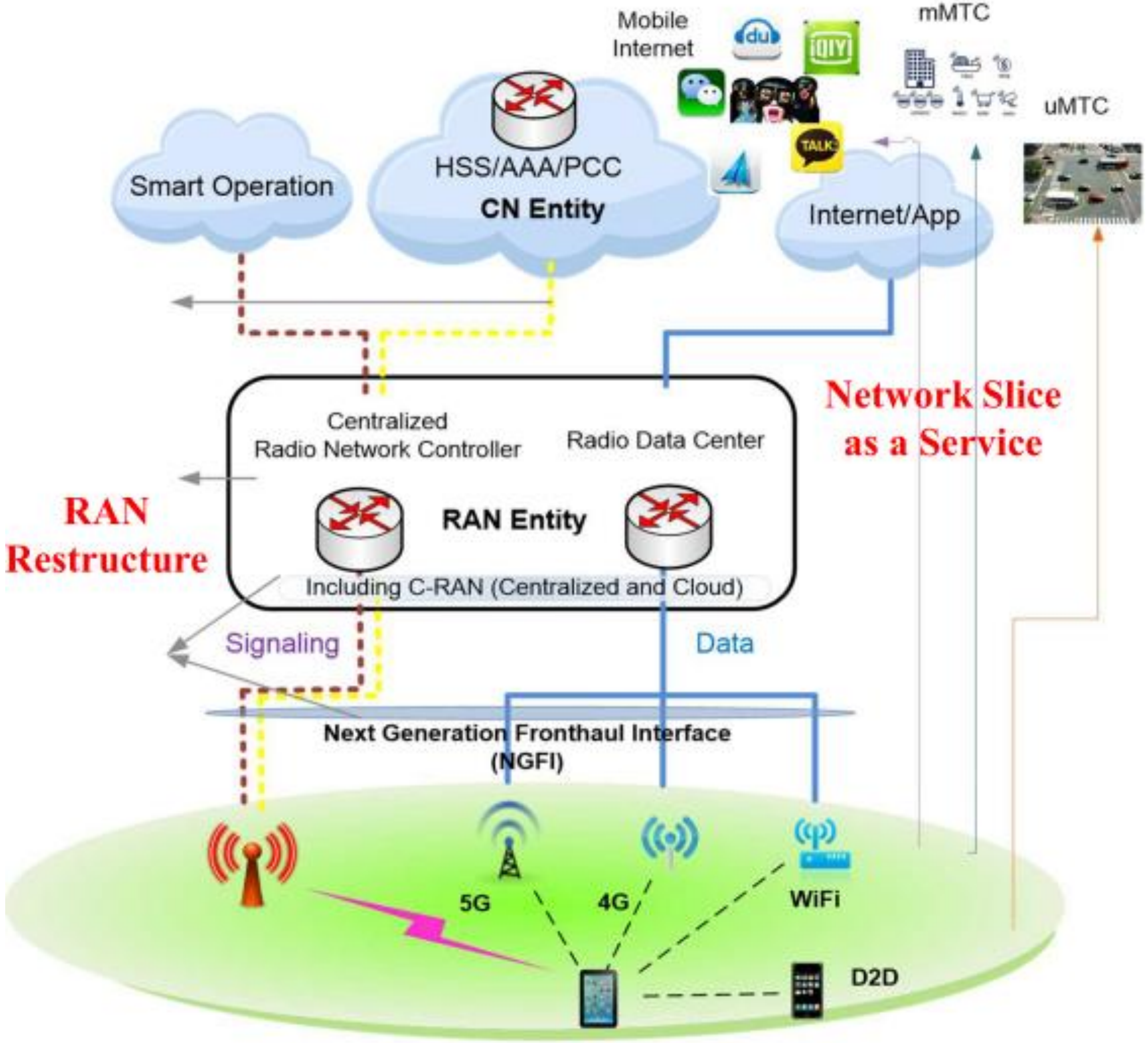
Acronyms

- RIT: Radio Interface Technology
- UCN: User-centric network (data)
  - Optimize user (device) performance, e.g., interference mitigation
- NGFI: Next-Generation Fronthaul Interfaces
  - Interface for exchanging signal information between baseband processing in C-RAN (IQ sample) and remote radio units
  - Used in C-RAN to minimize impact of interference, …
- SDAI: Software-Defined Air Interface (control)
  - Interface to manage PHY and link level: frame structure, waveform, multiple access, duplex mode, antenna configuration, ..
- MCD: Multi-level Centralized and Distribute protocol stack:
  - Coordinates decision making across the system (cell, UE)
- PTN: Packet Transport Network
- PON: Passive Optical Network

Technology Discussion

- The base stations have support for diverse front ends and antennas
  - Responsible for generating/transmitting baseband signal
  - Needed to deal with diversity of frequency bands, traffic loads
- All other processing is done in a “cloud RAN”
  - Responsible for both the sent/received data stream and for RAN control
- Standard protocols to coordinate between base stations and C-RAN:
  - MCD stack for control of PHY and cellular protocol functions using SDIA interface
  - UNC for RF signal data transfer based on NGFI interface

Cloud RAN (C-RAN)



- Aggressively move processing to the cloud
  - Network control, signaling protocols
  - Radio signal processing
- Assumes moving all processing to commodity platforms instead of custom HW
- Use of modern cloud, networking technologies
  - Virtualization, network functions (NFV), software defined networking
  - Can potentially be outsourced to cloud providers

Figure based on: https://www.itu.int/en/ITU-T/gsc/Documents/GSC-20/Session-6/GSC20_Session6_5G_Chih_IEEE.ppt

Why C-RAN? Standard Cloud Arguments

- Cheap compute resources
  - Economy of scale of operating large data centers
- Elastic resource pool
  - Size of the resource pool can adapt to the traffic load
  - Multiplexing of resources with other users/applications
- Flexible allocation of resources across applications
  - Relative load of different traffic classes, frequency bands
- Ability to outsourcing cloud management
  - Can be delegated to specialized cloud providers
  - Reduces infrastructure investment
- Virtualization offers isolation of services

C-RAN Challenges

- Transfer of signal data between base stations and C-RAN requires a lot of bandwidth
  - Supported by the NGFI interface
- Processing of the signal data is latency sensitive
  - Latency bounds are much tighter than for typically workloads
  - Need to be able to adapt to channel conditions
  - May need additional support in the cloud infrastructure
- RAN control needs to be driven by information obtained from signal data
  - Adjust transmit powers, antennas, …

Frequency Reuse

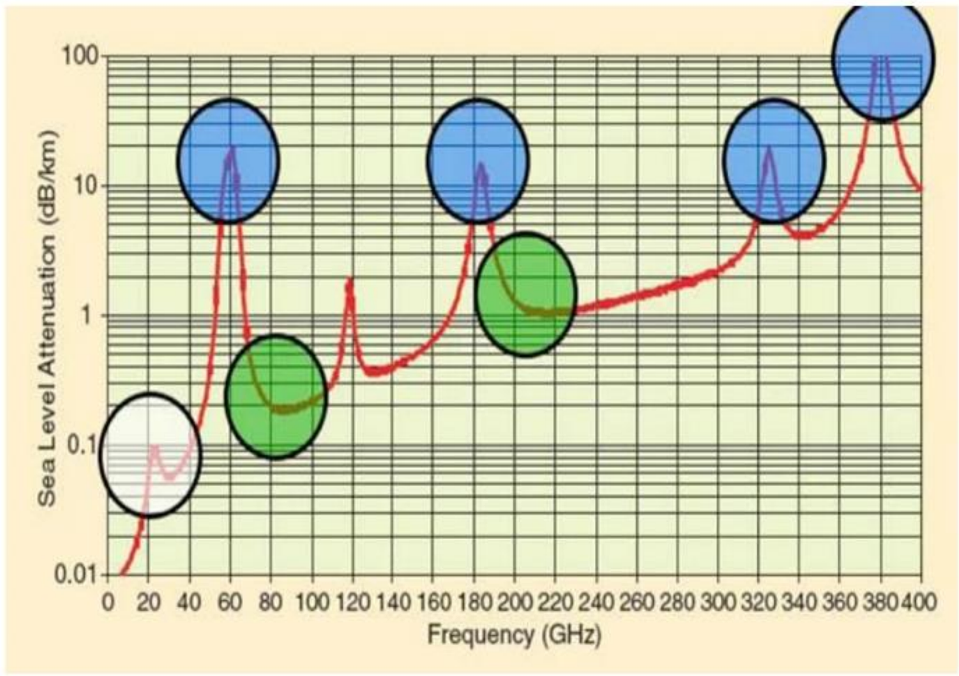
- Frequency reuse across cells has become increasingly aggressive:
  - Initially, macro cells with relatively static distribution of frequencies across cells
  - Next, introduction of micro, pico, etc. cells that are selectively deployed and can reuse frequencies more aggressively
  - Finally, more aggressive reuse using coordinated interference mitigation across cells
- Drive for frequency reuse is economics
- Goal: no cell designs, where frequencies are dynamically assigned and used “everywhere”
  - Very carefully limit interference during reuse

mmWave Offers Significant More Capacity

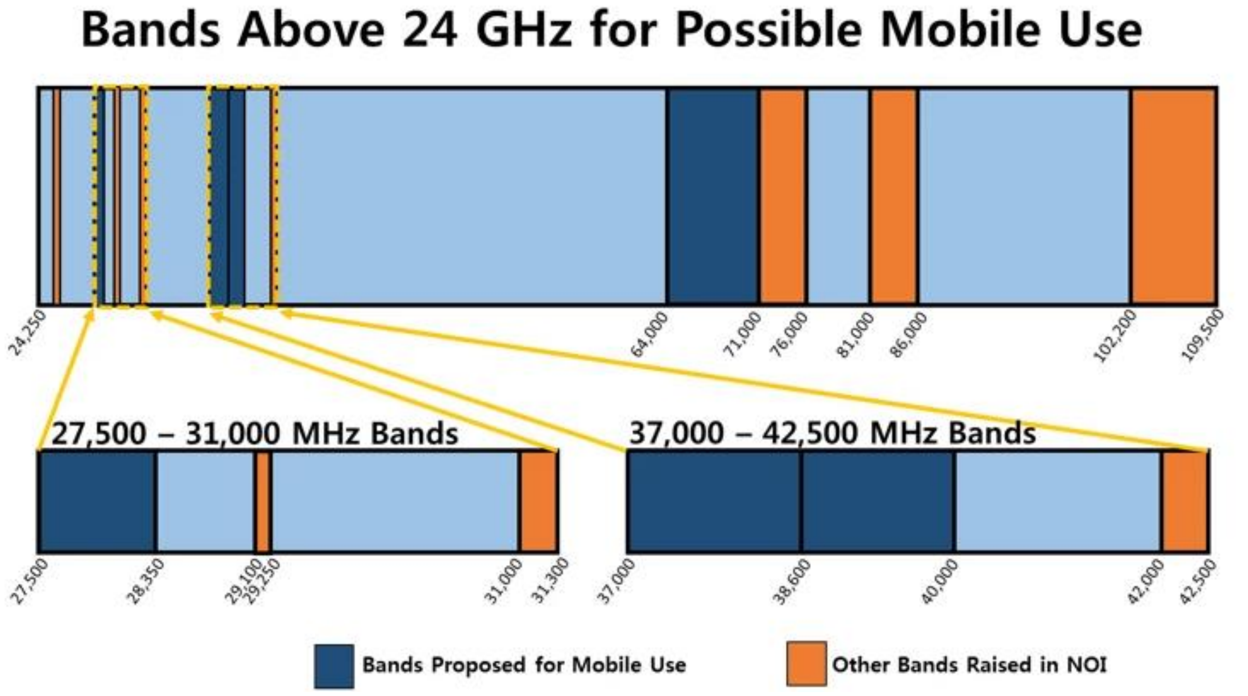
- There is a lot of spectrum available!
- Need to use beam forming to achieve reasonable range for mmWave
  - Possibly using large number of antennas (10s .. 100)
  - Technology similar to that discussed for 802.11ad
  - Challenges include establishing sessions, mobility, ..
- Best solution likely involves coordination between stations with “cm-wave” technologies
  - ~GHz technologies are used for coverage
  - mmWave is used for high capacity when needed

mmWave is Hard to Use

- Some mmWave frequencies are hard to use because of atmospheric absorption
  - E.g., 60GHz!



- Cellular operators measurements studies to identify frequencies that are commercially viable
  - 28, 38, and 73 GHz look promising

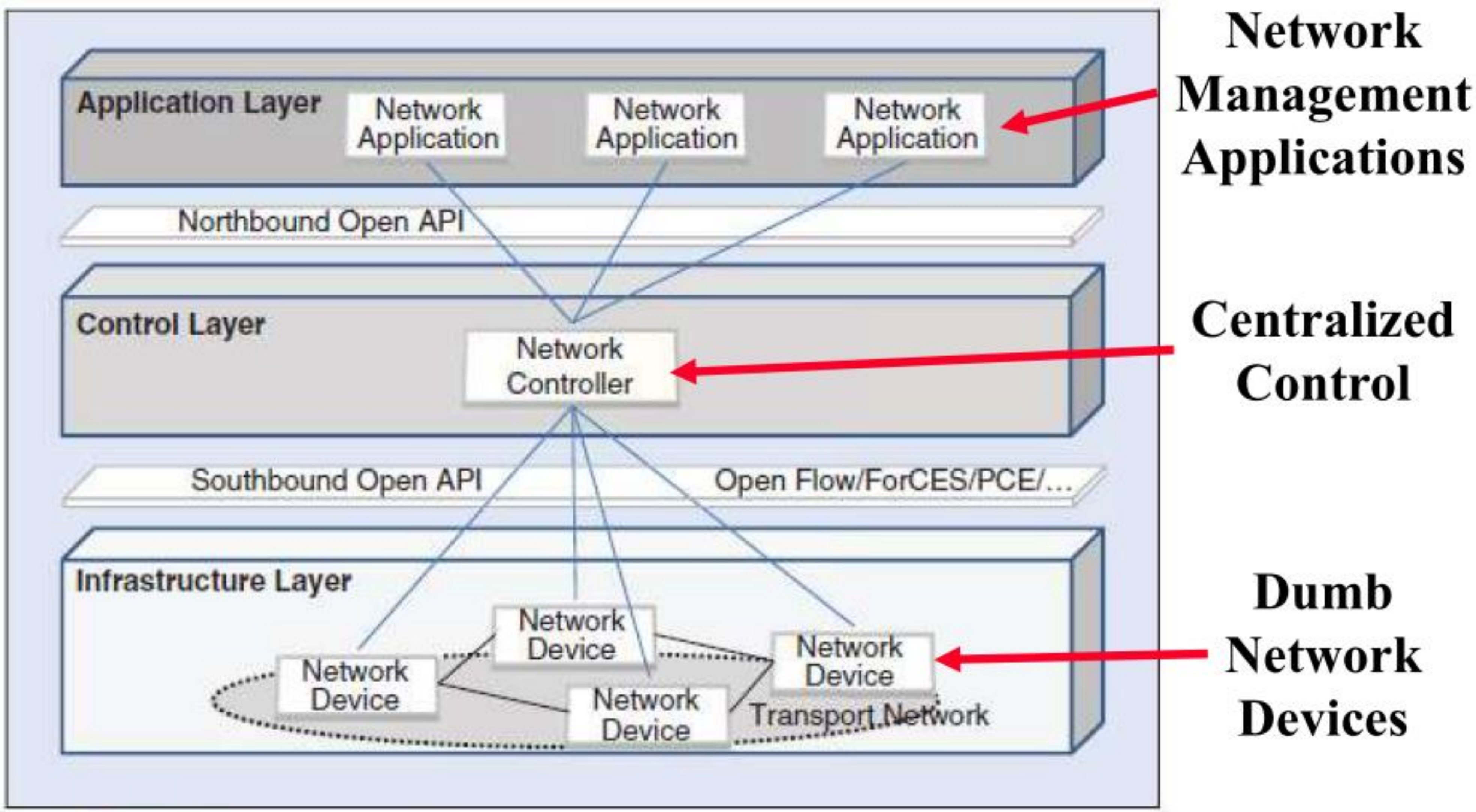


Ref: https://www.ni.com/zh-tw/innovations/white-papers/16/mmwave--the-battle-of-the-bands.html

Use New Network Technologies in Core Network

- Software Defined Networking (SDN)
  - Centralized control of the network
  - Provides more fine grain control over resources, e.g., bandwidth management, …
- Network Function Virtualization (NFV)
  - Cellular operators run a lot of “middleboxes” that provide value added services to users
  - Traditionally supported using custom hardware but increasingly supported by “Virtual Network Functions” running on commodity servers
  - Enabler for moving computing to cloud
- Network slicing using virtualization
  - Flexible way of sharing a single infrastructure between several network operators and their clients

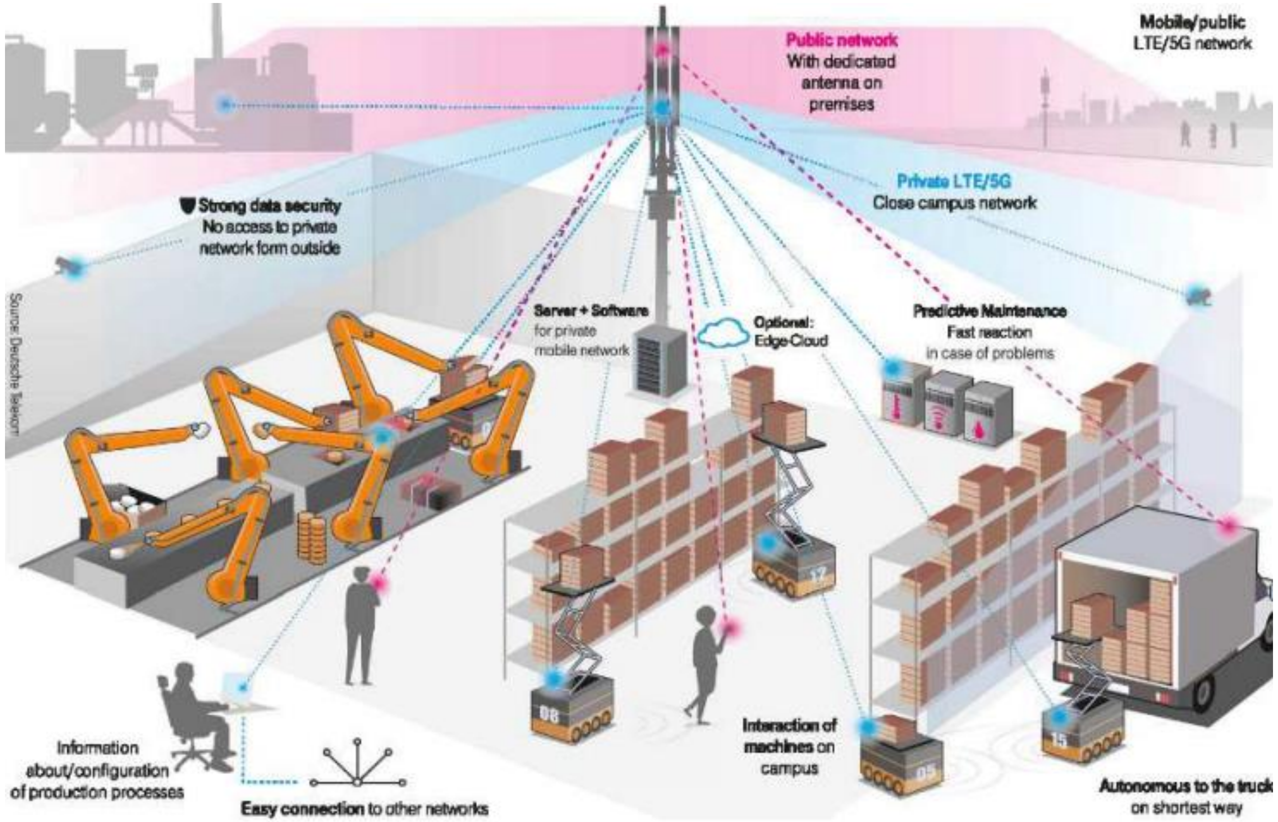
SDN Concept


Application Layer
Network Application
Network Application
Network Application
Northbound Open API
Control Layer
Network Controller
Southbound Open API
Open Flow/ForCES/PCE/...
Infrastructure Layer
Network Device
Network Device
Network Device
Network Device
Transport Network
Network Management Applications
Centralized Control
Dumb Network Devices

SDN Overview

- The control plane and data forwarding plane are separated
- A centralized controller maintains a complete view of the network resources
- Network applications manage resources, control network functions
  - Routing, managing QoS, traffic engineering, etc.
  - Obtain network view through northbound interface
- Uses southbound interface to collect network state and send instructions to devices
  - Protocol is called Openflow for today's IP protocols

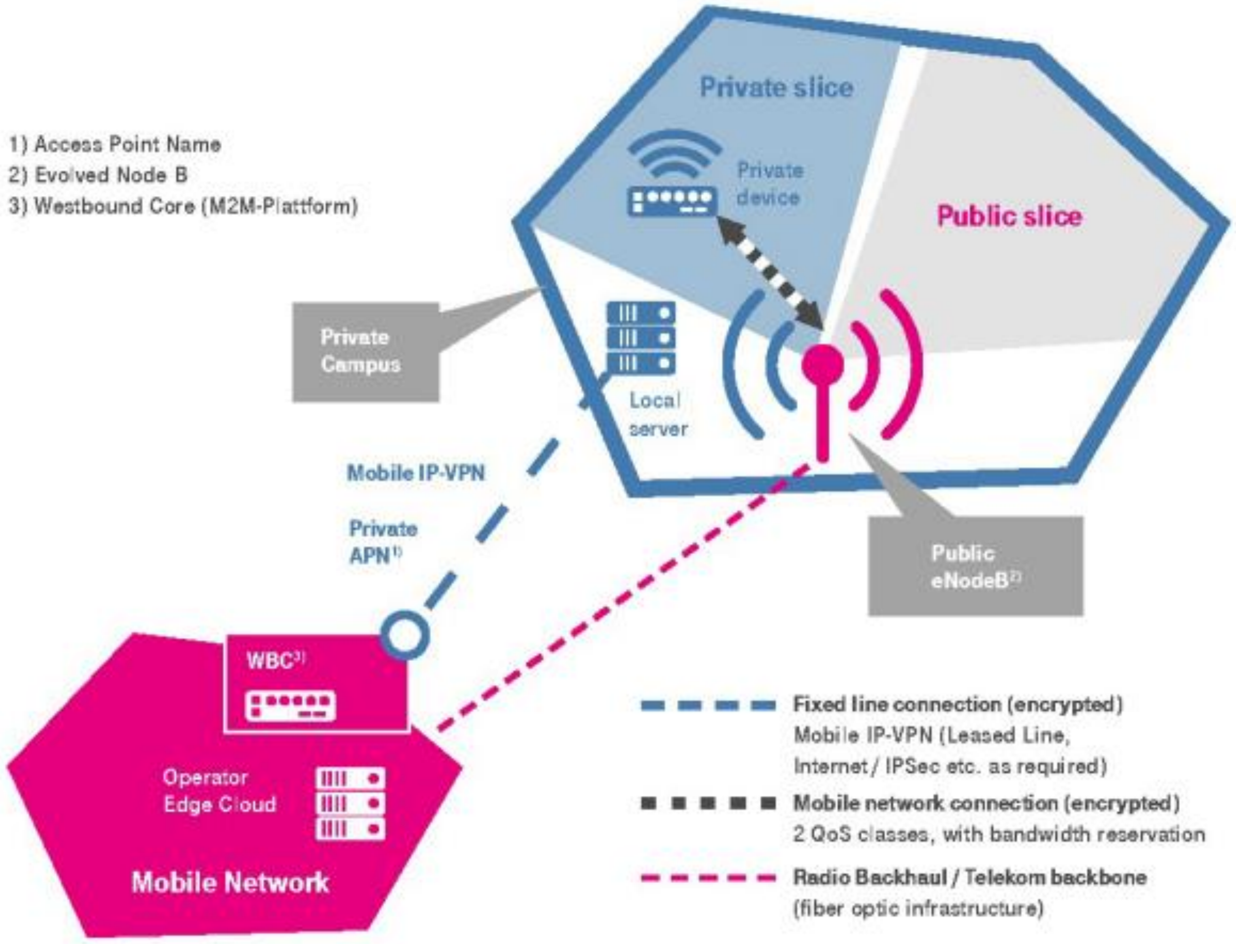
5G Campus Networks



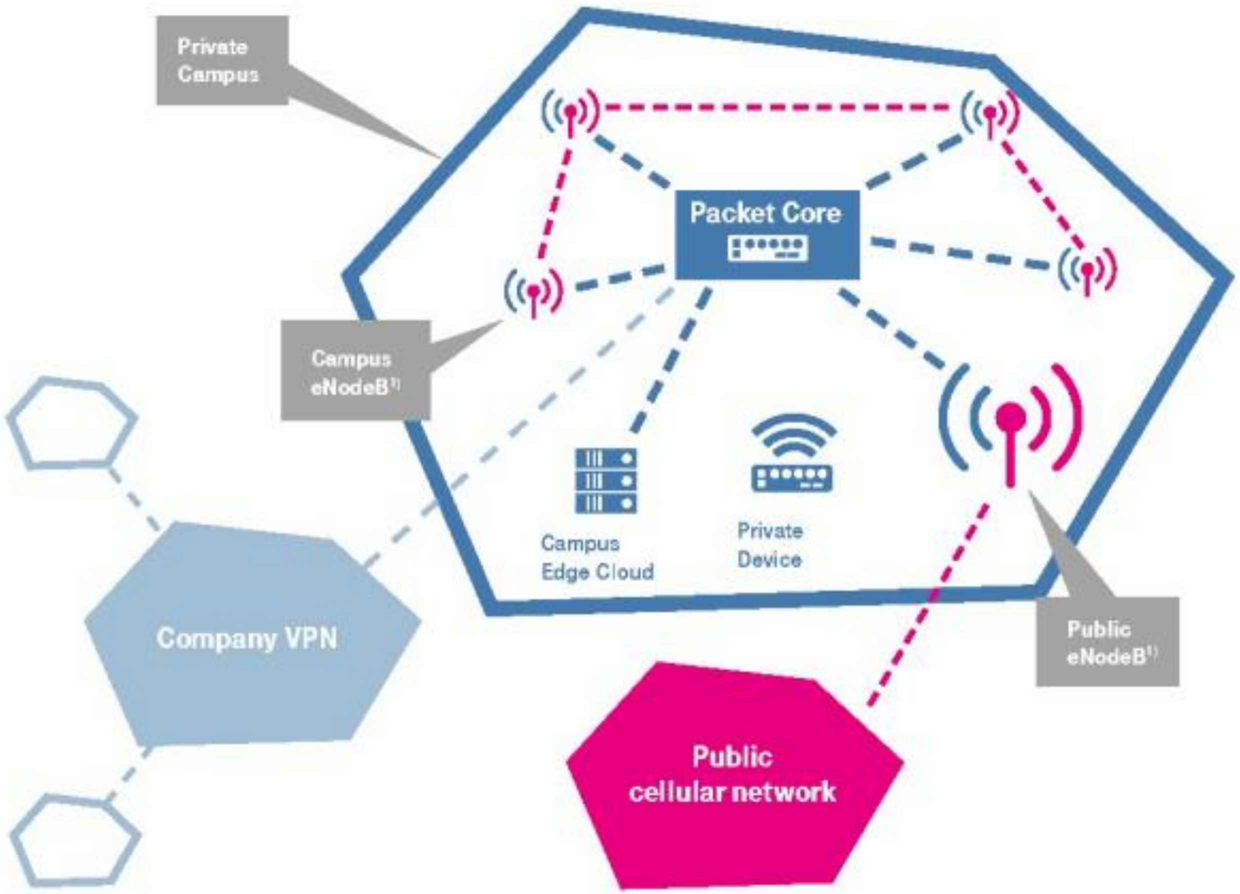
- Private cellular service for diverse applications
- Outsourcing of all wireless networking
- Different deployment models

Private Campus Connectivity

- Create a private slice with isolated resources from public networks
  - Separates traffic of employees and others
- Can include radio infrastructure on the campus
- Can provide high quality of service



Dedicated Mobile Networks



- Can be used by both employees and others on campus
- Uses on site radio infrastructure
- Provides superior performance