This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 16: LTE Advanced

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Spring Semester 2022

http://www.cs.cmu.edu/~prs/wirelessS22/

Announcements

- Sound issue for recording has been resolved
  - » The clip-on microphone is broken
  - » Not clear why it worked for some lectures
- Monday: Q&A for midterm
  - » Lectures 1-13
  - » Please submit lectures in advance (piazza)
- Midterm is on Wednesday
  - » Details on piazza
- No class on Friday
- Enjoy Springbreak!

Overview LTE

- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
- LTE advanced

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
  - » Scaling 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

OFDMA:
OFDM with Multiple Access

- LTE downlink uses OFDM with Multiple Access:
- In any time slot, multiple clients receive data on separate groups of subcarriers
  - » This is a form of FDMA (similar to 2G/GSM), but using groups of orthogonal subcarriers in
- For each group of subcarriers, multiple clients receive data in separate time slots
  - » TDMA (also similar to GSM)
  - » Multiple low bandwidth users can share subcarriers
- For each client, this enables frequency hopping to mitigate effects of narrowband fading

OFDM disadvantages SC-FDMA

- 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)
- Avoiding distortion requires increases in cost, size and power consumption
- To avoid this cost on mobile devices, the uplink uses Single-Carrier FDMA
  - » Does some preprocessing of the signal to reduce the high PAPR, at the cost of some loss in efficiency
  - » Provides better energy and cost efficiency for battery-operated mobiles

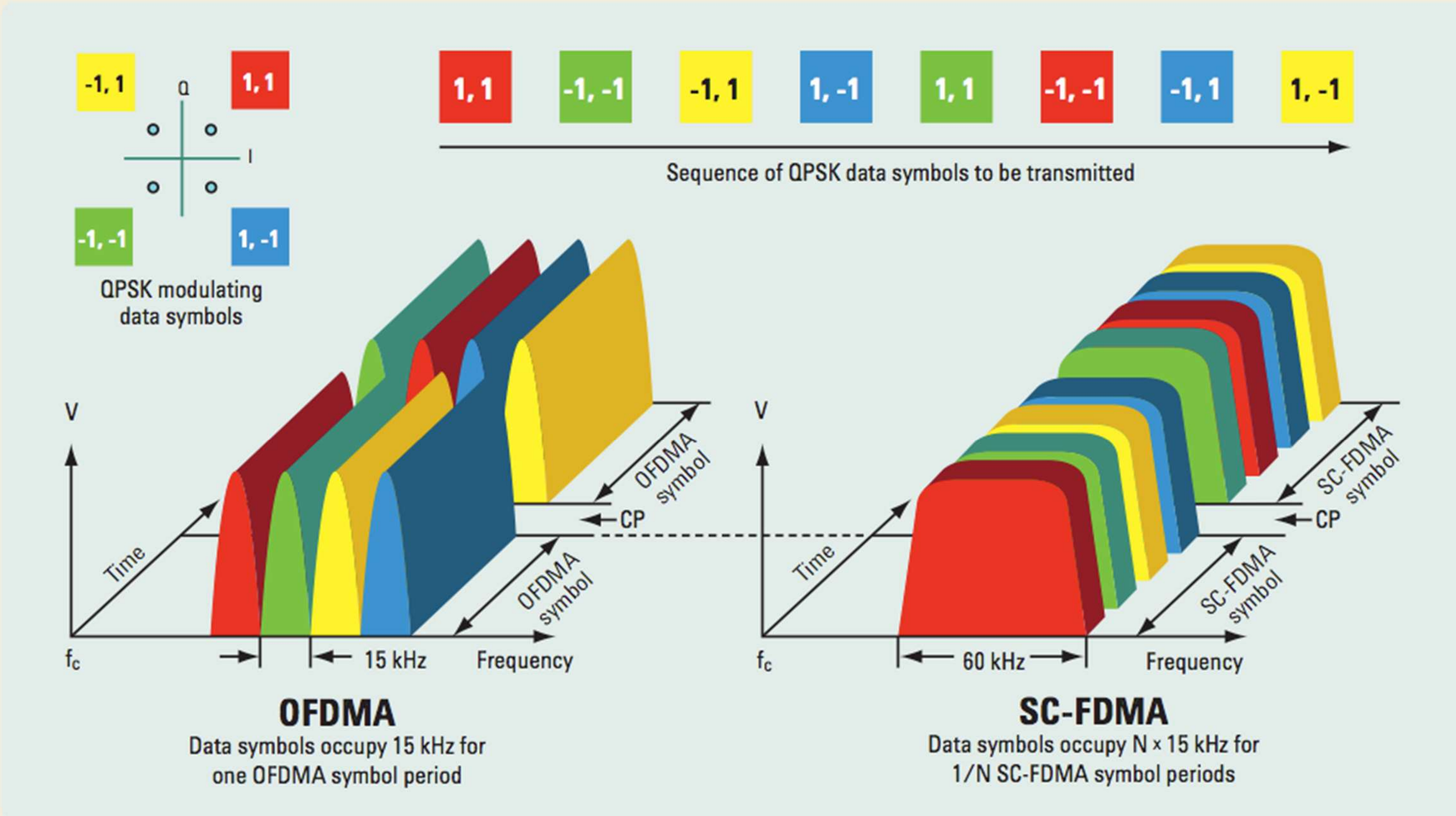
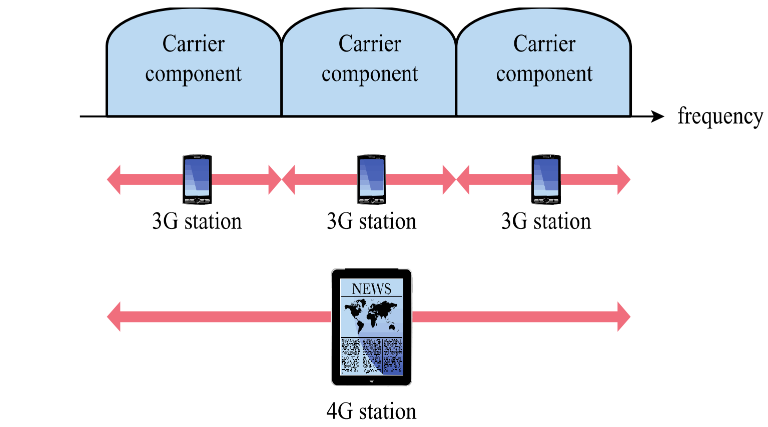


Figure 2. Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols

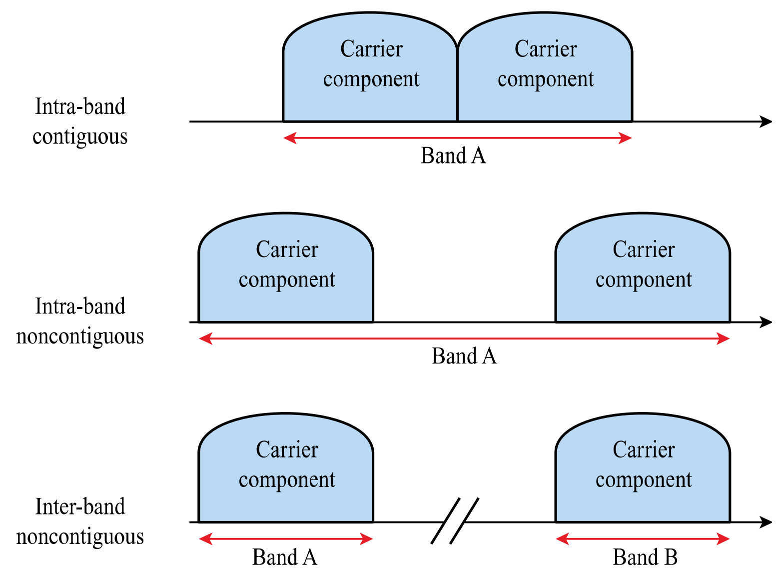
http://cp.literature.agilent.com/litweb/pdf/5989-7898EN.pdf

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



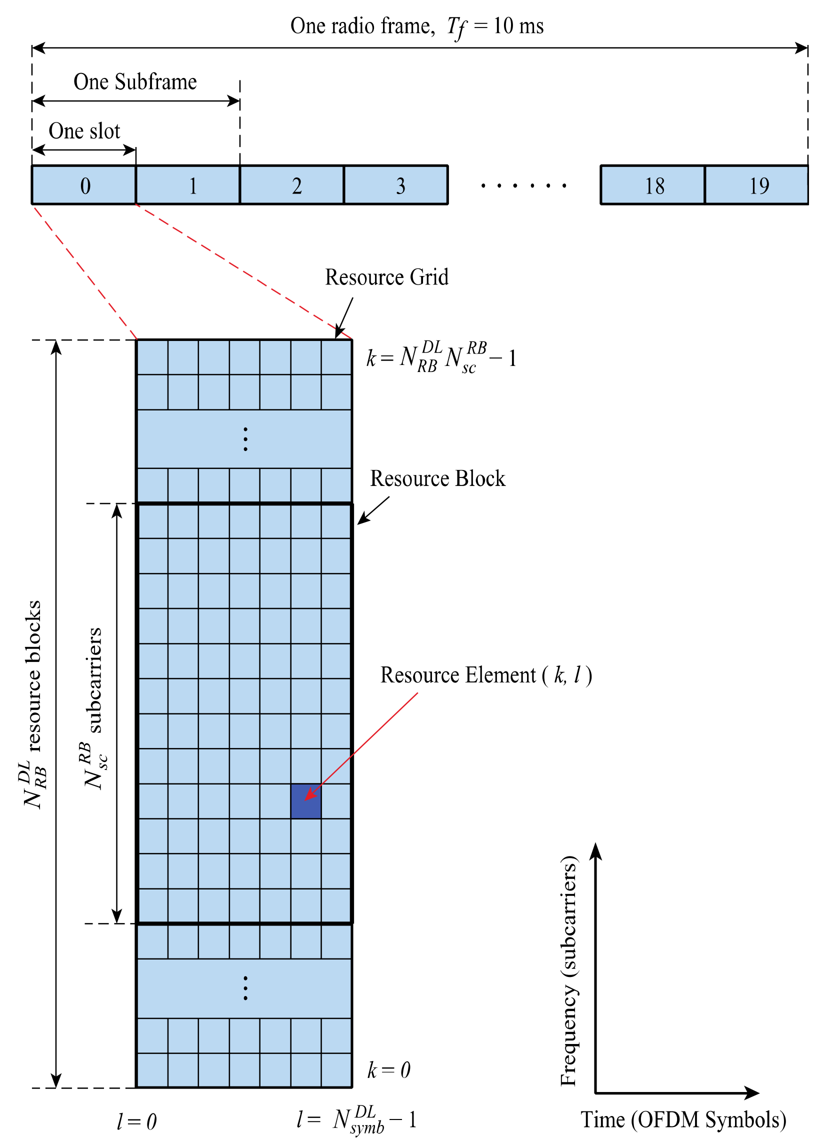
(a) Logical view of carrier aggregation



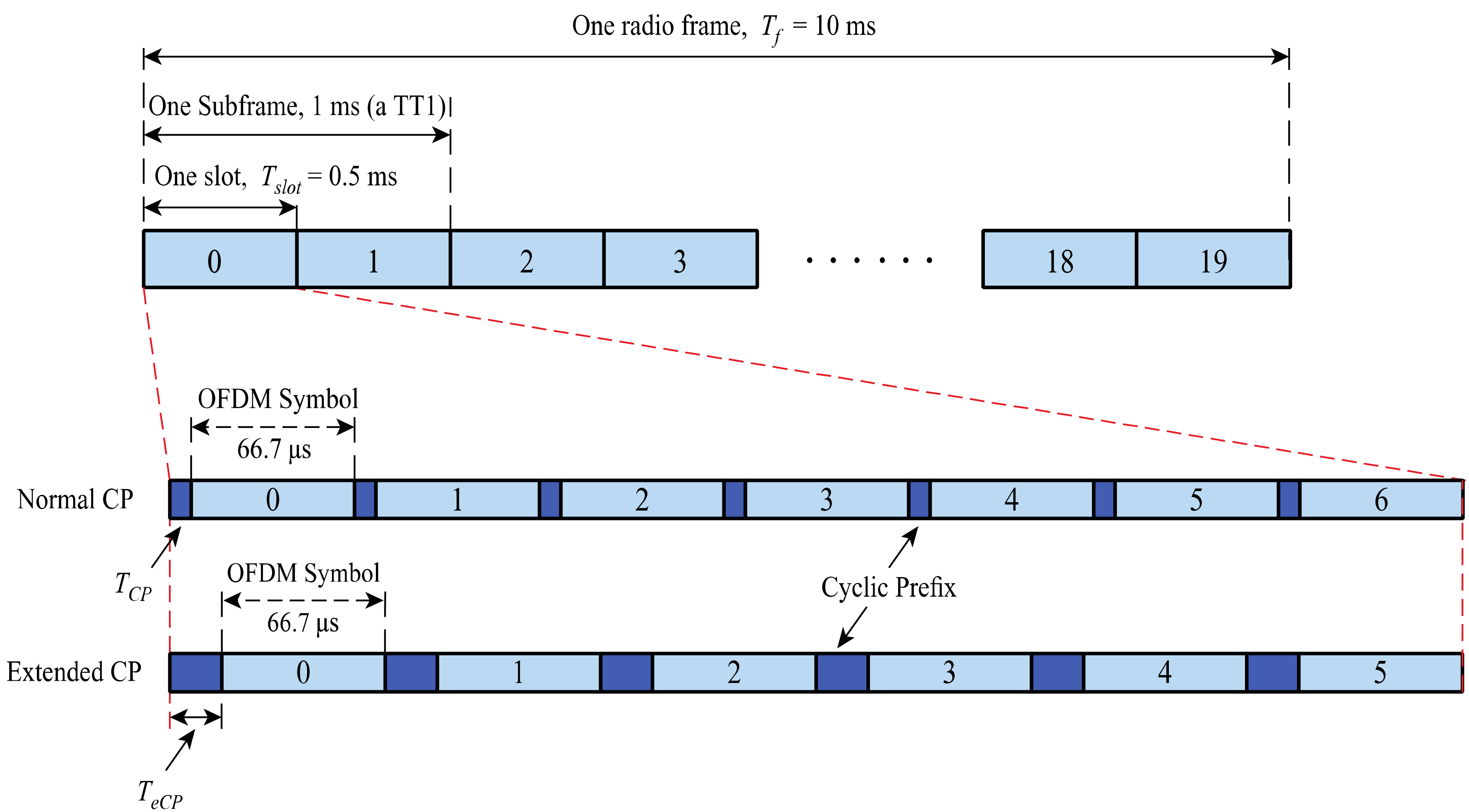
(b) Types of carrier aggregation

Resource Blocks

- **Physical resource allocation is based on a time-frequency grid**
- **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**



FDD Frame Structure



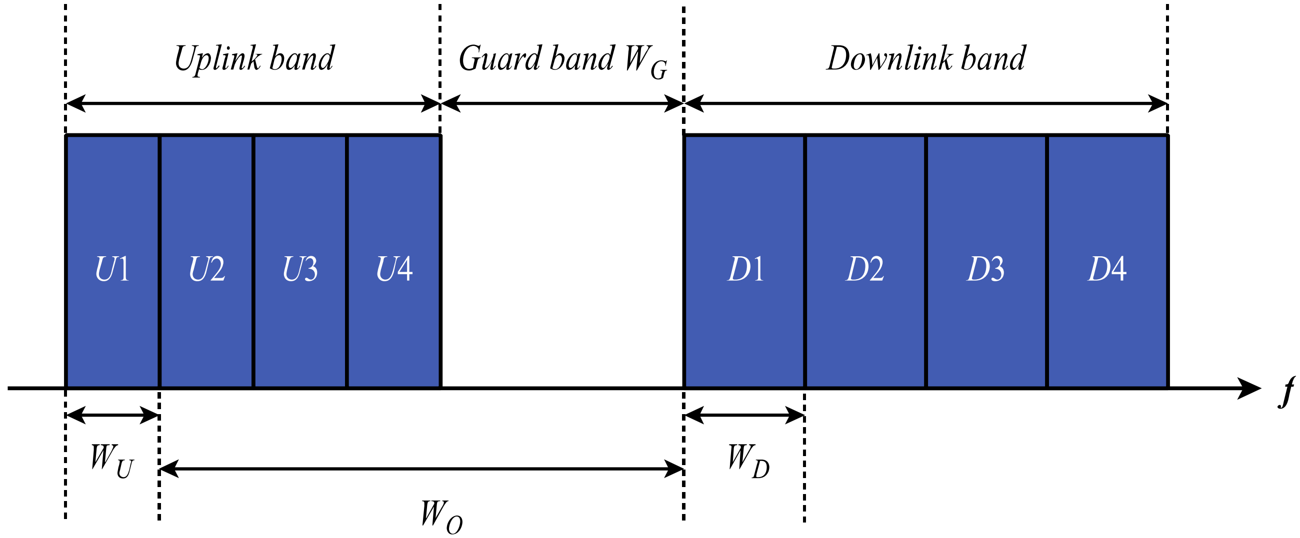
Resource Blocks

- 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
- *Multi-user 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, ..

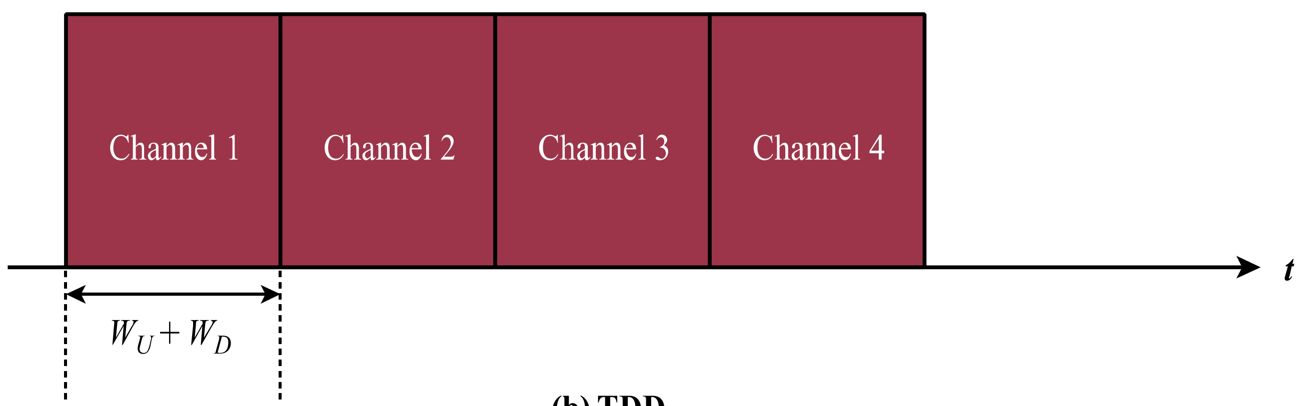
Managing Uplink and Downlink

- 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

Spectrum Allocation for FDD and TDD



(a) FDD



(b) TDD

Overview LTE

- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
  - OFDM refresher
- LTE advanced

LTE-Advanced

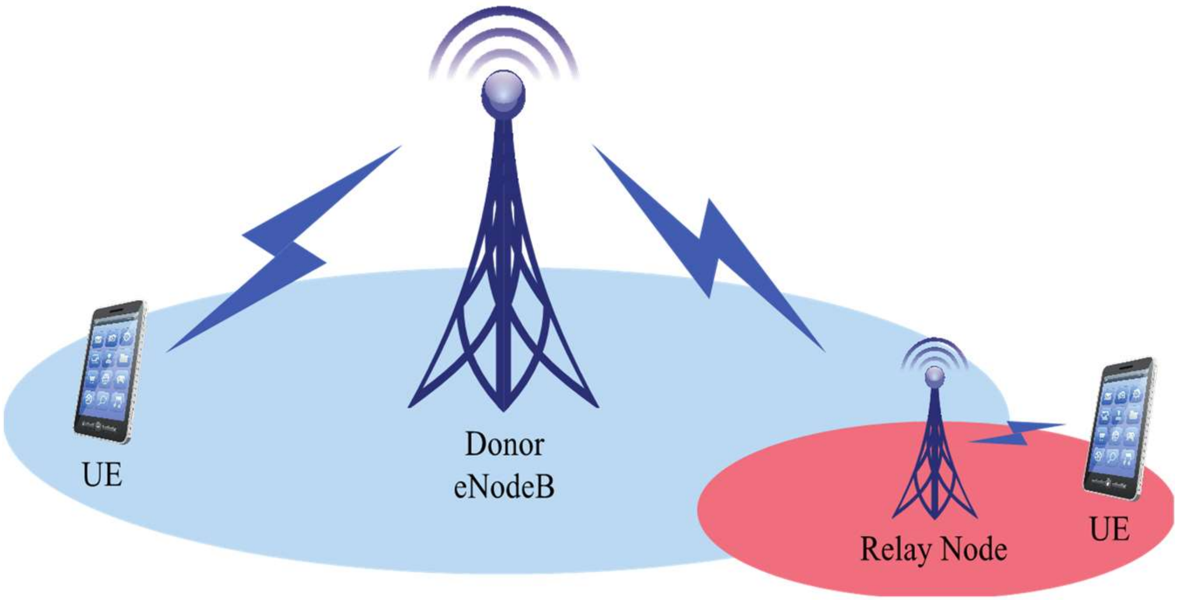
- Carrier aggregation – up to 100 MHz
- MIMO enhancements to support higher dimensional MIMO – up to 8 x 8
- Relay nodes
- Heterogeneous networks involving small cells such as femtocells, picocells, and relays
- Cooperative multipoint transmission and enhanced intercell interference coordination
- Voice 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		< 5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350—500 km/h

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
  - » Transmit a new signal to the base station



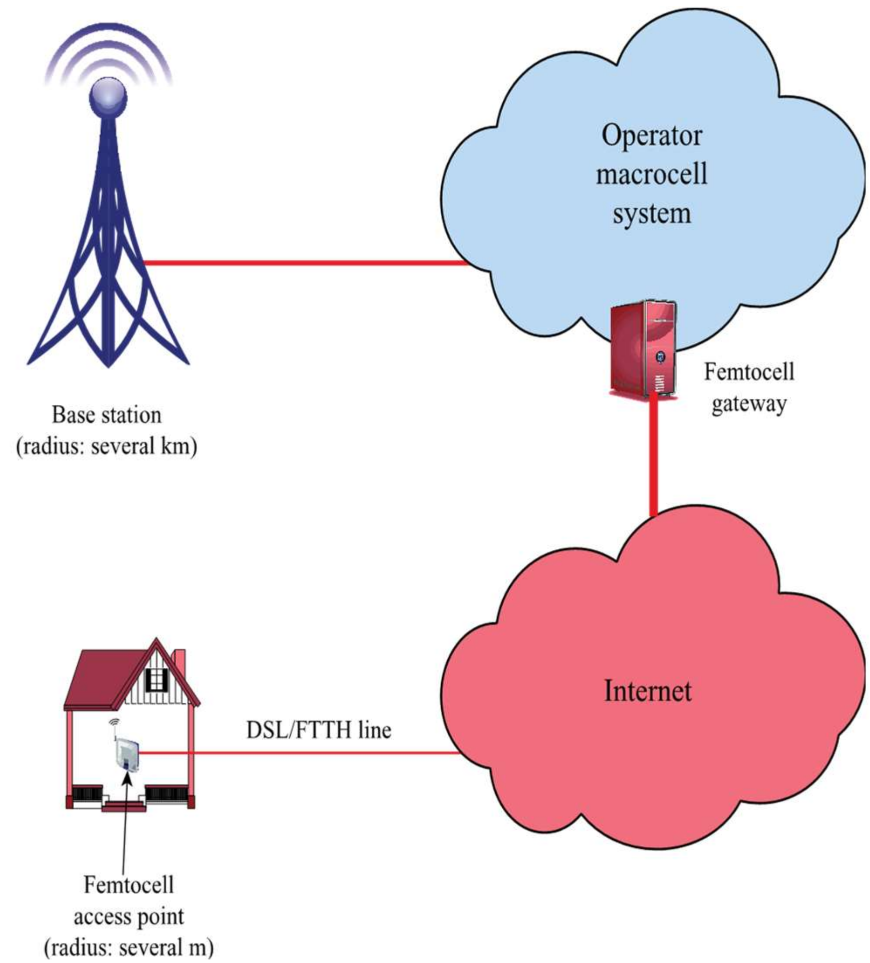
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies

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 Network Examples

- **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*)**



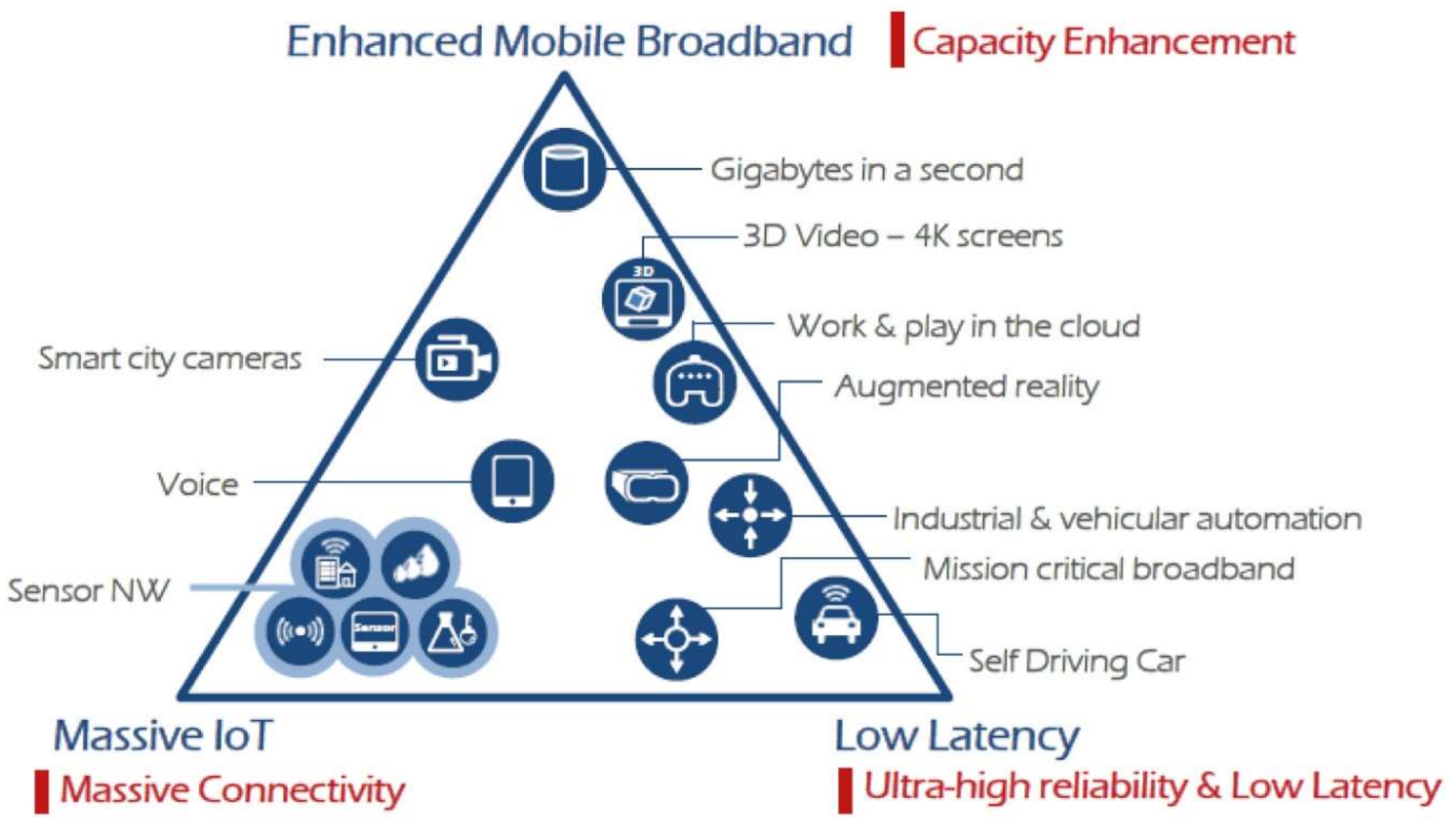
Trends

- Cloud RAN optimizes spectrum use
  - Goal is to reuse frequencies very aggressively
  - Leverage cloud technology to centralize the processing for many cells
- Standards are complex and rigid and need to support several generations
  - E.g., switch seamlessly from 4G to 3G
  - Still need to support 2G (legacy phones, voice)
- Scalability of infrastructure wrt signaling traffic is a growing concern
  - Hardware cannot keep up with changes in usage
- Wide-spread use of custom hardware
  - Move to commodity, programmable equipment

Overview 5G

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

5G Vision ITU
International Mobile Telecommunications



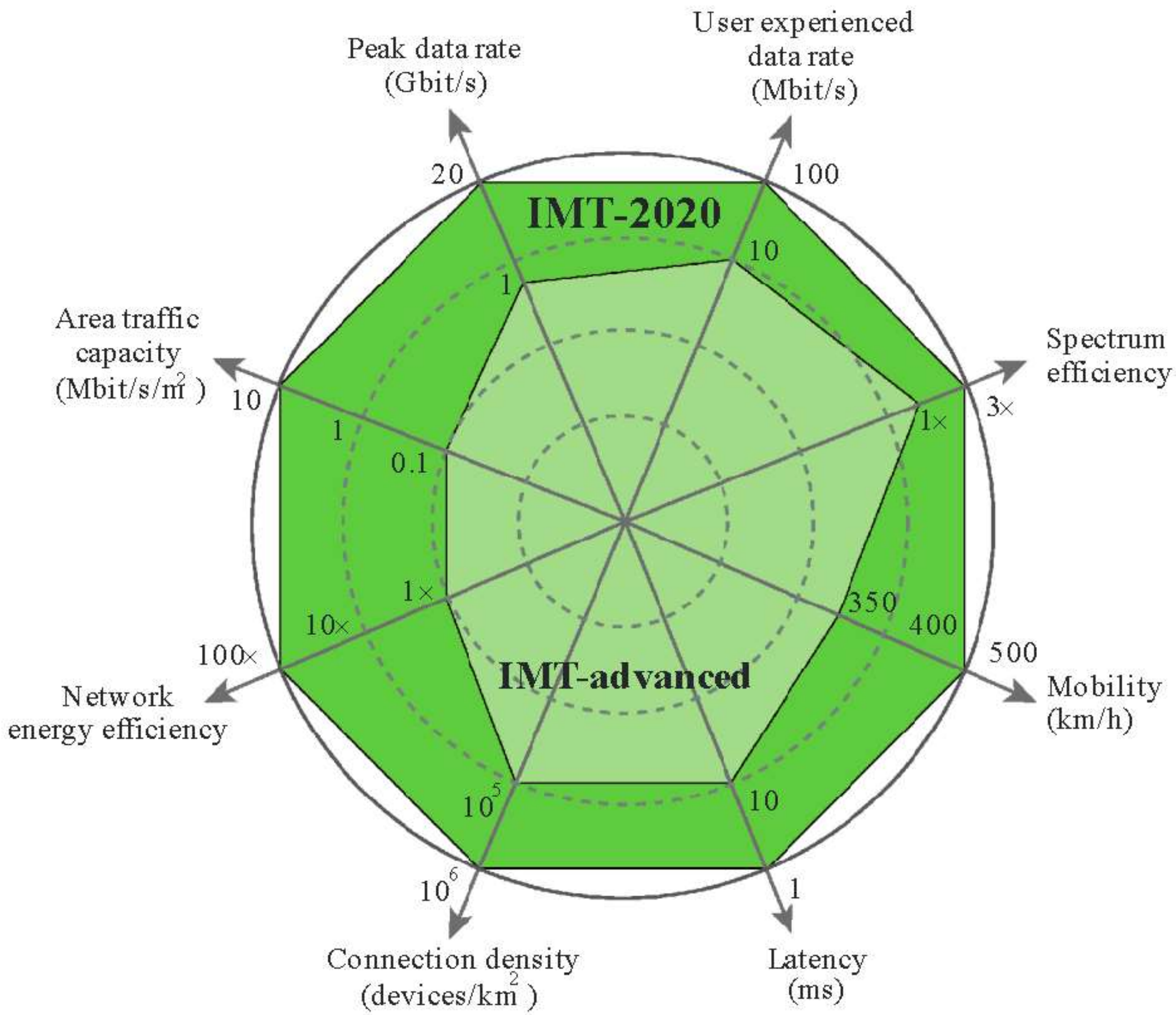
Faster 4G

Growing application domains

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

https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

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 2Ghz, e.g., 660-850 MHz
  - » Mid band: below 6 GHz, new bands, e.g., 2.5-3.7 GHz
    - – https://www.cnn.com/2021/03/14/tech/5g-spectrum-auction-att-verizon-tmobile/index.html
  - » 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

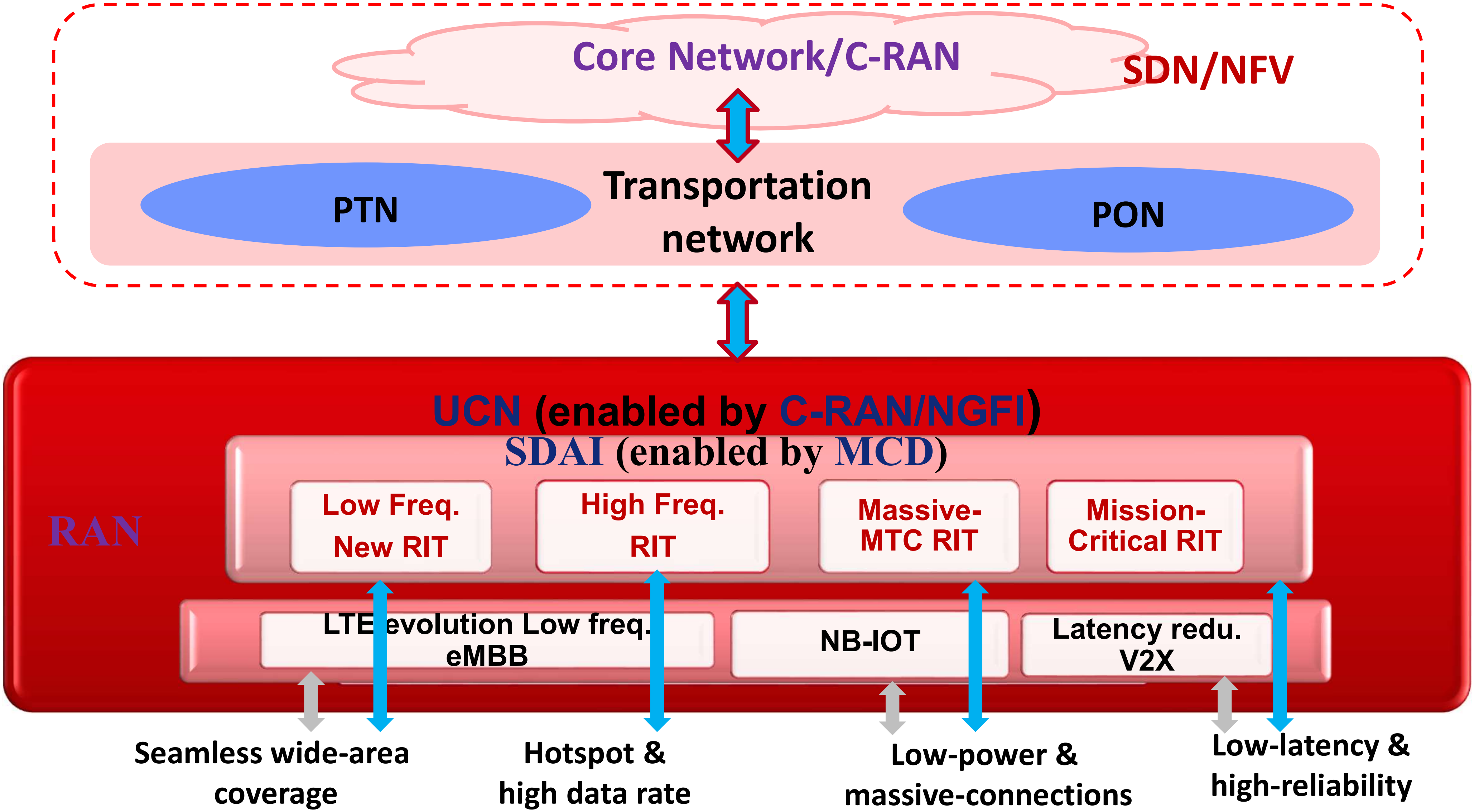


Figure based on: https://www.itu.int/en/ITU-T/gsc/Documents/GSC-20/Session-6/GSC20_Session6_5G_Chih_IEEE.ppt

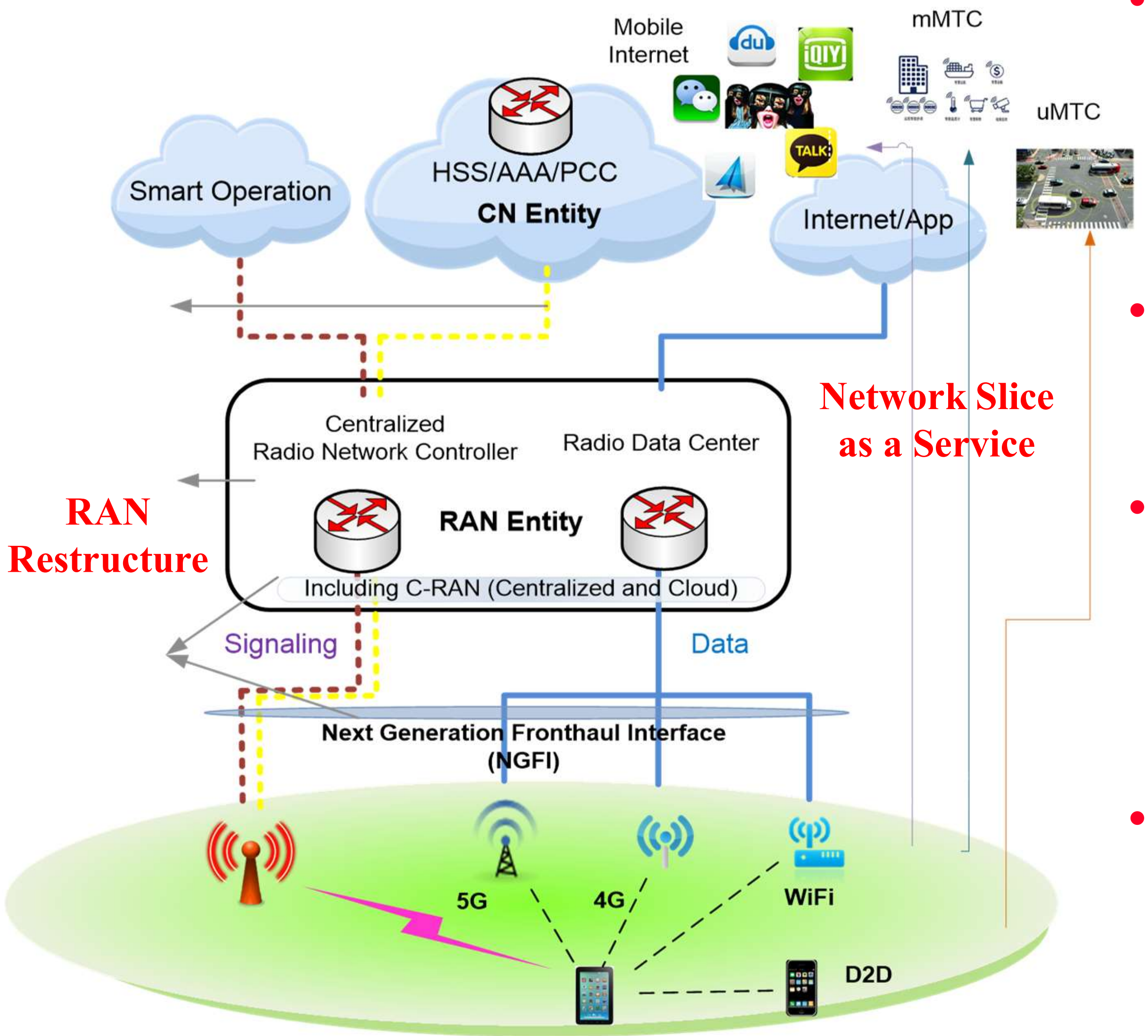
Acronyms

- **RIT: Radio Interface Technology**
- **UNC: 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 basestations 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 basestations 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 radio processing to the cloud
  - Network control, signaling protocols
  - Radio signal processing
- All processing to commodity platforms instead of custom HW
- Use of modern cloud and network technologies
  - Virtualization, NFV, SDN (later)
  - Could be outsourced to cloud providers
- Also:
  - Home Subscriber Service
  - Authentication, Authorization, Accounting (RADIUS)
  - Policy Charging Control

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