18-452/18-750
Wireless Networks and Applications
Lecture 16: LTE Advanced and 5G

Peter Steenkiste

Spring Semester 2024

http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- **P2 teams have been formed**
  - » Note that P2 handout has outline for the proposal
  - » Information on hardware needs is important
- **Coming week will be very busy, so I have adjusted the schedule**
  - » Friday: no class
  - » Monday: Q&A for the midterm
  - » Wednesday: midterm
  - » After midterm: restart the lectures

Overview LTE

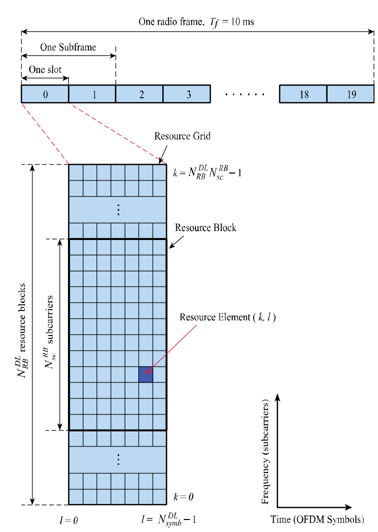
- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
- LTE advanced

Peter A. Steenkiste, CMU

3

Resource Blocks

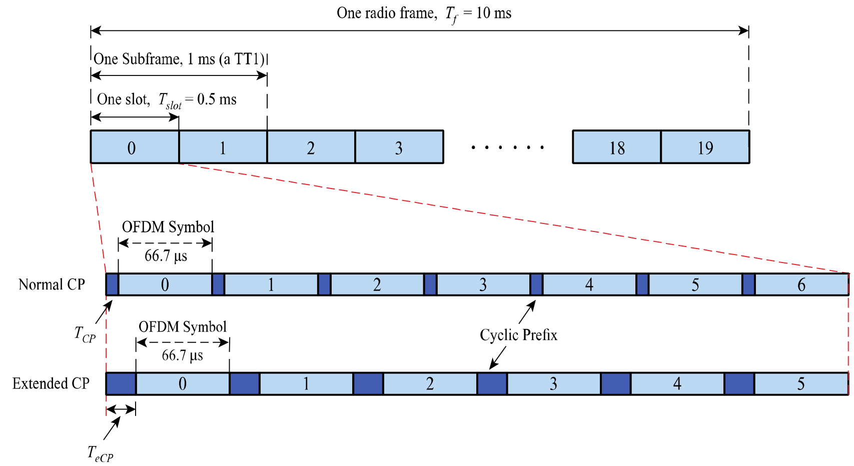
- Physical resource allocation is based on a time-frequency grid
- Each column is 6 or 7 OFDM symbols per slot
- Each row corresponds to a subcarrier of 15 kHz
  - » Some subcarriers are used for guard bands
  - » 10% of bandwidth is used for guard bands for channel bandwidths of 3 MHz and above



Peter A. Steenkiste, CMU

4

FDD Frame Structure



Peter A. Steenkiste, CMU

5

5

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, ..

Peter A. Steenkiste, CMU

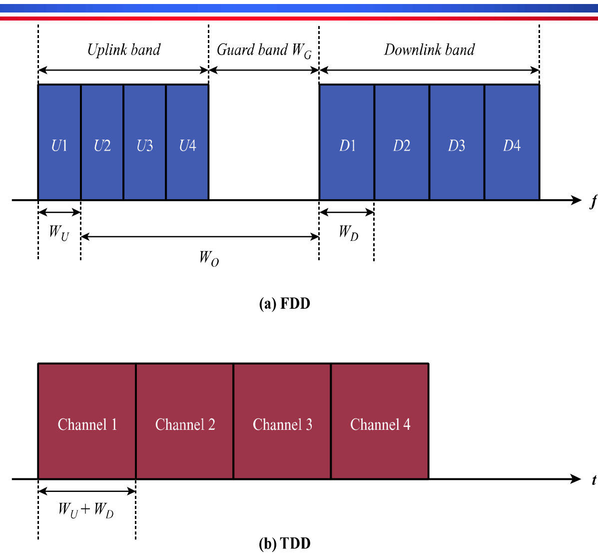
6

6

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



Overview LTE

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

Peter A. Steenkiste, CMU

9

9

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

Peter A. Steenkiste, CMU

10

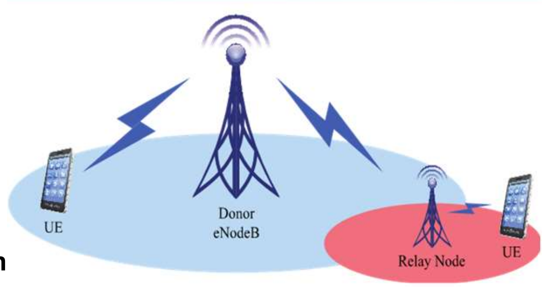
10

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



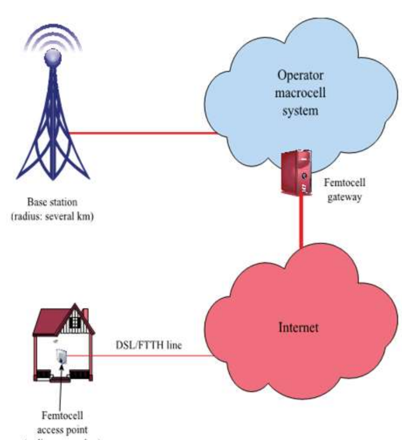
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies

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*)



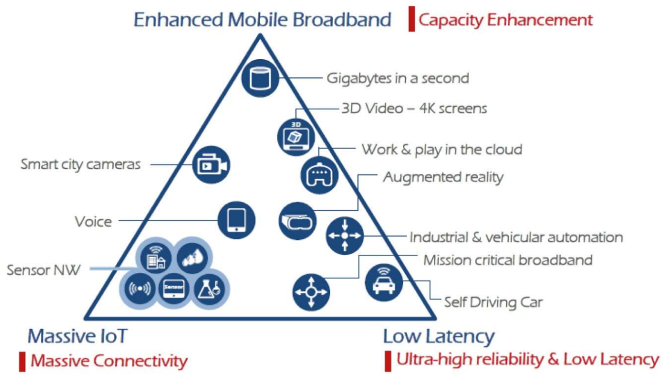
Trends

- 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

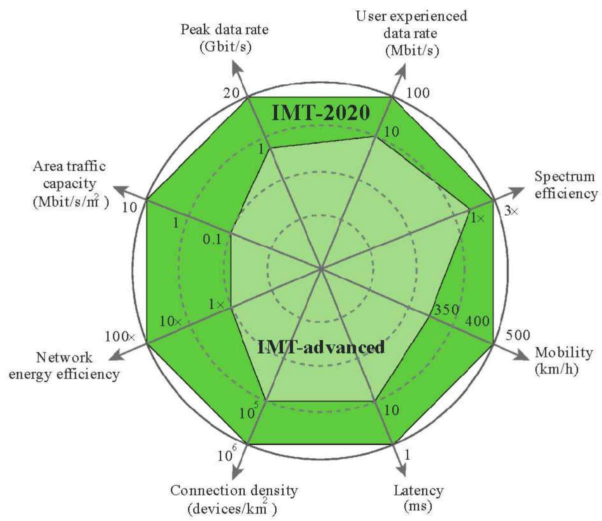
(Source: ETRI graphic, from ITU-R IMT 2020 requirements)

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

Support for Multiple Traffic Classes

- **Enhanced Mobile Broadband (eMBB)**
  - » Corresponds to the traditional traffic on cellular but with support for more demanding applications, e.g., volumetric (3D) video
- **Massive Machine-Type Communications (mMTC)**
  - » Basically IoT, but on a very large scale
- **Ultra-Reliable Low Latency Communications (UR-LLC)**
  - » Very low latency, with high reliability
  - » This is a diverse category (small control packets .. High volume) and diverse application domains
- **These service classes target specific application domains**
  - » In contrast, 4G QoS classes were generic

Performance Goals ITU



Peter A. Steenkiste, CMU

19

19

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

Peter A. Steenkiste, CMU

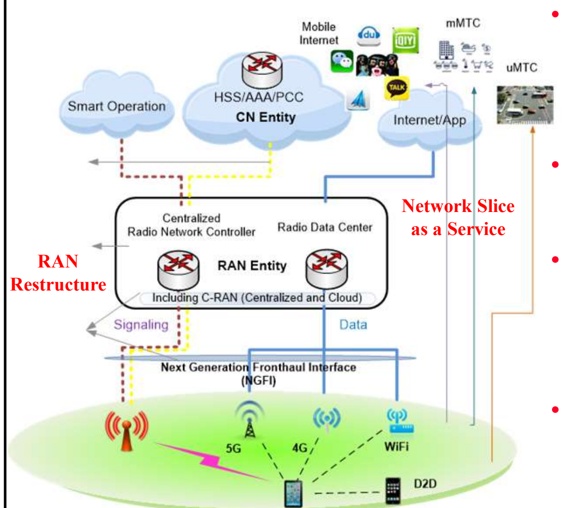
20

20

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

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

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

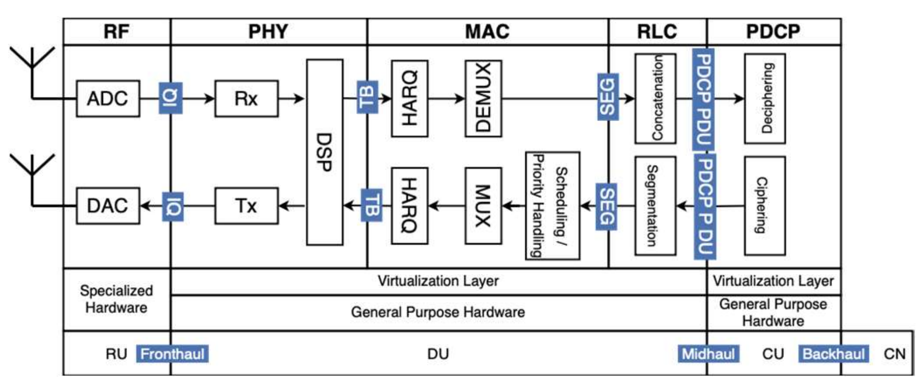
Why C-RAN?
Standard Cloud Arguments

- 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 basestations 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, …

Protocol Stack

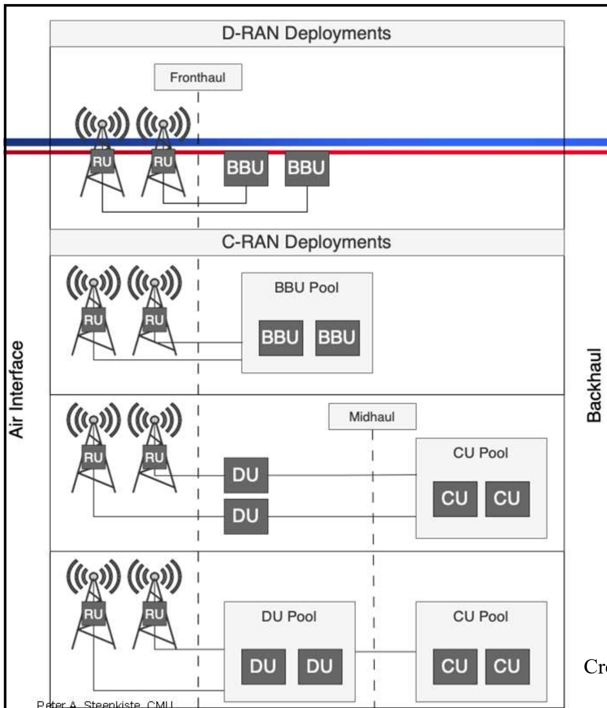


Credit: Sofia Martins

Protocol Overview

- Radio units (RUs) are the basestations
  - » Modulate the carrier signal
  - » Variety of antennas sending traffic of different types
- The Distributed Unit supports the cellular protocol stack
  - » BBU generates and processes the baseband signal
  - » The MAC implements error correction (HARQ), multiplexing/demultiplexing of the datastreams, prioritization (QoS), Radio Link Control does segmentation/concatenation
- The Centralized Unit (CU) implements the PDCP protocol
  - » Same as LTE: encryption, buffering, compression, ….

Deployment Models 5G



- 5G has several deployment models
- Offers flexibility depending on cell types, sizes, …

Credit: Sofia Martins

5G Deployment Models

- 5G NSA: Non-Standalone network
  - » Uses 5G technology for the data plane for 4G protocols for the control plane
  - » The 5G data plane uses New Radio (NR) specification
  - » It offers improved network capacity and user throughput
  - » Inherits some of the higher latencies of LTE
- 5G SA: Standalone network
  - » Uses the New Radio specification as well as the 5G data plane
  - » Does not yet support all features, e.g., UR-LLC, mMTC, ..

Frequency Reuse

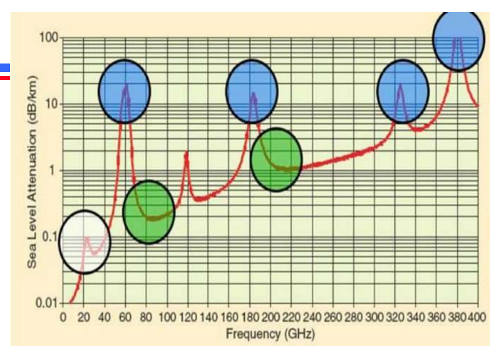
- Frequency reuse across cells has become increasingly aggressive:
  - » Initially, macro cells with relatively static distribution of frequencies across cells
  - » Next, introduction of micro, pico, etc. cells that are selectively deployed and can reuse frequencies more aggressively
  - » Finally, 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

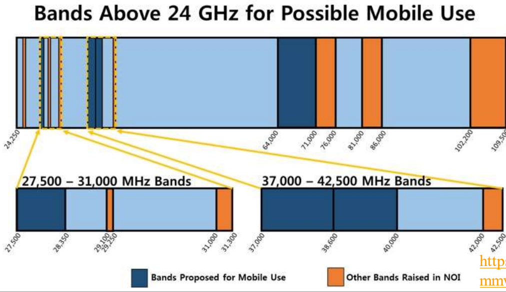
- There is a lot of spectrum available!
  » See next slide for the fine print
- Need to use beam forming to achieve reasonable range for mmWave
  » Possibly using large number of antennas (10s .. 100)
  » Technology similar to that discussed for 802.11ad
  » Challenges include establishing sessions, 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!



Bands Above 24 GHz for Possible Mobile Use



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

https://www.ni.com/en-us/innovations/white-papers/16/mmwave--the-battle-of-the-bands.html#section-1236278719

Use New Network Technologies in Core Network

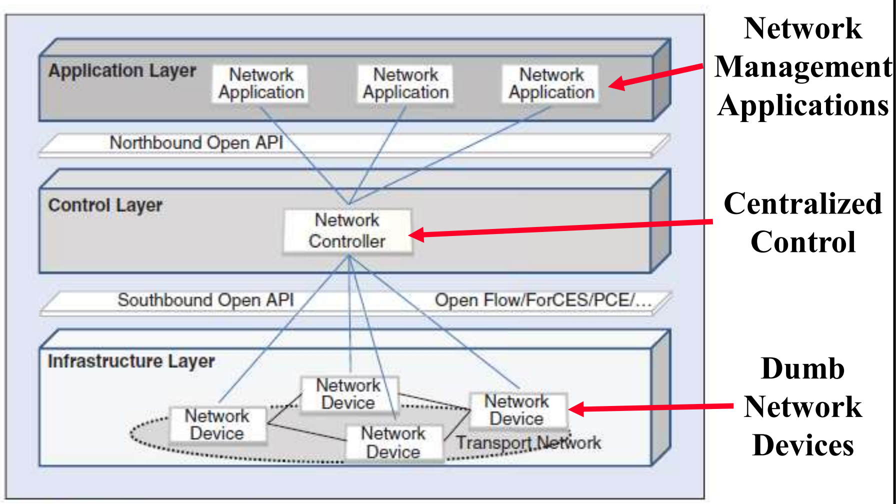
- Software Defined Networking (SDN)
  - » Centralized control of the network
  - » Provides more fine grain control over resources, e.g., bandwidth management, …
- Network Function Virtualization (NFV)
  - » Cellular operators run a lot of "middleboxes" that provide value added services to users
  -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

Peter A. Steenkiste, CMU

33

33

SDN concept



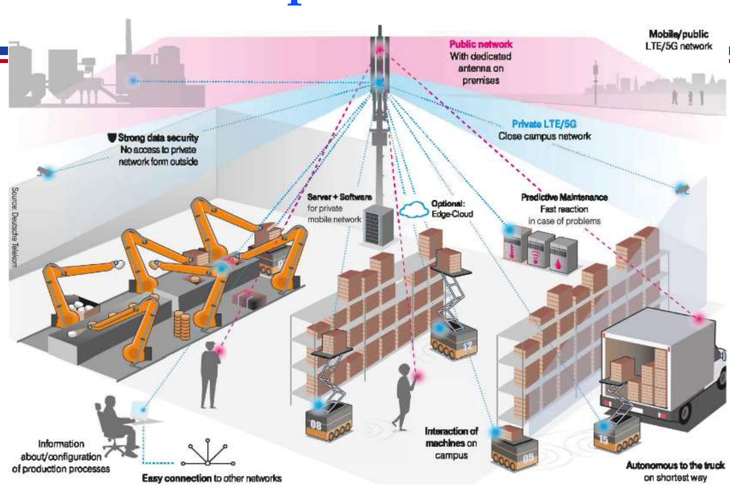
P. Demestichas, "5G on the horizon: key challenges for the radio-access network." *Vehicular Technology Magazine, IEEE* (2013)

34

SDN Overview

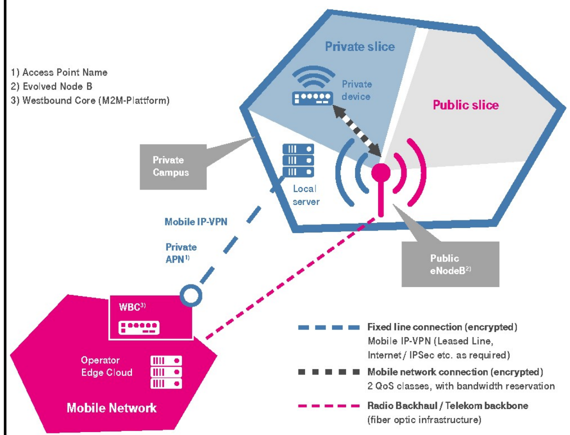
- The control plane and data forwarding plane are separated
- A centralized controller maintains a complete view of the network resources
- Network applications manage resources, control network functions
  - » Routing, managing QoS, traffic engineering, etc.
  - » Obtain network view through northbound 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



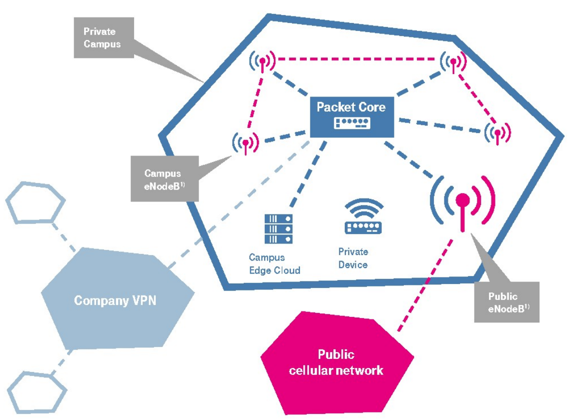
- Private cellular service for diverse applications
- Outsourcing of all wireless networking
- Different deployment models

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