34333: Mobile Communications and IoT

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2022

Contents

Introduction to Technologies for Mobile Communications and IoT

Notes

Practical information

- Exam date: F5A (wed 8-12)
  - Oral examination
  - Two days, 24/5 + TBD
- Lecturer: Lars Dittman
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- Book:
  - Martin Sauter: “From GSM to LTE-Advanced Pro and 5G An Introduction to Mobile Networks and Mobile Broadband”. Wiley, 2021
  - onlinelibrary.wiley.com

Frequencies

- Spectral Efficiency:
  - Relation between Bps and Hz - utilization of band

  - Usually below 10. More than 5 is difficult in mobile
- Frequencies are divided into below *1GHz*, *1-6GHz*, and above *6GHz*
- Either amplitude (ASK), frequency (FSK) or phase (PSK) is modulated
- In newer systems, QAM is used - see figure 1
- *2-3GHz* is often used for mobile communications
  - *5G* networking uses higher frequencies
- Below *5GHz*, absorption of water & oxygen can be ignored

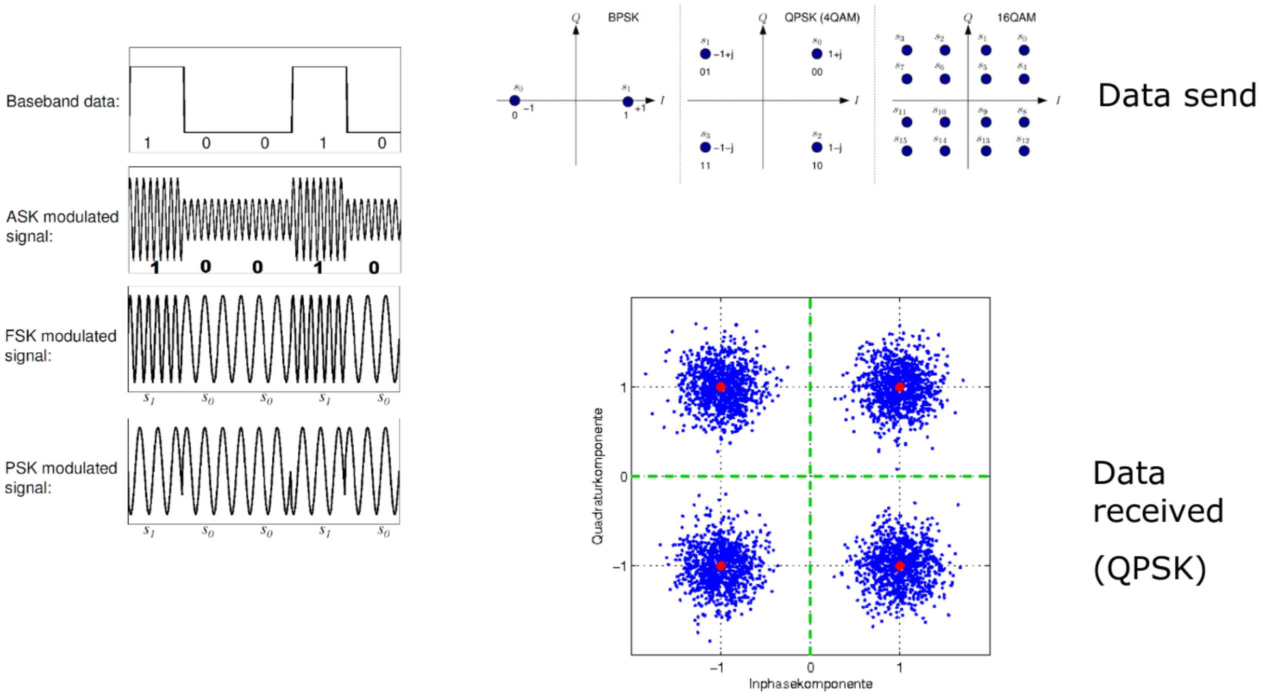

Figure 1: Standard Modulation Schemes

Topics covered

- Mobile communication networks and technologies
- Network architectures
- Protocols
- Signalling and procedures
- Modulation formats
- Services in mobile communication networks
- Network planning
- Intelligence and functionality in mobile communication networks
- Interoperability

Planes

- Data plane: what the user cares about, user traffic
- Control plane: behind the scenes, how the services are implemented
- Management plane: configuration, monitoring, management

Exercises

Build your own mobile network

Requirements

- Must be able to send and receive between terminals
- Same frequency as 2G, 4G, 5G
- Base stations

- Mobility required
  - Device tracking
  - Handover
- Modular QAM

Discussion

- Should all technologies be implemented?
  - Expensive to set up
  - *3G* is not needed for *4G*, *5G*, so should maybe die
  - Many devices use *GSM*, should stay
  - *5G* uses some *4G* infrastructure (will change)
- Number of stations
  - In Denmark: *TDC* & *TTNetworks* each have ~3500 base stations
  - *3* mostly cover bigger cities and loan TDC networks in rural areas
- Requirements
  - Battery life
  - Capacity management
  - High bit rates
  - Session control
  - Mobility management
  - Network management & control
    - Fault detection & recovery
    - Monitoring
    - Billing

GSM Fundamentals

Date: Wednesday 09.02.22

Lecture slides

Questions answered

- Why do we need cells?
- What is GSM?
- How does the GSM air interface work?

Notes

Mobile networks

- Coverage
- Capacity
- Limiting resource (spectrum)
- Divided into cells
  - Neighbouring cells do not share frequency
- 120° per antenna; one station covers 3 cells

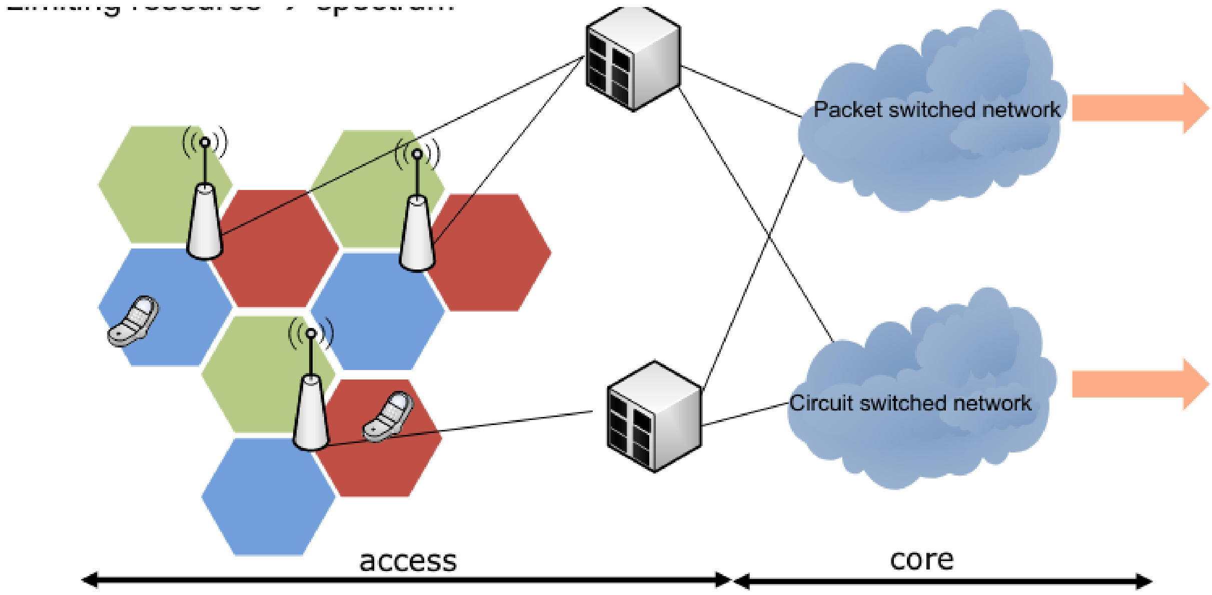

Figure 2: GSM Network

Multiplexing and duplexing schemes

- FDMA: Frequency division multiple access
- TDMA: Time division multiple access
    - Good for digital signals
- Duplexing:
    - SDD
    - TDD (*Time Division Duplex*)
    - FDD (*Frequency Divided Duplex*)

GSM

- 200+ countries
- digital
- Designed for voice services
- Combination of TDMA & FDMA
    - $200kHz$ channels, 8 timeslots ($0.577ms$ each)
- FDD
- Limited data transmission capabilities
- With GPRS/EDGE: packet based services (see lecture 04)
- Standards available at 3gpp.org

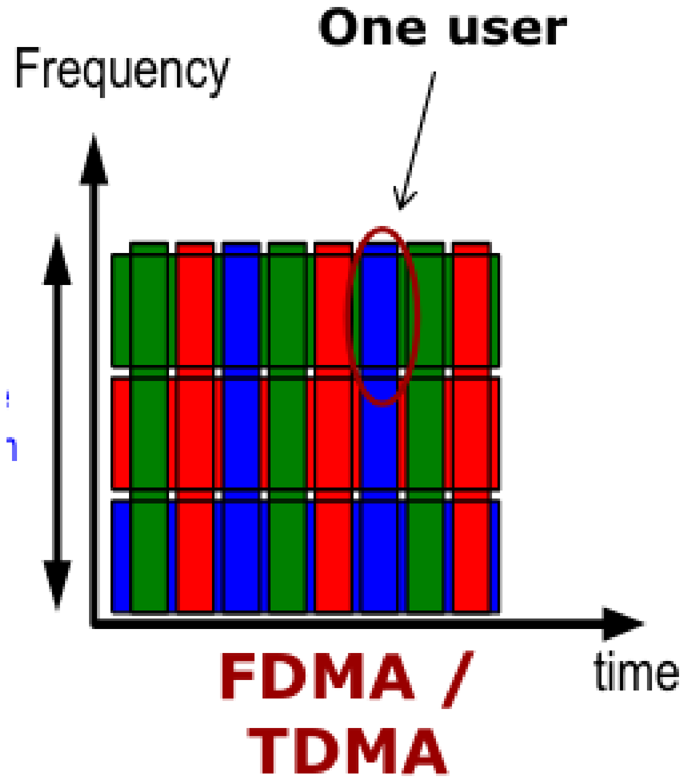

Figure 3: FDMA / TDMA

GSM services

- Voice
  - Compressed to $13kbps$ or $6.5kbps$ (recorded as $64kbps$)
  - $13kbps$: Full rate + Enhanced Full Rate - uses 1 timeslot
  - $6.5kbps$: Half Rate - Uses 0.5 timeslot
- Circuit switched service
  - Occupies capacity in consecutive frames as long as connected
- Circuit switched data connections
  - $9.6kbps$ (later $14.4kbps$)
  - HSCSD: $n \cdot 9.6/14.4kbps$)
  - GPRS / EDGE: 'always on' technology
- Short messaging service (*SMS*)

Normal GSM Burst

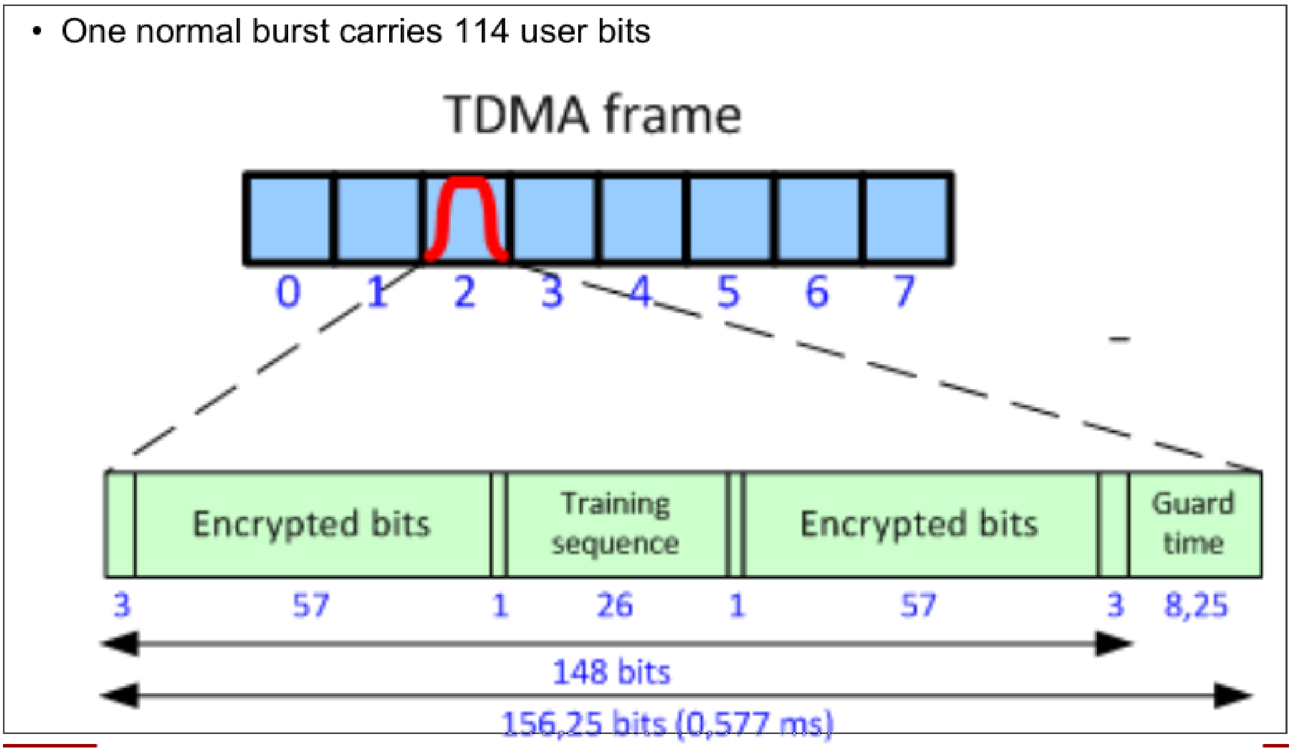

Figure 4: Normal TDMA Frame

See figure 4.

- Tails: both in front and in end
- Encrypted bits
- 1 bit fields: stealing bits
  - If user needs to send urgent data: flag these bits
- Training sequence
  - Fixed bit pattern set in the specifications
  - Combats multi path fading
- Encrypted bits
- Guard time
  - Empty frame

More bursts exist, see lecture presentation slide 15.

Error Correction & Interleaving

The user voice signal is compressed to 260 bits. This is then expanded to 456 bits with error correction codes. This code, however, cannot handle bursts of errors. Therefore, interleavers are used. These transpose a matrix containing all 456 bits of data + user correction. If a burst then happens, the errors are spread out and the receiver can handle them. Designed this way since bursts of errors are common in mobile communications. Two interleaving stages are applied, which improves this concept. See lecture slides.

Mobility Management

- Timing advances are used to account for wave propagation.
  - Guard Period (see figure 4) is used to allow the user to move further away from the base station while still sending within allowed time slot.
  - Access bursts contain a large *Guard Period*. These are sent with timing advance $= 0$, but the larger *GP* means that the signal is not overlapping. The base station then sends the required timing advance value.

GSM Capacity & Frequency Reuse

- One channel is for downlink, another channel for uplink
- Number of calls exceed capacity:
  - Either block client attempting to make calls
  - Reduce another call to half rate
  - Add new transceiver so you can transmit on another pair of frequencies (each new TRX gives 8 timeslots)
- Frequency reuse:
  - Operator must have at least 3 different frequency channels (see lecture slide 34)
    - Also possible to use e.g. 4 or 7.
- Frequency Hopping:
  - Stations can jump between frequencies instead of remaining on one single frequency: useful for random increase of interference
- Discontinuous transmission (DTX):
  - Only transmit when talking; frees up some timeslots and saves battery on mobile device

Review Questions

- Why do we need cells in a mobile network?
  - Needed for dividing capacity and coverage. Reuse of resources, increased coverage
- What is GSM?
- How does the GSM air interface work?
  - Multiplexing
    - FDMA / TDMA per cell
  - Duplexing
    - One frequency for uplink, another for downlink (FDD)
  - Voice channel mapping
    - 26 frame structure (24 for data, 1 for control, 1 for idle)

Next time: **more GSM details**

Exercises

Problem 1

- How many cells are needed?
  - 9
- How many sites are needed?
  - 3
- How many in Denmark?
  - 1925 cells, 642 sites

```
> A := R -> 3*sqrt(3)/2*R^2
> cell_area := A(3*km)
```

$$cell\_area := \frac{27\sqrt{3}\,km^2}{2}$$

```
>
> cph_area := 200*km^2
```

$$cph\_area := 200\,km^2$$

```
> cph_area / cell_area;
  num_of_cells := evalf(%)
```

$$\frac{400\sqrt{3}}{81}$$

$$num\_of\_cells := 8.553337324$$

```
> cells_per_site := 3
```

$$cells\_per\_site := 3$$

```
> num_of_sites := num_of_cells / cells_per_site
```

$$num\_of\_sites := 2.851112441$$

```
>
> area_of_denmark := 45000*km^2
```

$$area\_of\_denmark := 45000\,km^2$$

```
> num_of_cells_in_denmark := area_of_denmark / cell_area;
  evalf(%)
```

$$num\_of\_cells\_in\_denmark := \frac{10000\sqrt{3}}{9}$$

$$1924.500898$$

```
> sites_in_denmark := num_of_cells_in_denmark / 3;
  evalf(%)
```

$$sites\_in\_denmark := \frac{10000\sqrt{3}}{27}$$

$$641.5002993$$

Figure 5: Maple calculations

Problem 2

$200kHz$ per channel:

$2.4MHz/200KHz = 12$ channels. Each cell can then get 4 channels = 4 TRX's.

Problem 3

Each cell can accommodate 7 calls with 1 TRX (8-1 for control). One TRX per cell is therefore 21 calls at any given time inside the site.

With 2 TRX's per cell, each cell can accommodate $7 + 8 = 15$ calls. 3 cells therefore have a capacity of 45 simultaneous calls.

Problem 4

$120ms$ for 26 frames; each frame is 8 timeslots:

$$\frac{120ms}{26frames \cdot 8timeslots} = 576.93\mu s$$

Bitrate: $156.25bit$ per timeslot and $576.93\mu s$ gives a bitrate of:

$$R_{GSM} = \frac{156.25bit}{576.93\mu s} = 270.83kbit/s$$

Problem 5

The interference is caused by some FM radio picking up the signal from the antenna, since the radio waves have a relationship with the GSM band. Heard from the equipment as a low hum - caused by the phone repeating something 26 times per $120ms$, which equates to $\frac{26}{0.12ms} = 217Hz$, which is a low bass note.

An *SMS* negotiates something before sending, so the interference pattern is a bit different.

Problem 6

Fraction of use: only 114 bits out of 156.25 total time slot is used to send data. The utilization is:

$$\frac{156.25}{114} \approx 72.96$$

Some of this, however, is also used for error correction, so only about half of the data is actual data.

It is not really possible to avoid the data loss, since most of the transmitted bits are necessary.

Problem 7

The signal is sent at almost the speed of light, so $1km$ is about $3.3\mu s$ and $10km$ is $33\mu s$. To avoid collisions of transmissions, a timing advance is given to each client.

Problem 8

The control channel occupies 1 out of the total 26 frames. This can be used to transmit 114 bits of data, which gives a capacity of

$$\frac{114bit}{120ms} = 950bit/s$$

GPRS and EDGE

Date: Wednesday 23.02.22

Lecture slides

Agenda

- Pros & Cons of mobile Packet Switching
- New elements needed for GPRS
- Assigning capacity to GPRS
- What is EDGE?
- Mobility management in GPRS and EDGE

Notes

GSM Characteristics

- Designed for voice (13kbps constant bit rate channels)
- FDMA/TDMA + FDD (200kHz channels, 8 timeslots)
- Signalling
  - Associated signalling -> 26 frame structure on the same timeslot as voice
  - All other signalling -> 51 frame structure on reserved timeslots
- Mobility management

- Handover and cell reselection (location area updating)
- Limited to 14.4kbps data transmission
- HSCSD raised this to 4 timeslots ≈ 56.7kbps
  - Billing per minute, not data used
- GPRS
  - Packet switched
  - 70kbps realistically
  - Billing per volume
- EDGE
  - High speed version of GPRS
  - 200kbps

Data Services

- Required network upgrades
  - Old MSCs designed for 64kbps
  - New terminal capabilities
  - Keeping track of mobile users
- GRPS
  - GSM Overlay
  - Shares radio capabilities, core network is changed
  - Can be used for SMS/MMS
  - Packet switches -> statistical multiplexing
  - Same timeslots as voice -> some are marked for / dedicated to data
    * Unassigned timeslots used for data
    * Operator designs capacity sharing on per cell basis

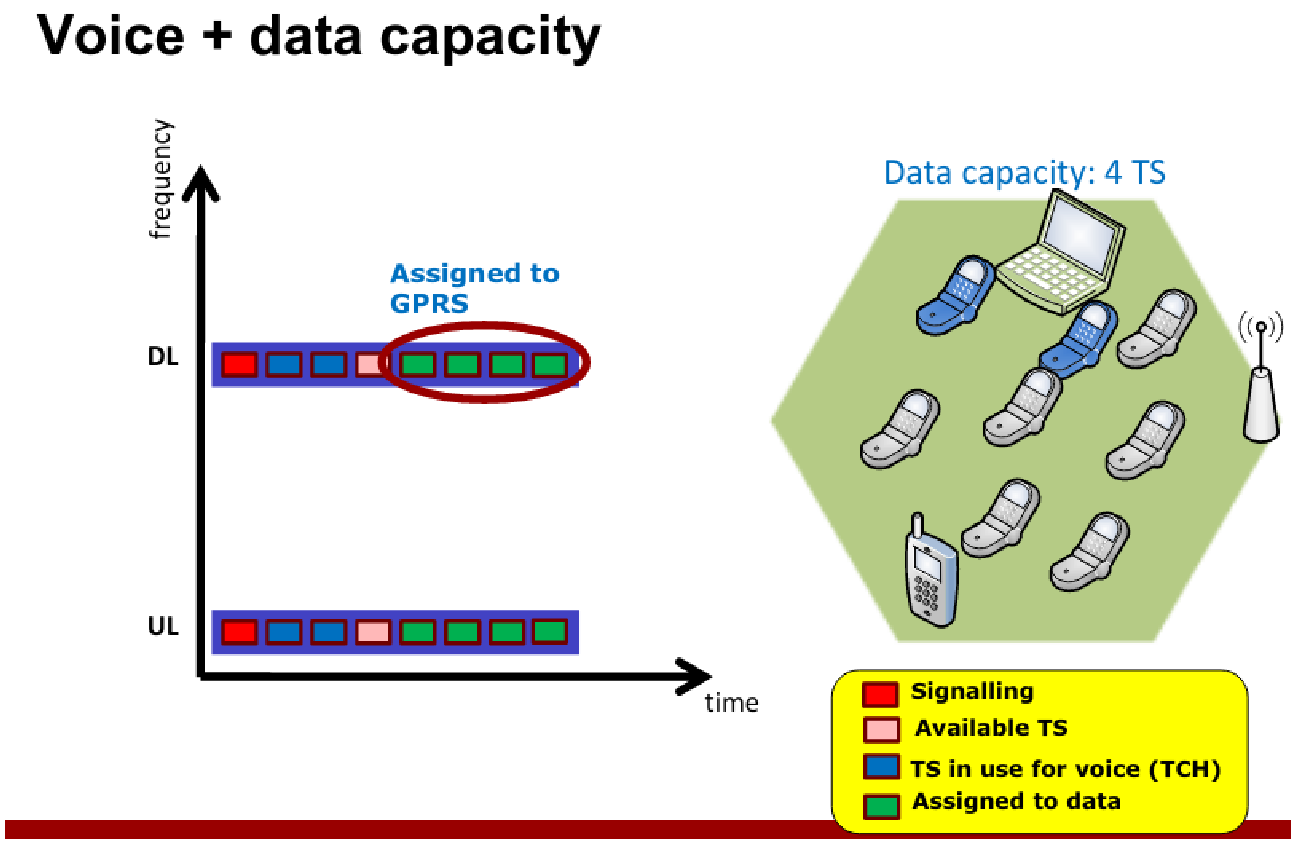

Figure 6: Voice + Data Capacity

Handling packets

- Upgrades

- BSS -> Packet Control Unit (PCU)

- New nodes
  - Packet core network
  - NSS -> two new nodes, SGSN(≈MSC, mobility), GGSN(“IP Router”) (core)
  - Must be able to handle terminals with differing capabilities

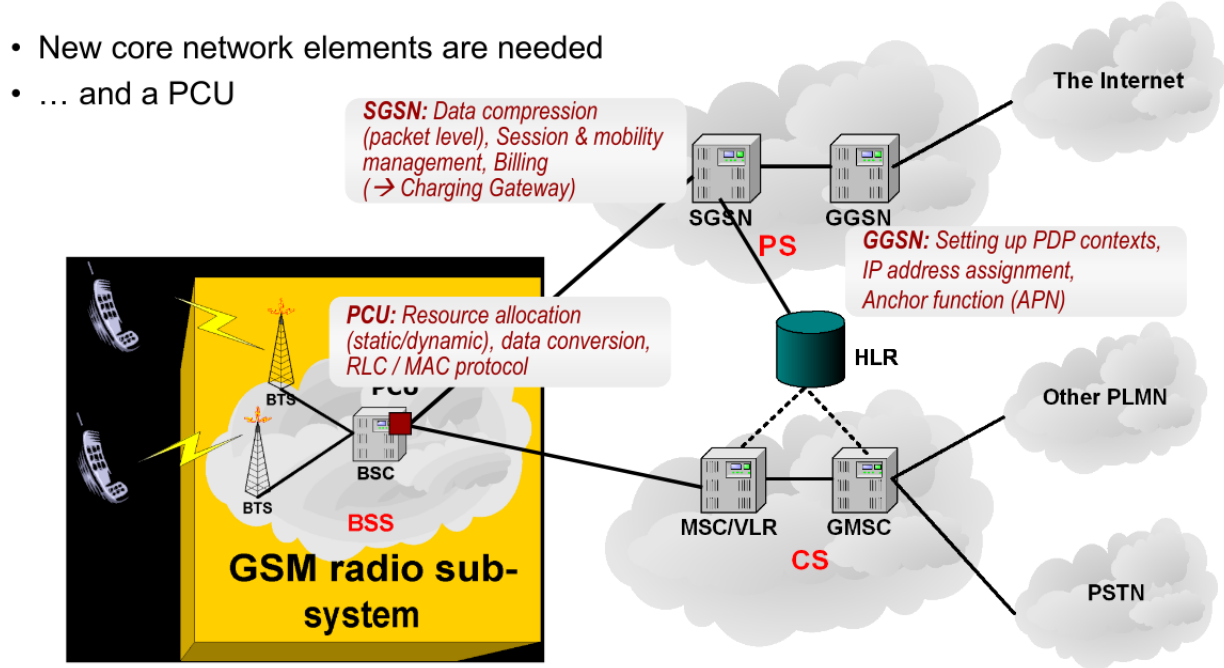

Figure 7: GSM -> GPRS Extension

- RLC / MAC used to fit packets into frames (only 114bits pr. user burst).
- SGSN:
  - Data compression
  - session & mobility management
  - Billing
- GGSN:
  - PDP Contexts,
  - IP Address assignment
  - Anchor function (APN)

Mobiles’ GPRS Capabilities

- Type
  - Type 1: Not able to send / receive at the same time
  - Type 2: Send and receive simultaneously
- More timeslots used for data -> more processing needed
  - May restrict older, slower phones
  - More processing -> less battery
- Classes
  - Class A: Simultaneous data and voice -> Dual Transfer Mode
  - Class B: Data or voice - paging on both
  - Class C: Data or voice - selected on start-up

Multislot class	Rx TS	Tx TS	Max sum	Type
1	1	1	2	1
3	2	2	3	1
8	4	1	5	1
10	4	2	5	1
13	3	3	N/A	2
18	8	8	N/A	2
25	8	3	N/A	1
29	8	8	N/A	1
32	5	3	6	1
40	6	1	7	1
45	6	6	7	1

Figure 8: Multislot Capability (common)

Data Transmission in GPRS

- Uses error correction
- Error correction scheme used depends on SNR (Signal to Noise Ratio)
- Adaptive selection of Coding Scheme (lecture slide 35)

Mobility and Session Management

- Overview on lecture slide 37
- In most cases, traffic is sent to the “home” GGSN while roaming
  - Data is sent from e.g. Sweden to Denmark, then to the internet

-Attachment ant detachment messages:

- Attachment is separate for voice and data
- Information about IMSI, IMEI, multislot capabilities
- A state is maintained for each mobile
  - Idle: mobile is not attached. No MM Context
  - Standby: attached. Network aware of RA, paging possible
  - Ready: Exact location known, data transmission possible (if PDP context exists)
  - Figure on lecture slide 39
- PDP Context:
  - Logical connection -> no resources allocated
- Procedure: MS sends PDP Activation Request to SGSN
  - Message includes APN - used to locate GGSN
  - Access permitted -> connection created to the GGSN

-GPRS Mobility Management:

- Capacity is allocated on a per packet basis
- Terminals do cell reselection if too many errors occur
  - Normally decided by terminal
  - Slow process (1-2s)
- Cell reselection during packet transfer -> packet lost
  - Something like TCP or UDP is relied on
- Cell reselection:

- Based on measurements by mobile (controlled by mobile)
- 3 cell modes:
  * NC0: Autonomous (MS decides)
  * NC1: Autonomous + report
  * NC2: Network
- Cell mode decided by network

-**Routing Areas:**

- Subset of location area
- Signalling load vs accuracy
- RA $\leq$ LA
- Cell reselection: new RA -> inform network
- SGSN's role in mobility management is $\approx$ MSC in voice communications
  - Same SGSN: routing area update, location information update
  - Other SGSN: Update location and SGSN information transfered, IP kept

EDGE

- Enhanced Data rates for GSM Evolution
- Changed modulation format (same symbol rate):
  - 8-PSK instead of GMSK (see slide 47) -> 3x bit rate
  - Max theoretical rate: 494.8kbps
  - More susceptible to noise -> higher SNR required
- Coding schemes and IR:
  - Adaptive selection of coding scheme (9 possibilities)
  - Incremental Redundancy (IR)
    * Start by sending 1/3 of bits (insert 0)
    * 2/3 of the bits (statistically) correct - 1/3 sent, 50% of guessed
    * Perhaps coding scheme can guess last third - otherwise retransmit
    * Second transmission: send other third
      · Statisticaly 5/6 bits correct
- GPRS/EDGE channel overview on lecture slide 52
  - 52 frame structure (26 for voice)
    * 2 timeslots for packet associated control channel, 2 idle
  - 4 frames per user request (even though it is not needed)
  - Uplink TBF (Temporary Block Flow):
    * Data transfer
    * Paging answer
    * RA update / GPRS attach
  - Downlink TBF
    * Data transfer
- Network mode of operation (NOM):
  - Nom I: CS paging during data transfer
  - NOM II: GPRS and GSM share signalling channels
  - NOM III: GPRS uses own signalling channels

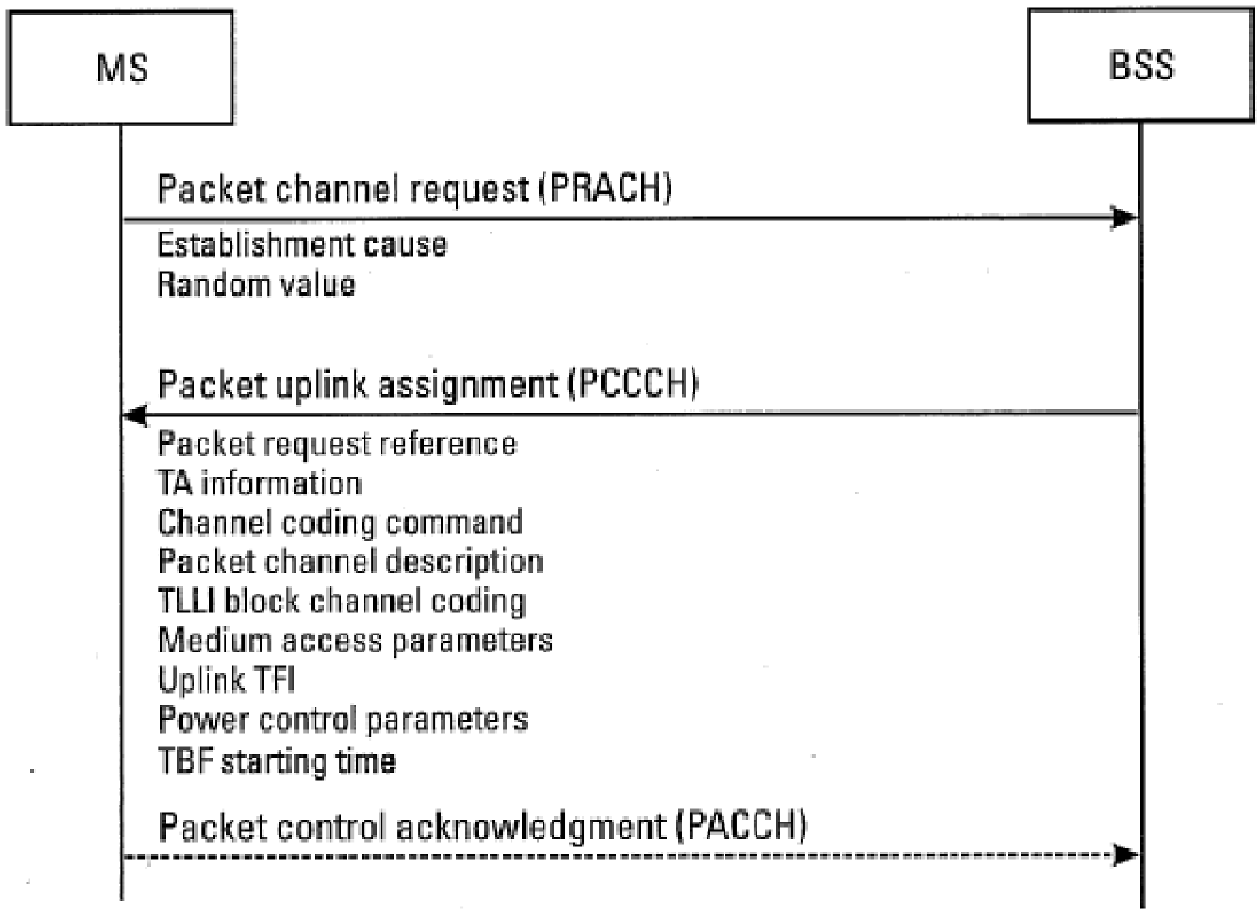

Figure 9: GPRS Uplink Medium Access

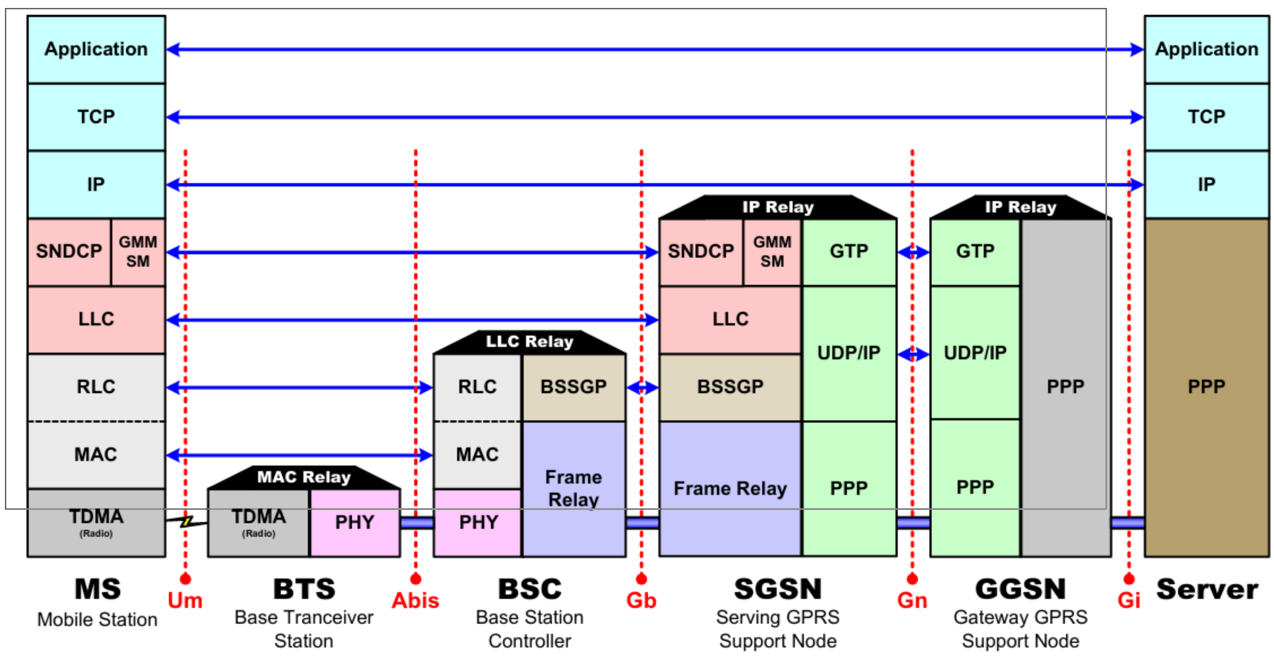

Figure 10: GPRS/EDGE Protocol Stack

Exercises

1: Packet data and Quality of Service

a) The user is only billed by data instead of by time. Benefit since internet traffic is often bursty. This often makes the usage cheaper.

b) It allows more efficient usage of the radio frequencies and allows for a simpler backend, since the traffic in packets is easy to handle with few cables. This also makes it cheaper to implement.

2: Data QoS

From a users point of view, a good QoS is one that allows everything the user wants to do - a voice call is not rejected and data packets are sent without hesitation. This makes a fair division of capacity necessary. By optimising the sending timeslots, the network can improve the performance of data services.

3: Cell Capacity

# of TRX	Assigned for data	Dedicated data TS	Total # of TS available	Maximum # of TS available for data	Maximum # of TS available for voice
1	4	0	**7**	**4**	**7**
1	4	2	7	4	5
2	4	0	15	4	15
2	4	2	15	4	13
3	4	4	23	4	19

Figure 11: Cell capacity table

If $\#maxdataTS + \#maxvoiceTS > total$, it is because the data timeslots are not dedicated to data and can instead be used to transmit voice calls. By doing this, the capacity can be more efficiently utilised.

4: Erlang Capacity

a)

- 0 timeslots: 2.9 Erlang
- 1 timeslot: 2.2 Erlang
- 2 timeslots: 1.6 Erlang

b) 300.000 users who each use $0.02erl$ will use $300.000 \cdot 0.02erl = 6000erl$. Each cell can then use 7 channels since none are dedicated to data, so $\frac{6000erl}{2.9erl} \approx 2069$ cells.

To calculate for other values of dedicated data channels, substitute $2.9erl$.

5: EDGE

To improve capacity, the coding schemes are better optimised and the sending scheme is changed. Instead of GMSK, 8-PSK is used. This utilises the ability to phase a signal to transmit more bits per symbol sent. Incremental redundancy is also used to increase the amount of bits sent per unit of time.

The maximum bitrate is $61.9\frac{bit}{s} \cdot 3 \approx 186\frac{bit}{s}$. This can only be reached, however, if the transmission situation is perfect; any noise will affect the coding scheme and incremental redundancy and thereby negatively affect the sending capacity. The 3 timeslots are also shared by anyone trying to use data traffic, so the load on the cell will heavily affect the transmission rates.

6: Mobility Basics

- In GSM, the network is in charge of cell changes with the help of the mobile unit. In GPRS, the mobile is in charge of changing cells.
-
- If a packet is being transmitted, it is simply lost, and must therefore be retransmitted.
- It is not necessary since the core network is in charge of everything after the immediate connection. The "foreign" core network will redirect all traffic to the "home" gateway; e.g. a Dane travelling to Australia will have all traffic redirected to Denmark before being sent to the internet.

UMTS - 3rd Gen Networks

Date: Wednesday 09.03.22

Lecture slides

Agenda

- UMTS Introduction
  - 3G mobile
  - Network Architecture Overview
- WCDMA principles
- UMTS Radio Access
- Mobility concepts in UMTS

Notes

UMTS and Architecture

- Release 99 -> first UMTS
  - R4: Minor
  - R5: HDSPA
  - R6: HSUPA (current)
  - R7: MIMO, TD-SCDMA
  - R8: LTE
- Designed for voice *and* data
- New radio interface, increased bandwidth
  - WCDMA, up to $384kbps$
  - 5MHz
- RAB (Radio Access Bearers)
  - Description of channel between user and network
- Strata -> subdivision of functionality
  - Access stratum
  - Non-access stratum

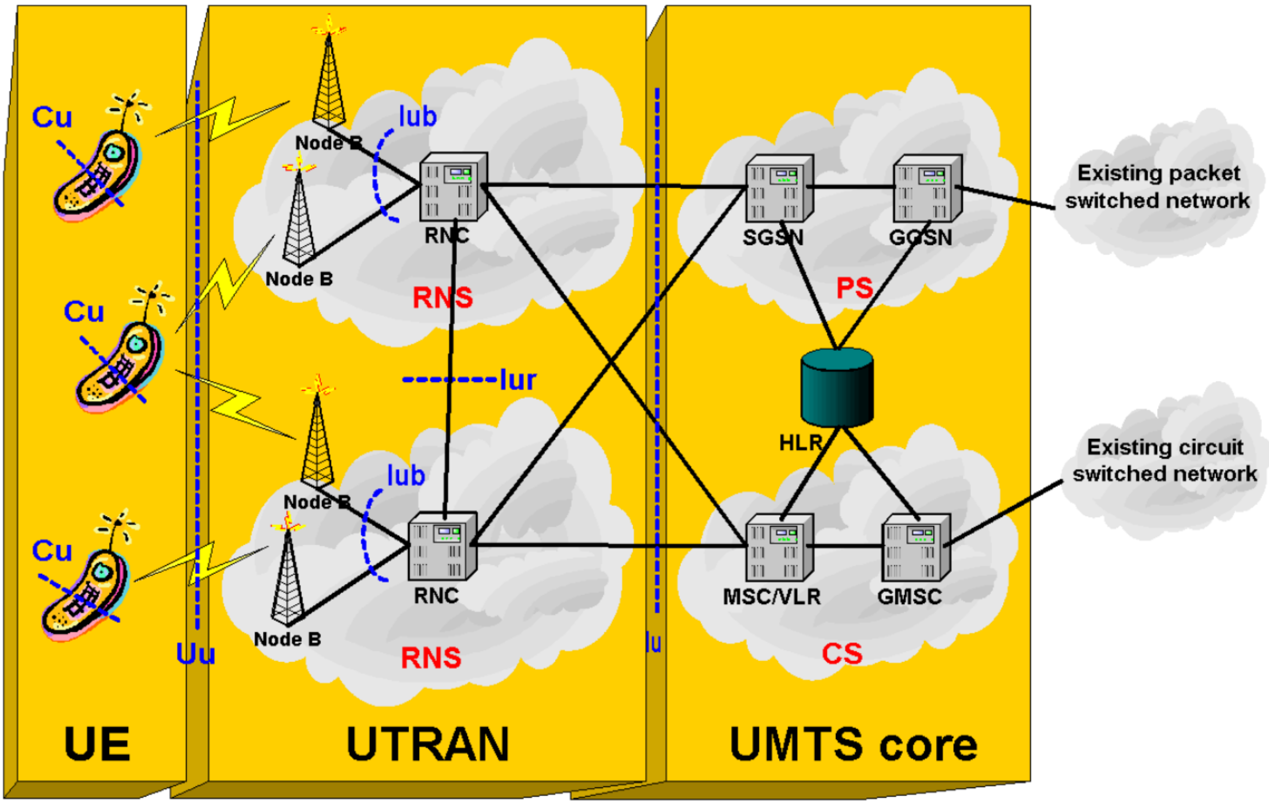

Figure 12: UMTS Network Structure

Base station controllers linked -> focus on capacity, not just coverage. Better for handover -> smaller cells -> more capacity.

Multiplexing

GSM used FDMA, TDMA - UMTS uses CDMA

CDMA Everyone transmits at the same frequency simultaneously. Uses more spectrum than necessary. Increases spectral efficiency.

Uses communication on orthogonal frequencies where the data is encoded on a carrier code wave.

Analogy: international dinner party

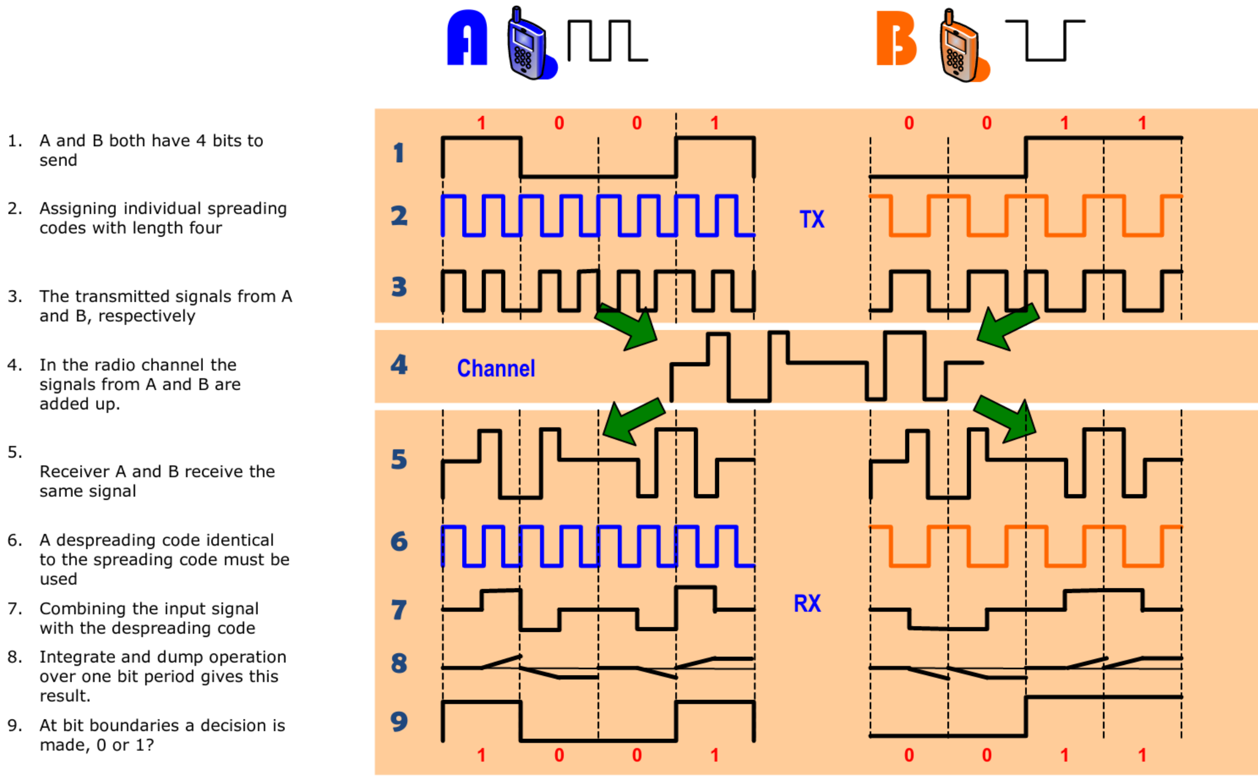

Figure 13: CDMA with multiple users

- Pros
  - Processing gain (lower bitrate = higher chance -> aggregate cells)
  - $12.2kb/s$ voice with $3.84Mchip/s$ gives $25dB$ gain
  - Frequency reuse (all cells use same frequency)
  - Spectral efficiency
- Cons
  - Coordination of code required
  - Limited by interference
  - Near/far problem
  - High synchronization requirements
    - -> need for advanced receivers and power control

WCDMA in UMTS

- Direct Sequence (transmitting on the same frequency over time)
  - Often frequency jumping in unlicensed bands (no controller)
- FDD and TDD versions
- 5MHz bands
  - Wideband-CDMA (previously 1MHz)
- 3.84 Megachips per second
- 1500Hz power control
- $10ms$ frame length (uplink multiplexing)

Spreading

- Data -> spreading -> modulation -> radio signal
  - Channelization increases bandwidth
  - Scrambling - no increase in bandwidth, merely increase in ability to reuse codes in neighbouring cells
- Channelization based on OVSF
- Multipath diversity no longer a problem
  - Difference in path length must be greater than a chip length (in UMTS $\approx 78m$
  - Rake receiver which counteracts the multipath

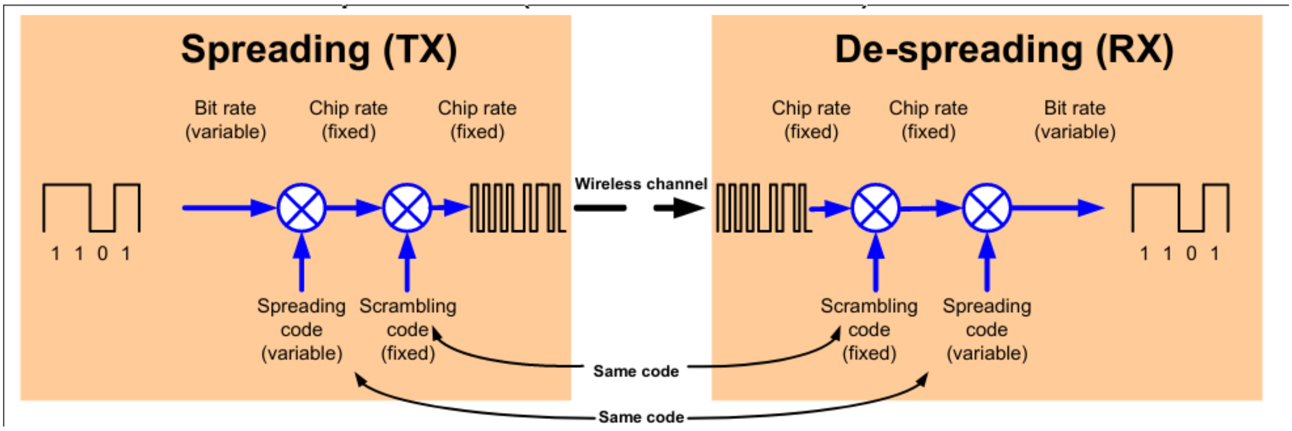

Figure 14: Spreading Example

UMTS Cell Capacity

- Each cell
  - 5MHz bandwidth
  - Number of users depends on
    * Distance from node B
    * Usage
    * Requirements to connections
- Capacity can be added by allocating more frequency bands
- Power control impacts capacity
- One OVSF tree per scrambling code

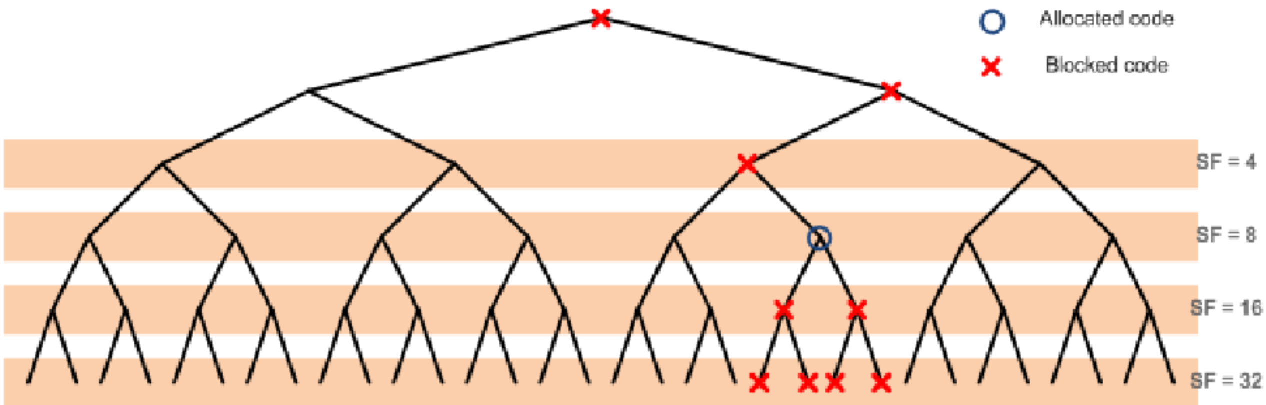

Figure 15: OVSF Allocation and Blocking Tree

Mobility Management

- Handover if in call, location/routing area update if idle
- In 2G: terminals determine cell. In 3G: network determines cell
- Intra cell mobility:
  - Not TDMA, so not a problem
  - Rake receivers handle delay, scrambling codes handle orthogonality
  - Power control handles power
- Inter cell
  - Cell edge situations must be considered
- Handover decisions made by RNC
  - Based on
    * RSSI (Received Signal Strength Indicator)

    - RSCP (Received Signal Code Power)
    - EcNo - chip energy to noise ratio ($= RSSI/RSCP$)
  - *Compressed mode* can be activated to monitor GSM cells
- Coverage area divided into cells
- Cells grouped into location areas
- Network decides station, so terminal may not be in the cell that it is connected to
- Location area update sent if cell moves to new area

Handover types

- Soft, softer
  - Only handled in access network
  - Connection to more than 1 cell at a time
  - More RNC's can be involved
    - Serving RNC (SRNC) -> connection to core
    - Drift RNC (DRNC)
    - Controlling RNC (CRNC)
  - SRNC relocation decided by core network
- Hard
  - Between frequency bands
  - Between cells (if macro diversity not supported)
  - Between FDD and TDD
- Inter system -> GSM
  - Compressed mode:
    - Used to monitor GSM cells while connected to UMTS
    - UMTS cells broadcast frequencies of neighbour GSM Cells

Core network mobility management

- Core network must know mobile position
- MSC handles circuit switched users
  - Mobility Management (MM) states
- SGSN handles packet switched users
  - Packet mobility mangement (PMM) state

Mobility states - CS & PS

- MM (CS)
  - MSC keeps track
  - MM detached
    - Device off
    - Location unknown
  - MM idle
    - Attached, inactive
    - MO call possible
    - MT call requires paging
  - MM connected
    - Active call in progress
    - Signalling and communication with network
- PMM (PS)
  - SGSN keeps track
  - PMM detached
    - Not turned on
    - Location unknown
  - PMM connected
    - Attached and PDP context active
    - SGSN only aware of current SRNC
  - PMM idle
    - No logical connection
    - No PDP context
    - During periods of inactivity (RNC decision)

Mobile's point of view

RRC states

- Network can set mobile into different RRC states
- Determines
  - Mobility management
  - Network resources consumed
  - Time to resume communication

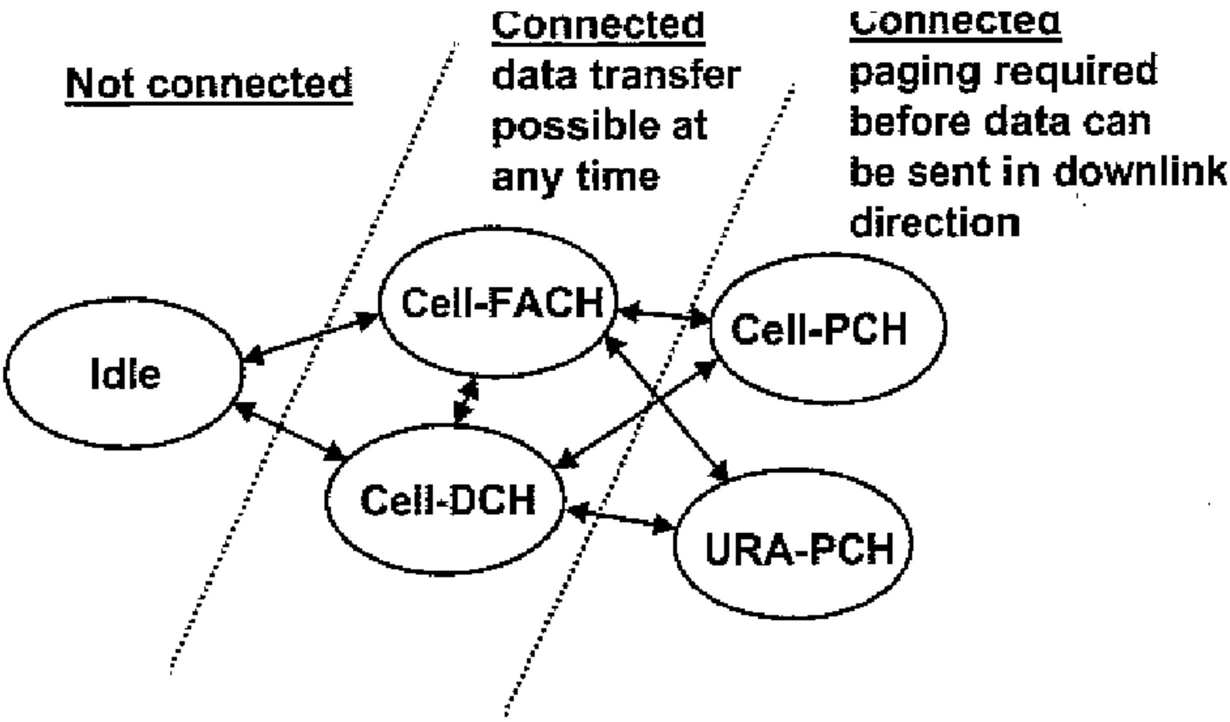

Figure 16: RRC States

Explanation of RRC states can be found in the lecture notes.

LTE 1: 3.9G Mobile Networks

Date: Wednesday 23.03.22

Lecture Slides

Notes

Misc

5g: most 5g uses $700MHz$ or $900MHz$ for coverage, and $2.6GHz$ or $3.4GHz$ for capacity.

LTE/M: Specific LTE designed for machine-to-machine communication. Most IOT uses GSM, however, since it's cheaper and more implemented.

LTE: Long Term Evolution, not quite 4g because of regulation. The entire standard was built for data/IP communication.

Goal for LTE

- Requirement for high bit rates and low latency -> more capacity
- Optimization for packet based traffic
- Not required for TCP/IP to retransmit - network retransmitting

- $100+ Mbps$ bit rates, latency $< 10ms$
- More functionality in Node B (called eNode B)

First release of LTE was in release 8 of the 3GPP standardization. Release 9 focused on WIMAX and LTE/UMTS interoperability. Release 10, LTE Advanced, was 4g.

LTE Radio Access

- Duplexing with FDD and TDD
- Multiplexing:
  - Downlink: OFDMA -> peak $300Mbps$
  - Uplink: SC-FDMA -> peak $75Mbps$
- Frequency Bands
  - 22 bands defined
  - Subcarriers in 3g: $1MHz$ / 4g: $15kHz$
  - 700, 850, 1800, 1900, 2100, 2600 MHz
  - 1800 and 2600 bands are being rolled out in DK
    * Different bands used in different countries
      · Roaming capacity worsened
  - Small subcarriers allow to choose based on subcarrier performance
- Multipath/ISI handled by cyclic extensions

Downlink Access Scheme / OFDMA:

- Scheduling in frequency and time
- 12 frequency subcarriers in a block
- Transmission is assigned some frequencies in some time
- Most carriers dedicate one frequency channel for voice services
  - VoLTE is bad under load
- Resources assigned as Physical Resource Blocks
  - 1ms subdivided into 14 individual symbols
  - 12 carriers, $15kHz$ each, $= 180kHz$
- Max total system bandwidth $20MHz$
  - Carriers can be placed on top of each other
  - Theoretically up to 6 cells on top, $= 120Mbps$
- Scheduler running in eNode
  - Every $1ms$ (in practice more often $2ms$)
  - Assigns PRB to users in chunks of $180kHz$.
  - Based on CQI feedback from terminals

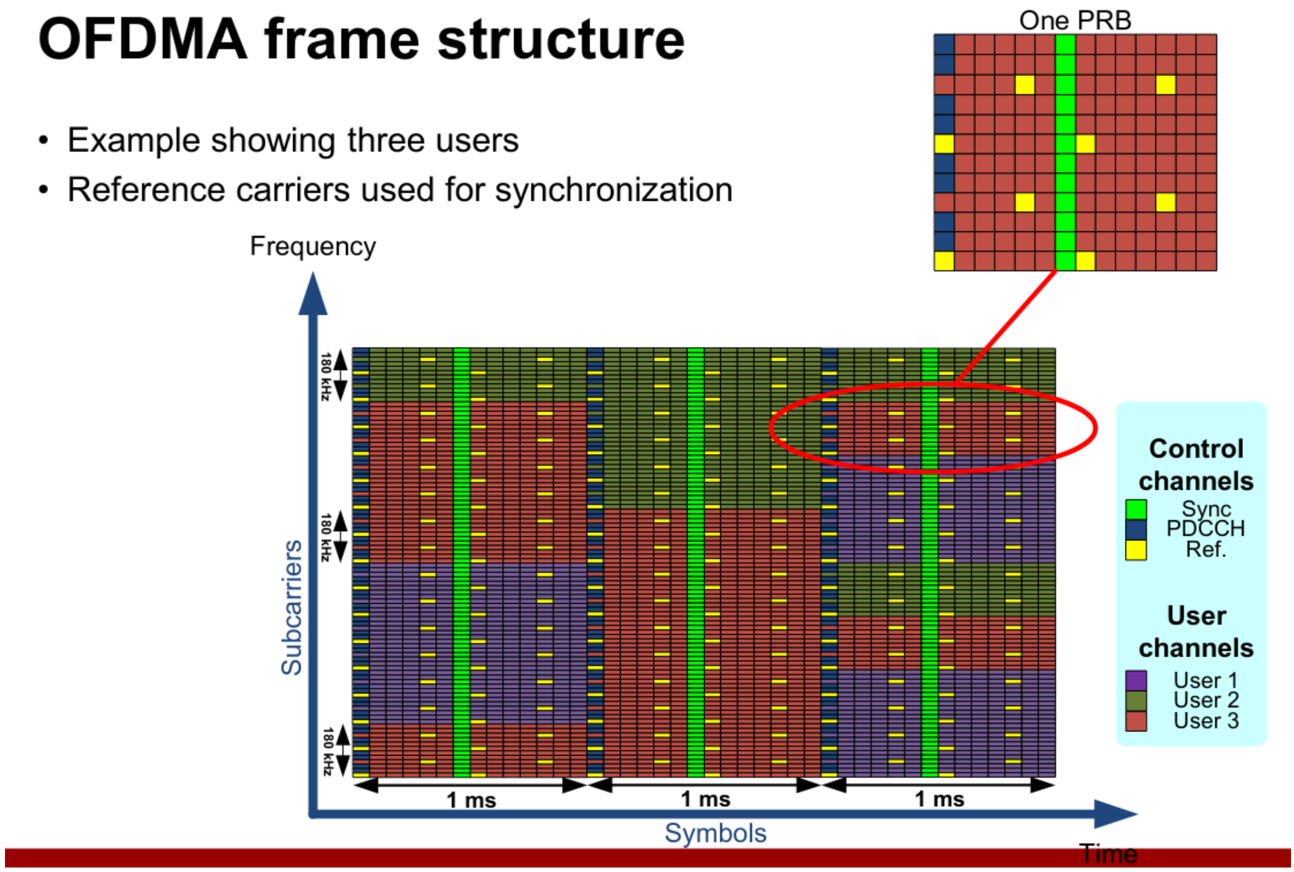

Figure 17: OFDMA Frame Structure

Guard time / guarding frequencies are not shown on the image.

Retransmission:

- L2 (MAC)
  - Hybrid ARQ (HARQ)
  - Stop and Wait (SAW)
- MIMO
  - 2x2, 4x4 or larger
  - Single user or multi user
  - DL Single user
  - UL Multi user
  - One UE must have 2 Rx, 1 Tx antenna

User Bit Rate

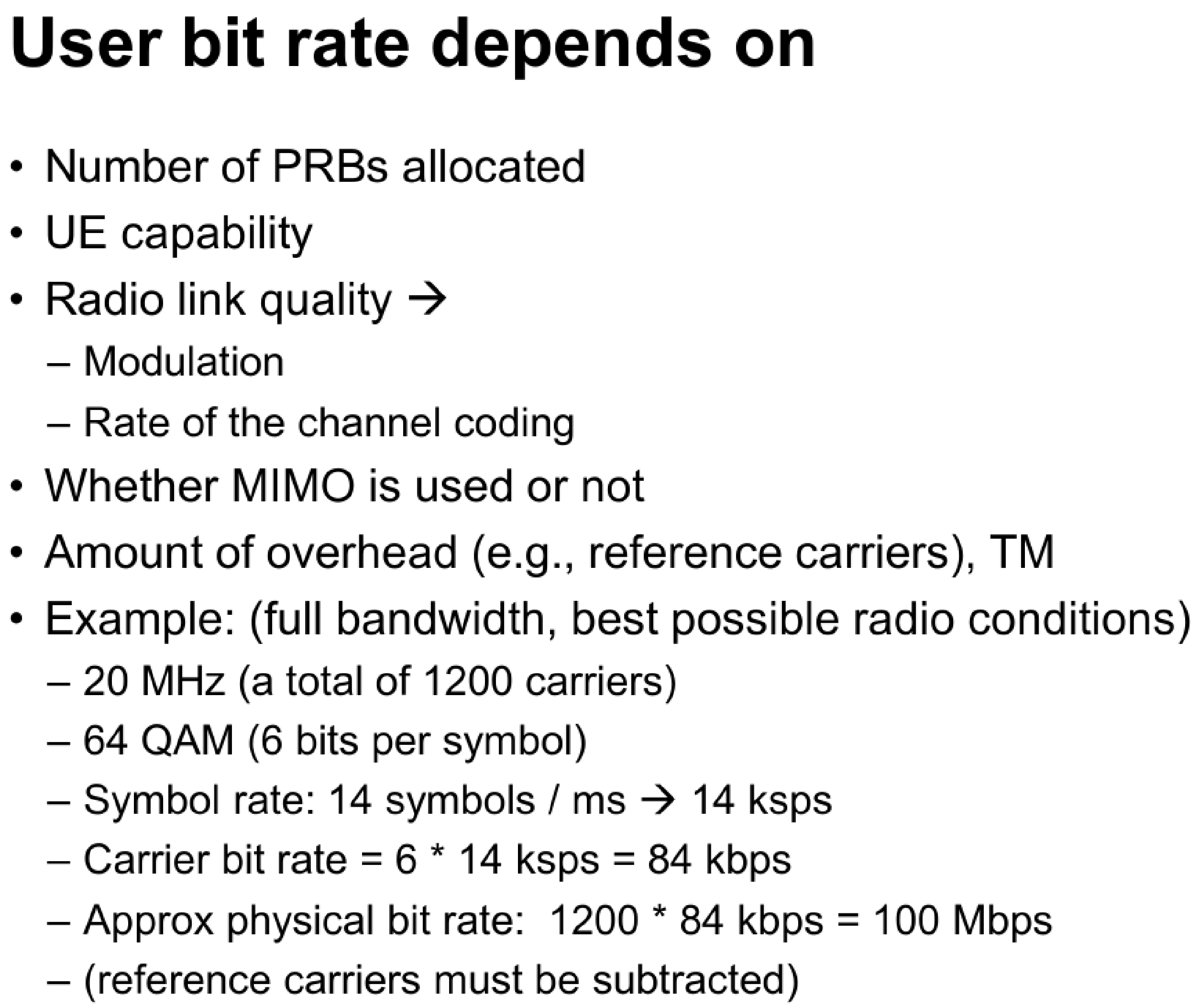

Figure 18: User Bit Rate Dependencies

Users are divided into categories, which are used to select the best possible MIMO technique and QAM.

LTE Network Capabilities can be found on lecture slides.

OFDMA Assessment

- Pros
  - Flexible and scalable
  - Narrow bandwidth carriers are favorable in mobile, multipath environment
  - High spectrum utilization
- Cons
  - Complex implementation
  - Carrier spacing must be accurately controlled to keep them orthogonal -> use digital FFT implementation
  - Scheduling is complex and requires computational power
  - Requires wideband amplifiers
    * Also why OFDMA is only used in uplink - easier to fit more complex antenna into base station

Uplink Access Scheme (SC-FDMA)

- Single Carrier FDMA
- Timing advance is used to ensure that frequencies do not overlap
  - Resolution $0.52\mu s$
- Still $15kHz$ carriers, but are combined before tx

LTE Network Architecture

- Step 1: Direct link from station controller (RNC) to "IP Router" (GGSN), bypassing SGSN, which also handles mobility information
- Step 2: RNC functionality into Node B (now eNodeB), SGSN only control information (now MME)
- Handovers are dealt with by the access network itself, not by the mobile unit. The UE can keep a connection with more than one base station at a time and the network behind will figure out where to send the information

Highlights:

- A lot of functionality condensed into eNodeB
- Clear separation of control and user plane functions
- Core network - user plane
  - S-GW
  - P-GW
- Core network - control plane
  - MME
  - HSS
  - PCRF
- Services domain
  - IMS based operator services

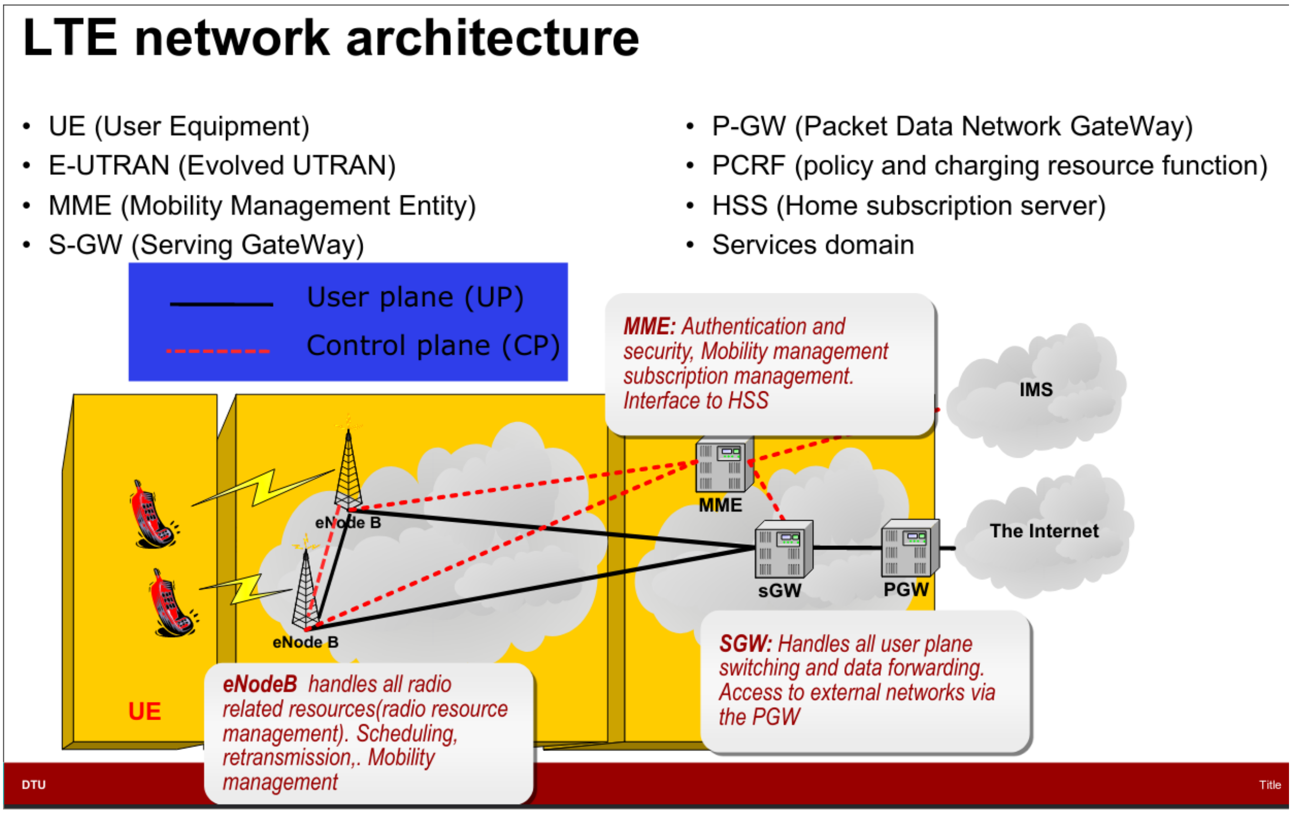

Figure 19: LTE Network Architecture

LTE Channels

- No dedicated channels -> only common, shared channels
- Frame Structure
  - 10ms frames
  - 0.5ms slot structure
  - 1 sub frame = two slots = 1ms
  - Allocation = 1 sub frame
  - One slot carries 7 symbols, which are used for data, signalling, reference symbols
- List of all channel names can be found on lecture slides (control, broadcast etc.)

Problems

Problems

1. New LTE network elements

a) MME handles mobility
b) E-UTRAN - Evolved Universal Terrestrial Radio Access Network - is the access network which handles traffic

2. LTE Capacity

a) 14 symbols / ms, 2 bit / symbol, 60 sub carriers:

$$60 \cdot 28 \frac{bit}{ms} = 60 \cdot 28 \frac{kbit}{s} = 1680 \frac{kbit}{s}$$

b) 64 QAM -> 6 bit per symbol. With 240 subcarriers:

$$240 \cdot 6 \frac{bit}{symbol} \cdot 14 \frac{symbol}{ms} = 20160 \frac{bit}{ms} = 20160 \frac{kbit}{s}$$

c) 16 QAM -> 4 bit per symbol. With 780 subcarriers:

$$780 \cdot 4 \frac{bit}{symbol} \cdot 14 \frac{symbol}{ms} = 43680 \frac{bit}{ms} = 43680 \frac{kbit}{s}$$

3. LTE Overhead

Some parts of a time slot is used for signalling and control information. There is also about 20% packet loss in LTE.

4. Reference Signal Ovehead

a) A lot of LTE communication depends on precise timing (e.g. timing advance). All UE's must then be synchronized.

5. Download Capacity Allocation

a) Give each user a horizontal "block"

Long Term Evolution II

Date: Wednesday 30.03.22

Lecture Slides

Notes

LTE Mobility

- Handover decisions
  - Mobile assisted, network controlled
  - Measurements by Mobile
  - Decision by network (eNode B)
  - Based on (different from GSM & UMTS):
    * RSSI (Received Signal Strength Indicator
    * RSRP (Reference Signal Received Power)
    * RSRQ (Received Signal Radio Quality)
      · $= RSRP/RSSI$
    * Only RSRP and RSRQ reported to network
- Intra cell
  - Mobility within a cell
  - Timing advance used to keep synchronization with the cell
- Inter cell
  - Cell edge situations must be taken into consideration
  - Cells use same frequency -> interference

Idle mode mobility:

- Coverage area divided into cells
- Cells grouped in tracking areas
- Send update if tracking area changes
- Cell reselection criteria
  - Best cell based on RSRP
  - Cell ranking
  - Hysteresis used to avoid ping-pong
  - Occurs if better cell is available for some time

Connected mode mobility:

- UE in RRC_CONNECTED state -> handover
- Controlled by network
- Options:
  - High strength + quality: stay
  - High strength + low quality: coordinate with neighbour
  - Low both: consider GSM/UMTS

LTE Handovers

- Within LTE:
  - X2 handover
  - S1 handover
- Intersystem handover -> GSM, UMTS
- X2 Handover:
  - Connects eNode Bs
  - When better cell than current is found:
    * Send measurements to current cell
    * eNode B establishes connection with X2
    * Target cell reserves capacity
    * UE switches - data forwarded over X2
    * Core network informed
    * Lossless -> late path switching
- Inter System:
  - If LTE RSRP low: consider another RAT (Radio Access Technology)
  - For decisions, see lecture slides
  - Procedure similar to S1 handover

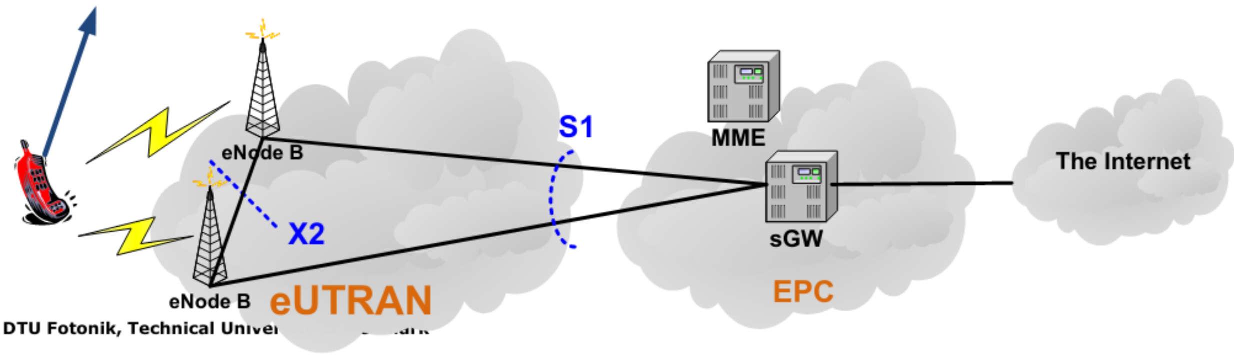

Figure 20: LTE Handovers

LTE Procedures

HARQ, timing advance, paging.

Specific procedures can be found in lecture slides.

- Power control:
  - Orthogonal carriers -> no real need for power control
  - Controlled by network
  - Only UL power control
    - Controls PSD (power spectral density)
    - Power changes with allocated bandwidth
    - Power control command -> ± 1 DB adjustment
- Cell Search:
  - Find suitable cell for camping:
    - Radio quality, cell not barred, try last cell or perform full
  - Look for synchronization signals
- Random Access:
  - Read BCH to get available preamble on PRACH using low power
  - If access granted: send data on PUSCH
  - Otherwise -> increase power and retry
  - Two types:
    - Contention based
    - Non-contention based -> used for handovers
- Network attach:
  - Purpose is to register the UE on the network

SMS & Voice

- SMS over SG
  - SG: new interface between MME (LTE) and MSC (GSM)
  - Sent over control plane interface (S1), not data
- Voice Fallback
  - Also uses SG
  - Slow due to inter-RAT handover
- VoLGA, VoLTE, VoIP
  - GAN (Generic Access Network): extending mobile network with WiFi access points - requires controller
    - VoLGA uses WiFi as alternative
  - VoLTE
    - Uses IMS (IP Multimedia Subsystem) + SIP + VoIP
  - OTT (Over The Top)
    - VoIP
    - E.g. Skype, WhatsApp
    - No QoS control

Miscellaneous LTE Overview

- Intercell Interference Coordination (ICIC)
  - All LTE eNode B use same frequencies
  - Neighbour eNode B coordinate TX power in various sub-carriers
- Self configuration
  - Configuration of Physical Cell ID (PCI)
  - Automatic Neighbour Relations (ANR)
  - Self Organizing Networks (SON)
    * Self configuration
    * Self optimization
    * Self healing
- Power Saving (DRX)
- LTE Advanced (true 4G)
  - Release 10, 11, and 12 -> enhancements of LTE
  - Up to 1Gpbs DL and 500Mbps UL
  - Carrier aggregation
  - Enhanced use of MIMO
    * UL single up to four
    * DL MIMO up to 8
  - CoMP (Coordinated Multi Point) TX & RX (multiple base stations)
  - Relays used to extend coverage / capacity

Exercises

1. LTE Handover Frequency

a) $120\frac{km}{h} = 2\frac{km}{min} \Rightarrow$ 90s per update. First after 3 minutes, second after 4.5 mins. 30 updates per hour.
b) Handover every 90s; 40 times per hour.

2. MME Load

a) 3000 user send 40 updates per hour; 7000 users send 30 updates per hour.

$$3000 \cdot 40 + 7000 \cdot 30 = 120000 + 210000 = 330000$$

b) If so many follow blue arrow, move the yellow so tracking area does not change along the route

3. X2 Interface

a) Interconnects eNode B's
b) Used in handover, ICIC, and CoMP

4. SG Interface and More

a) Between MME and MSC
b) Used for SMS, and RAT change (e.g. voice call)
c) Yes, as it is used for both control and SMS/voice

Week 10: IMS & VoLTE

Date: Wednesday 06.04.22

Lecture Slides

Motivation

In LTE: no more circuit switched networking, so how are voice services implemented?

VoLTE

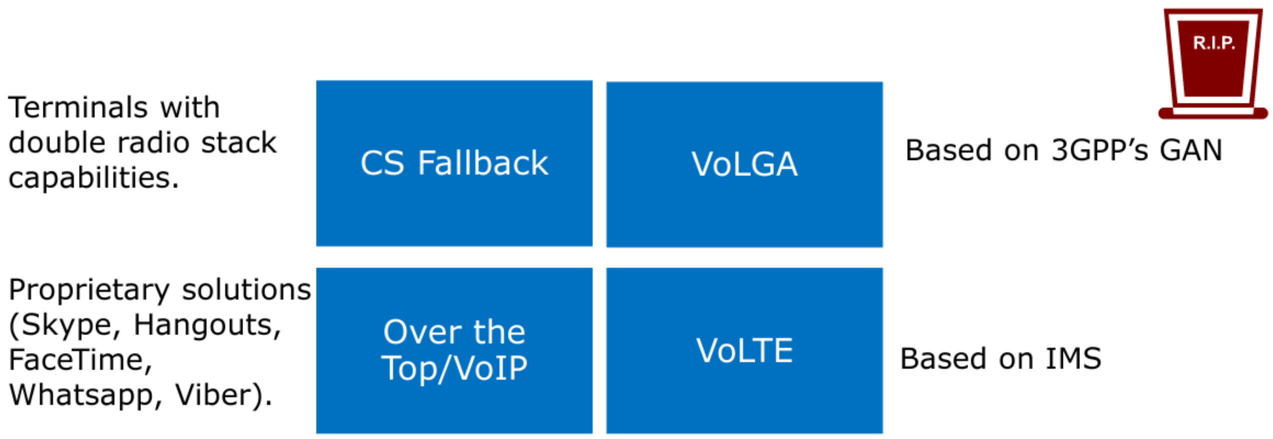

Figure 21: Voice in Mobile Networks

In fig. 21, OTT/VoIP was quickly dismissed and VoLGA also "died". CS Fallback and VoLTE are still used.

- Disadvantages of OTT:
  - No QoS
  - No phone number reuse
  - No handover
  - No interoperability
  - No emergency calls
- Benefits of VoLTE
  - Native phone dialer
  - SIM based number
  - Value added services

Voice in LTE

Requirements:

- Call setup
  - Signalling, end user identification
- Supplementary services
  - Display caller, privacy restrictions, forwarding, barring, conferencing, SMS
  - Uses XCAP (XML Configuration Access Protocol)
  - Required: DTMF tones, alerting tones, emergency calls, Single Radio Voice Call Continuity (SRVCC, handover to SC), roaming
- Transfer of voice data
- In a mobile network
  - Roaming, handover

Protocols:

- RTP - Real-time Transport Protocol (uses UDP)
- RTCP - Real-time Transport Control Protocol (UDP)
- SDP - Session Description Protocol (TCP)
- SIP - Session Initiation Protocol (TCP)

SIP

Protocols for initiating sessions. Used with SDP that describes the session. SIP is the "invitation card", SDP the contents.

Key Elements

- A user has a UA to represent tem in SIP
- Each user has SIP identifier, URI
  - Similar to eMail
  - User needs to be located -> UA performs user's registration

URI: `sip:alice@example.dk`

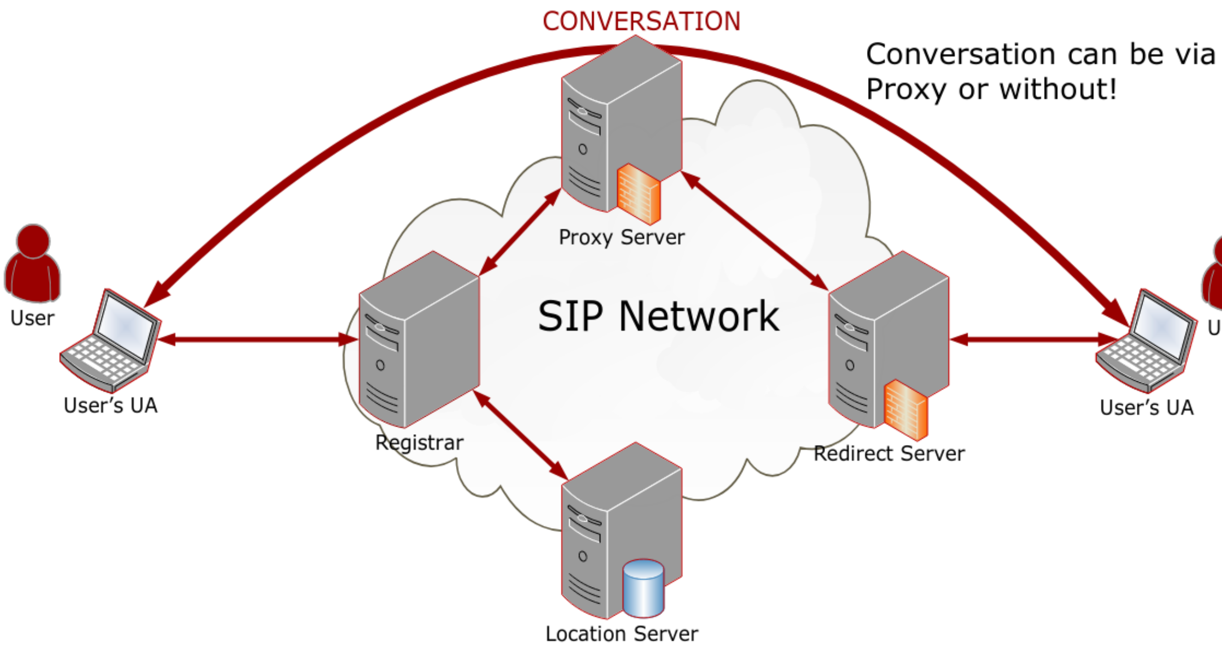

Figure 22: SIP Architecture

Most operators would use the proxy method, since this gives the operator knowledge of the call details (when it ends).

Operations

Operations follow the request/response principle. Following operatins exist:

- Operations
  - REGISTER
  - INVITE (with session description)
  - ACK
  - CANCEL
  - BYE
  - OPTIONS (capabilities)
- Responses
  - 100-199 Informational
  - 200-299 Success
  - 300-399 Redirection
  - 400-499 Client Error
  - 500-599 Server Error
  - 600-699 Global Failure

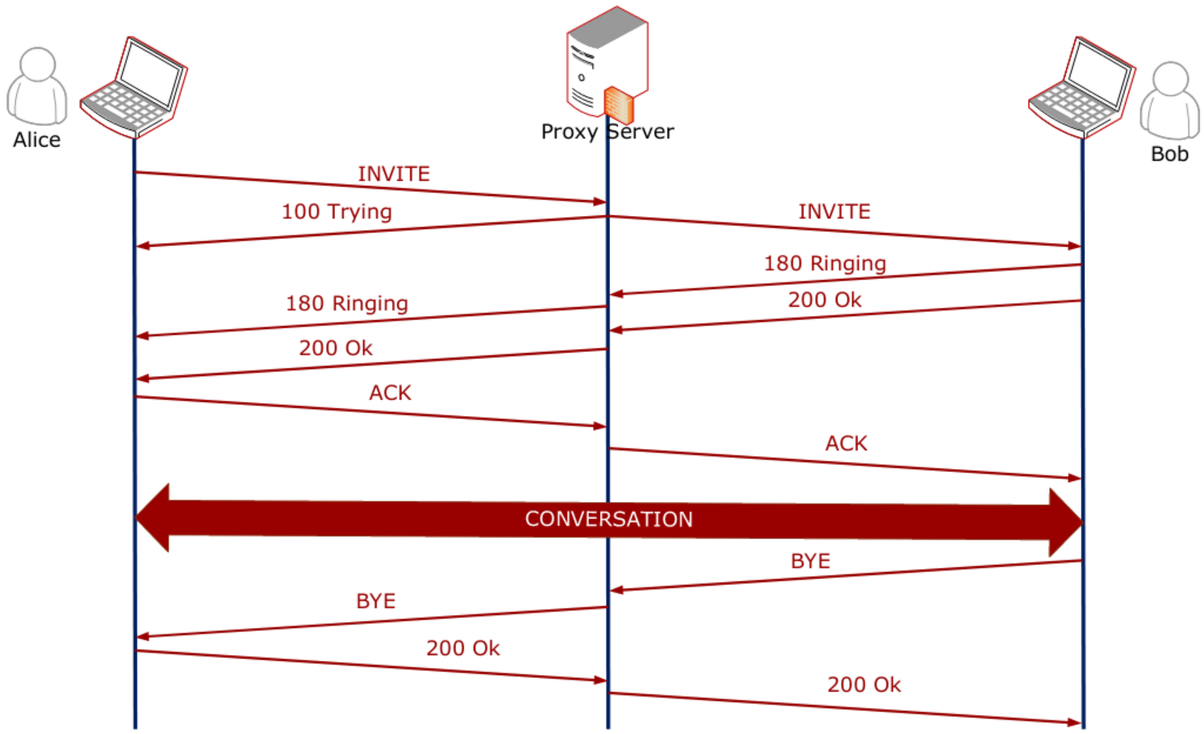

Figure 23: SIP Operation with Proxy

The proxy is not a part of the call itself; only the signalling regarding the call. This ensure minimal delay in the actual conversation while keeping operator control.

SIP in general works on any IP network, e.g. LTE. This does not, however, ensure mobility & others; IMS is therefore a mobile version of SIP.

IMS - IP Multimedia Subsystem

IMS Overview

- CSCF: Call Session Control Function
  - S-CSCF: Serving
    - Provices authentication and registration, session control
  - P- : Proxy
    - First contact point for all users of the network
  - I- : Interrogating
    - Contact point for retrieving information regarding subscribers and services of the network -> contact point for external connections to subscribers of that network
- MGCF: Media Gate Control Function
- PCRF: Policy Control Resource Function
  - QoS provisioning, charging subscribers
- AS: Application Server

Architecture on lecture slides; looks strange because of compression.

Voice Services in LTE

VoLTE example

- Signalling from eNodeB -> S-GW -> P-GW -> P-CSCF -> S-CSCF
  - or from P-GW to Internet
- Ensures QoS control

Misc. Details

- Early media
  - Alerting tones
  - Ringback tones
  - Generated by originating device or the network
- DTMF tones
- Roaming

Interworking with other networks

- Must be able to interwork with other mobile and fixed networks
  - Especially important for voice traffic
- Challenges:
  - Translation of IMS ID (SIP URI) to phone number (E.164)
  - Translation of services in PSTN, 2G, 3G networks (SS7-IN)
  - Media transcoding
    * Full rate, half rate GSM
    * NB-AMR in UMTS/LTE
    * G.711 in PSTN
- WiFi calling:
  - IMS works on *any* IP network
  - New Device -> ePDG
    * Terminates IPSec tunnel (WiFi -> PEC/IMS)

Exercises

1. IMS Deployment

a. The operator can handle calls with only a packet switched network as well as ensuring QoS.

b. You need 3 different types of CSCF, an MGCF, a PCRF, and an AS. This is then connected to the P-GW of the existing LTE network.

c. It must be possible to 1) translate SIP URI to E.164, 2) translate services in PSTN, and 3) transcode media in the correct formats, e.g. half-rate GSM.

2. Dimensioning of an IMS Network for VoLTE

a. $1000000 \cdot 70$ calls per hour.

b. 5 messages to the caller, 4 to the receiver, $= 9$ messages.

c. 35000 calls, 9 messages per call, $= 35000 \cdot 9 = 315000$ packets per hour.

$\frac{315000}{3600} \approx 88$ packets per second.

d. HSS, transcoding gateway.

e. 9 messages per call, 5 seconds to complete setup, $\Rightarrow \frac{9}{5} = 1.8\frac{message}{second}$.

Message size: LTE Header + IP Header + L4 header + Application Data

Each call takes up $15 + 20 + 20 + 600 = 655\frac{bit}{message}$ and $1.8\frac{message}{second} \Rightarrow 655 \cdot 1.8\frac{bit}{second}$.

f. $(15 + 20 + 8 + 8 + 30) \cdot 8 = 648\frac{bit}{s}$ per conversation payload.

g. With $648bit$, there must be a bitrate (if that message is to be transmitted in 100ms) of $\frac{648bit}{0.1s} = 6480\frac{bit}{s}$.

h. Propagation delay: $\frac{2000km}{300000\frac{km}{2}} = \frac{1}{150}s$. The network then only has $0.1s - 2 \cdot \frac{1}{150}s = 86.6ms$ to send the packet. The required bitrate is then $\frac{648bit}{0.0866s} \approx 7500\frac{bit}{s}$.

i. We are assuming that the propagation delay is only distance; there are however multiple devices / servers on the way, which will raise the delay.

Lecture 11: 5g (NSA)

Date: Wednesday 20.04.22

Lecture slides

Background and Outlook

- Successor to LTE - not just for high-speed internet
- Massive Machine Type Communications, enhanced mobile broadband, ultra-reliable low-latency communication
- Growing need for broadband (exponential increase in traffic volume)
  - Increase in Fixed Wireless Access (FWA) traffic
- First specifications (release 15) in 2017

Frequency and Deployment

- Problems:
  - Higher frequency $\Rightarrow$ increased path/penetration loss
  - Wide channel $\Rightarrow$ higher capacity
  - Sub-1GHz to 3GHz already allocated
- Solutions
  - New frequency bands: $\approx$ 3.5GHz or $\approx$ 26GHz
- Frequency ranges: FR1 & FR2
  - Frequency range 1: 410MHz - 7.125GHz
  - FR2: 24GHz - 71GHz
- Goal: Standalone architecture, expensive
  - If operator already has 4G: *Non-Standalone Artitecture*
  - Which CN handles control plane?
  - Which RAN(s) handle user plane? Multiple RAN in parallel?
  - 3GPP standard has multiple deployment options

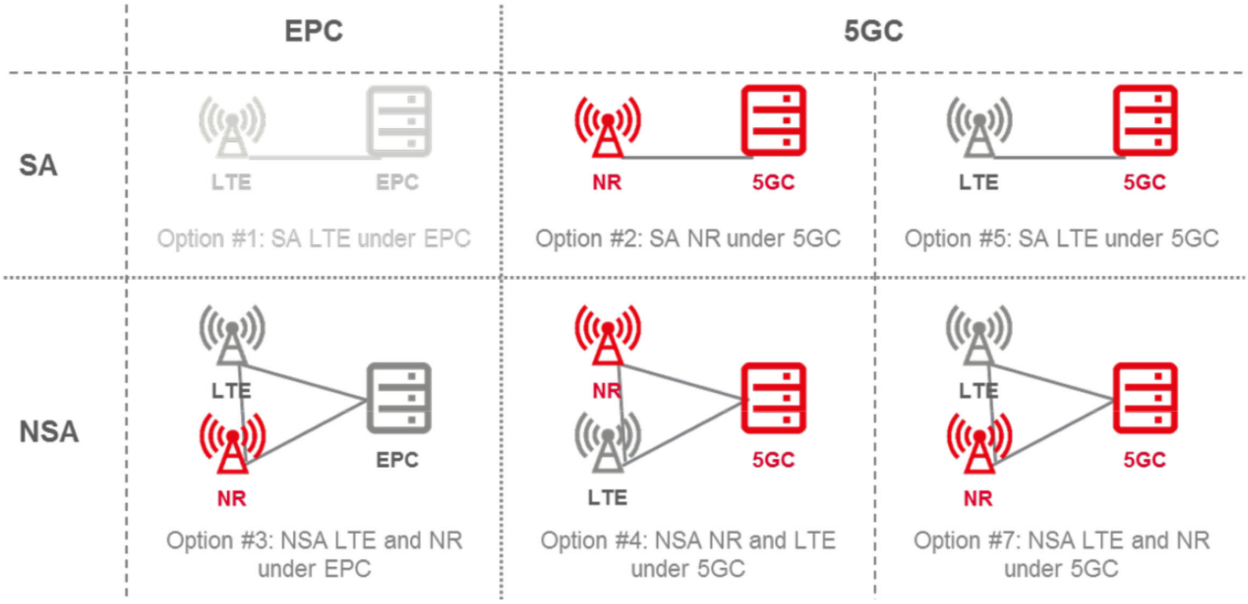

Figure 24: 5G Deployment Options

Option #3 is the most common in DK. Control traffic sent by LTE radio, traffic by 5G radio. With this architecture, all control information is sent over LTE radio. When the UE is attached (has IP, verified etc), traffic is sent by 5G radio. Independent scheduling in 4G and 5G radios.

5G New Radio

- Older generations: 2G: FDD only, 3G & 4G: FDD with TDD as option
- 5G: TDD in new bands(3.5GHz & 26GHz)
- 5G: Multiple use-cases $\Rightarrow$ more flexible radio interface required
- Subcarrier bandwidth: depends on numerology
- Advantage of higher numerology:
  - Shorter time to transmit symbol $\Rightarrow$ lower latency
- 5G NR Downlink:
  - 1 frame(10ms) = 10 subframes (1ms)
  - 1 physical resource lbock = 12 sub-carriers, 14 symbols
- Wider frequency bands for 5G:
  - (20MHz for LTE)
  - 100MHz for 5G @ 3.5GHz, 400MHz @ 26GHz
- $\Rightarrow$ Too many subcarriers if subcarrier $\approx$ 15 kHz
  - Complex implementation
- Wider subcarriers $\Rightarrow$ shorter T_{sym}
  - Problems with delay spread in large cells
  - May not be a problem since the range of increased frequency is heavily reduced

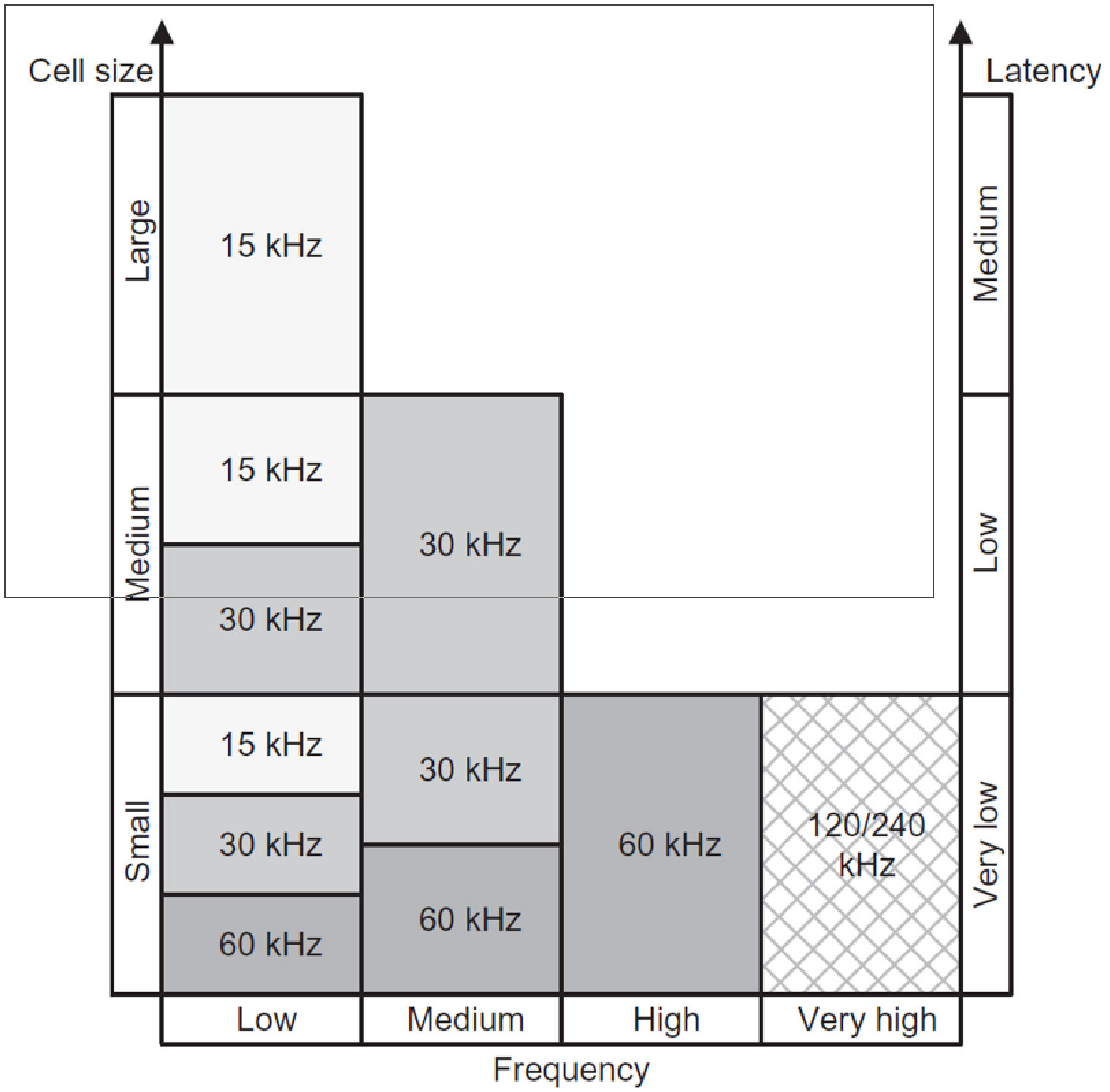

Figure 25: Subcarrier Spacing, Cell Size, and Latency

- Bandwidth part: defines a part of the frequency band (or the entire frequency band - UEs can switch between different (up to four) BWPs.
    - Option for reducing device energy consumption while sacrificing some capacity / bandwidth

Synchronization

- UEs must be synchronized with cell
    - Requires well-known synchronization signals and broadcast information (PBCH)

5G NR - TDD & FDD

- Asymmetrical DL/UL configuration
    - Required configuration for Danish operators
    - Special slots in time division can be used for either uplink or downlink, since internet traffic is mostly downlink
- LTE primarily uses FDD in sub-3GHz bands

- Long term: 5G should replace LTE ⇒ 5G should be able to use LTE's allocated FDD bands ⇒ need for FDD-mode for 5G
- How?
  - Switch entirely (refarming) - bad for subscribers without 5G
  - Share frequency bands between LTe and 5G - Dynamic Spectrum Sharing
- E.g. MBSFN: use part of LTe for broadcast - allocate some time slots

Active Antenna Systems and MIMO

- 2x2/4x4 MIMO not sufficient - need for 16x16, 64x64…
- Allows beamforming, single-user MIMO, multi-user MIMO
  - Multi-user MIMO: careful control of timing and beamforming allows the antenna to send to multiple users at the same time
- Because of difference in wave distribution based on frequency, beamforming etc. is easier with TDD.

5G EN-DC operation - Split Bearer

- EN-DC mode means "anchor at 4G - add capacity via 5G"
- Cell search + network attach in LTE
- Switch to RRC-Active mode ⇒ establish radio access bearer
  - User can now communicate via LTE
- if UE is 5G capable:
  - UE is instructed to measure on nearby gNB cells & return measurements
- If UE in range of gNB:
  - UE jumps to 5G
- Additional:
  - UE must be equipped with multiple transmitters
  - Only some combinations of LTE-band and 5G-band is permitted

Problems

Problem 1: Path Loss

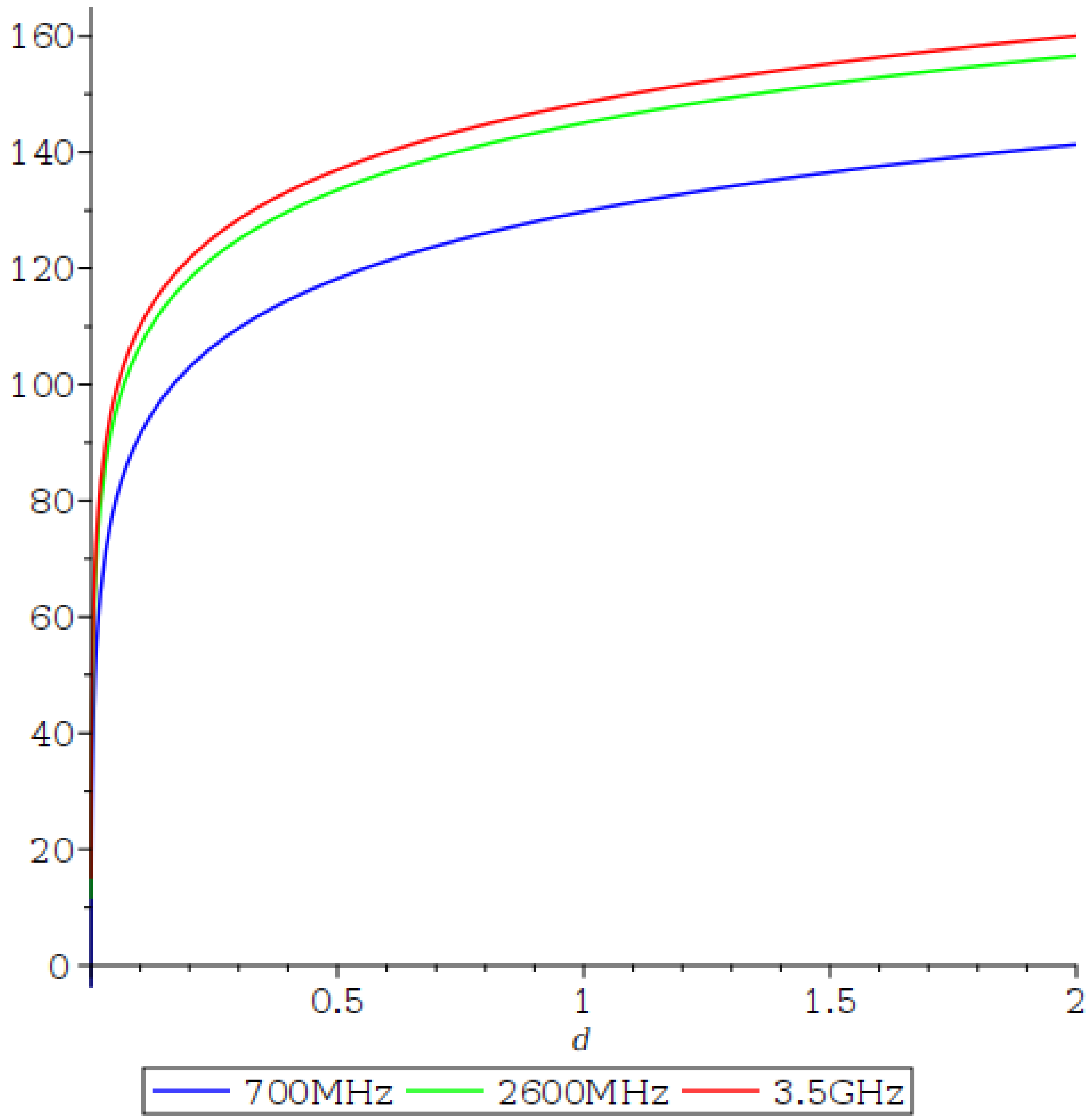

Figure 26: Path loss as a function of distance

$$L(700, 0.5) = 118.23$$
$$L(2600, 0.5) = 133.51$$
$$L(3600, 0.5) = 137.29$$

Problem 2: TDD vs FDD in 5G

With FDD, it is possible to do asymmetrical up-/downlink bands. Beamforming is also easier to implement with TDD.

Problem 3: TDD Configuration in 5G

Empty slots: timing advance necessitates the empty slots & when the mobile begins broadcasting, there is a short amount of time in which the antenna is not at full power.

256QAM $\Rightarrow$ 8 bit pr. symbol. DL: 3 slots @ 14 OFDM symbols: $3 \cdot 14 \cdot 8$. Also 1 slot with 10 symbols: $3 \cdot 10 \cdot 8$. All in all: $3 \cdot 14 \cdot 8 + 10 \cdot 8 = 416$ bit every 2.5 ms = $166 kbit/s$. 512 kbit/s uplink.

Problem 4: PBCH Capacity

The entire block is 20 PRB or 240 subcarriers. Sending on 4 slots is then $4 \cdot 240 = 960$. Added with PSS, this is $960 + 192 = 1152$. With QPSK, this is $2 \cdot 1152 = 2304$ bit per 0.5ms. This is then 4.6 mbit per second capacity in the physical broadcast channel.

Problem 5: EN-DC Operation

This method is used to increase capacity with 5G radio; it makes no sense to have the added capacity on a lower frequency. The control traffic (LTE) also has longer range on a lower frequency $\Rightarrow$ more reliable.

Week 12: 5G Mobile Networks Part II

Date: Wednesday 27.04.22

Lecture slides

EN-DC Split Carrier

E-UTRAN New Radio Dual Connectivity. “Anchor at 4G - Add capacity on 5G.” Detailed diagram on lecture slide 43.

EN-DC Connection

To add 5G: 4G base station identifies connected UE with 5G capability. UE measures individual beams and communicates to base station. Specific figure on lecture slides - this shows option 3x of the 5G deployment.

Since data is sent on separate networks and perhaps in a different order, packets are tagged with sequence numbers to order them.

EN-DC split-carrier tier-down

In some cases, it is necessary to shift down to 4G if 5G range is not large enough and the UE travels outside of given range.

Handover in Split-Bearer

Simplest handover: drop NR carrier -> LTE handover to new LTE cell -> adding NR carrier. Of course only 4G connectivity while this handover is in progress.

Dual handover: Independent handover for LTE and NR. Requires suitable cells in both technologies and X2 interface between eNB/gNB in two sites. First do a NR handover, then an LTE handover. 5G connectivity is preserved while handover is in progress.

5G SA Network Architecture

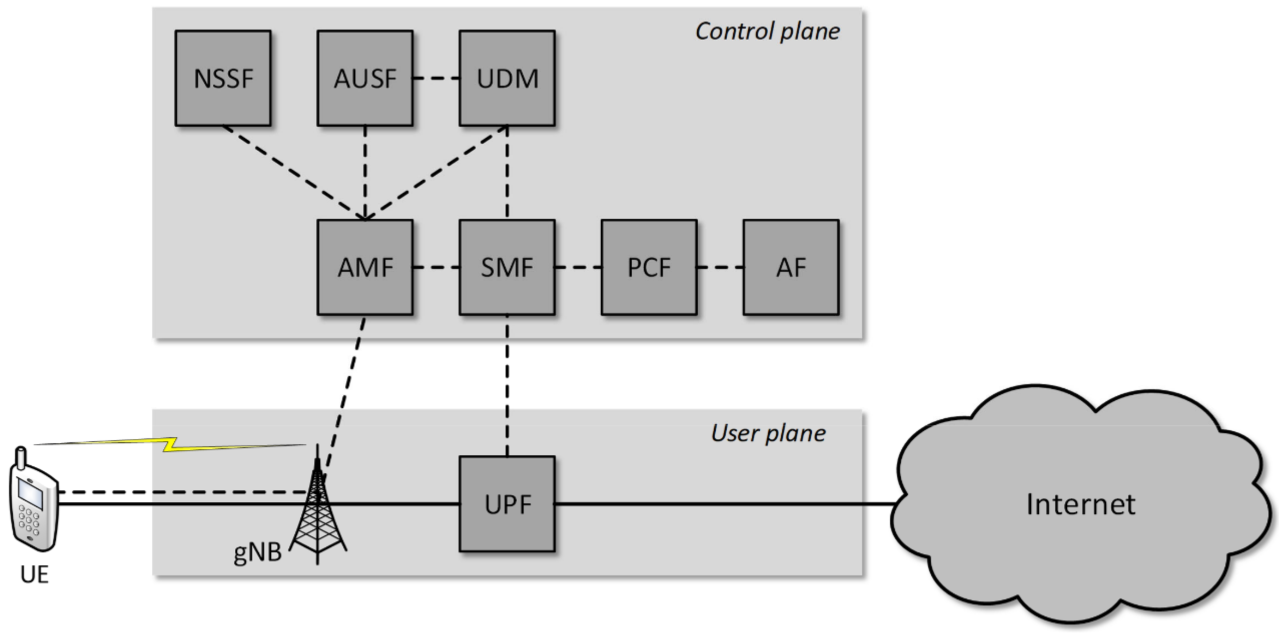

Figure 27: 5G Stand-Alone Network Architecture

- Action Management Function
- Service Management Function
- Policy control function
- UDM stores user data
- Authentication user service function
- Network slicing server function

Architecture defines network *functions* instead of network *devices*. The hardware is no longer in focus; this supports the virtualisation of the network functions.

- Stateless instead of stateful interaction between functions
  - Service user sends request with all necessary arguments to service provider
  - Service provider executes service and replies but does not store anything
  - Similar to RESTful web services

5G SA Procedures

Connection Management

Managing a logical signalling connection between UE and AMF. Used for auth, registration, area updating etc.

Registration

Registration request is sent to gNB. This is forwarded to an AMF, which does a challenge/response with the UE using Subscriber Permanent Identifier (SUPI, alternative to IMSI).

Session Mangement

- Establishing a session: configuring the core network to permit sending and receiving IP packets
- Assigning a local IP address to UE

Mobility Management

UE does measurement reports while connected. If one cell is better, the network can initiate a handover. The traffic is routed to the new gNB and through the old gNB through XN interface. New gNB asks for session modification, and resources are released on old gNB.

Tunnelling

- IP packets to/from E routed in backhaul using tunnelling. In case of handover:
  - UPF changes destination address in outer header for new gNB
  - No change in UE's IP address
  - No change in "inner" IP-packet

Tracking

- Instead of having area updating, we reuse the registration process.
- In registration, UE is informed of a set of TAI's
- If UE camps on cell with TAI not in set, perform registration procedure
- Set of TAI's may be UE specific

Security

- Mutual authentication of UE and network
- Encryption of traffic on radio interface.
- Transmission of IMSI in cleartext avoided
  - SUPI is sent as SUCI (*concealed* identifier)
- More secure roaming - foreign network receives SUPI, keys, ..., only *after* the home network is sure that the UE is really in the foreign network
- Additional authentication methods supported, e.g. EAP
  - Mostly relevant for private 5G networks
- Newer SIM cards include public IP of the operator - SUPI encrypted with public key

Telephony in 5G Mobile Networks

- 5G NSA: VoLTE capacity requirements small $\Rightarrow$ handled by 4G network
- 5G SA:
  - NR supports voice $\Rightarrow$ VoLTE over NR
  - Otherwise; fall-back to VoLTE over LTE

Network Slicing & Cloud RANs

Slicing

Network slicing: a logical slicing of a network instead of physical division.

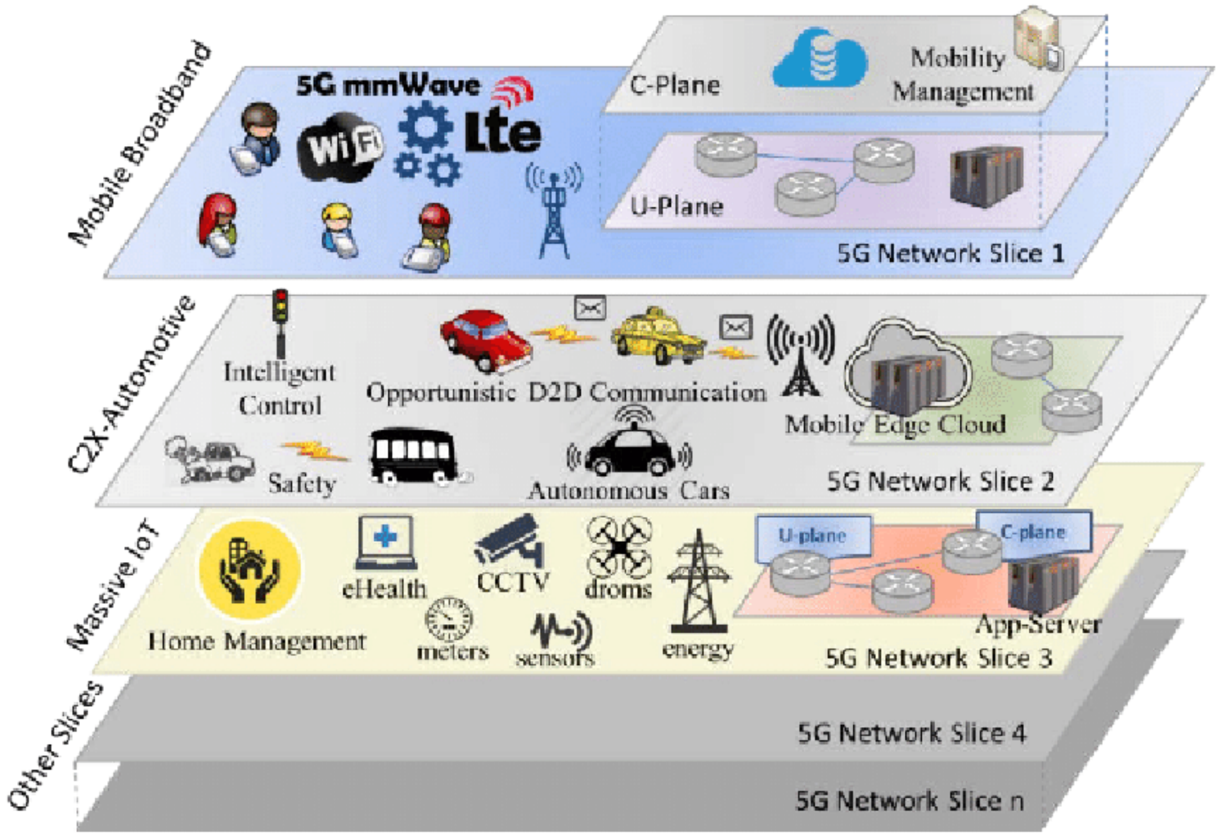

Figure 28: 5G Network Slicing

- UE perspective:
  - Grouping similar devices into a slice, e.g smart phones, sensors
- Network perspective
  - Partitioning physical resources into logically isolated virtual networks
- Requirements
  - Slices are independent, e.g. traffic overload in one slice does not affect other slices
  - Different slices can use different network functions
  - Slices can be created dynamically (if available physical network resources)

Cloud RAN's

Instead of expensive and large electronics at the base of antennas, move the actual electronics closer to the antenna. The base-band units are, however, mostly software $\Rightarrow$ create BBU pool elsewhere.

Pros & cons:

- Load sharing
- Inter-cell coordination
- Fronthail network: transports I- and Q- samples directly $\Rightarrow$ very tight timing requirements
  - Simpler with direct optical link
  - Harder with switched transport network
    - TSN - Time Sensitive Network extensions to Ethernet

Exercises

Problem 1: EN-DC Split Carrier

Since only 3x routes the traffic through the NR, only this has to reconfigure the core network in order to resume traffic.

In case 3: change the core network after 4G handover is completed. In case 3x, core reconfiguration is done after 5G handover.

Problem 2: 5G SA Reference Architecture

There are no benefits of having both: they both just forward IP packets to the user. May have been a good idea once, but networking has gotten more powerful since.

UDM in 5G is equivalent to the HSS (Home Subscriber Server) in 4G.

Problem 3: RRC and CM States in 5G SA

UE has an existing connection - UE and tower are aware of each other. Signalling messages can however not be sent. To establish signalling, only one resource (radio) must be allocated. Useful e.g. when the device's apps send pings.

Problem 4: Handover

a) Informs the old gNB that it does not have to expect more packets and the new gNB that it no longer has to expect packages from the old gNB.

b) With no tunnelling, handovers could be solved by updating all routing tables in the core network.

Problem 5: Tracking Areas in 5G SA

By guessing mobility patterns of specific users, the area updating can be simplified. This reduces the amount of re-registration required.

Problem 6: MNVO's

Slicing is both separating the network and assigning resources, so an MVNO would just be creating more slices in the network.