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Lecture 5: Evolved Radio Access Networks

ELEC-E7230 Mobile Communications Systems

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Outline

- Background
  - Motivation, requirements, RAN architectu
- Long-Term Evolution (LTE) Release 8
  - LTE downlink and uplink PHY
  - LTE radio protocols and channels
  - LTE Radio Resource Management
- LTE-Advanced (LTE-A) Release 10/11
  - LTE-Advanced carrier aggregation
  - LTE-A relaying
  - CoMP and extended MIMO
- LTE-A (Release 12)
  - Small cell and femtocell enhancements
  - Proximity services
  - FDD-TDD Carrier Aggregation
- LTE-A Pro (Release 13/14)

LTE/LTE-Advanced Standardisation

Release	Rel.8	Rel.9	Rel.10	Rel.11	Rel.12	Rel.13	Rel. 14
Freeze date	3/2009	3/2010	9/2010	3/2011	3/2015	3/2016	06/2017
Comment	First LTE		LTE-A			LTE-A Pro →	

- 3GPP = Third Generation Partnership Project
- Standards delivered in rolling versions or ***Releases***
- After "freezing", a Release no further functions can be added
- In this lecture's LTE-Advanced and LTE-Advanced Pro discussions follows Rel.10-14.

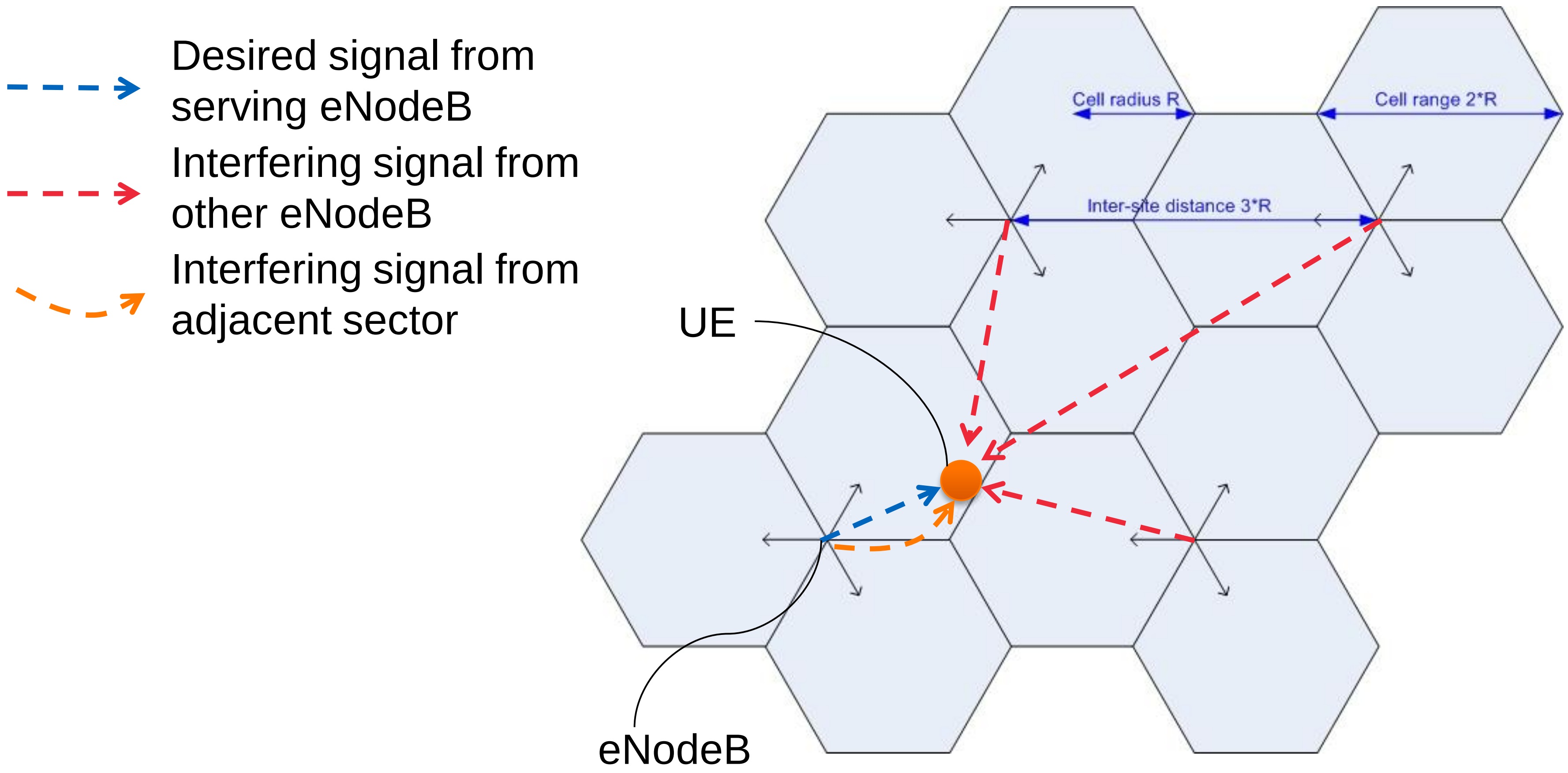
LTE Performance Aspects

KPIs Background

- Signal to Interference and Noise Ratio (SINR)
  - Ratio or power of desired signal to total interference and thermal noise

- Throughput (TP)
  - Data transferred (bits per second)

Interference in LTE, illustration



Mapping between SINR and throughput

- SINR determines the Modulation and Coding Scheme (MCS) that is usable for particular link

Table 7.1 Lookup table for mapping SINR estimate to modulation scheme and coding rate

CQI index	Modulation	Coding rate	Spectral efficiency (bps/Hz)	SINR estimate (dB)
1	QPSK	0.0762	0.1523	−6.7
2	QPSK	0.1172	0.2344	−4.7
3	QPSK	0.1885	0.3770	−2.3
4	QPSK	0.3008	0.6016	0.2
5	QPSK	0.4385	0.8770	2.4
6	QPSK	0.5879	1.1758	4.3
7	16QAM	0.3691	1.4766	5.9
8	16QAM	0.4785	1.9141	8.1
9	16QAM	0.6016	2.4063	10.3
10	64QAM	0.4551	2.7305	11.7
11	64QAM	0.5537	3.3223	14.1
12	64QAM	0.6504	3.9023	16.3
13	64QAM	0.7539	4.5234	18.7
14	64QAM	0.8525	5.1152	21.0
15	64QAM	0.9258	5.5547	22.7

Source: Understanding LTE with Matlab, H. Zarrinkoub

Mapping between SINR and throughput

- Modified Shannon formula for mapping SINR to throughput (TP)
  - BW = Bandwidth allocated to UE (in Hz)
  - SINR (in linear scale, not dB) and TP in bps
  - BW_{eff} = Effective bandwith to account for overheads of cyclic prefix, reference signals, practical filter implementations
  - $SINR_{eff}$ = adjusts SINR for practical implementation inefficiencies etc.
  - Correction factors BW_{eff} and $SINR_{eff}$ are obtained from link-level simulations
  - BW_{PRB} = Bandwidth of one PRB (180 KHz)
  - N_{PRB} = Number of PRBs allocated to UE (scheduling)
  - SE = spectral efficiency (bps/Hz)

$$TP = BW \cdot BW_{eff} \cdot \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right)$$

$$TP = \underbrace{N_{PRB} \cdot BW_{PRB}}_{BW} \cdot \underbrace{BW_{eff} \cdot \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right)}_{SE}$$

$$TP = N_{PRB} \cdot BW_{PRB} \cdot SE$$

Part I:
LTE-Advanced Rel. 10/11

Realised LTE peak rates and LTE-Advanced performance requirements

- Recall the realized LTE Rel.8 peak rates:
  - In downlink 150 Mbps can be achieved on 20 MHz bandwidth with 2x2 MIMO 300 Mbps can be achieved on 20MHz band if 4x4 MIMO is used.
  - In uplink 75 Mbps can be reached in LTE Rel.8 with single transmit antenna in UE.
- LTE-Advanced targets
  - 1 Gbps with 4x4 MIMO in downlink and 500 Mbps in uplink
  - Note the large improvement target in UL peak rate due to demands from services with higher uplink demands (e.g. user generated content like video streaming)

LTE-Advanced Requirements

- LTE-Advanced was decided to be an *evolution of LTE*.
  - That is, *LTE-Advanced is backwards compatible with LTE Release 8*:
    - LTE Release 8 terminals can work in a LTE-Advanced network
    - LTE-Advanced terminals can work in a LTE Release 8 network

- More homogeneous distribution of the user experience over the coverage area.

- Low power consumption aimed in both eNodeB's and UE's
  - Note that LTE Rel.8/9 focused on UE power consumption
  - With more denser eNodeB deployment with some possibly working off-grid, eNodeB energy efficiency also critical

LTE-Advanced enhancements

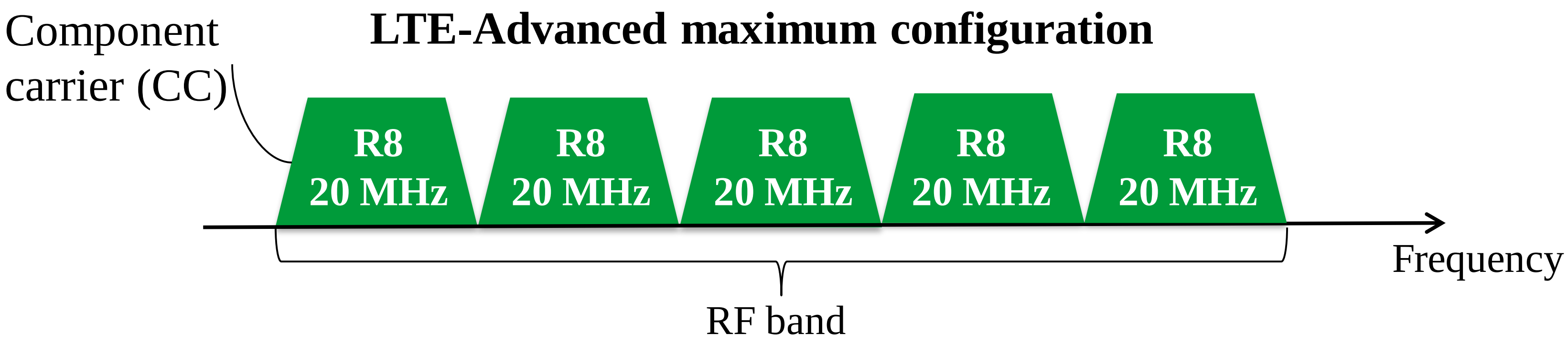
- A number of LTE-Advanced enhancements were the proposed (3GPP Rel. 10/11) to address those requirements
  - **LTE-Advanced carrier aggregation**
  - LTE-A relaying
  - CoMP
  - Extended MIMO

1- LTE-Advanced Carrier Aggregation (Rel.10/11)

Principles of Carrier Aggregation

Principle

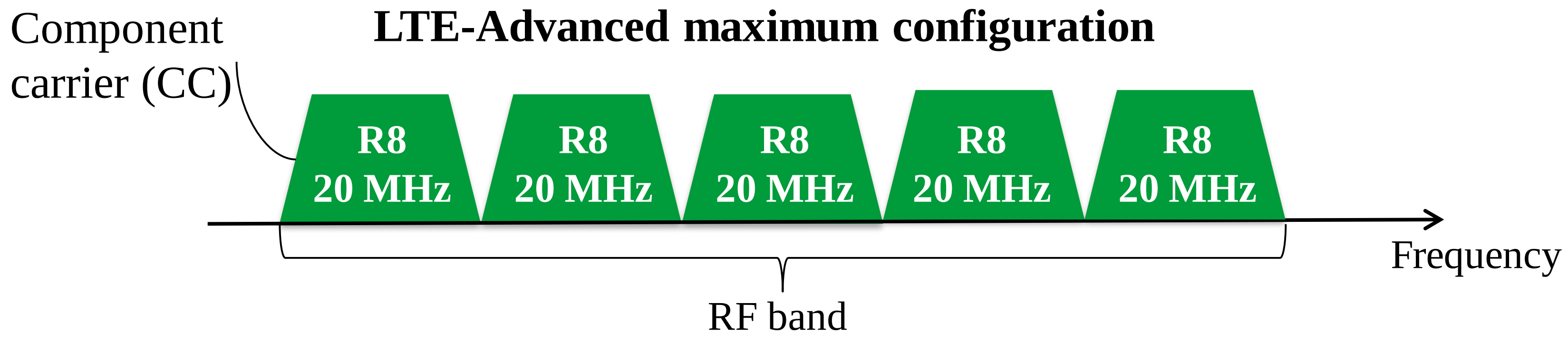
- The LTE-Advanced target peak data rate of 1 Gbps in downlink and 500 Mbps in uplink can be achieved with bandwidth extension from 20 MHz **up to 100 MHz**.
- In LTE-Advanced this extension is achieved through **carrier aggregation**
- By combining N LTE Release 8 **Component Carriers** (CC) together to form N x LTE bandwidth → up to 5 x 20 MHz = 100 MHz operation bandwidth could be obtained



Principle

$$TP = N_{PRB} \cdot BW_{PRB} \cdot BW_{eff} \cdot \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right)$$

Bandwidth (B)	1.4MHz	3 MHz	5MHz	10MHz	15MHz	20MHz
Resource Blocks (N_{prb})	6	15	25	50	75	100



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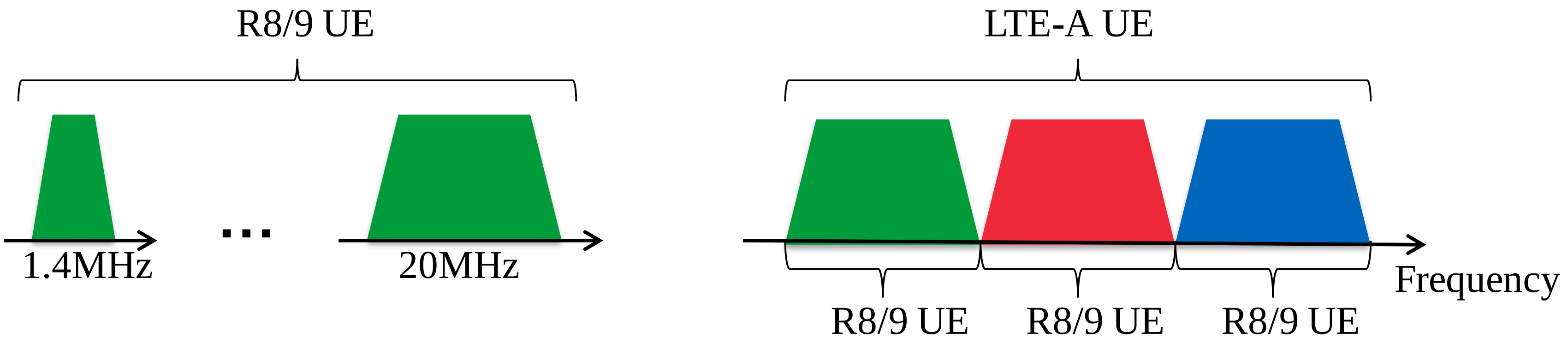
Backward compatibility with Rel.8/9

- LTE Rel.8/9 terminals can receive/transmit *only one component carrier*
- LTE-Advanced terminals may receive/transmit on *multiple component carriers (CCs) simultaneously* to reach higher data rates.



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Example LTE Rel. 8/9 frequency bands

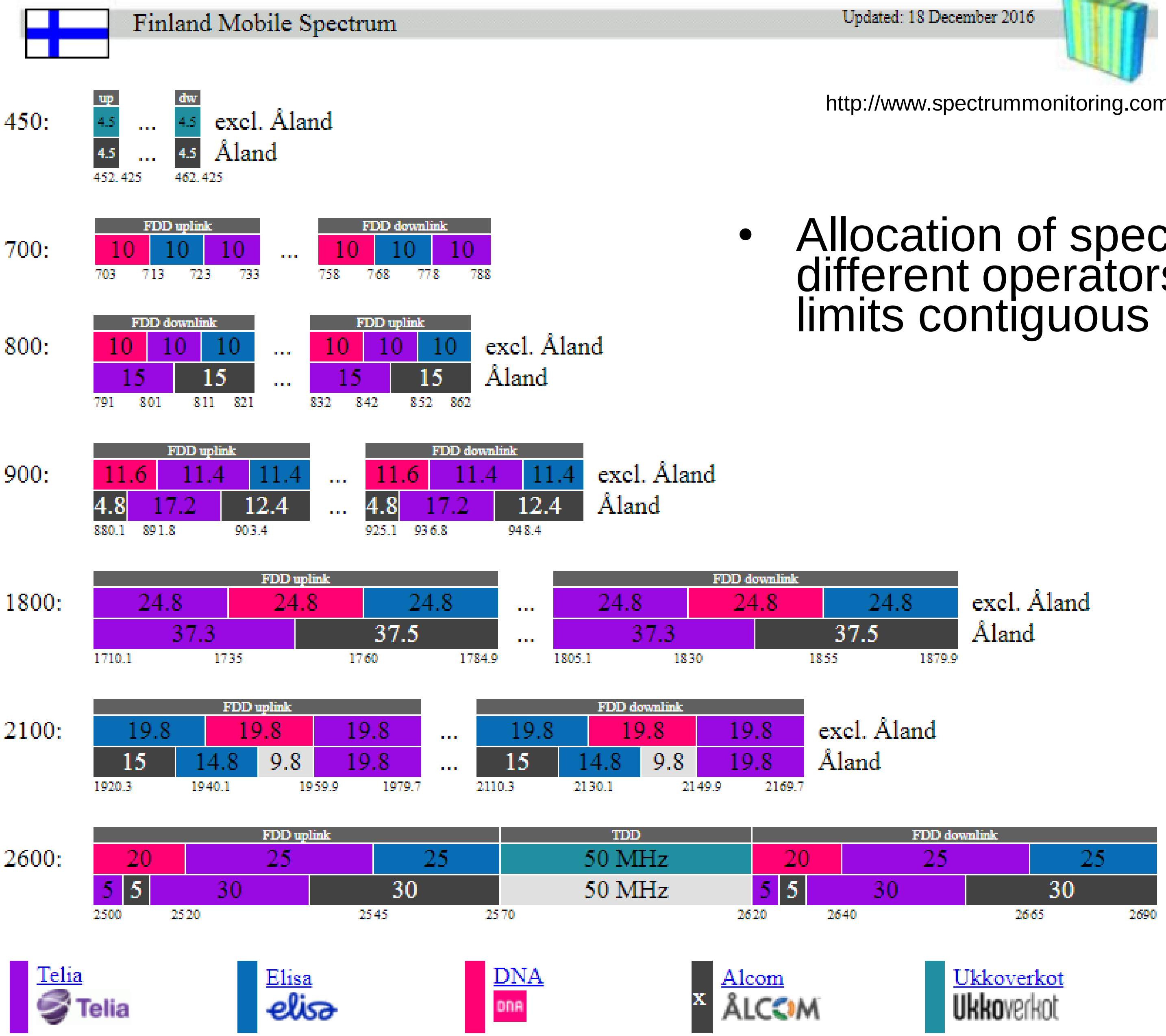
– Note below no contiguous allocation of 100 MHz in LTE frequency bands

Band	Uplink (MHz)	Downlink (MHz)	Region
1	1920 - 1980	2110 - 2170	Europe, Asia
3	1710 - 1785	1805 - 1880	Europe, Asia, Americas
5	824 - 849	869 - 894	Americas, Korea,
7	2500 - 2570	2620 - 2690	Europe, Asia, Canada, Korea
8	880 - 915	925 - 960	Europe. Japan, Latin America
13	777 - 787	746 - 756	Americas, Verizon

For more, see:

http://www.etsi.org/deliver/etsi_ts/136100_136199/136104/11.02.00_60/ts_136104v110200p.pdf

Example band allocation (Finland)



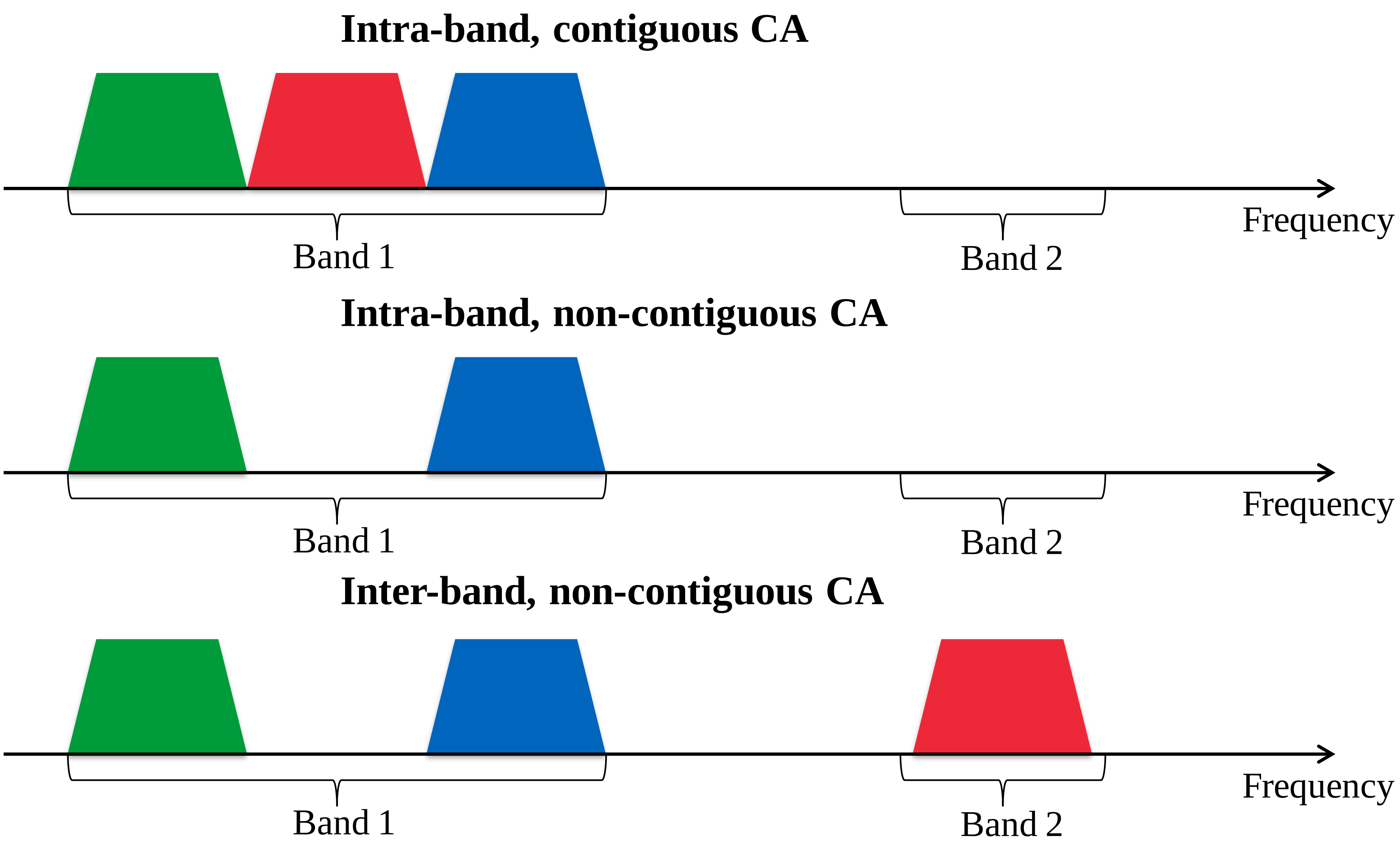
http://www.spectrummonitoring.com/frequencies/#Finland

- Allocation of spectrum to different operators further limits contiguous bands!

Contiguous vs non-contiguous CA

- In practice it seems that in the low frequency band (< 4 GHz) it will be difficult to allocate continuous 100 MHz bandwidth for a mobile network.
- ***The non-contiguous CA*** *technique provides a practical approach to enable mobile network operators to fully utilize their current spectrum resources*
  - Thus, to use also currently unused scattered frequency bands and those already allocated for some legacy systems, such as GSM and 3G systems.

Carrier Aggregation types



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UE categories for CA

- 3GPP specifies UE categories for placing devices into specific segments according to combined DL and UL capabilities (MIMO, modulation level, CA etc.), as shown in example table below.

UE Category	Carrier Aggregation	MIMO	DL Peak Rate	Commercial Availability
Category 4	10 + 10 MHz DL 10 MHz UL	2 x 2	150 Mbps	2013
Category 6	20 + 20 MHz DL 20 MHz UL	2 x 2	300 Mbps	2014
Category 9	20 + 20 +20 MHz DL 20 MHz UL	2 x 2	250 Mbps	2015
Category 11/12	4 × 20 MHz DL 20 + 20 MHz UL	2 x 2	600 Mbps	2016

UE Categories (as of 07/2020)

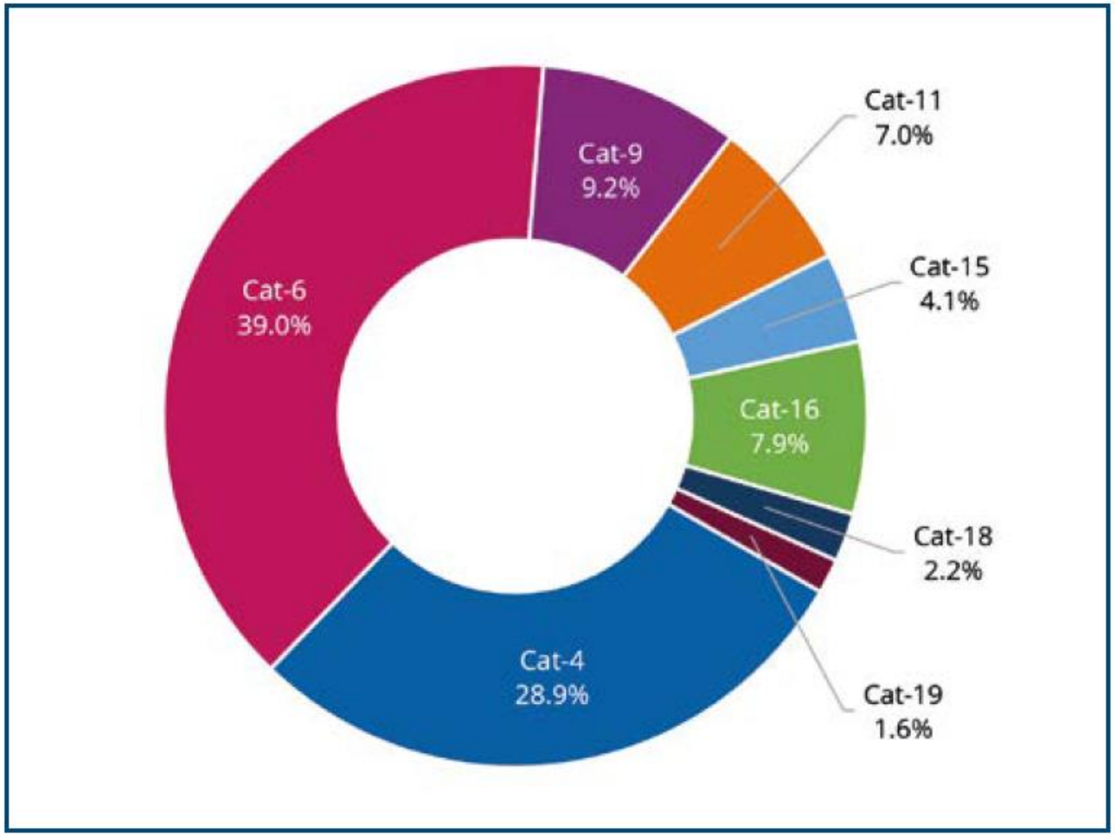
- Higher UE category devices still a small fraction of all LTE devices
- 54% of LTE devices (9080 devices) support speeds up to Category 4
- 11% of LTE devices (1,778 devices) can support up to Category 6

Source: GSA Report LTE Ecosystem Report,:Status Update , 07/2020

Apple iPhone X
(UE category 12)

CA network status (as 05/2020)

Figure 3: Distribution of LTE-Advanced networks by UE category (base: 315 networks)



Source: Gigabit LTE Networks: Analysis of Developments Worldwide, 05/2020

Primary and secondary Component Carriers

Primary and secondary CC

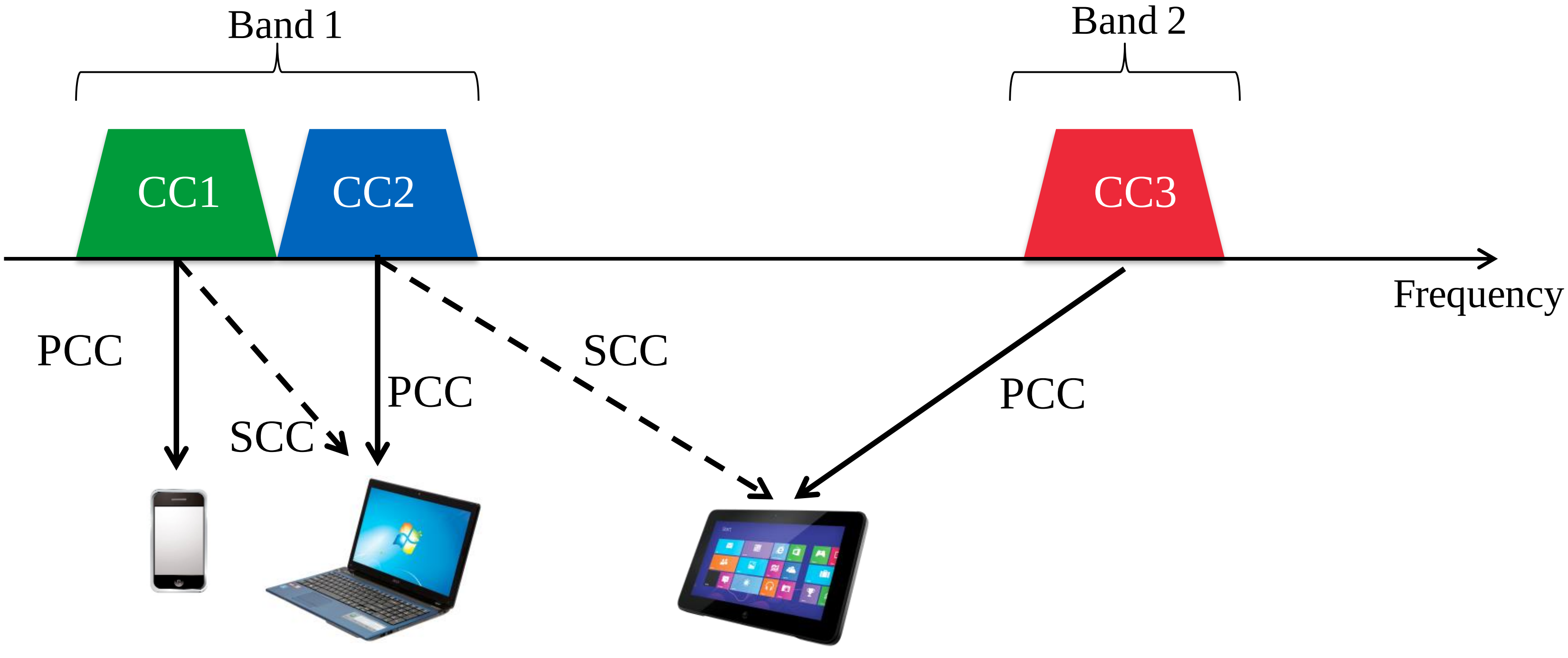
- When UE first establishes connection with eNodeB, only one CC is attached for downlink and uplink directions.
- Corresponding CCs are known as *primary CCs* (PCCs) for both downlink and uplink, and the related cell is the *primary serving cell* (PCell).
- Based on the traffic load and QoS requirements, UE can be attached with additional one (or more) CC, known as *secondary* CC (SCC) which correspond to the *secondary serving cell* (SCell).

Primary and secondary CC

- The PCC serves as an anchor CC for the user and it is used for basic connectivity functionalities
- The SCCs carry only user data and dedicated signaling information
  - PDSCH (physical DL shared channel), PUSCH (physical UL shared channel), and PDCCH (physical DL control channel)
- Since user connection greatly depends on PCC, it should be robust in both downlink and uplink
  - PCC should be selected such that it provides ubiquitous coverage and best overall signal quality (best CQI)
- When UE is moving within the eNodeB service area the PCC may be changed
  - CC with best signal quality
  - Load balancing carried out between CCs

Primary and secondary CC

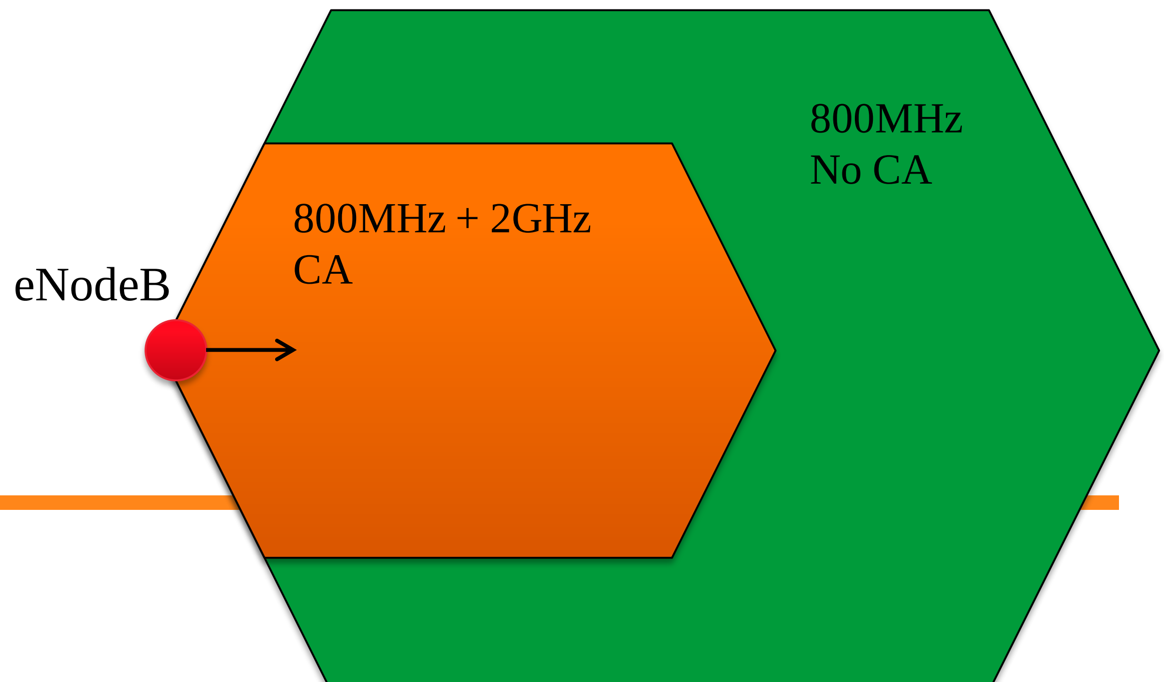
- The PCC/SCC configuration is UE-specific and can be different for different UEs served by the same eNodeB.



Interesting CA deployment scenarios

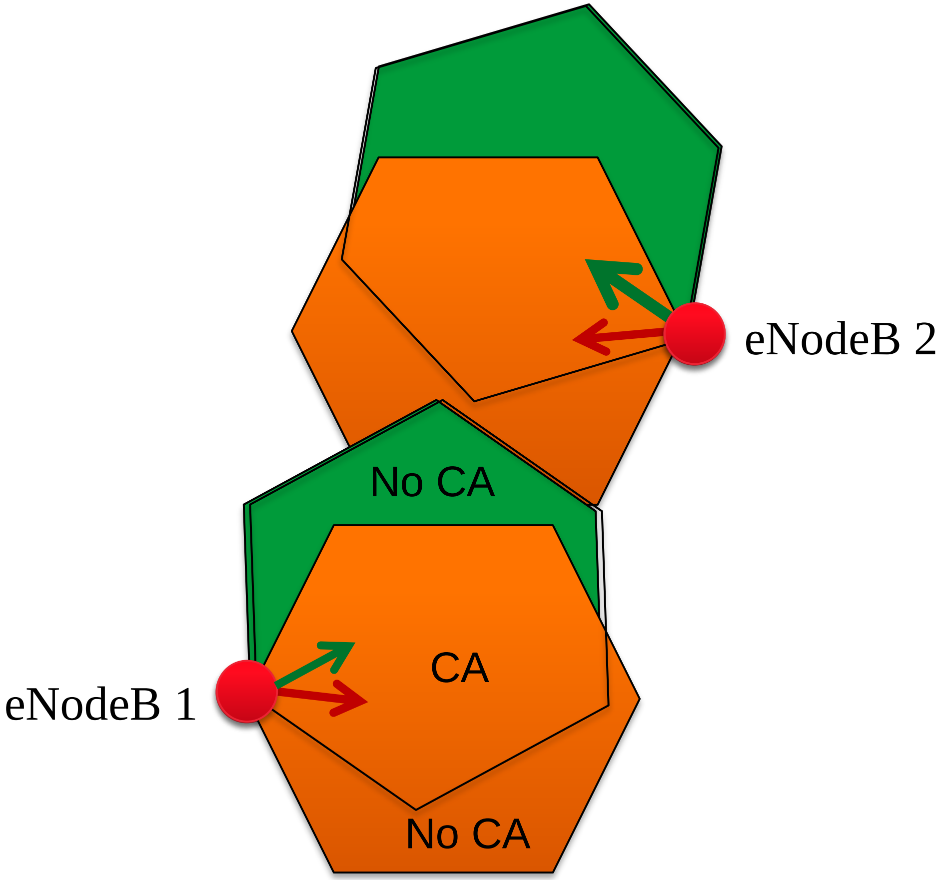
Interesting CA deployment scenarios

- Coverage areas of inter-band non-contiguous component carriers usually different
- Example 1: Large frequency separation between CCs
  – Interesting CA scenario occurs when operator uses non-contiguous interband CA e.g. 2GHz and 800MHz bands for LTE
  – CA not utilised in areas where CC bands coverage do not overlap



Interesting CA deployment scenarios

- Example 2: Antenna azimuth (directions) are not the same for all CCs to reduce interference with neighbouring cell



2. LTE-Advanced Relaying (Rel. 10)

Why relays for LTE?

Recall some key requirements for LTE-Advanced

- 1 Gbps on the downlink and 500 Mbps on the uplink.
- Higher peak and average spectral efficiencies than in LTE Rel'8.
- More homogeneous distribution of the user experience over the coverage area.

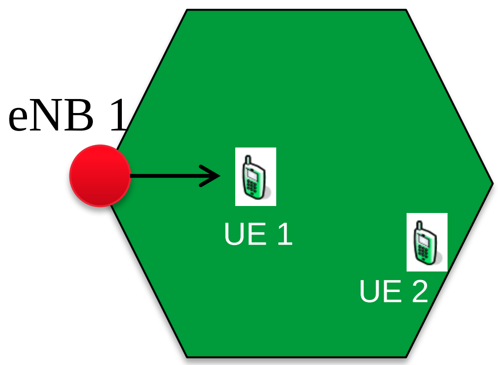
Performance limitations at the cell edge

- Cell edge users have low received signal strength

$$TP = N_{PRB} \cdot BW_{PRB} \cdot BW_{eff} \cdot \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right)$$

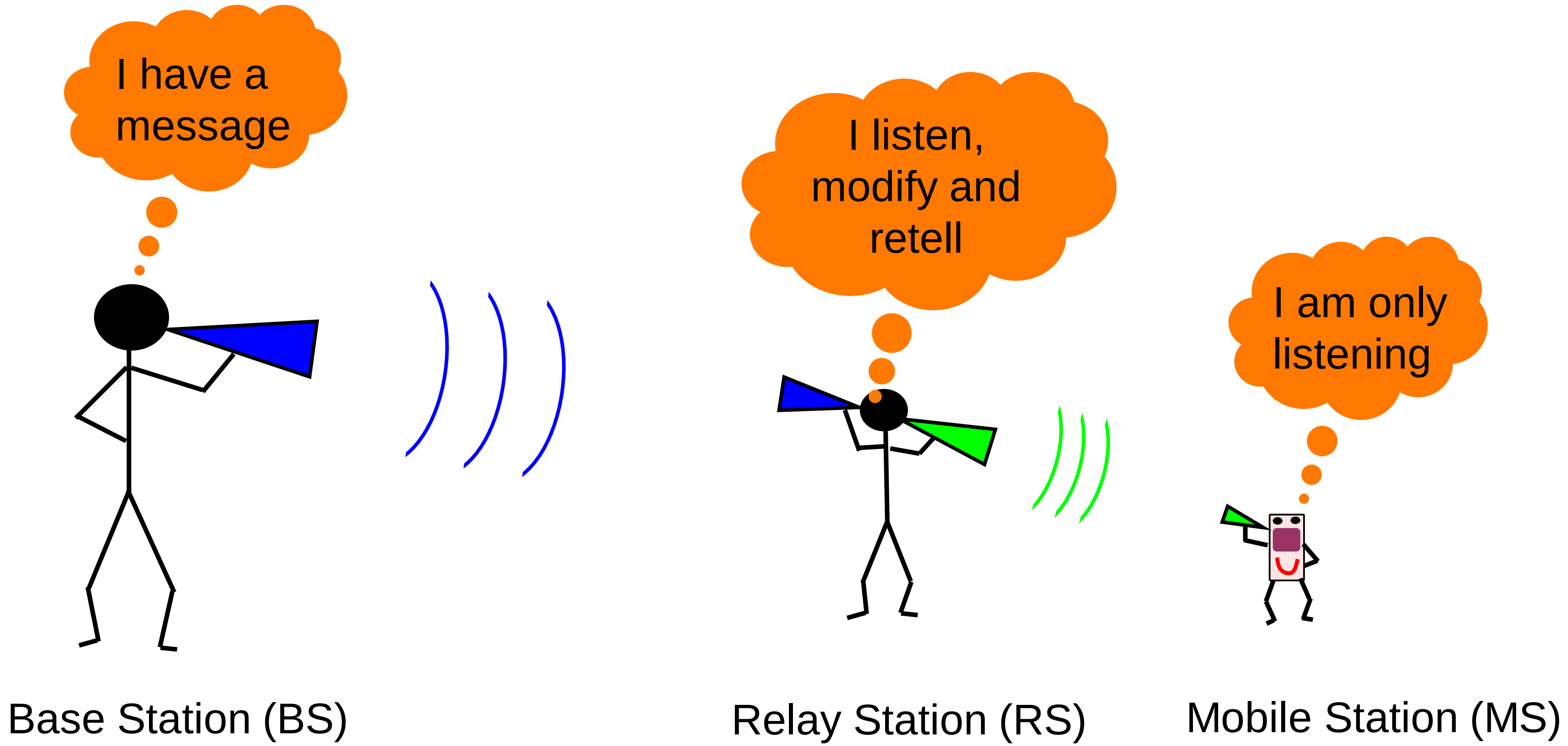
UE 1 in cell center
- Strong signal from serving BS (eNB1)

UE 2 at cell edge
- Weak signal from serving BS (eNB1)



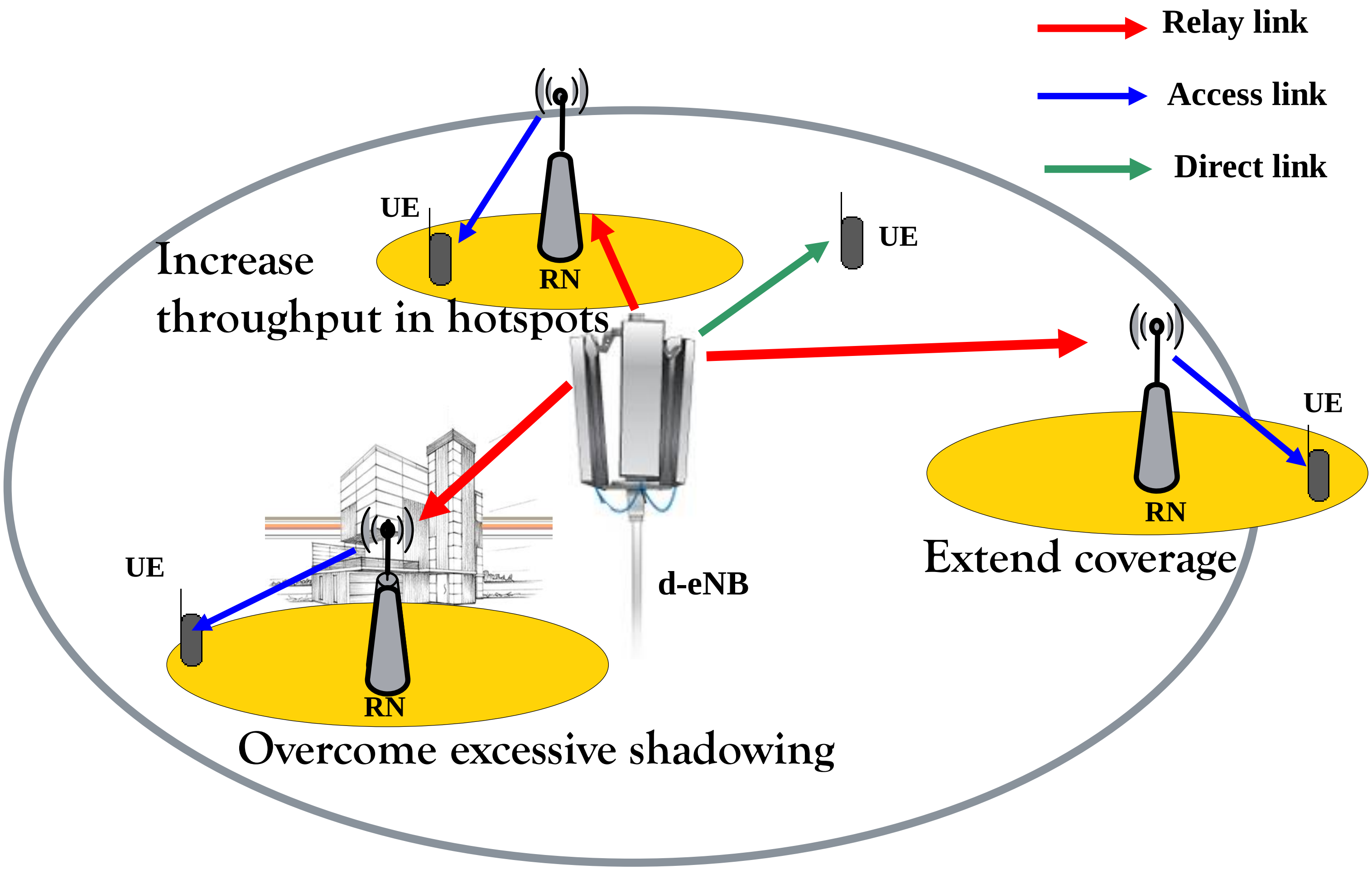
Repeaters (amplify and forward relays) are well known and used in 2-3G networks.

Wireless relay: Principle



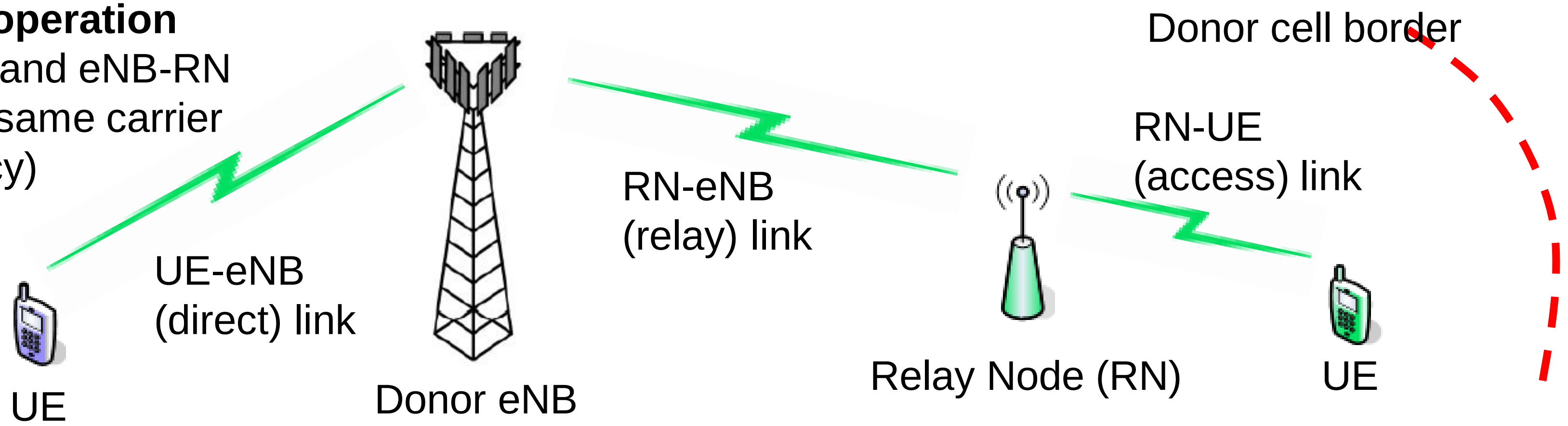
The rest of this lectures considers mainly relays that detect, encode and retransmit (decode and forward) a signal between base station and terminal

Benefits from relaying

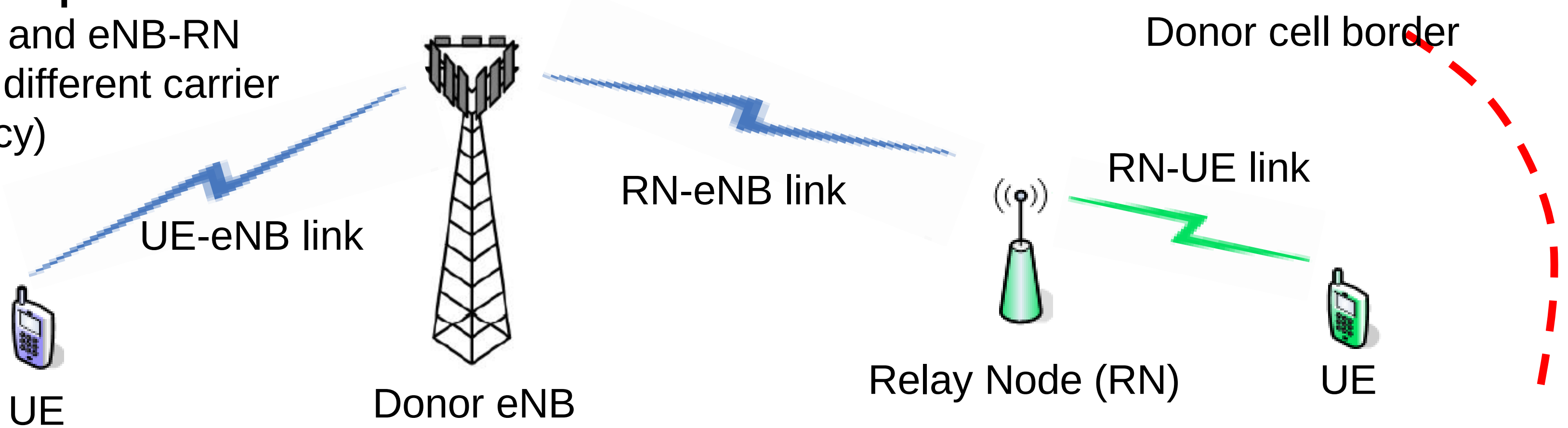


Inband operation/outband operation

Inband operation
(RN-UE and eNB-RN links on same carrier frequency)



Outband operation
(RN-UE and eNB-RN links on different carrier frequency)



3. Coordinated Multipoint (CoMP) Transmission and Receiption (Rel. 10)

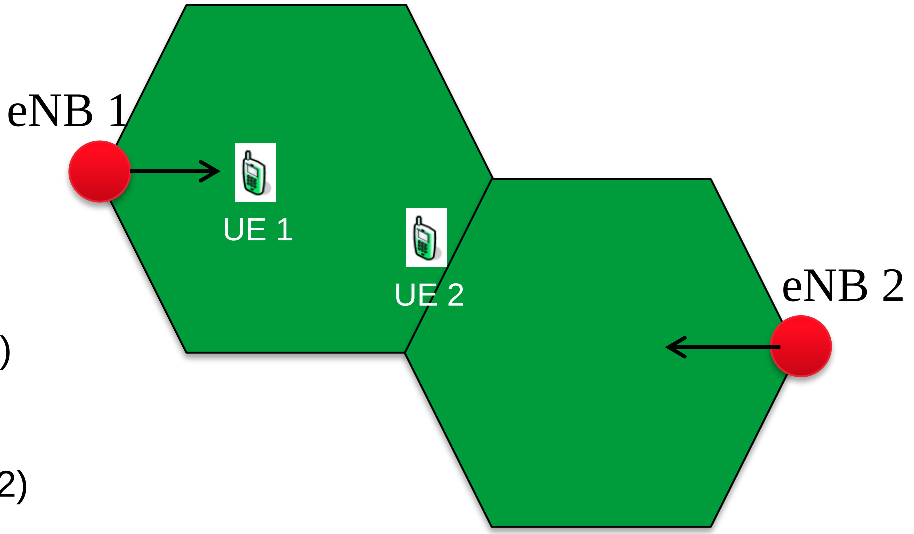
Idea of CoMP

- CoMP targets performance improvements through reduction in intercell interference
  - Increased SINR

$$TP = N_{PRB} \cdot BW_{PRB} \cdot BW_{eff} \cdot \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right)$$

Idea of CoMP

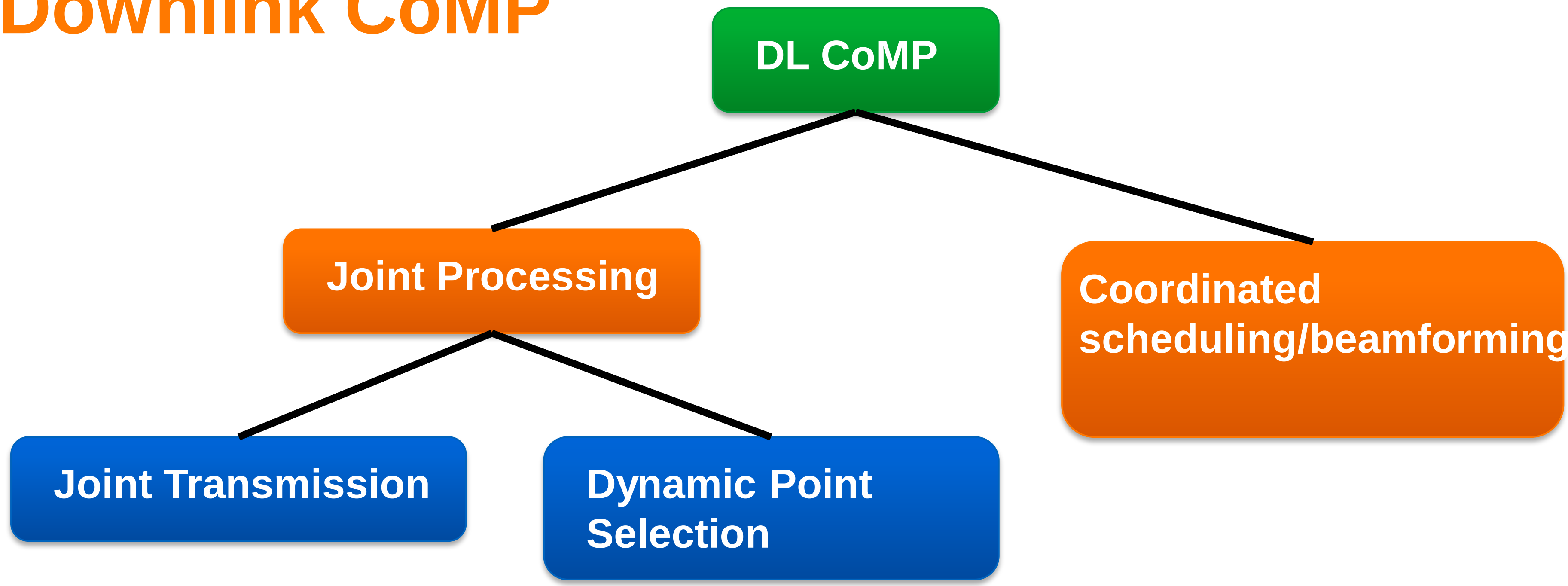
- Cell edge user typically suffer the most from inter-cell interference.
  - *Downlink*: Inter-cell interference occurs due to parallel transmissions from adjacent base stations
  - *Uplink*: Intercell interference occurs due to simultaneous transmission (on the same time-frequency blocks) by users in adjacent cells.
- The goal of the CoMP is to further minimize inter-cell interference for adjacent cells that are operating on the same frequency



UE 1 in cell center
- Strong signal from serving BS (eNB1), weak interferer (eNB2)

UE 2 at cell edge
- Weak signal from serving BS (eNB1), strong interferer (eNB2)

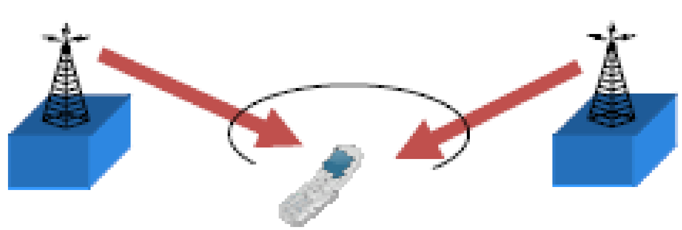
Downlink CoMP



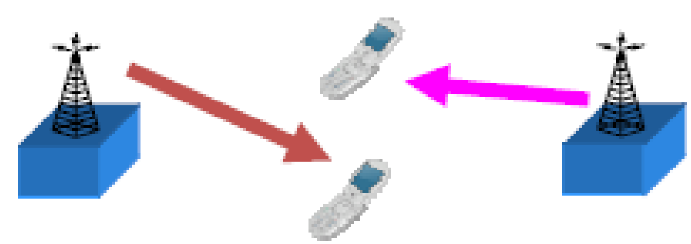
Joint Transmission (JT): Transmission executed from multiple points at a time
Dynamic Point Selection (DPS): Transmission executed from one point at a time. Also known as dynamic cell selection

Coordinated scheduling/beamforming: Data to a UE is transmitted from one transmission point. The scheduling decisions as well as transmission beams are coordinated to control the interference

Coherent combining or dynamic cell selection



Joint transmission/dynamic cell selection



Coordinated scheduling/beamforming

Downlink CoMP

- ***Joint processing schemes for transmitting in the downlink:***
  - ☺ Improve the received signal quality and strength.
  - ☺ Actively cancel the interference from transmissions that are intended for other UEs.
  - ☹ This form of CoMP places a high demand onto the backhaul network because the copies of same data need to be sent to each transmission point that will be transmitting it to the UE.
- ***Coordinated scheduling and or beamforming :***
  - ☺ Backhaul requirements are reduced since only scheduling decisions and details of beams needs to be coordinated between multiple transmission points
  - 😐Relatively lower SINR gains compared to joint processing schemes (particularly on cell edge)

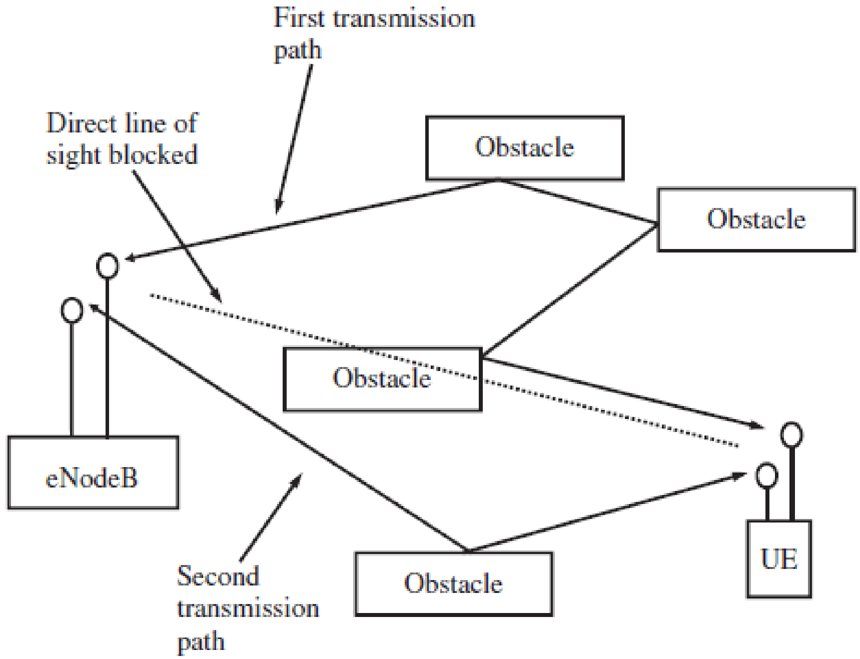
Joint transmission/dynamic cell selection

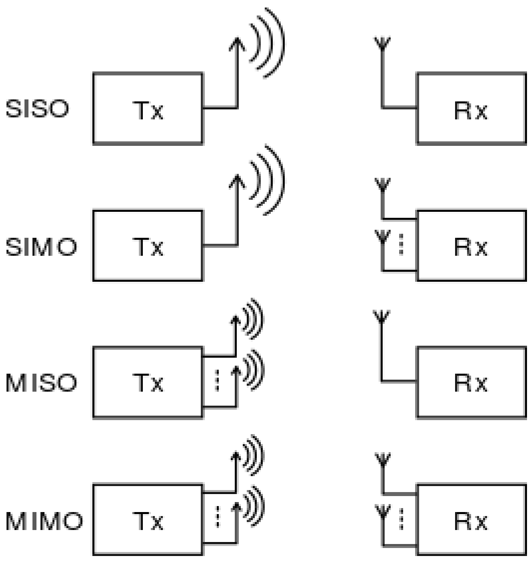
Coordinated scheduling/beamforming

3.4 LTE-Advanced (Rel. 10) extended Multiple Input Multiple Output (MIMO)

Benefits of multi-antenna techniques

- Multiple antennas at the transmitter and/or the receiver may achieve different aims:
  - Provide additional diversity against fading on the radio channel
  - Can be used to "shape" the antenna beam (beamforming) in a certain way e.g. to maximize the overall antenna gain in the direction of the target receiver or transmitter
  - Spatial multiplexing by enabling transport multiple data streams within the same limited channel bandwidth





Source: M. Sauter, From GSM to LTE ..

Performance Improvements

- BW_{eff} and $SINR_{eff}$ are factors that are selected such that SE approximates the LTE link spectral efficiency.
- Factors BW_{eff} and $SINR_{eff}$ depend on the number of antennas and physical layer performance.
- M = number of data streams

$$TP = M \cdot N_{PRB} \cdot BW_{PRB} \cdot BW_{eff} \cdot \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right)$$

MIMO	M	BW_{eff}	$SINR_{eff}$
SIMO 1x2	1	0.62	1.8
MIMO 2x2	2	0.42	0.85
MIMO 4x4	4	0.40	1.1
MIMO 8x8	8	0.33	1.4

Downlink MIMO

- Downlink MIMO schemes are extended/enhanced from Rel.8 LTE
  - Support for up to 8 TX antennas, (instead of 4TX supported by LTE Rel. 8).
  - Roughly equivalent to doubling the spectral efficiency

		LTE Rel.8	LTE-A target
Peak data rate	DL	300 Mbps (4x4 MIMO, 20 MHz)	1 Gbps (8x8 MIMO, 20 + 20 MHz)
Peak spectral efficiency	DL	15 bps/Hz	30 bps/Hz

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Part II:
LTE-A (Rel. 12) and LTE-A Pro (Rel. 13-14) Enhancements

3GPP Release 12-14 Requirements

- Requirements/motivations for release 12 enhancements
  - Increase capacity
  - Enhance coverage
  - Improve coordination (between cells)
  - Reduce cost

- Requirements/motivations for Rel. 13
  - Continue/complete developments of enhancements introduced in LTE-Advanced Release 12
  - Enhance interworking with Wi-Fi
  - **Enhance network for IoT**

- Requirements/motivation for Rel. 14
  - Improvement to LTE efficiency
  - Enhanced utilization of unlicensed bands
  - **Specify enablers of new services / verticals**

Source: Nokia

Selected LTE-A/Pro Rel. 12-14 enhancements considered in the lecture

- LTE-Advanced Release 12
  - Frequency Division DuplexTime Division Duplex Carrier Aggregation (FDD-TDD CA)
  - Small cell and femtocell enhancements
  - Proximity Service (ProSe)

- LTE-Advanced Release 13
  - Licensed Assisted Access (LAA) Using LTE
  - Carrier Aggregation (CA) Enhancements
  - LTE-Wireless Local Area Network (WLAN) Radio Level Integration

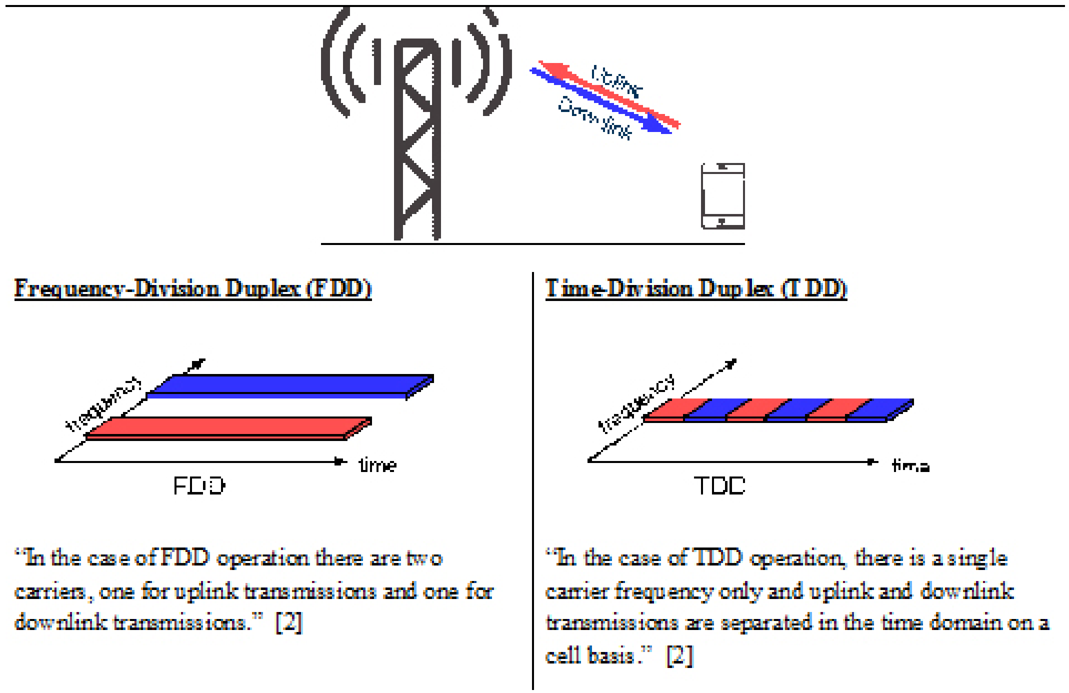
- LTE-Advanced Release 14
  - Enhanced LAA (eLAA)
  - Enhanced LTE-WLAN Aggregation
  - Support for vehicle-to-everything (V2X) connectivity

- **Longer list of Rel. 12-14 enhancements available in the annex**

FDD-TDD Carrier Aggregation (Rel. 12)

FDD-TDD Carrier Aggregation

- LTE uses two duplexing modes
  - Frequency Division Duplexing (FDD): DL and UL transmissions occur at same time in different paired carriers
  - Time Division Duplexing (TDD): DL and UL transmissions occur in same unpaired carrier but different times (subframes)



Source: https://www.ericsson.com/research-blog/boosting-data-rates-lte/

FDD-TDD Carrier Aggregation

Green bands are paired FDD bands

An operator may have licenses for both FDD and TDD bands

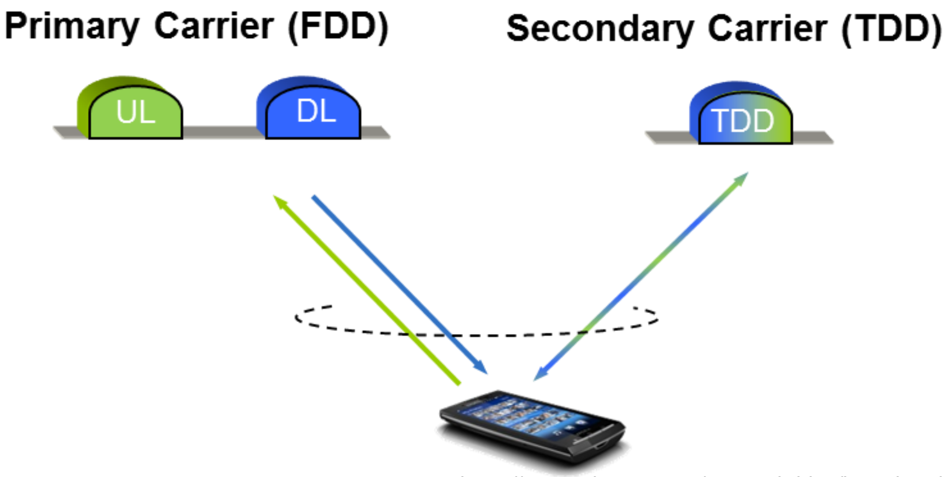
Yellow bands are unpaired TDD bands

Source: telecomstudy18

Band	UL (MHz)	DL (MHz)	Simp. BW (MHz)	Total BW (MHz)	Mode	Notes
1	1920 - 1980	2110 - 2170	60	120	FDD	EMEA, Japan
2	1850 - 1910	1930 - 1990	60	120	FDD	Quad band GSM
3	1710 - 1785	1805 - 1880	75	150	FDD	Quad band GSM. DCS 1800
4	1710 - 1755	2110 - 2155	45	90	FDD	AWS
5	824 - 849	869 - 894	25	50	FDD	Quad band GSM
6	830 - 840	875 - 885	10	20	FDD	Not applicable to 3GPP
7	2500 - 2570	2620 - 2690	70	140	FDD	EMEA
8	880 - 915	925 - 960	35	70	FDD	Quad band GSM. GSM 900
9	1749.9 - 1784.9	1844.9 - 1879.9	35	70	FDD	1700 MHz. Japan
10	1710 - 1770	2110 - 2170	60	120	FDD	Extended AWS
11	1427.9 - 1452.9	1475.9 - 1500.9	25	50	FDD	1.5 GHz Lower, Japan
12	698 - 716	728 - 746	18	36	FDD	Lower 700 MHz, C Spire+USCC-LTE
	N/A	716 - 722	6	6	DL only	Originally Ch.55 for QCOM mDTV venture - MediaFLO. Spectrum was sold to AT&T.
13	777 - 787	746 - 756	10	20	FDD	Upper 700 MHz, VzW-LTE
14	788 - 798	758 - 768	10	20	FDD	US FCC Public Safety
15	1900 - 1920	2600 - 2620	20	40	FDD	
16	2010 - 2025	2585 - 2600	15	30	FDD	
17	704 - 716	734 - 746	12	24	FDD	AT&T-LTE
18	815 - 830	860 - 875	15	30	FDD	Japan 800 MHz Lower
19	830 - 845	875 - 890	15	30	FDD	Japan 800 MHz Upper
20	832 - 862	791 - 821	30	60	FDD	800 MHz EMEA
21	1447.9 - 1462.9	1495.9 - 1510.9	15	30	FDD	1.5 GHz Upper. Japan
22	3410 - 3490	3510 -3590	80	160	FDD	3.5G
24	1626.5 - 1660.5	1525 - 1559	34	68	FDD	
25	1850 - 1915	1930 - 1995	65	130	FDD	AWS-G. Sprint LTE within this band
	1915 - 1920	1995 - 2000	5	10	FDD	AWS-H, will be auctioned by Feb. 2015.
26	814 - 849	859 - 894	35	70	FDD	Sprint / Nextel iDen
27	807 - 824	852 - 869	17	34	FDD	Lower 850 MHz
28	703 - 748	758 - 803	45	90	FDD	700 MHz APAC
	2000 - 2020	2180 - 2200	20	40	FDD	Dish Network to deploy LTE-A by 2016.
33	1900 - 1920		20		TDD	
34	2010 - 2025		15		TDD	China Mobile (CM) TD-SCDMA
35	1850 - 1910		60		TDD	
36	1930 - 1990		60		TDD	
37	1910 - 1930		20		TDD	
38	2570 - 2620		50		TDD	European - TD-LTE
39	1880 - 1920		40		TDD	CM TD-SCDMA
40	2300 - 2400		100		TDD	CM TD-LTE
41	2496 - 2690		194		TDD	TDD 2.5 GHz
42	3400 - 3600		200		TDD	TDD 3.5 GHz
43	3600 - 3800		200		TDD	TDD 3.6 GHz
44	703 - 803		100		TDD	700 MHz APAC

FDD-TDD Carrier Aggregation

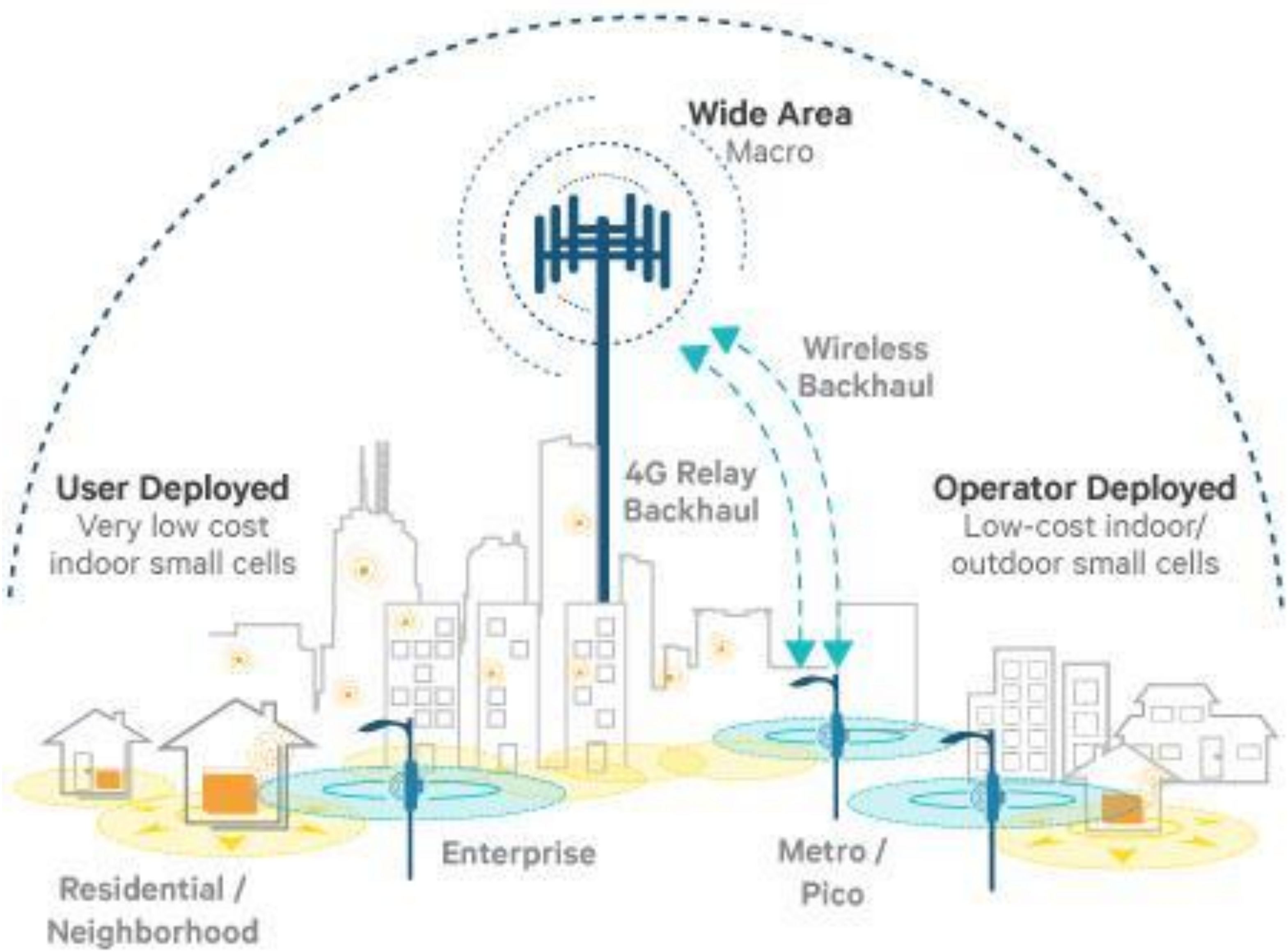
- In Release 10/11 carrier aggregation occurs in one duplexing mode at a time (either FDD CA specified in R10 or TDD CA in R11)
- Release 12 specifies combined FDD-TDD carrier aggregation
  - Enhances capacity in the primary FDD or TDD system
  - Primary component carrier can be either in FDD or TDD band (figure below only shows FDD case)
  - Enables load balancing (e.g. moving some of the load from FDD carriers to a TDD carrier)



Source: https://www.ericsson.com/research-blog/boosting-data-rates-lte/

Small cell and femtocell enhancements (Rel. 12)

Small Cells



Source: Qualcomm

Why Small Cells are Important?

- Reusing spectrum resources by network densification (more cell sites) is more straightforward way of scaling network capacity
  - Deploying more small cells to complement macro cells
  - Relevant approach in evolved 4G but even more important in 5G (ultradense network, hyperdense deployments etc.)

Technique	Capacity Gain
Frequency Division	5
Modulation techniques	5
Access to wider range of frequency spectrum	25
Frequency reuse through more cell sites	1600

Source: Small Cell Forum

Challenges of Network Densification

- Interference increases with network densification
  - $\Rightarrow$ each added small cell is a source of interference to others
- Using legacy macro control signaling for small cells (e.g. reference symbols) is inefficient
  - $\Rightarrow$ not always needed in small cell areas
- Denser networks means more frequent handovers
  - $\Rightarrow$ handover failures, more signaling etc.
- Denser networks means more sites requiring powering and backhauling
  - $\Rightarrow$ need for more energy efficiency and efficient backhaul capacity utilization

Small cell enhancements in Release 12

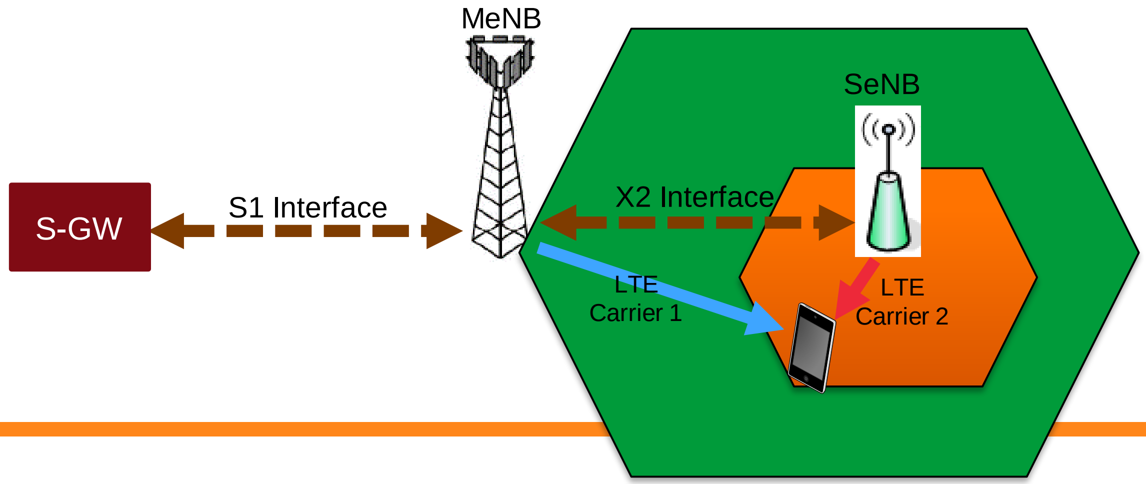
1. Increase available spectrum with dual connectivity with macro and small cell layers
2. Improve spectral efficiency with higher order modulation
3. Improve spectral efficiency by reducing overhead
4. Small cell ON/OFF for reduce interference and load balancing/shifting
5. Improve handover with mobility enhancements
6. Etc

- Let us briefly look at enhancements (1) and (2)

Dual Connectivity

Dual Connectivity

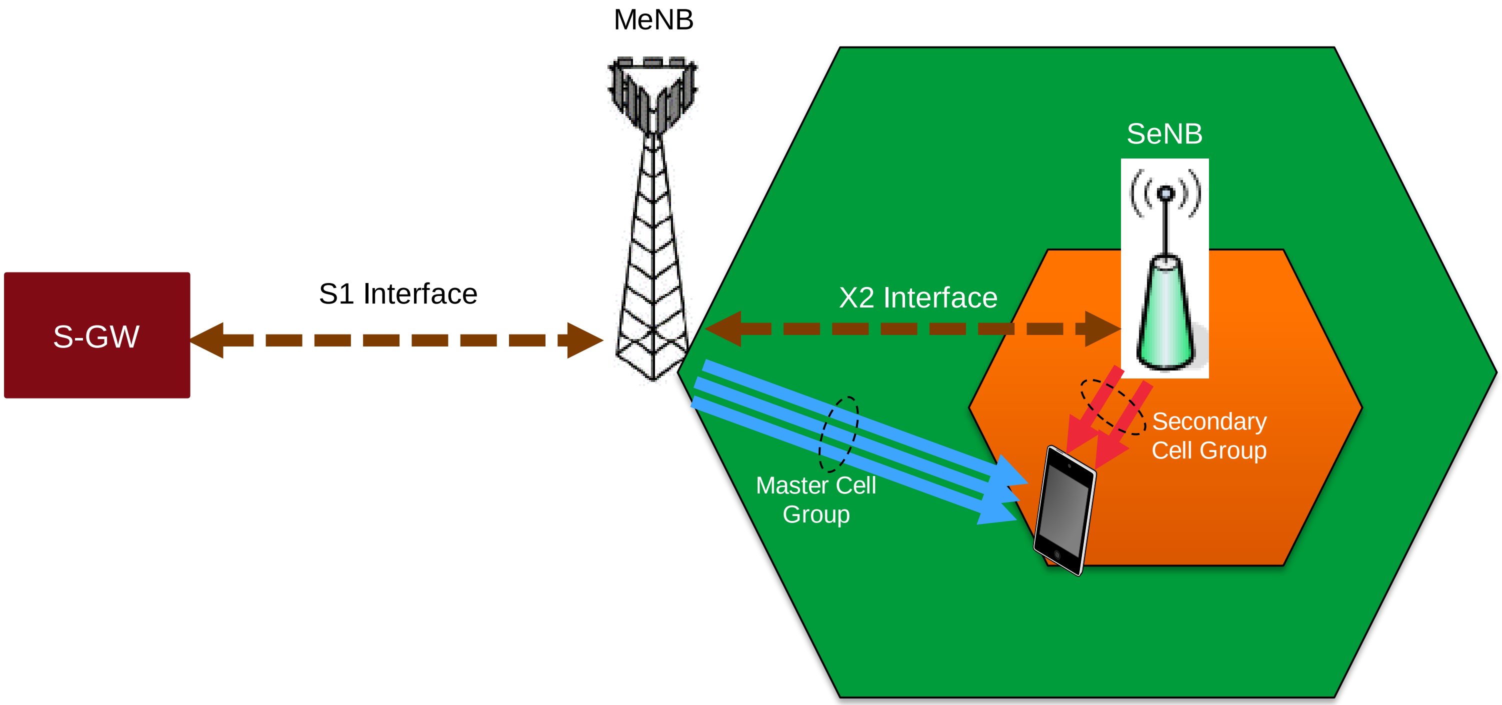
- Dual connectivity increases user throughput by allocating users with **component carriers from two different eNBs**
  - Also known as inter-site carrier aggregation (note: conventional carrier aggregation combines carriers from same eNB)
  - Initially specified in Release 12 (downlink only) and further refined in Release 13 (uplink added)
  - Master eNB (MeNB) and Secondary eNB (SeNB, typically a small cell)
  - Note: Dual connectivity differs from CoMP Joint Transmission because eNBs utilise different carriers (non-overlapping frequency bands) and are also not duplicating the data stream to the users!



Source: Rhodes&Schwartz

Dual Connectivity

- Carrier aggregation also possible in dual connectivity
  - Component carriers from MeNB are part of a Master Cell Group
  - Component carriers of SeNB are part of a Secondary Cell Group
  - Both the Master Cell Group and Secondary Cell Group must have one primary component carrier each

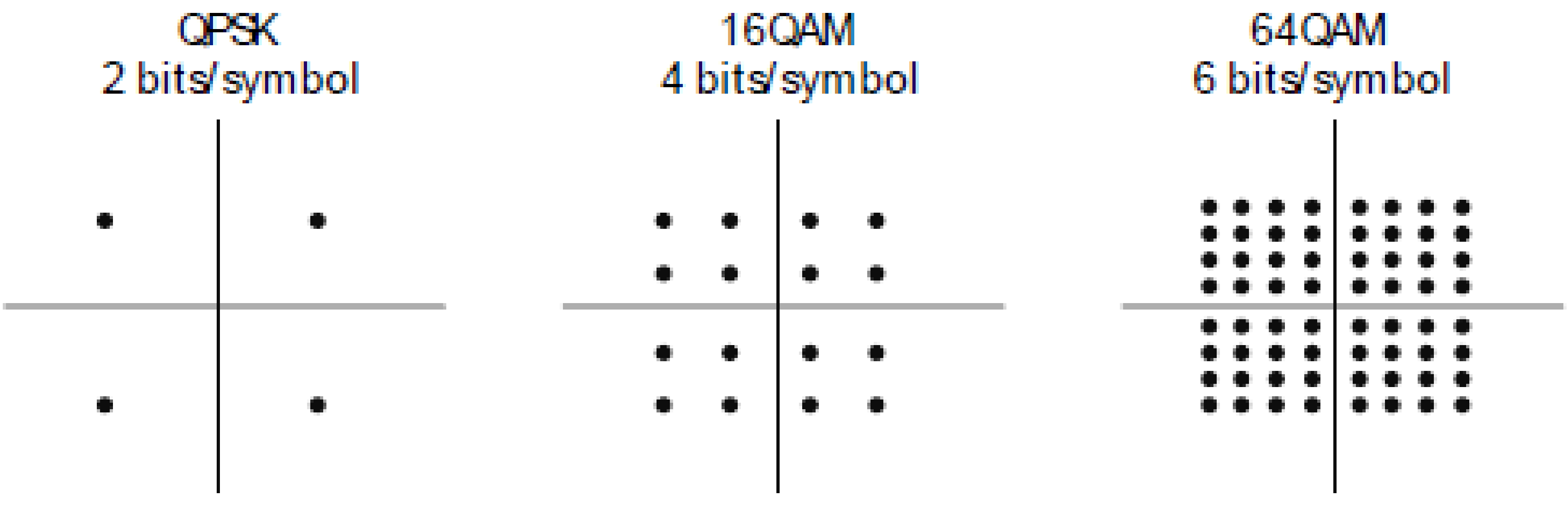


Source: Rhodes&Schwartz

Higher Order Modulation

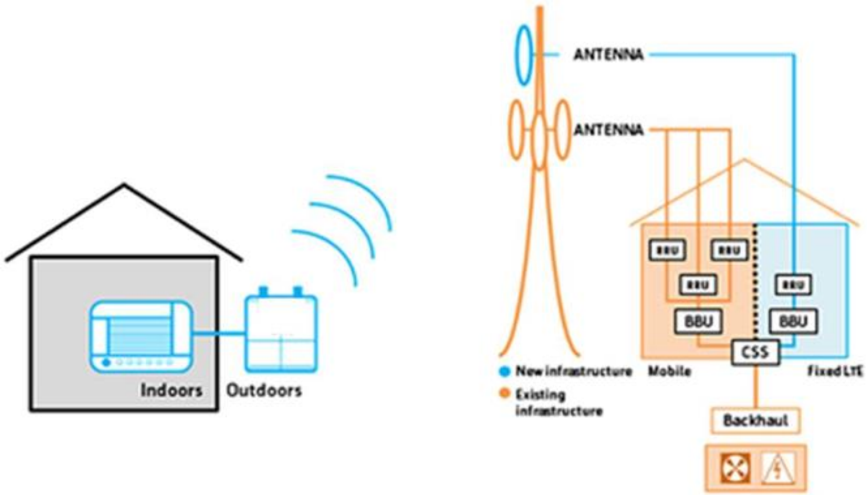
Higher Order Modulation

- In Release 8-11 the LTE modulation schemes where QPSK, 16QAM and 64QAM
- Higher order modulation schemes limited by achievable SINR



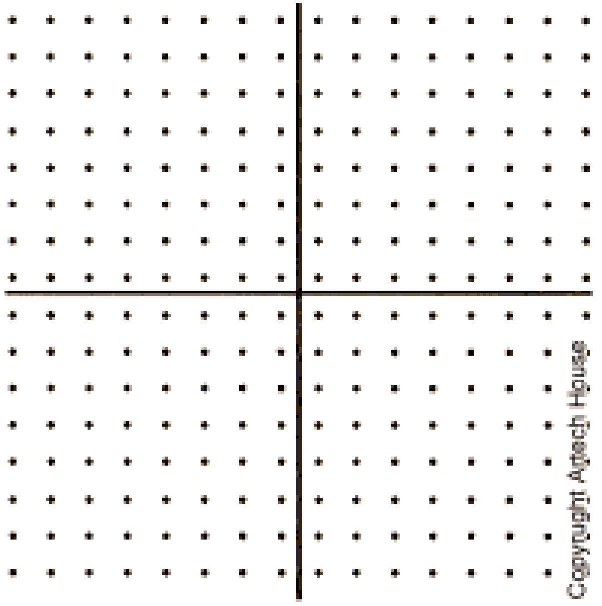
Higher Order Modulation

- Higher SINR possible for indoor small cells or outdoor stationary short line-of-sight conditions (e.g. fixed LTE customer premises equipment [CPE])
- Possible to use 256QAM (8 bits/symbol) to increase spectral efficiency particularly in the downlink



The fixed LTE concept. Everything in blue is Fixed LTE; everything in orange is existing Mobile LTE equipment

Source: Telenor



Ideal 256 QAM constellation

Higher Order Modulation

- Rel. 12 adds 256QAM modulation and coding schemes (MCS) but without increasing the uplink CQI signalling
  - Some previous MCS replaced in a new CQI table
  - Higher level signaling used to switch between conventional and new CQI table when UE reports very high quality channel measurements

Legacy 4-bit CQI table

CQI index	modulation	code rate x 1024	efficiency	
0	out of range			
1	QPSK	78	0.1523	
2	QPSK	120	0.2344	X
3	QPSK	193	0.3770	
4	QPSK	308	0.6016	X
5	QPSK	449	0.8770	
6	QPSK	602	1.1758	X
7	16QAM	378	1.4766	
8	16QAM	490	1.9141	
9	16QAM	616	2.4063	
10	64QAM	466	2.7305	
11	64QAM	567	3.3223	
12	64QAM	666	3.9023	
13	64QAM	772	4.5234	
14	64QAM	873	5.1152	
15	64QAM	948	5.5547	X

Release 12 CQI table

CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	193	0.3770
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8	64QAM	567	3.3223
9	64QAM	666	3.9023
10	64QAM	772	4.5234
11	64QAM	873	5.1152
12	256QAM	711	5.5547
13	256QAM	797	6.2266
14	256QAM	885	6.9141
15	256QAM	948	7.4063

Source: Sharetechnote

Proximity Services (ProSe) (Rel. 12)

Proximity Services (ProSe)

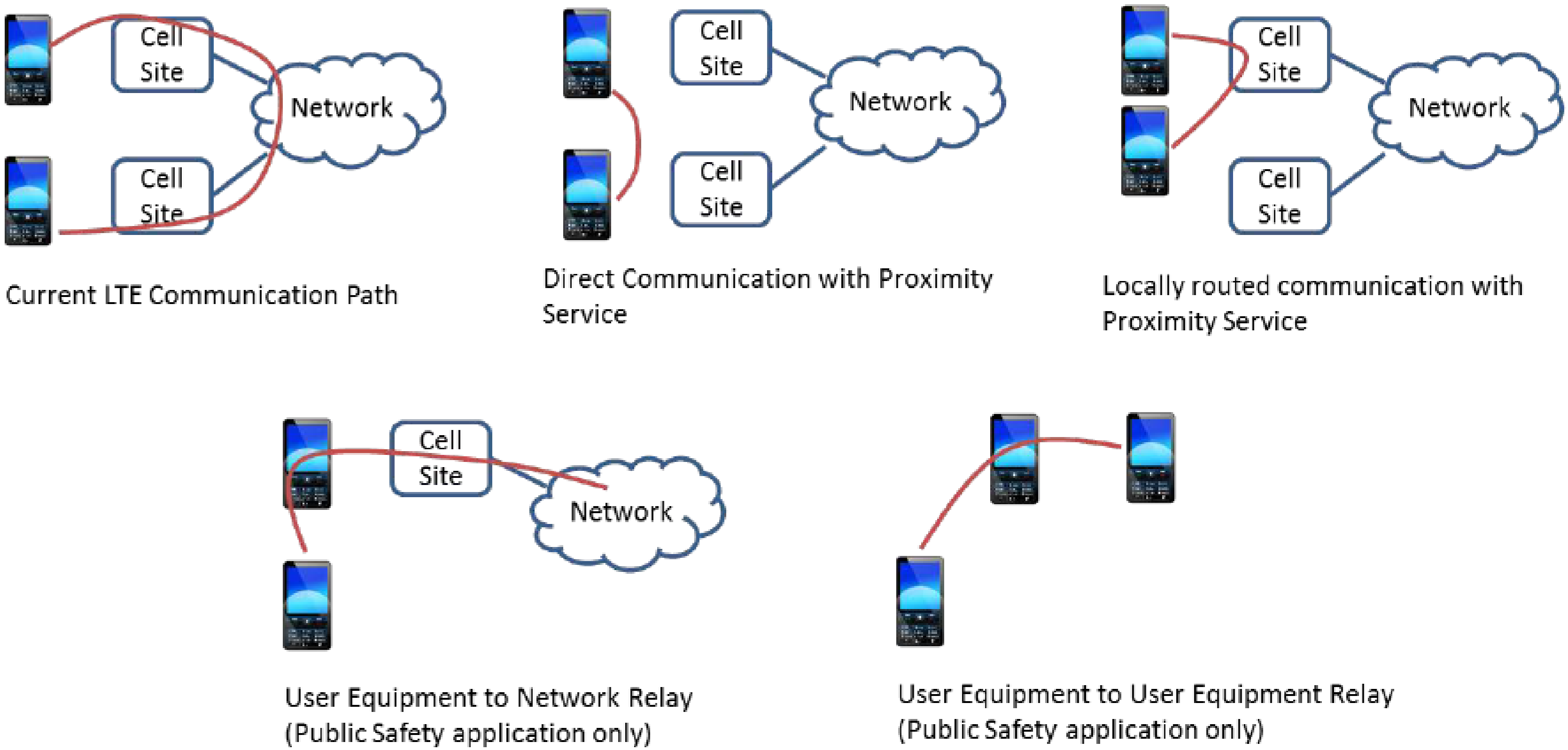
- Proximity services (ProSe) enhancements mostly refer to device-to-device (D2D) communications
  - UE pair communicate directly with each other

- ProSe work in 3GPP Rel. 12 is divided into:
  1. **Direct communications**
  2. Device discovery
- Direct communications is motivated by public safety communications scenarios

	Within LTE network coverage	Outside LTE network coverage
Discovery	Non public safety & public safety	Not supported
Direct Communication	Public safety only	Public safety only

LTE for Public Safety Communications

- ProSe for direct communications in public safety communications

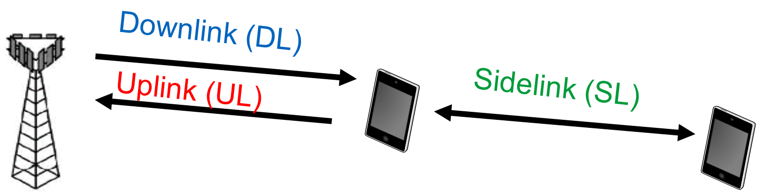


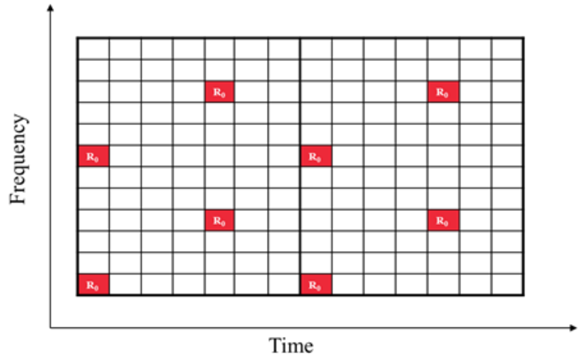
Proximity Service Examples

Source: 3GPP White Paper, Delivering Public Safety Communications with LTE, September 2, 2013,

ProSe Architecture

- ProSe introduces a **sidelink (SL)** to existing uplink (UL) and downlink (DL)
- D2D sidelink uses resources allocated from the existing LTE UL
  - For FDD LTE: SL assigned resources from subframes on the UL frequency
  - For TDD LTE: SL assigned resources from subframes assigned to UL in TDD.
- But why use UL LTE resources for SL and not DL resources?
  - UL subframes usually less occupied than those on the DL.
  - DL subframes usually never empty as at very least they will be carrying the cell specific reference signals (CRS) transmitted.
- D2D SL is itself TDD-based even if cellular LTE is FDD

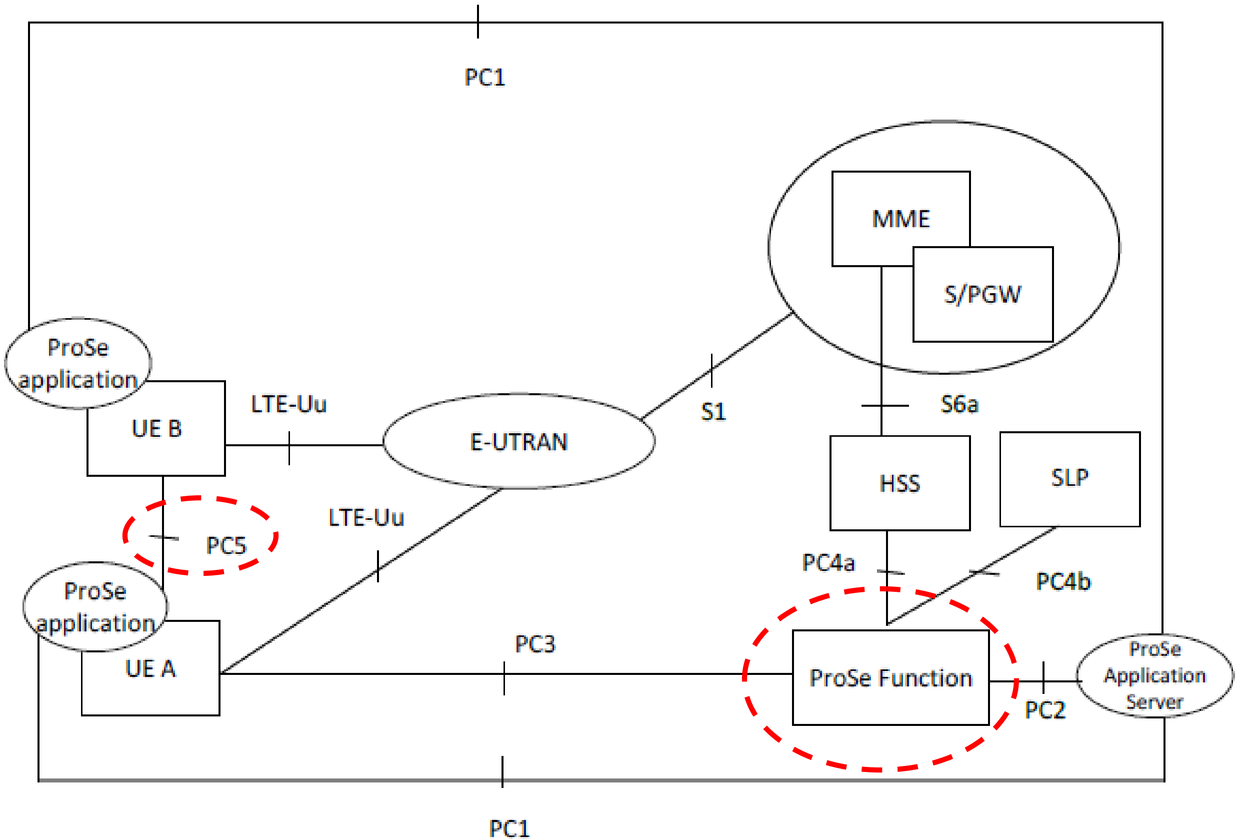




Cell specific reference signal locations in a resource element when using one antenna port and normal CP.

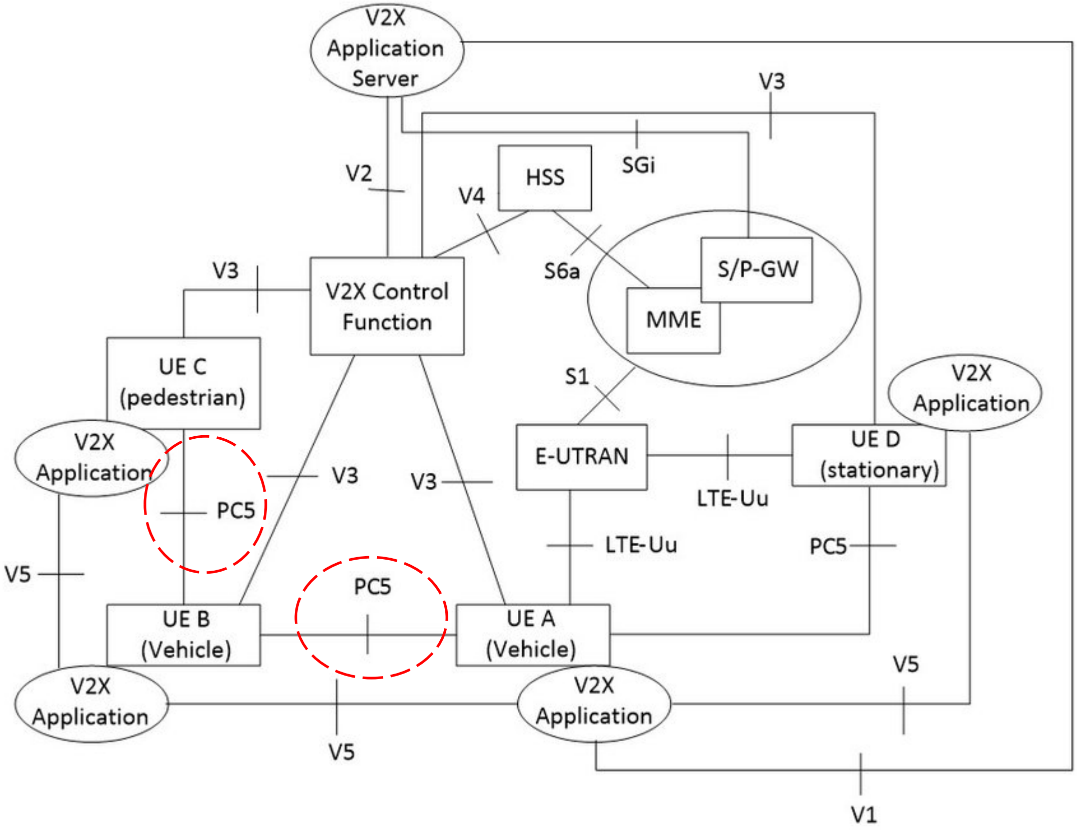
ProSe Architecture

- Sidelink introduced as **P5 interface** between UEs
- **ProSe Function** and **Prose Application Server** introduced to EPC to manage direct discovery, authenticate ProSe UEs, enable ProSe apps etc



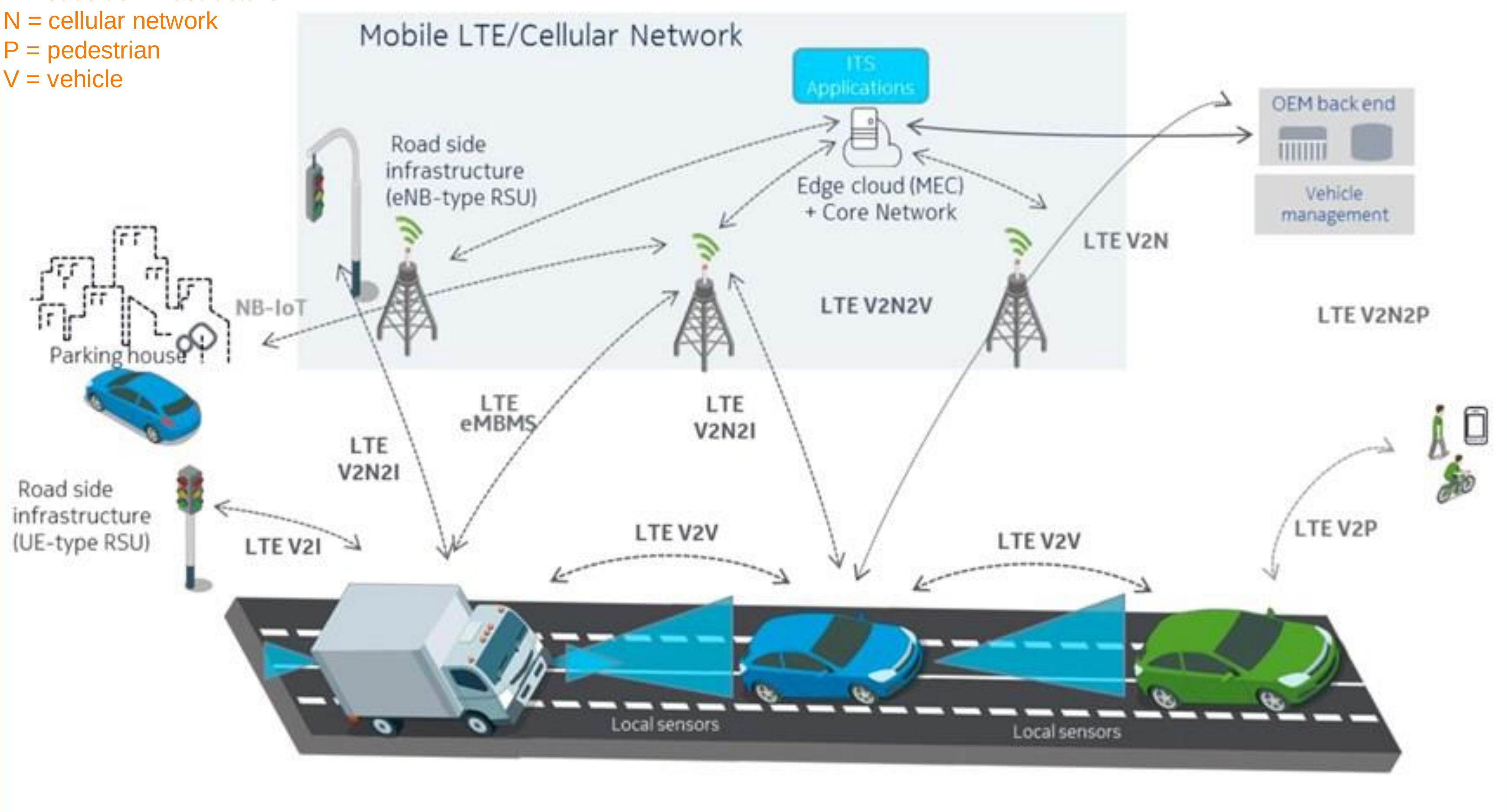
Rel 14: Support for connected vehicles based on LTE sidelink

- LTE sidelink (PC5 interface) critical part of the LTE-based cellular vehicle-to-everything communications (C-V2X) architecture



Different C-V2X scenarios

I = roadside infrastructure
N = cellular network
P = pedestrian
V = vehicle

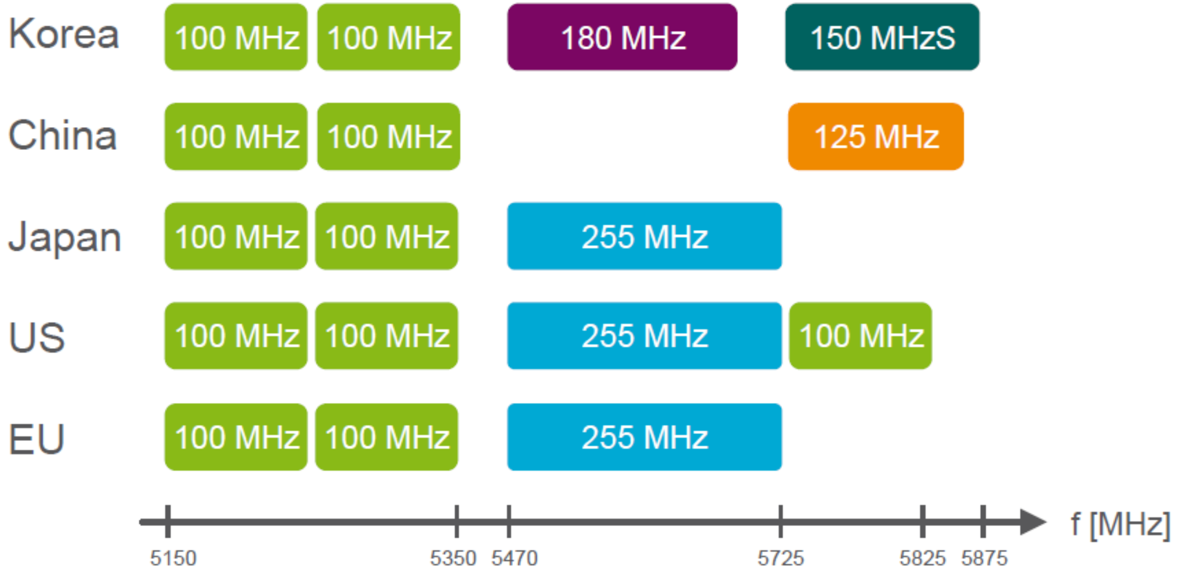


Source: NGMN

Licensed Assisted Access (LAA) and LTE-WLAN Aggregation (LWA) (Rel. 13)

Motivation for LAA and LWA

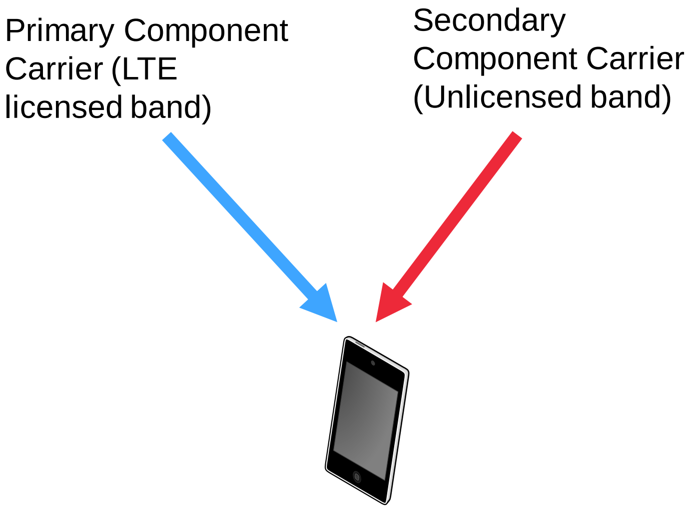
- Recall: Conventional carrier aggregation limited by shortage of spectrum in traditional paired FDD and unpaired TDD LTE bands
- Signifant unlicensed (free) bandwidth in the 5 GHz band
- In hotspot areas, possible to use licensed LTE bands and unlicensed WLAN/Wi-Fi bands
  - Multiradio UEs typically support the licensed LTE and unlicensed WI-Fi connections
  - However, switching between LTE and Wi-Fi is not always seamless/inconvenient as it may requires reconnecting, re-athuthentication etc.



Source: Ericsson

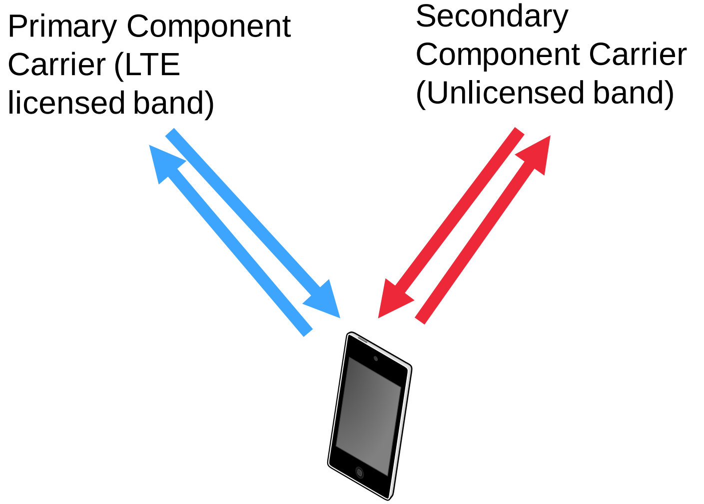
LTE License Assisted Access (LAA)

- Release 13 LTE-LAA is essentially a downlink carrier aggregation technique
- Utilises component carriers from licensed and unlicensed bands
  - Primary component carrier is always from licensed band (licensed carrier for control and mobility)
  - One or more Secondary component carriers from 5 GHz unlicensed bands
- More component carriers in Release 13:
  - Release 10-12 carrier aggregation: up to 5 component carriers (20 MHz x 5 = 100 MHz)
  - Release 13 carrier aggregation: up to **32 component carriers (20 MHz x 32 = 640 MHz)**



Rel. 14: Enhanced LAA (eLAA)

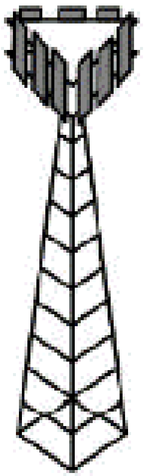
- Release 14 eLAA adds licensed/ unlicensed carrier aggregation in uplink (to DL supported in Rel. 13)



LTE License Assisted Access (LAA)

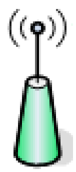
- In 3GPP deployment scenarios:
  - Macro cells use only the licensed band
  - Small cells may use licensed or unlicensed band

Macro eNB



Licensed band

Small cell eNB



Licensed band

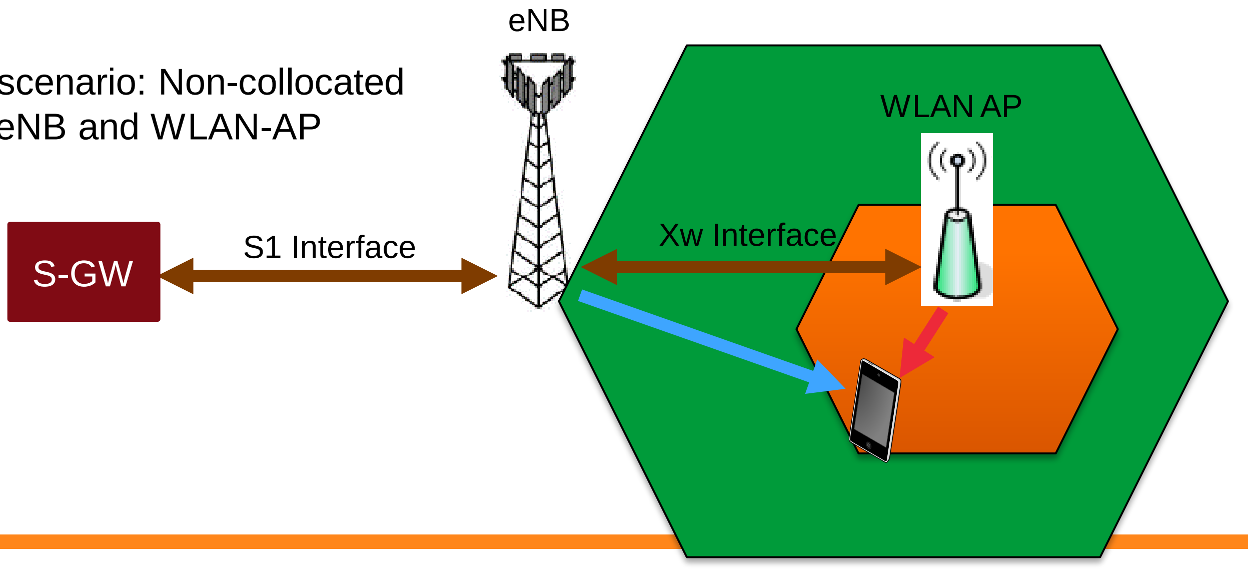
"…To improve app coverage indoors in any size or type of commercial building – whether that's a suburban shopping center, train station or a high-rise office building – Ericsson is adding Licensed Assisted Access (LAA) to its indoor small cell portfolio, the Ericsson Radio Dot System and RBS 6402 Indoor Picocell. LAA introduces the security and performance associated with high-performance LTE networks to spectrum available in the 5 GHz band."

https://www.ericsson.com/thecompany/press/mediakits/laa

LTE-WLAN Aggregation (LWA)

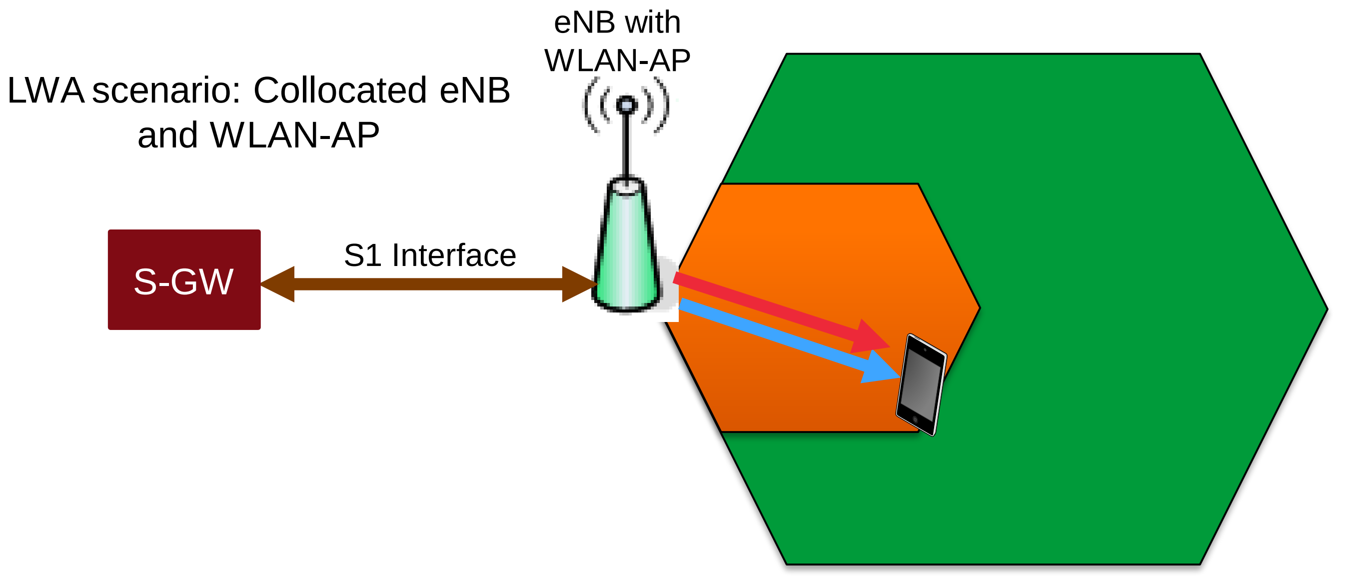
- LWA increases user throughput by utilizing LTE and WLAN radio resources (carriers) simultaneously
  - A type of carrier aggregation with WLAN carrier being one of the component carriers
  - Similar to Release 12 Dual Connectivity, but the Secondary eNB (SeNB) is replaced by a WLAN access point (AP)
- Release 13 specifies a new interface (**Xw**) between eNB and WLAN AP

LWA scenario: Non-collocated eNB and WLAN-AP

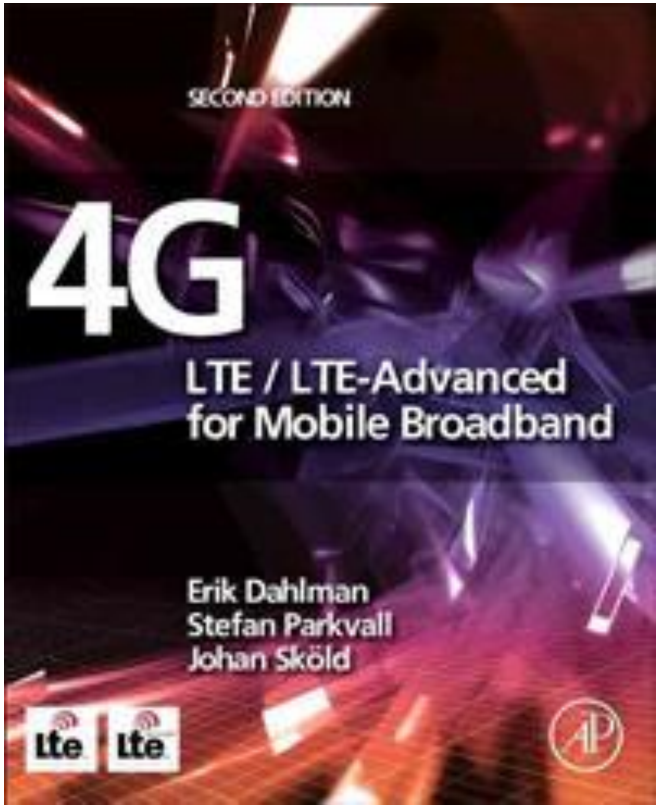


LTE-WLAN Aggregation (LWA)

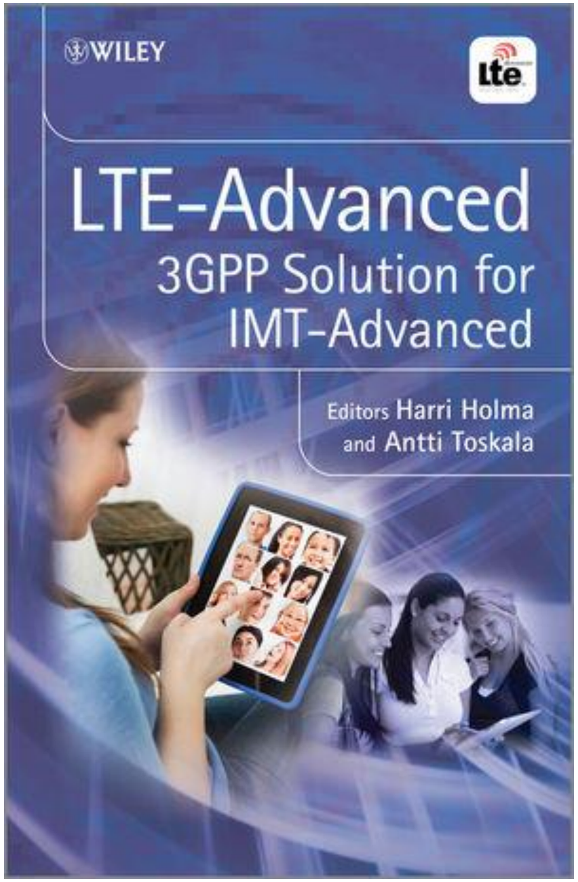
- LWA deployment scenario for collocated eNB and WLAN-AP
  - Typical in multiradio small cells
  - Scenario could also be assumed for WLAN-AP with ideal backhaul to eNB



Further Reading



https://aalto.finna.fi/Record/alli.826936



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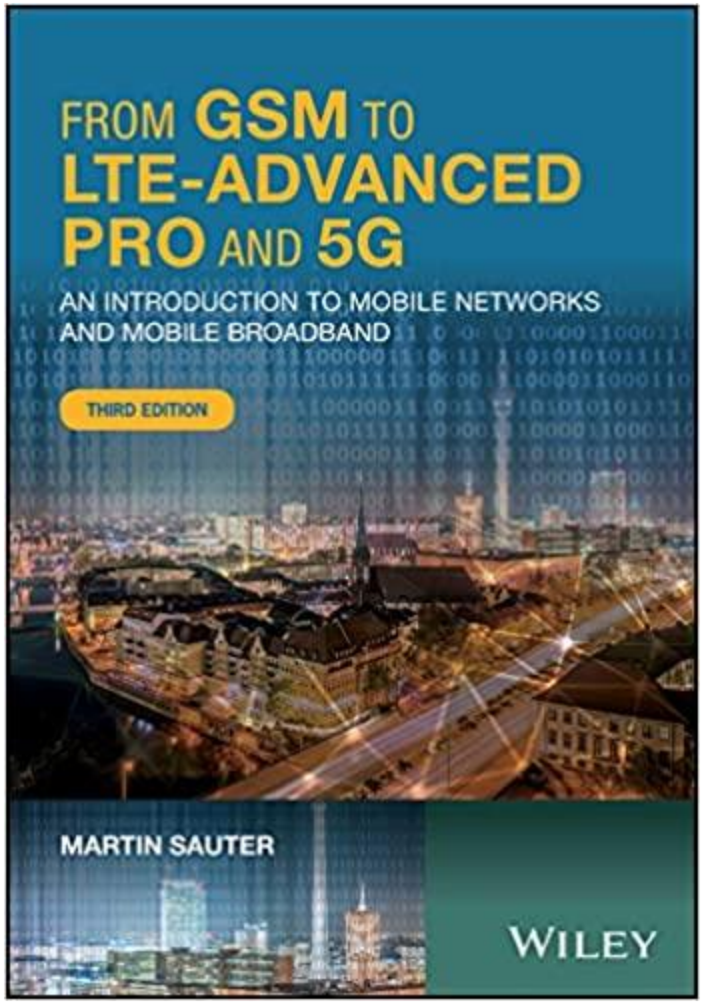
Aalto University

Further Reading



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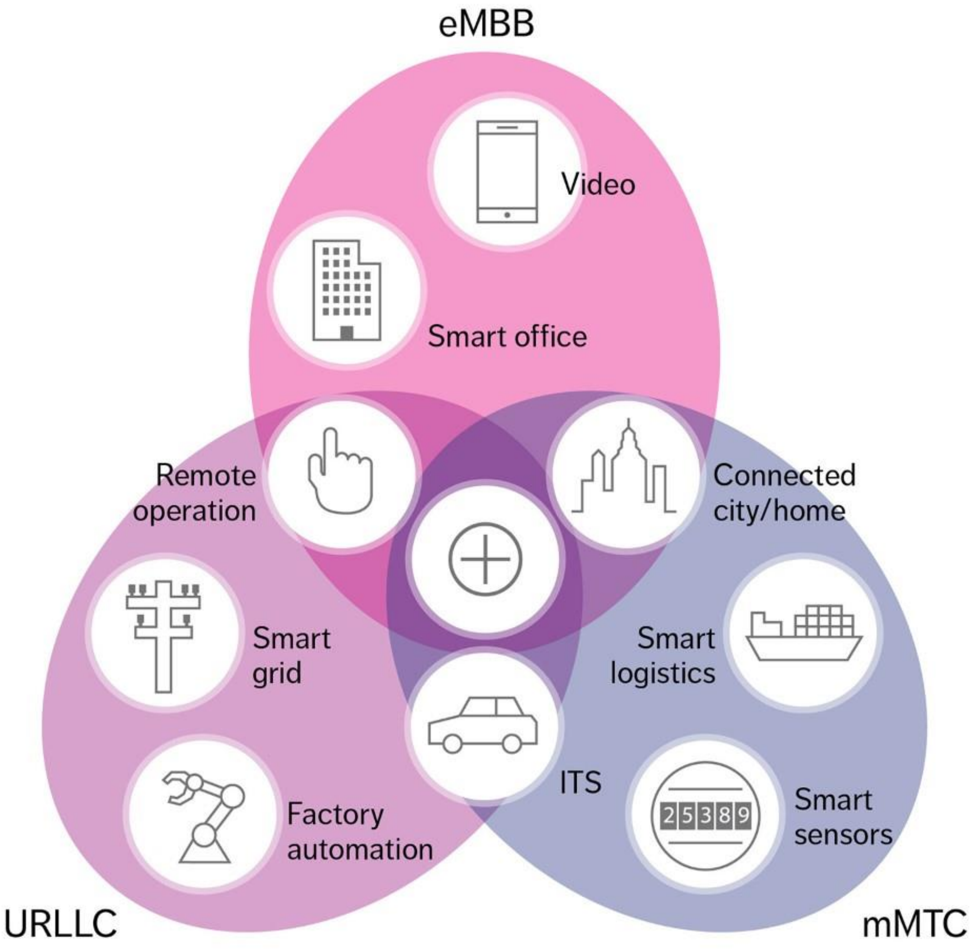
Next Lecture

- 5G New Radio (Release 15)



Thank You!

LTE-Advanced Release 12 Highlights

- Frequency Division DuplexTime Division Duplex Carrier Aggregation (FDD-TDD CA)
- Small cell and femtocell enhancements
- Proximity Service (ProSe)
- Downlink enhancements for MIMO antenna systems
- Machine Type Communication (MTC)
- User Equipment (UE) receive enhancements to mitigate/cancel interference
- Self Optimizing Networks (SON)
- Heterogeneous Network (HetNet) mobility
- Multimedia Broadcast/Multicast Services (MBMS)
- Local Internet Protocol Access/Selected Internet Protocol Traffic Offload (LIPA/SIPTO)
- Enhanced International Mobile Telecommunications Advanced (eIMTA)

LTE-A Pro Rel. 13 E-UTRAN Highlights

- Self-Optimizing Networks (SON) for Active Antenna System (AAS) Deployments
- Elevation Beamforming (EBF) and Full Dimension (FD) Multi-Input Multi-Output (MIMO)
- Enhanced Signaling for Inter-eNB Coordinated Multi-Point (CoMP)
- Further LTE Physical Layer Enhancements for Machine Type Communication (MTC)
- Indoor Positioning Enhancements
- Licensed Assisted Access (LAA) Using LTE
- Carrier Aggregation (CA) Enhancements
- Downlink Multi-User Superposition Transmission (MUST)
- Radio Access Network (RAN) Aspects of RAN Sharing Enhancements
- Enhanced LTE Device-To-Device (D2D) Proximity Services (ProSe)
- Dual Connectivity Enhancements
- LTE-Wireless Local Area Network (WLAN) Radio Level Integration
- Radio Access Network (RAN) Enhancements for Extended Discontinuous Reception (DRX) in LTE

LTE-A Pro Rel. 14 E-UTRAN Highlights

- Improvement to LTE efficiency, such as,
  - Enhancements on FD-MIMO for LTE
  - Uplink Capacity Enhancements for LTE
  - Further enhancements to CoMP operation
  - Study on enhancement of VoLTE
  - L2 latency reduction techniques for LTE
  - Signalling reduction to enable light connection for LTE
  - Mobility enhancement in LTE
  - Flexible eNB-ID and Cell-ID in E-UTRAN
- Offload to unlicensed
  - Enhanced LAA (eLAA)
  - Enhanced LTE-WLAN Aggregation
- Enablers of new services / verticals, such as,
  - Support for V2V services based on LTE sidelink
  - eMBMS enhancements in LTE
  - Further Enhancements to LTE D2D
  - UE to Network Relays for IoT and Wearables
  - Further Indoor Positioning enhancements for UTRA and LTE