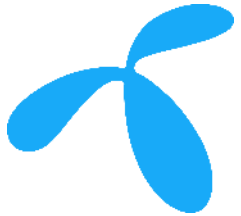


Spectrum Management

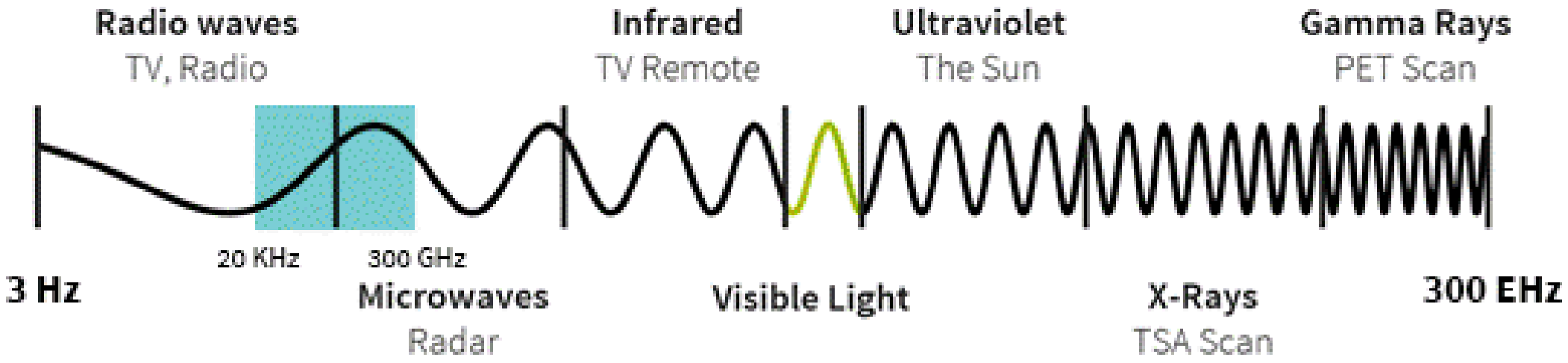
16 May 2024

Guest lecture – Chalmers University

Per Hjalmar Lehne, Telenor Research - per-hjalmar.lehne@telenor.com – +47 916 94 909

Why should we care about spectrum?

- Spectrum refers to the invisible radio frequencies that wireless signals travel over.
- Those signals are what enable us to make calls from our mobile devices, tag our friends on Instagram, call an Uber, pull up directions to a destination, and do everything on our mobile devices



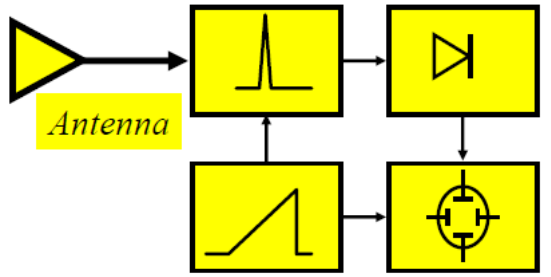
Spectrum Management

- Support material:
  - Tjelta T., Struzak R. Spectrum management overview, *The Radio Science Bulletin*, No 400, March 2012

What is spectrum?

$$S(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$$

- **Mathematical concept?**
  - An abstract concept of no practical value, only later accepted as a mathematical tool
    - 1822: Concept of spectrum (J.B.Fourier, 1768-1830)
- **Measurable physical quantity?**
  - A physical object.
    - 1888 Hertz experiments
  - Radio waves can transport energy and information at distance with no wires
    - 1895: Marconi and Popov experiments & applications
- **Common (public) resource?**
  - A natural freely accessible public resource: everybody can profit from its exploitation
    - 1901: First transatlantic wireless transmission
- **Marketed commodity?**
  - A commodity is either grown or produced naturally in the environment
    - The prices of these commodities are primarily based on their demand and supply.



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- Global, regional and national regulations
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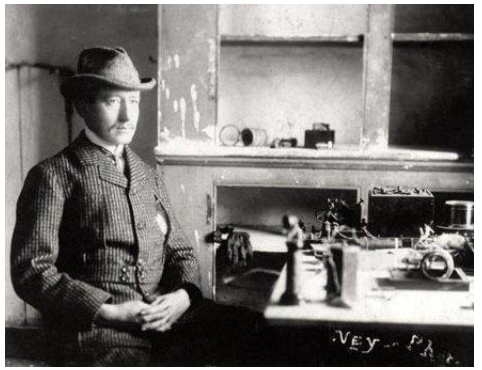
Commercial use of spectrum started with maritime radio telegraphy

- **Intense unregulated competition resulted in interference and commercial restrictions on use**
- The Marconi Wireless Company was very aggressive in its effort to create a monopoly, by establishing shore stations and prohibiting handling messages from ships not using Marconi equipment
- Others, e.g. Telefunken, did the same



Guglielmo Marconi (1874 – 1937)

1902
Prince Henry of Prussia attempts to send a message from his ship to President Roosevelt of the U.S

Refused handled by a Marconi operator

Contacts Kaiser Wilhelm of Prussia who proposes an international Convention to regulate maritime communications

1903
Preliminary Conference on Wireless Telegraphy

Proposes a protocol to require all stations to inter-communicate and to accept messages from all ships

1906
The first International Radiotelegraph Convention was signed

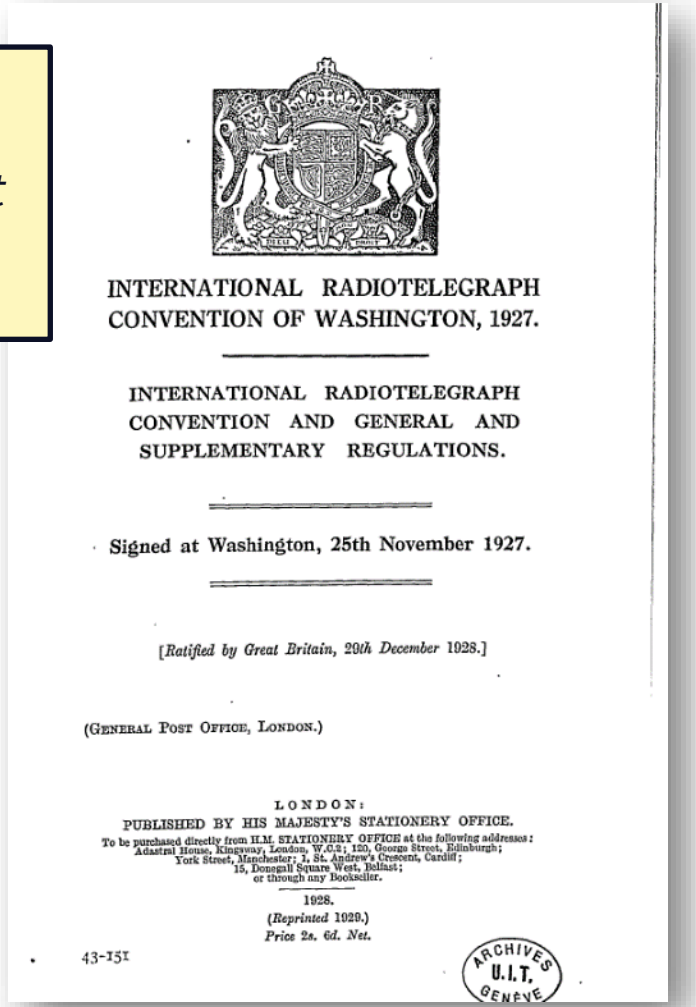
1912
The Titanic disaster

The 2nd International Radiotelegraph Conference agreed on a common wavelength for ships' radio distress signals

The birth of spectrum management came with the rise of broadcast radio

- 1927
  - General and Supplementary regulations
  - Articles about frequency allocations
  - Frequencies are allocated to specific service:
    - Fixed, Mobile, Broadcast, Amateur, ..
  - The creation of the International Radio Consultative Committee – CCIR
    (Comité consultatif international pour la radio)
  - Became part of ITU in 1932 – Name change to ITU-R in 1992
    - ITU Radiocommunication Sector
    - http://www.itu.int/ITU-R

Agreements on global spectrum usage also created an environment for business and economy of scale.



INTERNATIONAL RADIOTELEGRAPH CONVENTION OF WASHINGTON, 1927.

INTERNATIONAL RADIOTELEGRAPH CONVENTION AND GENERAL AND SUPPLEMENTARY REGULATIONS.

Signed at Washington, 25th November 1927.

[*Ratified by Great Britain, 29th December* 1928.]

(GENERAL POST OFFICE, LONDON.)

LONDON:
PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE.
To be purchased directly from H.M. STATIONERY OFFICE at the following addresses:
Adastral House, Kingsway, London, W.C.2; 120, George Street, Edinburgh;
York Street, Manchester; 1, St. Andrew's Crescent, Cardiff;
15, Donegall Square West, Belfast;
or through any Bookseller.

1928.
(*Reprinted* 1929.)
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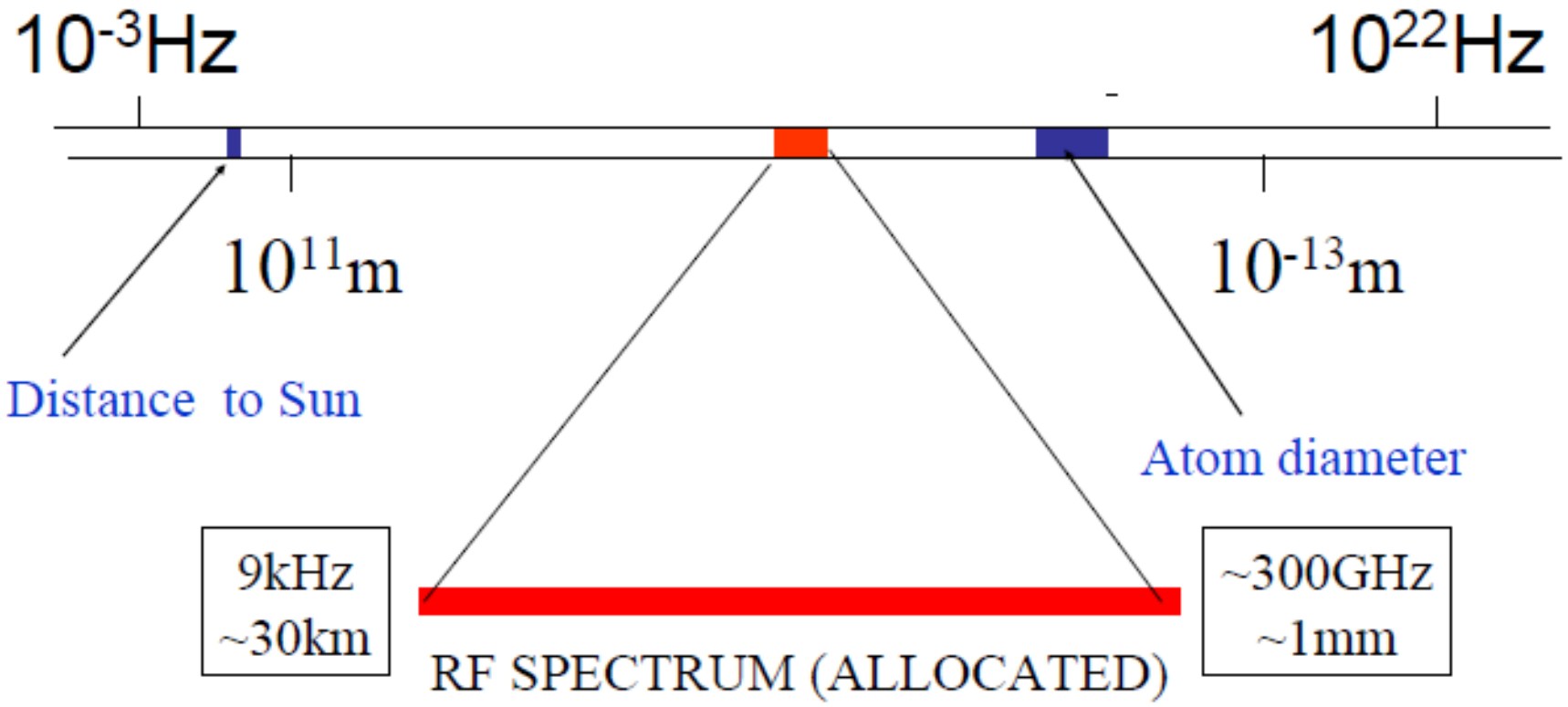
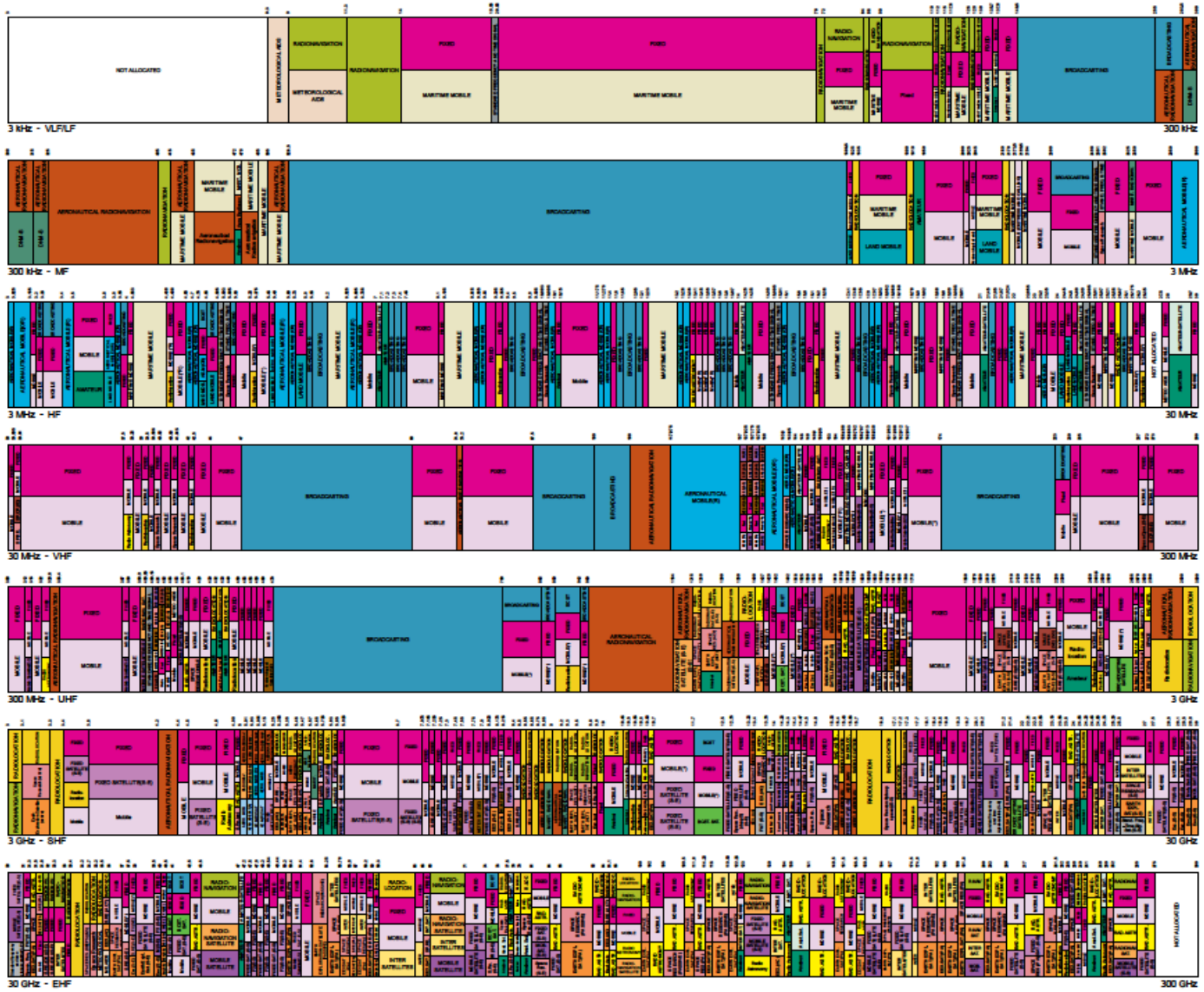
What part of spectrum is regulated?



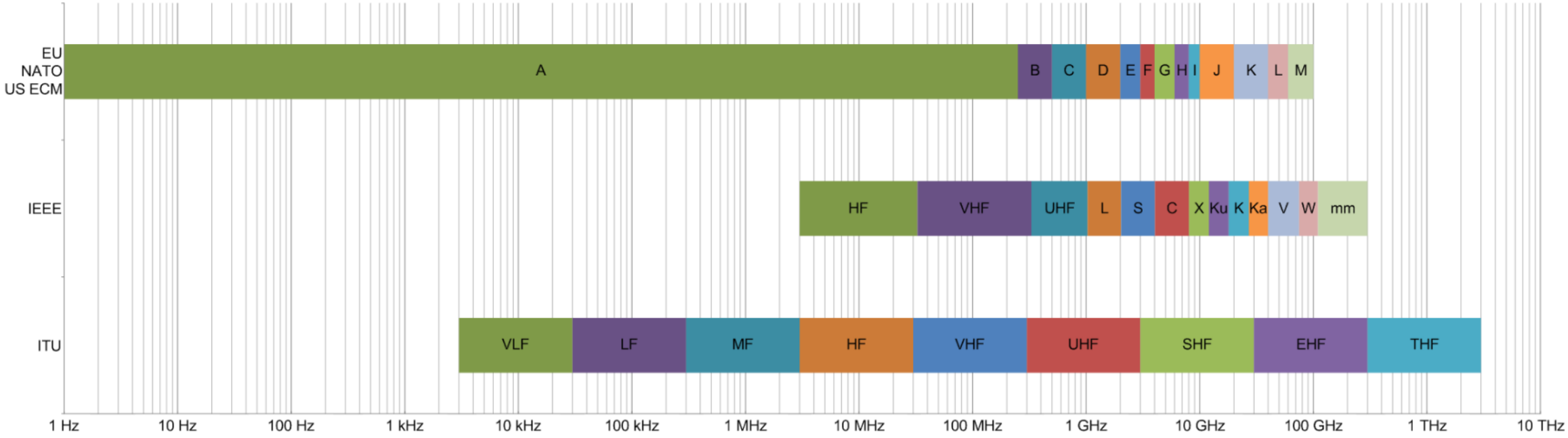
NORWAY

FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM



Frequency band designations



Spectrum is today managed on three levels

- **Global level:**
  - By the *International Telecommunications Union Radio Sector* – ITU-R, the continuation of CCIR (www.itu.int)
    - From 1947 ITU is a UN Agency
- **The regional level:**
  - In Europe by CEPT/European Communications Committee (ECC) (www.cept.com/ecc)
- **The national level:**
  - The national regulators:
  - In Sweden: The Swedish Post and Telecom Authority – PTS (www.pts.se)
  - In Norway: the National Communications Authority – NKOM (www.nkom.no)
  - Other influencal national regulators are Ofcom in the UK (www.ofcom.org.uk) and FCC in the US (www.fcc.gov)

European Conference of Postal and Telecommunications Administrations

- 48 European countries cooperating to regulate posts, radio spectrum and communications networks

Nasjonal kommunikasjons-myndighet

Global management:

The International Telecommunications Union Radiocommunication Sector – ITU-R

- **The ITU Radiocommunication Sector (ITU-R)**
  - One of the three sectors of the International Telecommunication Union (ITU) and is responsible for radio communication.
- **Role:**
  - Manage the international radio-frequency spectrum and satellite orbit resources
  - Develop standards for radiocommunication systems with the objective of ensuring the effective use of the spectrum.
- **The strategic goal of the ITU-R is threefold**, and includes (source: www.itu.int):
  - To ensure **interference-free operations of radiocommunication systems** by implementing the Radio Regulations and regional agreements;
  - To establish Recommendations intended to **assure the necessary performance and quality** in operating radiocommunication systems;
  - To seek ways and means to ensure the **rational, equitable, efficient and economical use of the radio-frequency spectrum** and satellite-orbit resources and to promote flexibility for future expansion and new technological developments.

ITU-R is required to allocate spectrum and register frequency allocation, orbital positions and other parameters of satellites, "in order to avoid harmful interference between radio stations of different countries"

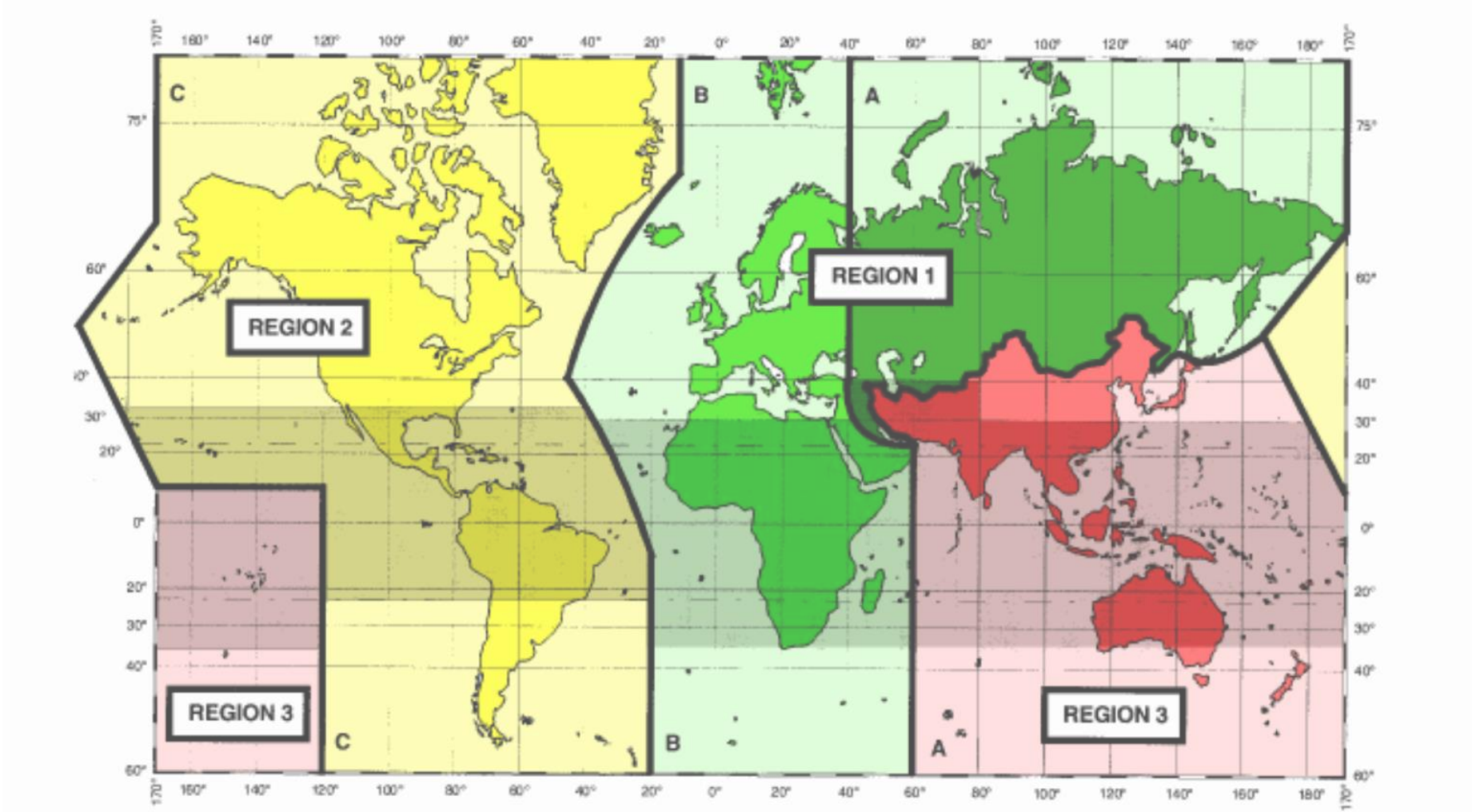
ITU-R World Radio Conference (WRC) is the highest level of decision for global spectrum management

- World Radio Conferences (WRC) are held every three to four years.
  - Last one was in 2019 – WRC-19; the upcoming is in 2023 – WRC-23
- Previous to WRC-19 a number of Mobile service bands have been identified for IMT (IMT-2000, IMT-Advanced, IMT-2020)
- WRC-19 allocated several new bands above 26 GHz for IMT-2020
- Bands already identified for IMT is also identified for IMT-2020

- ***IMT:*** *International Mobile Telecommunications*
- ***IMT-2000:*** *3G technology*
- ***IMT-Advanced:*** *4G technology*
- ***IMT-2020:*** *5G technology*

The ITU-R regions

To ease the global harmonization, some regional differences are recognized.



The ITU-R Radio Regulations (RR) are issued every three to four years

- **An International Treaty** that defines how radio waves and satellite orbits should (or should not) be used and managed
  - Ratified by, and legally binding in, all countries (~190 in total)
    - Basic set of rules
    - Three regions
    - Frequency allocation table - FAT
    - Frequency Plans' databases
    - Master International Frequency Register (MIFR) database
    - What to do in case of harmful interference
- Discussed and revised on World Radio Conferences (WRC)

Definitions from the RR

		Example
Administration:	Any **governmental department or service** responsible for discharging the obligations undertaken in the Constitution of the International Telecommunication Union, in the Convention of the International Telecommunication Union and in the Administrative Regulations.	The Swedish Post and Telecom Authority (PTS) The Norwegian Communications Authority (NKOM) Ofcom – UK FCC – US
Allocation (of a frequency band):	**Entry in the Table of Frequency Allocations** of a given frequency band for the purpose of its use by one or more terrestrial or space radiocommunication services, or the radio astronomy service under specified conditions. • distribution of frequencies to radio services (on a primary or on a secondary basis)	Example on next slide
Allotment (of a radio frequency or radio frequency channel):	**Entry of a designated frequency channel in an agreed plan**, adopted by a competent conference, for use by one or more administrations for a terrestrial or space radiocommunication service in one or more identified countries or geographical areas, and under specified conditions. • distribution of frequencies to geographical areas or countries	The 3GPP band designations for mobile
Assignment (of a radio frequency or radio frequency channel):	**Authorization given by an administration** for a radio station to use a radio frequency or radio frequency channel under specified conditions. • distribution of frequencies to users or radio stations.	Operators' licenses

The Frequency Allocation Table (FAT)
ITU-R RR Article 5

890 – 942
FIXED
MOBILE
BROADCASTING
Radiolocation

Primary allocations are written in CAPITAL letters

Secondary allocation are written in Small letters

Allocation to services		
Region 1	**Region 2**	**Region 3**
890-942 FIXED MOBILE except aeronautical mobile 5.317A BROADCASTING 5.322 Radiolocation 5.323	**890-902** FIXED MOBILE except aeronautical mobile 5.317A Radiolocation 5.318 5.325 **902-928** FIXED Amateur Mobile except aeronautical mobile 5.325A Radiolocation 5.150 5.325 5.326 **928-942** FIXED MOBILE except aeronautical mobile 5.317A Radiolocation 5.325	**890-942** FIXED MOBILE 5.317A BROADCASTING Radiolocation 5.327
942-960 FIXED MOBILE except aeronautical mobile 5.317A BROADCASTING 5.322 5.323	**942-960** FIXED MOBILE 5.317A	**942-960** FIXED MOBILE 5.317A BROADCASTING 5.320
960-1 164	AERONAUTICAL MOBILE (R) 5.327A AERONAUTICAL RADIONAVIGATION 5.328	
1 164-1 215	AERONAUTICAL RADIONAVIGATION 5.328	

Regional and national management

- **The regional level is used for harmonization within a geographical area and sometimes to align policies**
  - Europe: CEPT/ECC – European Communications Committee - http://www.cept.org/ecc/
  - Asia: APT – Asia-Pacific Telecommunity - http://www.apt.int/
  - Africa: ATU – African Telecommunications Union - http://www.atu-uat.org/
  - America: CITEL – Inter-American Telecommunication Commission - https://www.citel.oas.org/

- **National regulatory authorities manage spectrum following three different models:**
  - Administrative model – Authority decides in much detail on the rights to use spectrum
  - Trading model – Spectrum is auctioned, especially used for mobile
  - Free model – Spectrum commons, like spectrum for WLAN

Frequency Allocations Table (FAT) – Sweden example

Allokerat band enligt ITU-RR	Allokerade tjänster enligt ITU-RR	Användning	Frekvensband	Duplexband	Anmärkning
890 - 942	FAST RADIO MOBIL RADIO UTOM LUFTFARTSRADIO 5.317A Radiolokalisering	Digitala cellulära system	880 - 915	925 - 960	Blocktillstånd Undantag från tillståndsplikt 2009/114/EG 2009/766/EG 2010/166/EU 2010/167/EU 2011/251/EU
		Övrigt	915 - 916		
		Kortdistansradio (SRD)	916 - 921		
		GSM-R	921 - 925	876 - 880	ECC/DEC/(02)05 ECC/DEC/(02)10
		Digitala cellulära system	925 - 960	880 - 915	Blocktillstånd Undantag från tillståndsplikt 2009/114/EG 2009/766/EG 2010/166/EU 2010/167/EU 2011/251/EU

890 – 942
Digital cellular
Short range devices
GSM-R

https://pts.se/globalassets/startpage/dokument/legala-dokument/foreskrifter/radio/ptsfs-2015_3-allmanna-rad-frekvensplanen.pdf

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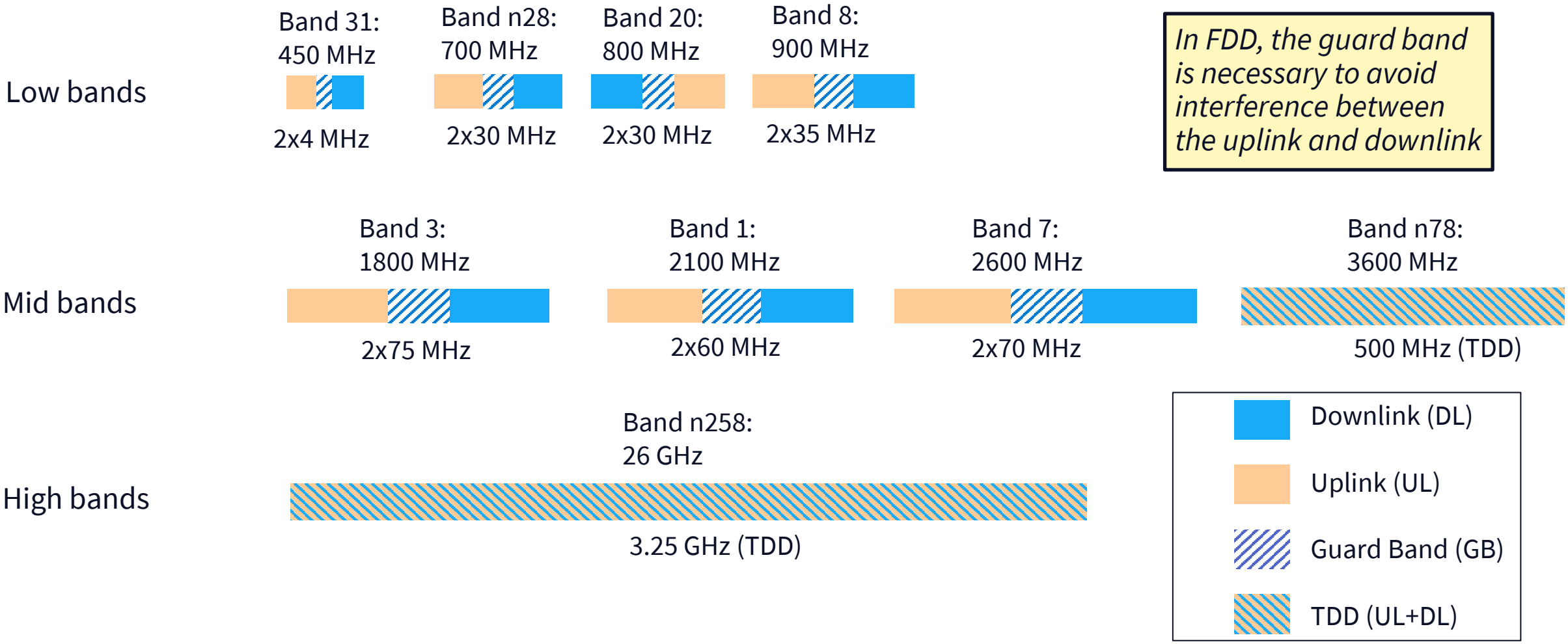
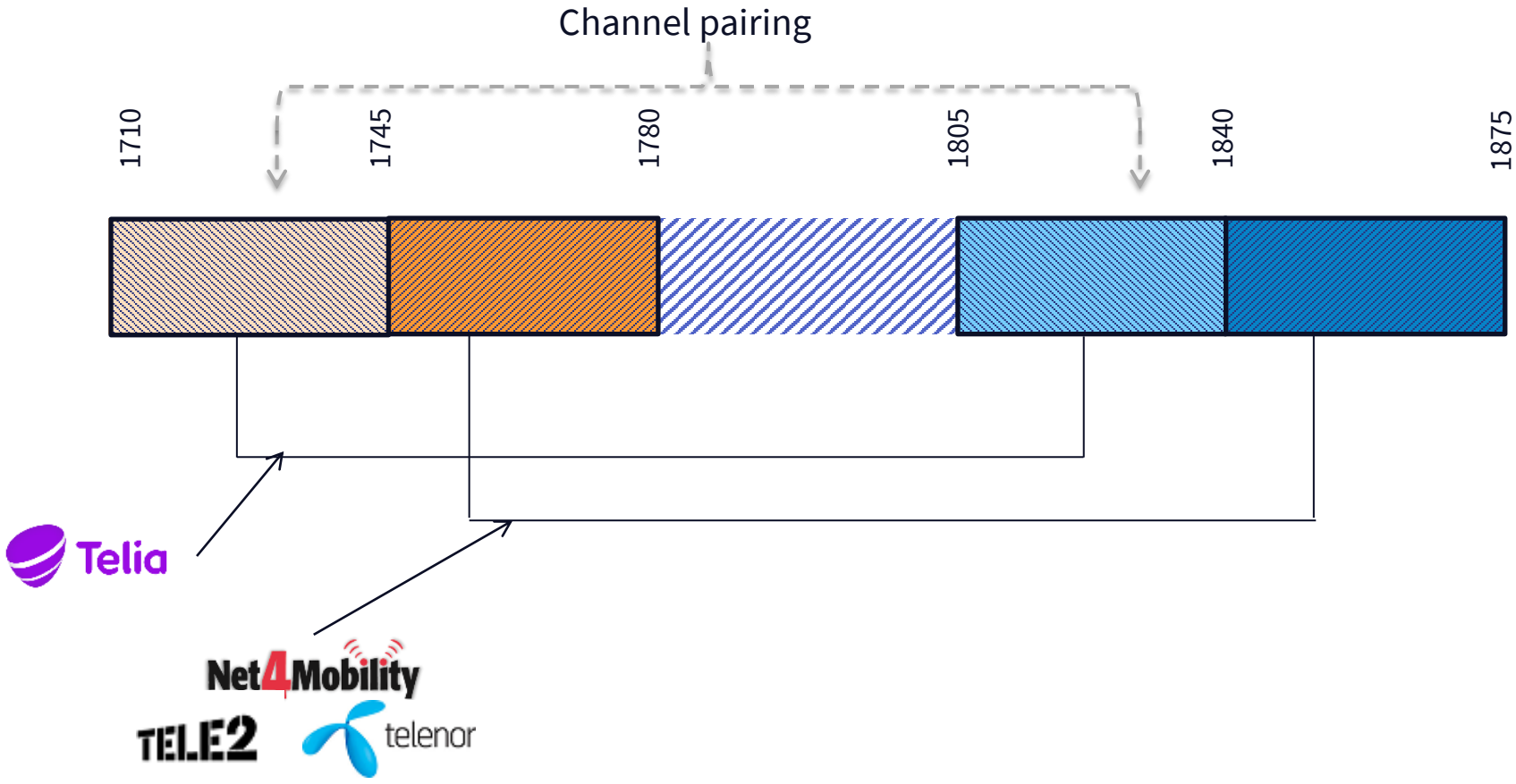
Main bands used for 2G – 5G; FDD and TDD (Europe)



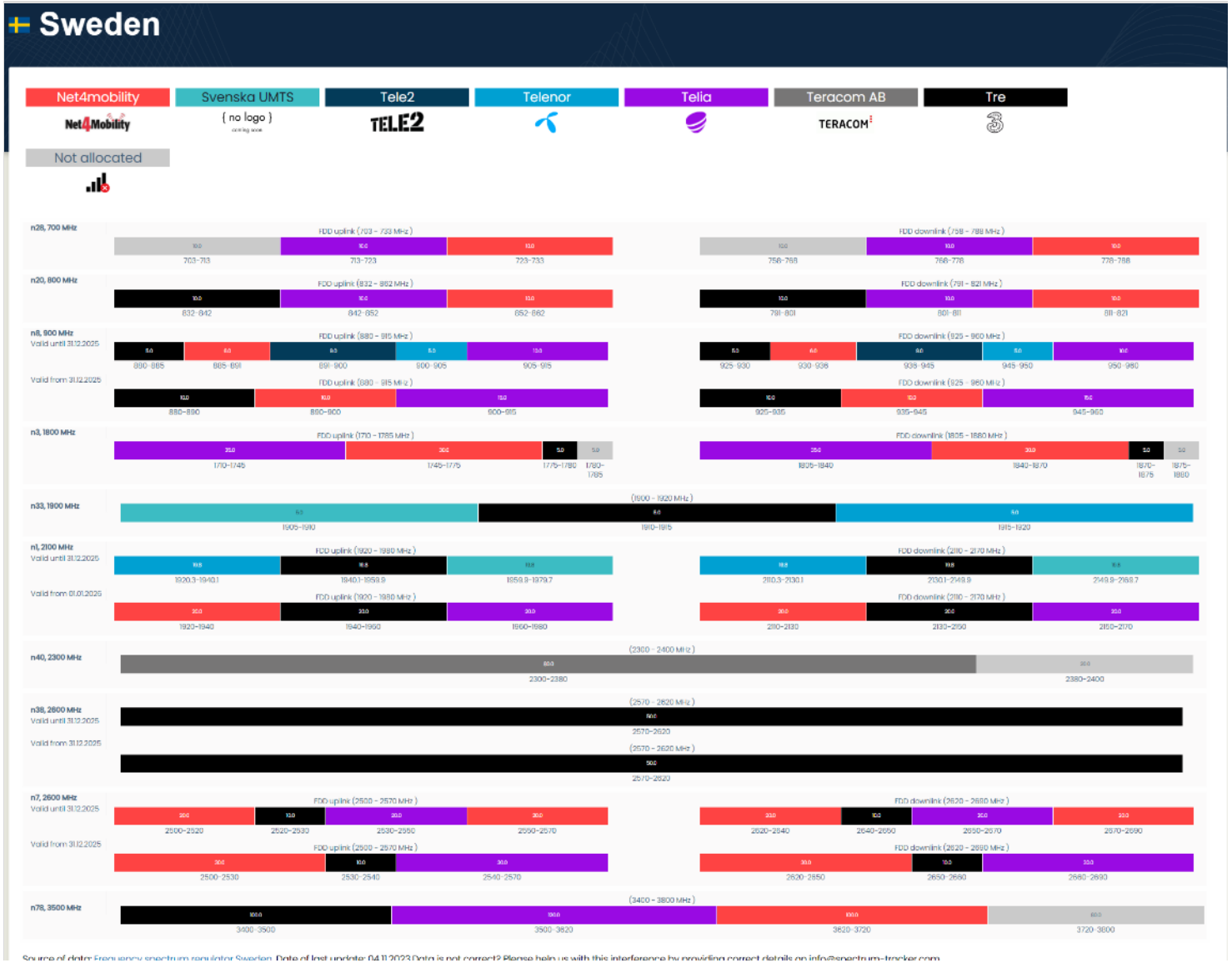
Assignments are given to several operators

Example: Band 3; 1800 MHz



Swedish frequency assignments

- Source: Spectrum tracker.com
  - https://www.spectrum-tracker.com/Sweden



Channel plan for mobile bands

- **Channel plan made by 3GPP (https://www.3gpp.org)**
- **Defines Channel numbers and frequencies for uplink and downlink**
  - 2G: ARFCN = Absolute Radio Frequency Channel Number
    - Channel raster = 200 kHz
  - 3G: UARFCN = UTRA Absolute Radio Frequency Channel Number
    - Channel raster = 200 kHz
  - 4G: EARFCN = E-UTRA Absolute Radio Frequency Channel Number
    - Channel raster = 100 kHz
  - 5G: NR-ARFCN = New Radio Absolute Radio Frequency Number
    - Channel raster = 15 kHz, 100 kHz, 60 kHz; dependent on specific band

- **Channel numbers are not the same for 2G, 3G, 4G or 5G in the same bands**
  - ARFCN ≠ UARFCN ≠ EARFCN ≠ NR-ARFCN

Example, channel numbering

Band 8, «900 MHz»	**Channel number range (N_{UL}/N_{DL})**	**Formula**	**Frequency range, UL/DL (MHz)**
4G/LTE [1)]	20750 – 21449 (EARFCN)	$F_{UL} = 2500+0.1*(N_{UL}-20750)$	**2500.0 – 2569.9 MHz**
	2750 – 3449 (EARFCN)	$F_{DL} = 2620+0.1*(N_{DL}-2750)$	**2620.0 – 2689.9 MHz**
Band n78, «3.6 GHz»	**Channel number range (N_{REF})**	**Formula**	**Frequency range, TDD (MHz)**
5G NR [2)]	620000 – 653333 (NR-AFRCN)	$F_{REF} = 3000+0.015*(N_{REF}-600000)$	**3300.0 – 3800.0 MHz**

1) 3GPP TS 36.104
2) 3GPP TS 38.101

The details on how the channel numerology is defined are found in the relevant 3GPP documents on www.3gpp.org

Channel numbering plan for LTE

Most common bands in Europe:

E-UTRA Operating Band	Downlink			Uplink		
	F_{DL_low} [MHz]	$N_{Offs-DL}$	Range of N_{DL}	F_{UL_low} [MHz]	$N_{Offs-UL}$	Range of N_{UL}
1	**2110**	**0**	**0 – 599**	**1920**	**18000**	**18000 – 18599**
3	**1805**	**1200**	**1200 – 1949**	**1710**	**19200**	**19200 – 19949**
7	**2620**	**2750**	**2750 – 3449**	**2500**	**20750**	**20750 – 21449**
8	**925**	**3450**	**3450 – 3799**	**880**	**21450**	**21450 – 21799**
20	**791**	**6150**	**6150 - 6449**	**832**	**24150**	**24150 - 24449**

Source: 3GPP TS 36.104, see: https://www.3gpp.org/specifications-technologies/specifications-by-series

5G NR frequency bands

Frequency range designation		Corresponding frequency range
FR1		410 MHz – 7125 MHz
FR2	FR2-1	24250 MHz – 52600 MHz
	FR2-2	52600 MHz – 71000 MHz

FR1 (examples):

NR operating band	Uplink (UL) *operating band* BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) *operating band* BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD

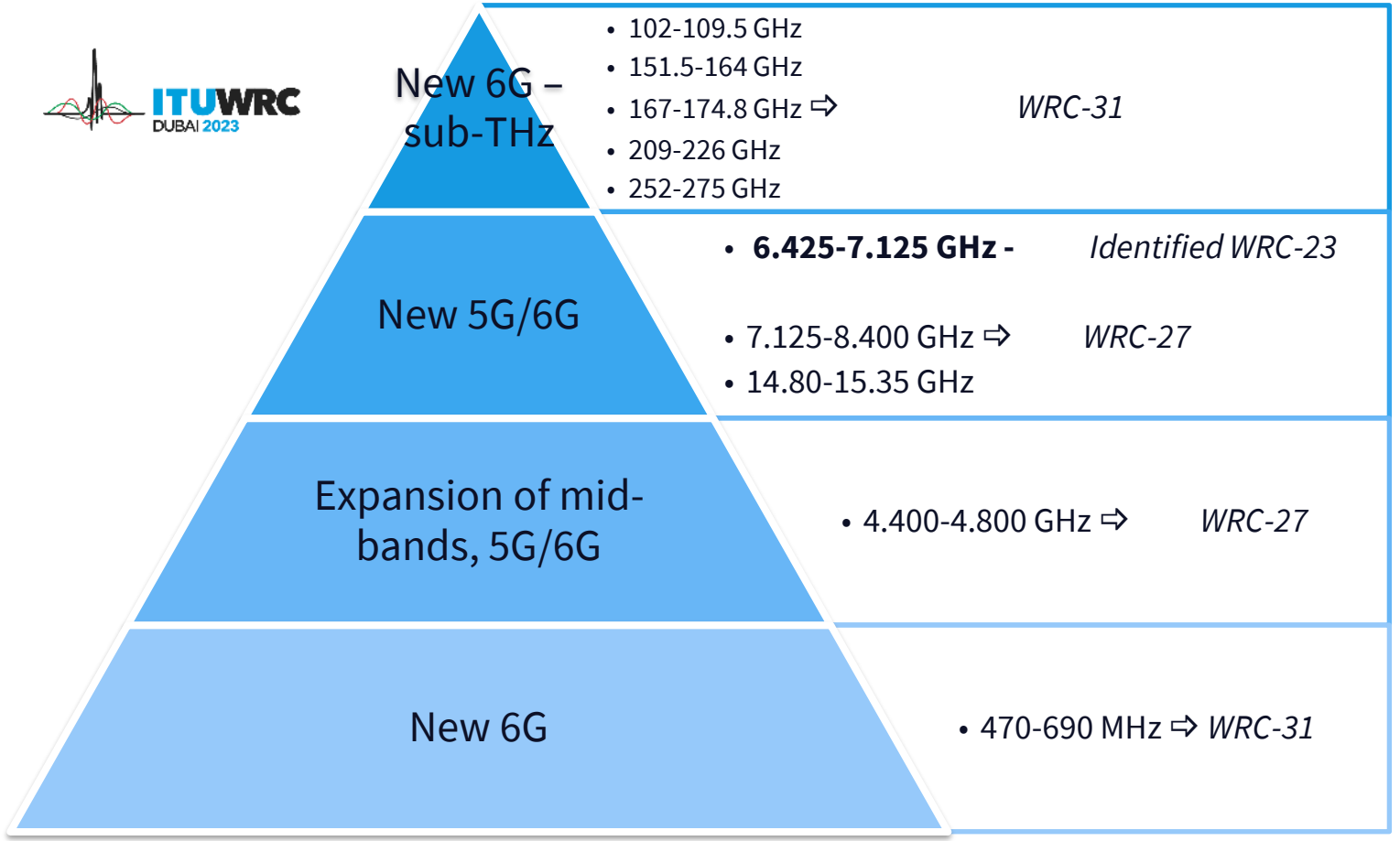
FR2 (examples):

Operating Band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}	
n257	26500 MHz – 29500 MHz	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	TDD
n259	39500 MHz – 43500 MHz	39500 MHz – 43500 MHz	TDD
n260	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	TDD

Source: 3GPP TS 38.104, see: https://www.3gpp.org/specifications-technologies/specifications-by-series

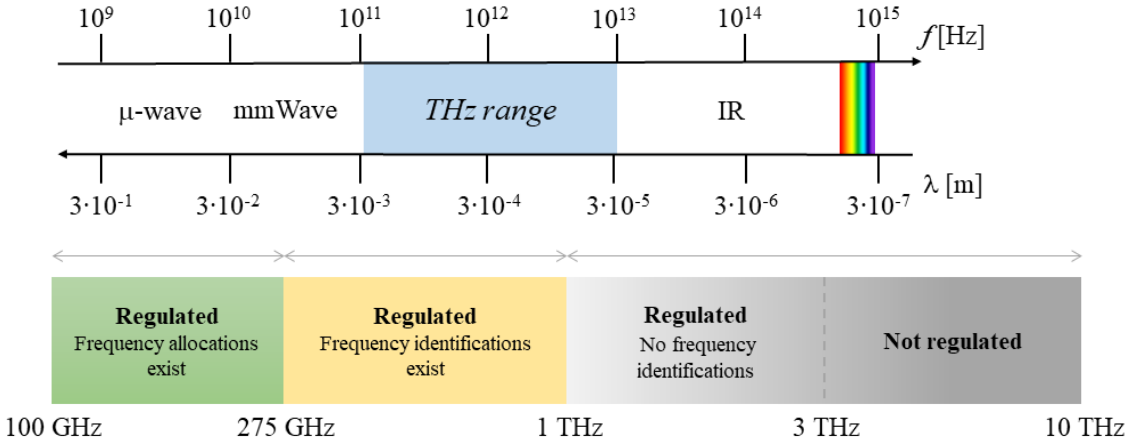
More spectrum for IMT identified and for study

- **6.425-7.125 GHz has been identified for IMT at WRC-23**
- Further bands will be studied towards coming World Radio Conferences for possible IMT identifications

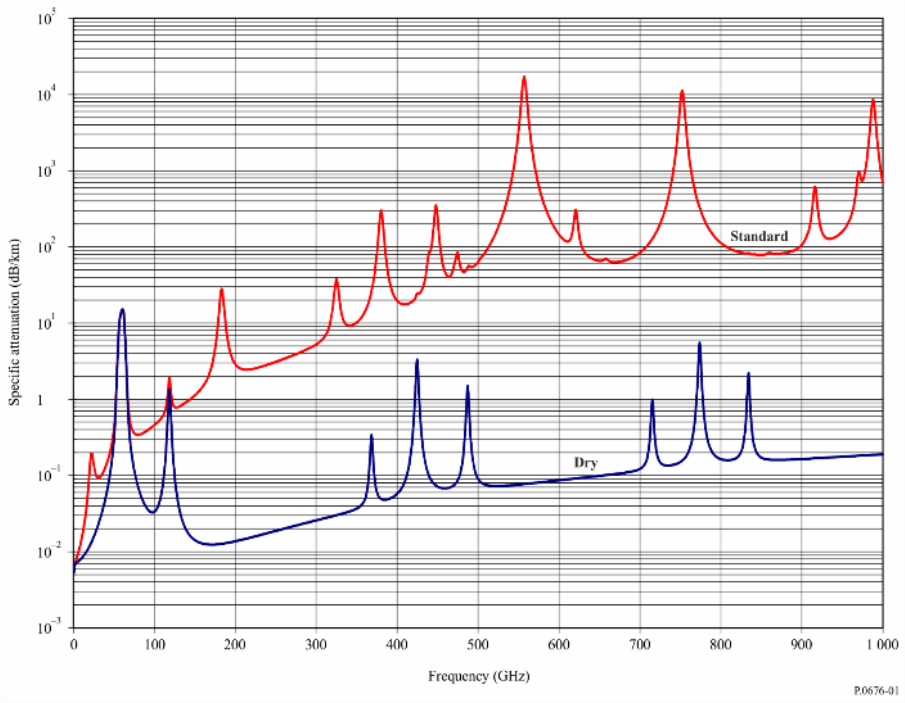


Beyond 5G and towards 6G – approaching THz

- **Frequencies above 100 GHz are being explored for 6G**
- 580 GHz of spectrum has been identified as interesting:
  - 8 bands in the range 100-275 GHz
  - 12 bands in the range 275-1000 GHz
  - Spectrum above 1000 GHz is free to use
- IEEE 802.15.3d: High Data Rate Wireless Multi-Media Networks, 252-450 GHz
  - Data rates up to 100 Gb/s using BW between 2.16 and 69.12 GHz



Source: ETSI GR THz 002 V1.1.1 (2024-03): «TeraHertz technology (THz); Identification of frequency bands of interest for THz communication systems».
https://www.etsi.org/deliver/etsi_gr/THz/001_099/002/01.01.01_60/gr_THz002v010101p.pdf



Specific attenuation due to atmospheric gases
(Source: ITU-R Rec P.676-13. "Attenuation by atmospheric gases and related effects", August 2022.)

Assigning spectrum to mobile operators by auctions:
Example: Swedish 900 MHz, 2.1 and 2.6 GHz auctions

PTS

Industry

PTS > News > Press releases > 2023 >

4.23 BSEK = 360 M€;

360 M€/330 MHz/10 M (Pop) = 0.11 €/MHz/Pop

The auction in the 900 MHz, 2.1 GHz and 2.6 GHz bands is concluded

9/21/2023

Three bidders won licences in all frequency bands 900 MHz, 2.1 GHz and 2.6 GHz. The total auction proceeds amount to just over 4.23 billion SEK.

After 3 days of auction and 26 clock rounds, the auction in the 900 MHz, 2.1 GHz and 2.6 GHz bands is concluded. Three bidders won licences. The total auction proceeds amount to 4.23 billion SEK, which goes to the treasury.

- We see that there is a spread of spectrum holdings, which provides good conditions for good end consumer competition. We also see that the auction has worked well as a tool for distributing frequencies, says Dan Sjöblom, PTS' Director-General.

Telia Sverige AB, Hi3G Access AB and Net4Mobility HB won licences in the auction as follows:

https://pts.se/en/news/press-releases/2023/the-auctions-in-the-900-mhz-2.1-ghz-and-2.6-ghz-bands-are-concluded/

Telia Sverige AB, Hi3G Access AB and Net4Mobility HB won licences in the auction as follows:

Bidder	Licence (quantity and band)	Auction proceeds per frequency band: (SEK)
Telia Sverige AB	2×15 MHz i 900 MHz-bandet	833 176 563
	2×20 MHz i 2,1 GHz-bandet	190 468 456
	2×30 MHz i 2,6 GHz-bandet	528 815 766
Hi3G Access AB	2×10 MHz i 900 MHz-bandet	701 564 274
	2×20 MHz i 2,1 GHz-bandet	190 468 456
	2×10 MHz samt 40 MHz (TDD) i 2,6 GHz-bandet	319 471 922
Net4Mobility HB	2×10 MHz i 900 MHz-bandet	755 451 044
	2×20 MHz i 2,1 GHz-bandet	190 468 456
	2×30 MHz i 2,6 GHz-bandet	528 815 766

The value of an amount of spectrum

- **Case Example – Mobile Broadband in Oslo:**
  - Urban part of Oslo: Area: 135 km^2; Population: 600.000 people
  - Expected penetration: 40%
  - Average usage in peak hour: 500 kbit/s (downlink, mobile receive)

Different investments can give you the same performance. Which one is most optimal?

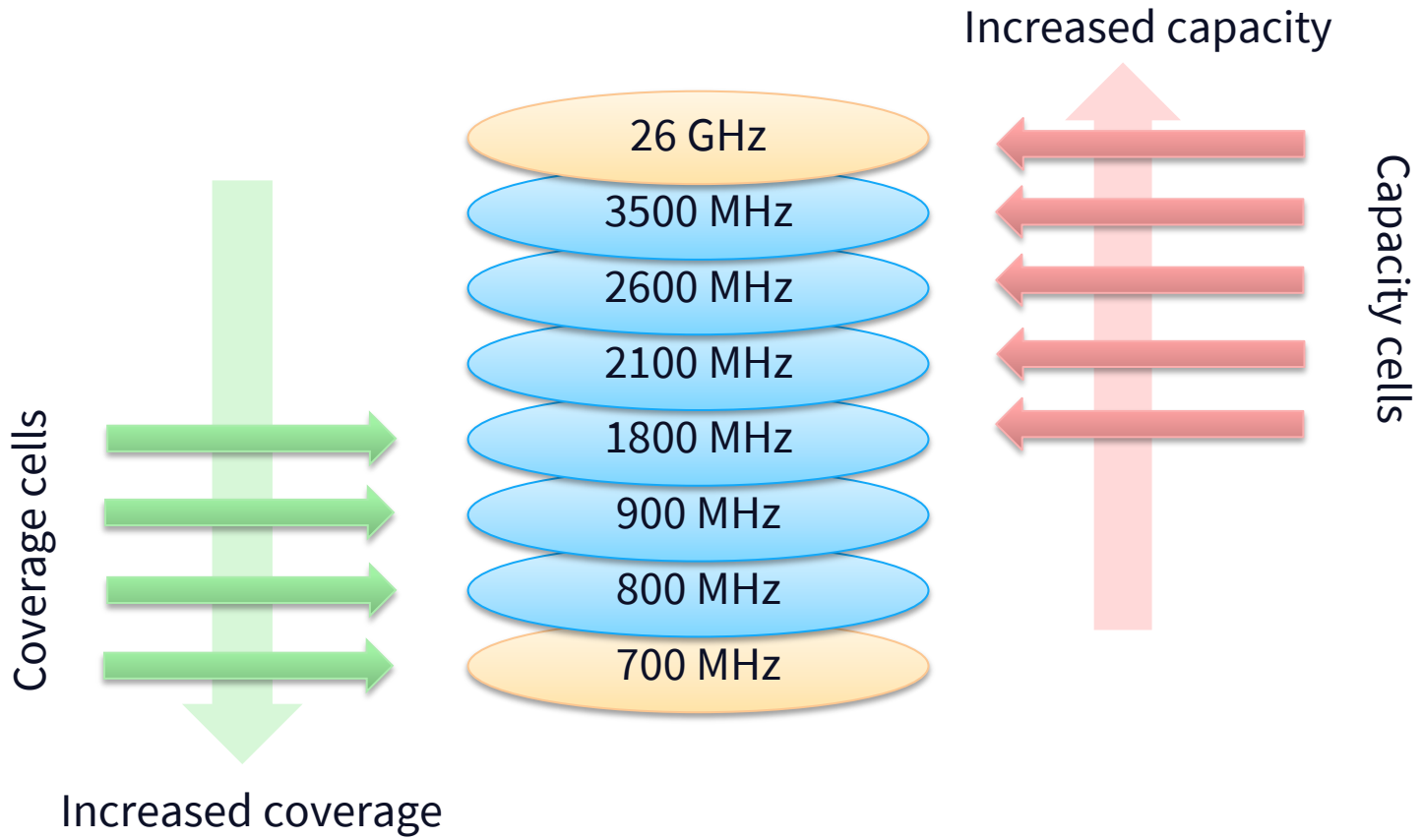
- **Case 1 – 2x40 MHz spectrum:**
  - Traffic / site: 96 Mb/s
  - Number of sites needed: 1250

- **Case 2 – 2x60 MHz spectrum:**
  - Traffic / site: 144 Mb/s
  - Number of sites needed: 833

- **Conclusion:**
  - (provided Case 1 is profitable) The value of the additional 2x20 MHz spectrum in this example is equal to the cost of 417 sites (1250-833)

Spectrum strategies and site planning

- Two main considerations must be taken into account when deploying spectrum on radio sites:
  - Capacity
  - Coverage
- A suitable combination of bands make sure both requirements are met.



Regulations restricts out-of-band emissions

- Adjacent Channel Leakage power Ratio – ACLR
  - the ratio of the filtered mean power centred on the assigned channel frequency to the filtered mean power centred on an adjacent channel frequency
    - Table 6.6.2.1-1: Base Station ACLR in paired spectrum (Source: 3GPP TS 36.104)

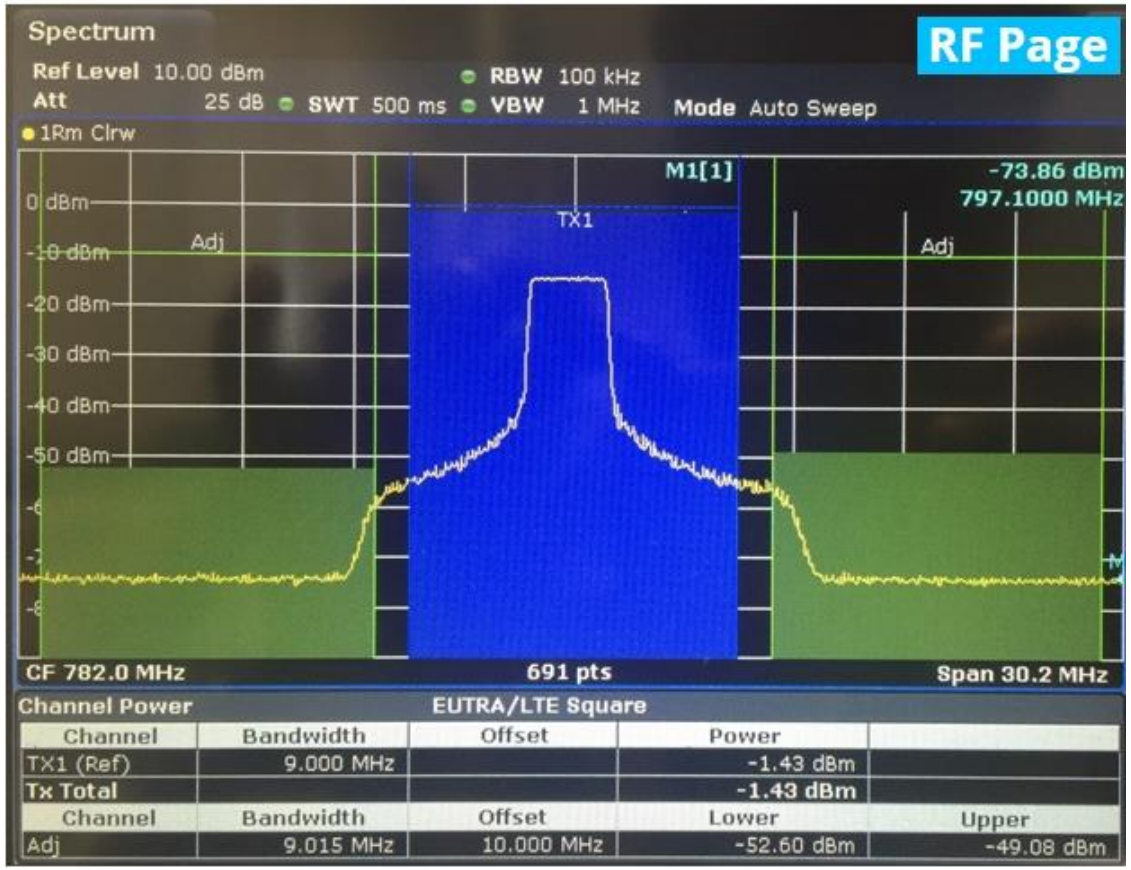
EXAMPLE

Channel bandwidth of E-UTRA lowest/highest carrier transmitted $BW_{Channel}$ [MHz]	BS adjacent channel centre frequency offset below the lowest or above the highest carrier centre frequency transmitted	Assumed adjacent channel carrier (informative)	Filter on the adjacent channel frequency and corresponding filter bandwidth	ACLR limit
1.4, 3.0, 5, 10, 15, 20	$BW_{Channel}$	E-UTRA of same BW	Square (BW_{Config})	45 dB
	2 x $BW_{Channel}$	E-UTRA of same BW	Square (BW_{Config})	45 dB
	$BW_{Channel}$ /2 + 2.5 MHz	3.84 Mcps UTRA	RRC (3.84 Mcps)	45 dB
	$BW_{Channel}$ /2 + 7.5 MHz	3.84 Mcps UTRA	RRC (3.84 Mcps)	45 dB

NOTE 1: $BW_{Channel}$ and BW_{Config} are the channel bandwidth and transmission bandwidth configuration of the E-UTRA lowest/highest carrier transmitted on the assigned channel frequency.

NOTE 2: The RRC filter shall be equivalent to the transmit pulse shape filter defined in TS 25.104 [6], with a chip rate as defined in this table.

Adjacent Channel Leakage power Ratio – ACLR



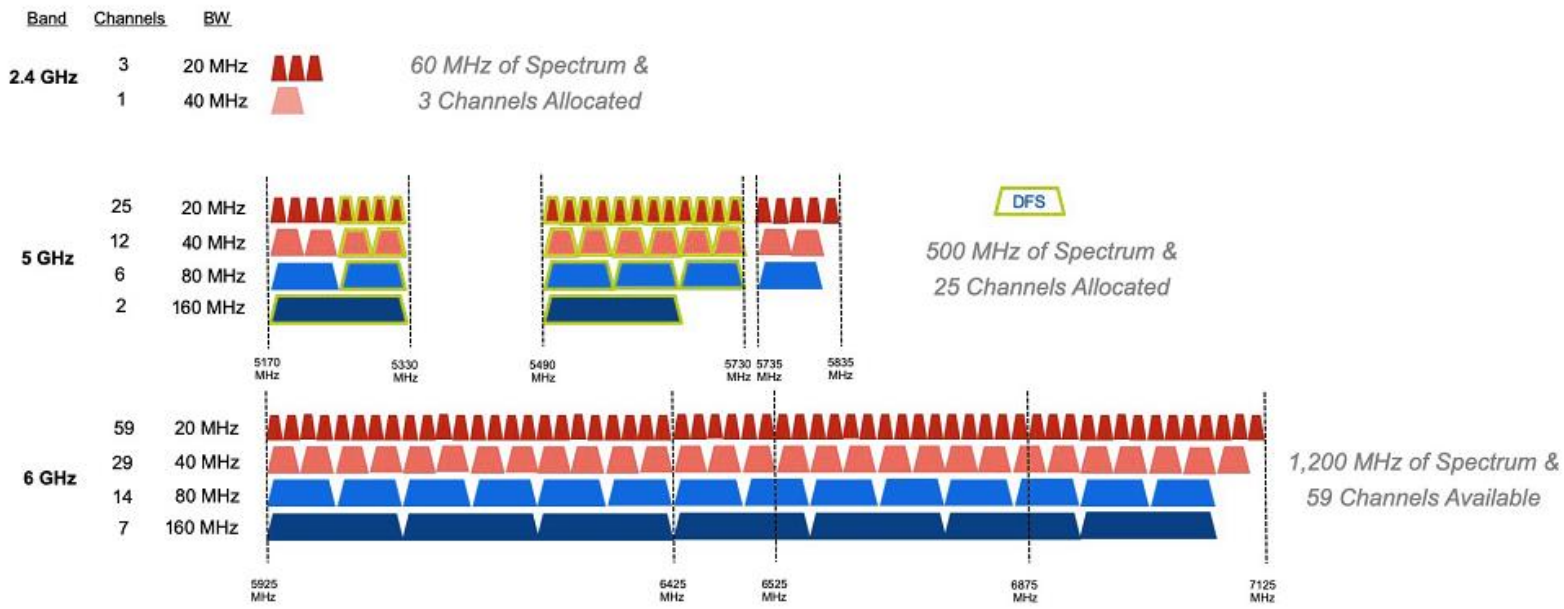
- The unwanted frequency generated by second or third order intermodulation distortion of the devices which fall near to the transmitting frequency band.
- Cause distortion in other neighboring channel's transmission
- Affects the system efficiency.
- ACLR measured with a reference transmit signal

  – Source: https://www.rfpage.com/aclr-measurement-in-lte/

Unlicensed spectrum – commons

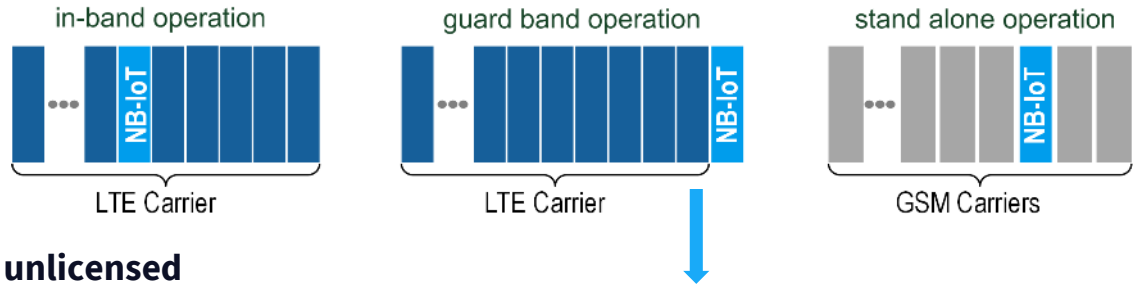
EXAMPLES

- **ISM-bands (Industrial, Scientific and Medicine) – mostly global**
  - 2.4-2.5 GHz: Wi-Fi, Bluetooth, etc.
  - 5.725–5.875 GHz: Wi-Fi
  - 433 MHz: e.g remote control (car keys, etc.)
- *NEW :* 5.925-7.125 GHz: Wi-Fi 6e
- **U-NII-bands (Unlicensed National Information Infrastructure) – USA**
  - 5.150-5.725 GHz: Wi-Fi
- This spectrum is shared among the users based on a few simple rules
- There is no need for a license to use this spectrum as long as the basic rules are respected:
  - Power (EIRP) and power spectrum density constraints:
    - E.g 100 mW for the 2.4 GHz band; 200 mW – 1 W for the 5 GHz bands



Spectrum for Internet of Things - IoT

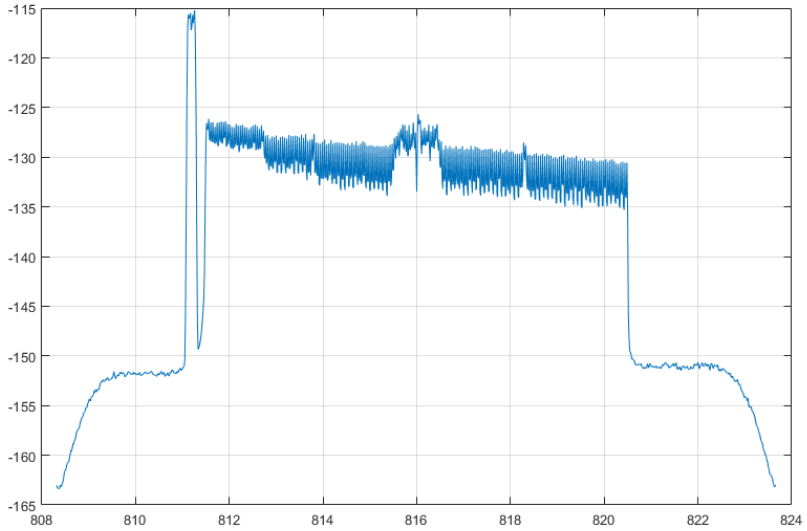
- **Cellular IoT technologies will use parts of the licensed bands**
  - Long Term Evolution for Machines (eMTC/LTE-M)
  - Narrowband IoT (NB-IoT)



- **Proprietary Low Power Wide Area Network (LPWAN) technologies use unlicensed bands:**
  - Europe: 867 – 869 MHz
  - US: 902 – 928 MHz
  - China: 470 – 510 MHz
  - Japan, Korea: 920 – 925 MHz

LoRa Alliance

sigfox



- **Example**:
  - *LoRa and LoRaWAN*: An LPWAN global standard for carrier-operated networks, adopted by the LoRa Alliance
  - *SIGFOX*: A French company building wireless networks to connect low energy objects

Spectrum in a wider context – a 6G perspective
Future goals for spectrum use:

- **Provide additional capacity**: Ideally the spectrum to be made available will be enough using the existing grid of base stations, reducing the cost of identifying, acquiring and deploying additional base station sites by operators
- **Support high data rate services**: new services such as XR and holographic presence require the support of high data rates. For high data rates, large bandwidths are needed. These large bandwidths are typically easier to find in higher frequency ranges
- **Support mobility:** Spectrum is needed that can combine high data rates and the continuous coverage that is required for mobility.

  – Source: Stefan Wendt etal.: "Environmental, social and economic drivers and goals for 6G". Hexa-X-II Deliverable D1.1. https://hexa-x-ii.eu/wp-content/uploads/2023/07/Hexa-X-II_D1.1_final-website.pdf

- **Support wide area coverage:** 6G should be available everywhere, and with service continuity (when user/device is moving). For wide area coverage, lower frequency ranges are more suitable due to radio wave propagation characteristics
- **Provide indoor coverage:** new high data rate applications like mobile AR/VR communication and gaming are expected to also be used indoors, increasing the volumes of indoor mobile data
- **Service continuity**: mobile data applications increasingly require seamless continuation of connectivity travelling across e.g., outdoor-indoor, urban-rural, private-public situations.
- **Enable positioning and sensing**: Joint sensing and communication may be new technology advancements in 6G. Both base stations and mobile devices can be transmitters and/or receivers. In general, higher frequency ranges imply more accurate positioning and sensing

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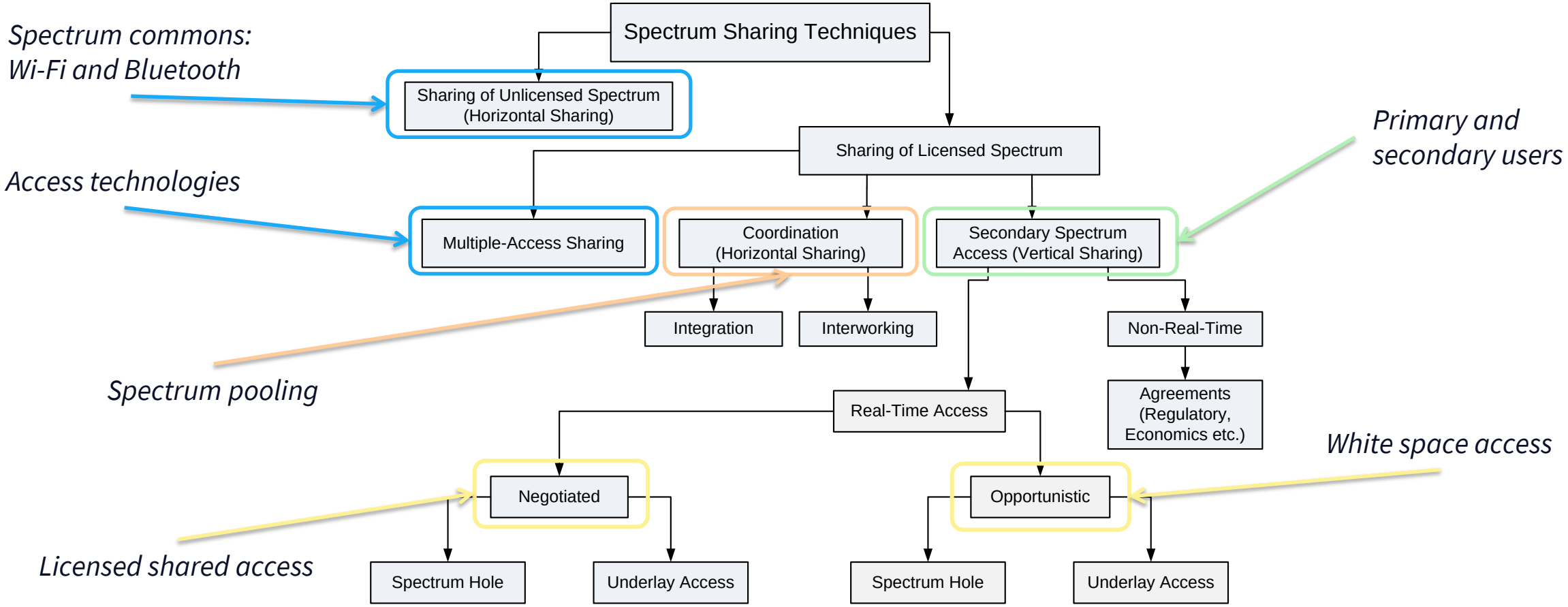
Future trends: Spectrum sharing and trading



- Source: Wyglinski A M., Nekovee M., Hou Y T. *Cognitive Radio Communications and Networks*. Academic Press (Elsevier), MA, USA. 2010. ISBN 978-0-12-374715-0.

Regulatory options for spectrum licensing

Individual authorisation (Individual rights of use)		**General authorisation** (No individual rights of use)	
Individual licence	**Light-licensing**		**Licence-exempt**
• Individual frequency planning / coordination • Traditional procedure for issuing licences	• Individual frequency planning / coordination • Simplified procedure compared to traditional procedure for issuing licences • With limitations in the number of users	• No individual frequency planning / coordination • Registration and/or notification • No limitations in the number of users nor need for coordination	• No individual frequency planning / coordination • No registration nor notification

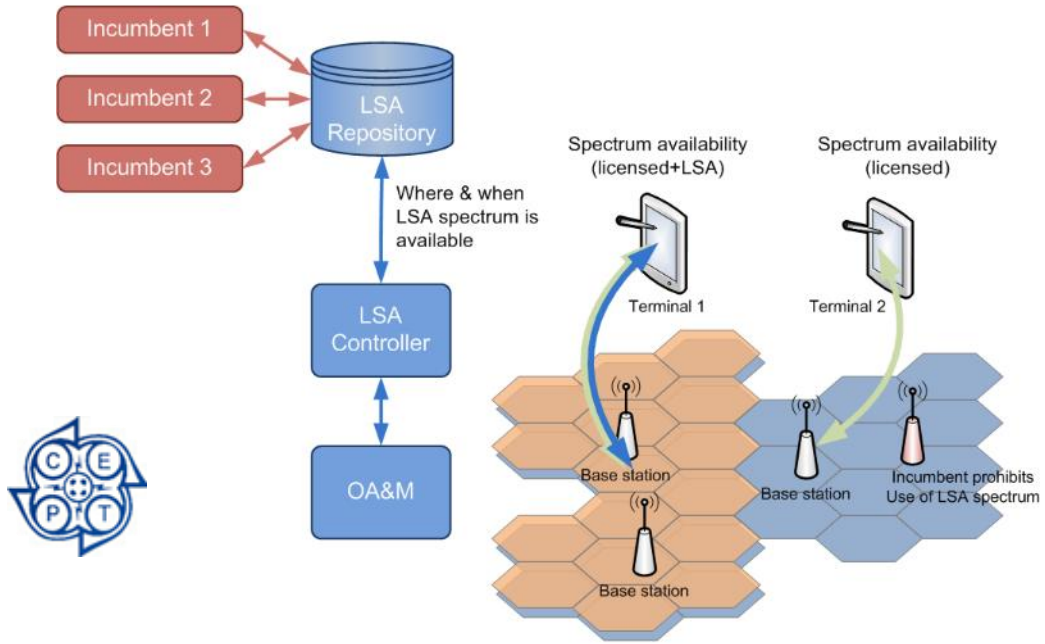
More regulations

Less regulations

Source: ECC Report 132: «Light licensing, License-exempt and Commons», Electronic Communications Committee, Moscow 2009

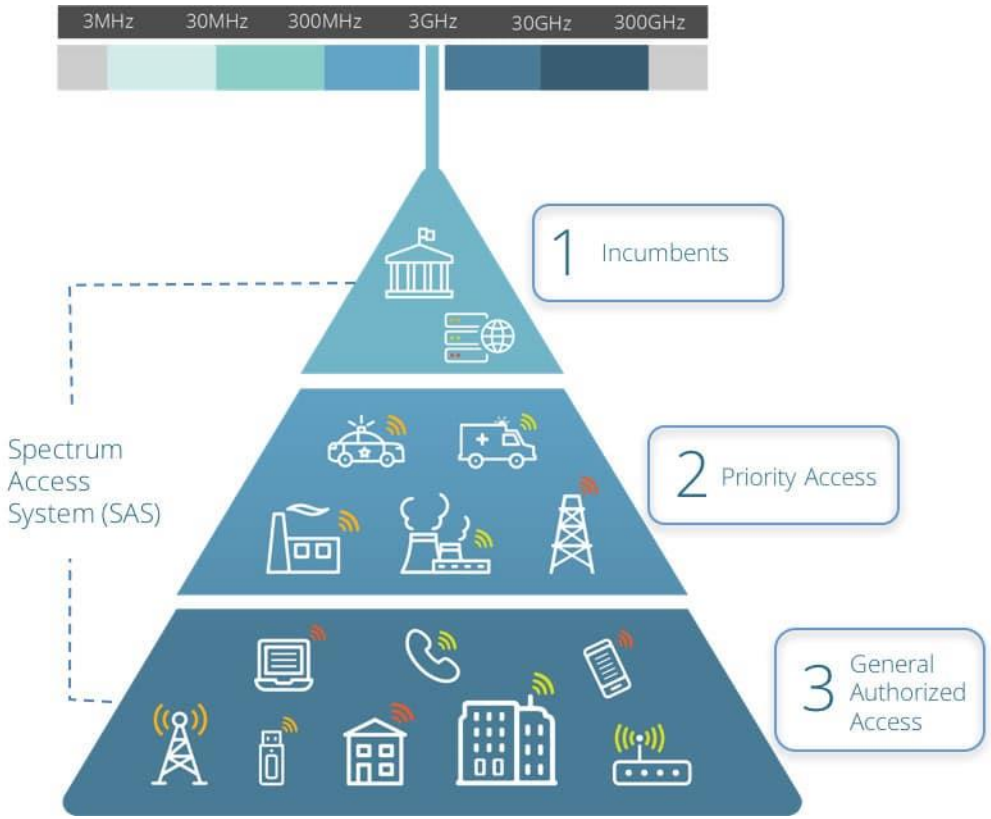
Examples of Secondary Spectrum Access (1)

- **Licensed Shared Access (LSA)**
  - A framework to share spectrum between a limited amount of users
  - The existing spectrum user(s) (“the incumbent(s)”) would share spectrum with one or several licensed LSA users (”LSA licensee(s)”) in accordance with a set of pre-defined conditions
  - Several European trials in the 2.3 GHz band
    - Spain, Italy, France Finland, The Netherlands, Portugal – 2015-2019
  - Implementations:
    - The Netherlands, 2019: PMSE booking in the 2.3-2.4 GHz band
      - (PMSE: Program Making and Special Events)

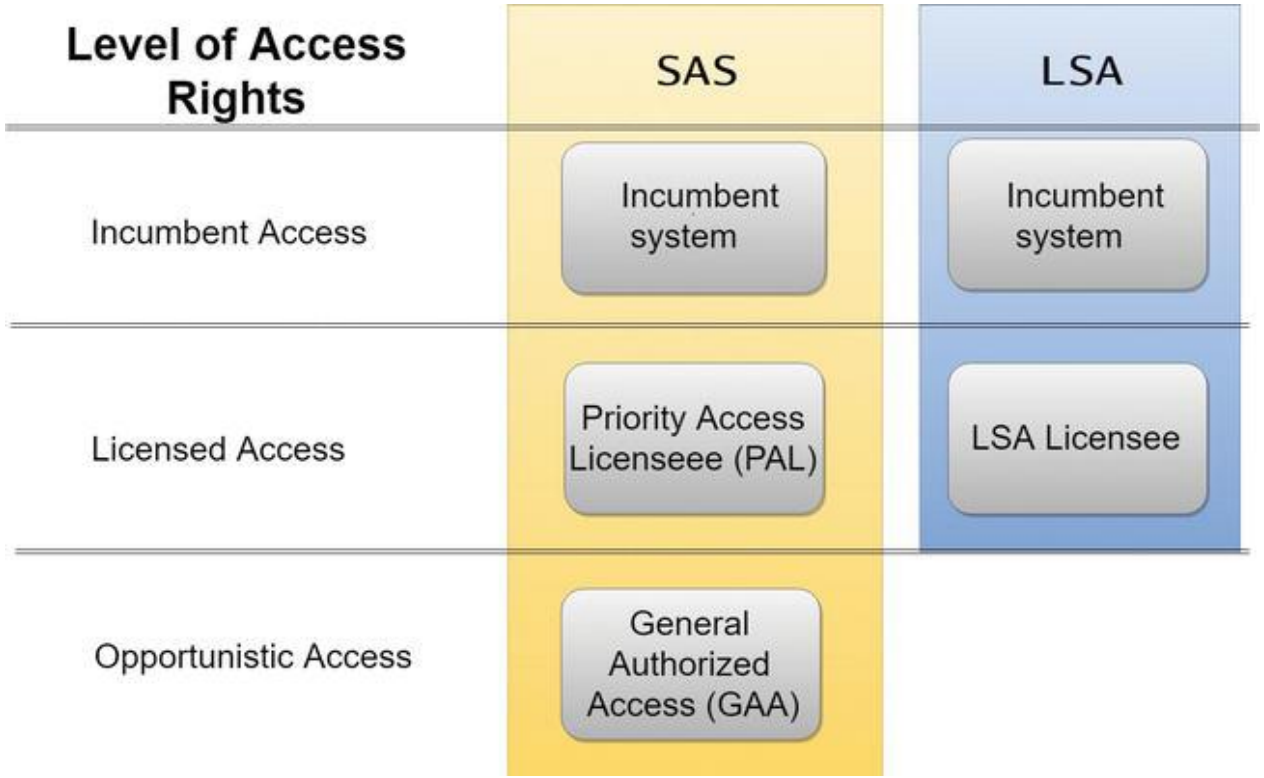


Examples of Secondary Spectrum Access (2)

- **Spectrum Access System (SAS)**
- Citizens Broadband Radio Services (CBRS)
  - FCC Three-tier approach - 2015 in the frequency range: 3550-3700 MHz,.
  - The novel three-tier sharing framework coordinates spectrum access among the incumbent military radars, satellite earth stations, and new commercial users.
  - Spectrum Access System (SAS) works as the spectrum controller
  - The three tiers of use are Incumbent, Priority Access License (PAL), and General Authorized Access (GAA).



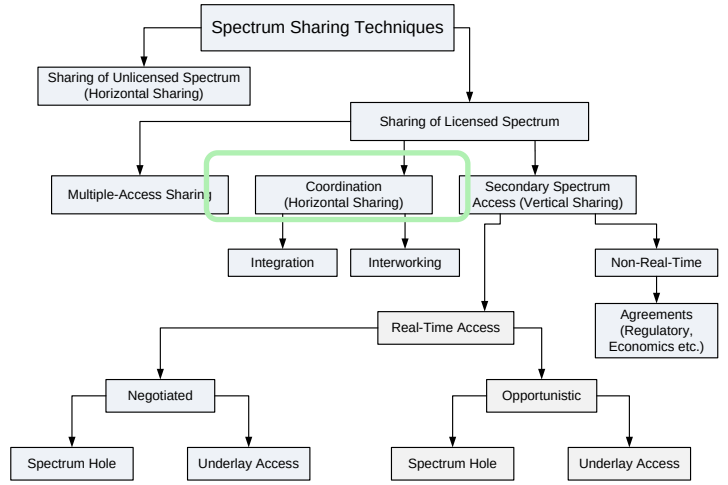
Comparing SAS and LSA sharing models



- J. Kalliovaara, T. Jokela, H. Kokkinen, and J. Paavola, "Licensed Shared Access Evolution to Provide Exclusive and Dynamic Shared Spectrum Access for Novel 5G Use Cases", in *Cognitive Radio in 4G/5G Wireless Communication Systems*. London, United Kingdom: IntechOpen, 2018 [Online]. Available: https://www.intechopen.com/chapters/62440, doi: 10.5772/intechopen.79553

Spectrum pooling

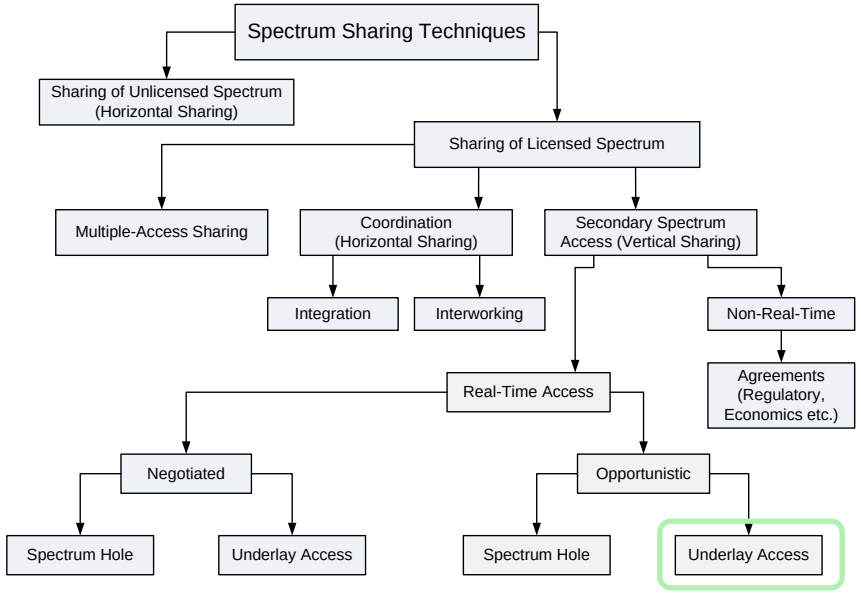
- Network sharing among operators are becoming commonplace
  - The next step in providing more cost-efficient networks
  - Operators share a common network infrastructure: base stations, etc.
- Network sharing can be done on several levels:
  - Site sharing, RAN sharing, shared core etc.



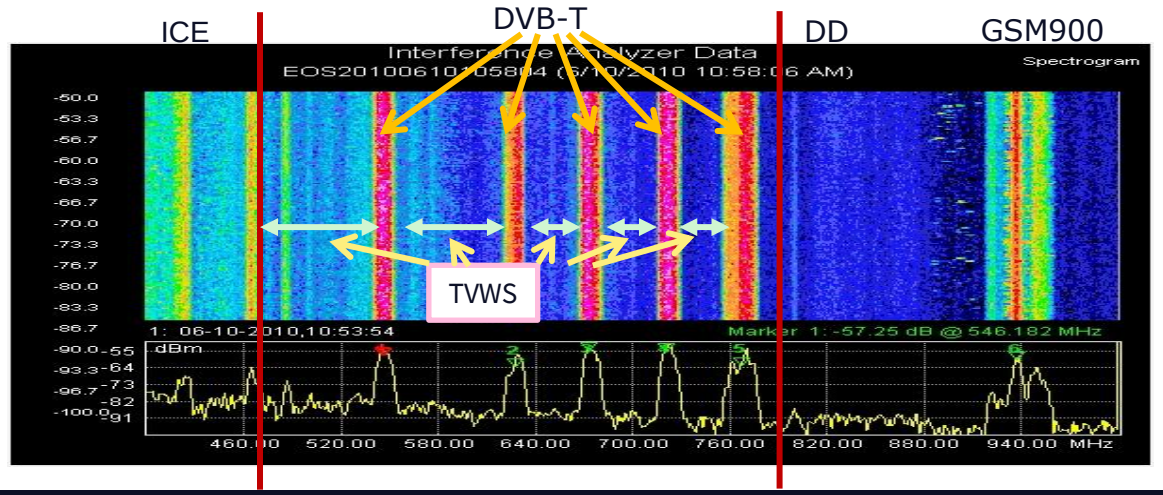
- Spectrum sharing can be a part of it, if the national regulator allows
  - This is called *spectrum pooling*
- Telenor and Tele2 are sharing network and spectrum in Sweden through the joint venture Net4Mobility (700, 800, 900, 1800, 2600, 3500 MHz bands).

Opportunistic access

- **«White Space» access**
  - 'White Space' is a label indicating a part of the spectrum, which is available for a radiocommunication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis (CEPT Report 24).
- **Primary and secondary users**
- Spectrum holes are identified by use of a database, possibly assisted by sensing
  - Secondary user must not interfere with primary user
- Allowed in the UK and US for the TV-band: 470 – 790 MHz
- Commercial spectrum databases are driven on a licensed basis:
  - E.g. Google and Microsoft



Spectrum scan – Oslo - 2010



Spectrum trading

- Current practices in spectrum trading (CEPT/ECC):
  - "General authorizations" is basically the type of regulation used for licence-exempt bands like the 2.4 GHz ISM band.
    - Frequency bands under general authorization are not tradable.
  - "Individual right of use" is what commonly is referred to as licensed bands, like e.g. the IMT bands.
    - Legal frameworks for spectrum rights are regulated at the national level.
    - Within EU, "rights of use" are transferrable and there is a harmonised regulatory framework in the context of Electronic Communications Networks & Services (ECN&S).
    - The framework also distinguishes between trading and leasing with a focus on trading.
- In Europe, 18 of the 22 CEPT countries allow trading of usage rights. It has been allowed since 1997 (in Denmark) and most of the other countries opened for this between 2002 and 2006.

CEPT/ECC. *Description of Practices Relative to Trading of Spectrum Rights of Use*. ECC Report 169. Paris, May 2011.

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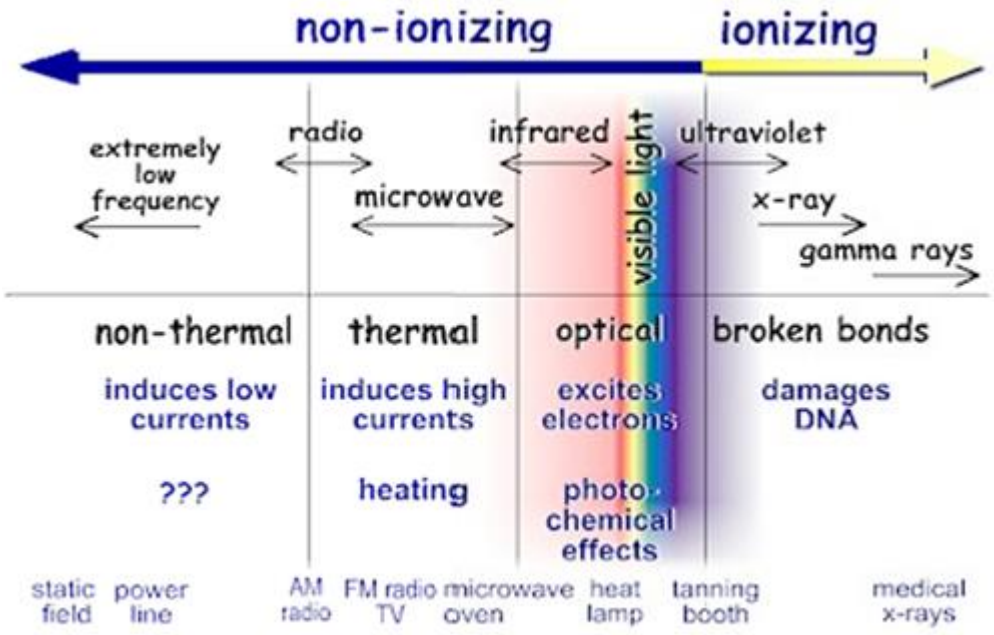
EMF = Electromagnetic Fields

- Are electromagnetic fields dangerous to the health?



By Glenna Shields, U.S. Environmental Protection Agency. - Types of Radiation in the Electromagnetic Spectrum. U.S. Environmental Protection Agency (EPA). Archived from the original on 2002-10-19., Public Domain, https://commons.wikimedia.org/w/index.php?curid=30252375

The New York Times

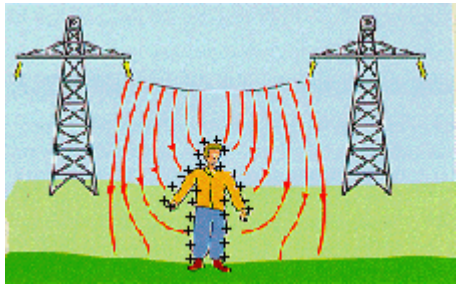
The 5G Health Hazard That Isn't

How one scientist and his inaccurate chart led to unwarranted fears of wireless technology.

Golden Cosmos

What happens when you are exposed to electromagnetic fields?

- Both electric and magnetic fields induce *voltages and currents in the body* but even directly beneath a high voltage transmission line, the induced currents are very small compared to thresholds for producing shock and other electrical effects



- *Heating* is the main biological effect of the electromagnetic fields of radiofrequency fields. (In microwave ovens this fact is employed to warm up food.)
- The heating effect of radiowaves forms the underlying basis for current guidelines

World Health Organization

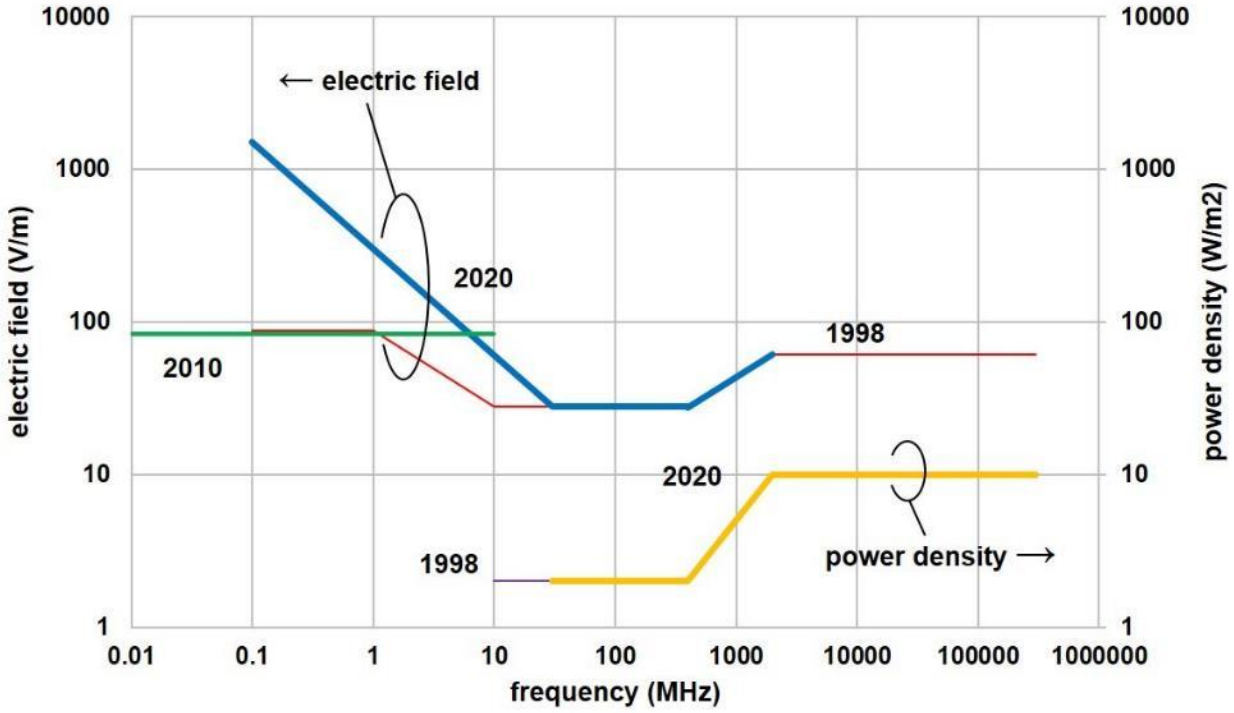
Main source: World Health Organization (WHO): https://www.who.int/peh-emf/en/

What are safe exposure limits and who makes them?

- Who decides on guidelines?
  - Countries set their own national standards for exposure to EMF
    - Sweden: Strålsäkerhetsmyndigheten; https://www.stralsakerhetsmyndigheten.se/
  - Majority follows guidelines set by the *International Commission of Non-Ionizing Radiation Protection* (ICNIRP); https://www.icnirp.org/.
    - ICNIRP is an NGO recognized by WHO

- What are guidelines based on?
  - Not a precise line between safety and hazard
  - To date, the only health effect from RF fields identified in scientific reviews has been related to an increase in body temperature (> 1 °C)
    - Exposure at very high field intensity found only in certain industrial facilities, such as RF heaters
  - Safety margins used in defining the exposure limits:
    - Factor 10 for workers (1/10, 10 %),
    - Factor 50 for the public (1/50; 2 %)

EMF limiting guidelines defined by ICNIRP



Whole body average reference levels for the general public for the ICNIRP (1998), ICNIRP (2010) and ICNIRP (2020) guidelines, for the 100 kHz to 300 GHz frequency range. Note that the units of the two y-axes (i.e. electric field and power density) are independent of each other. (Source: ICNIRP: https://www.icnirp.org/en/differences.html)

	Mobile phone base station frequency		Microwave oven frequency
Frequency	900 MHz	1.8 GHz	2.45 GHz
	Power density (W/m^2)		
Public exposure limits (1x)	4.5	9	10
Occupational exposure limits (5x)	22.5	45	

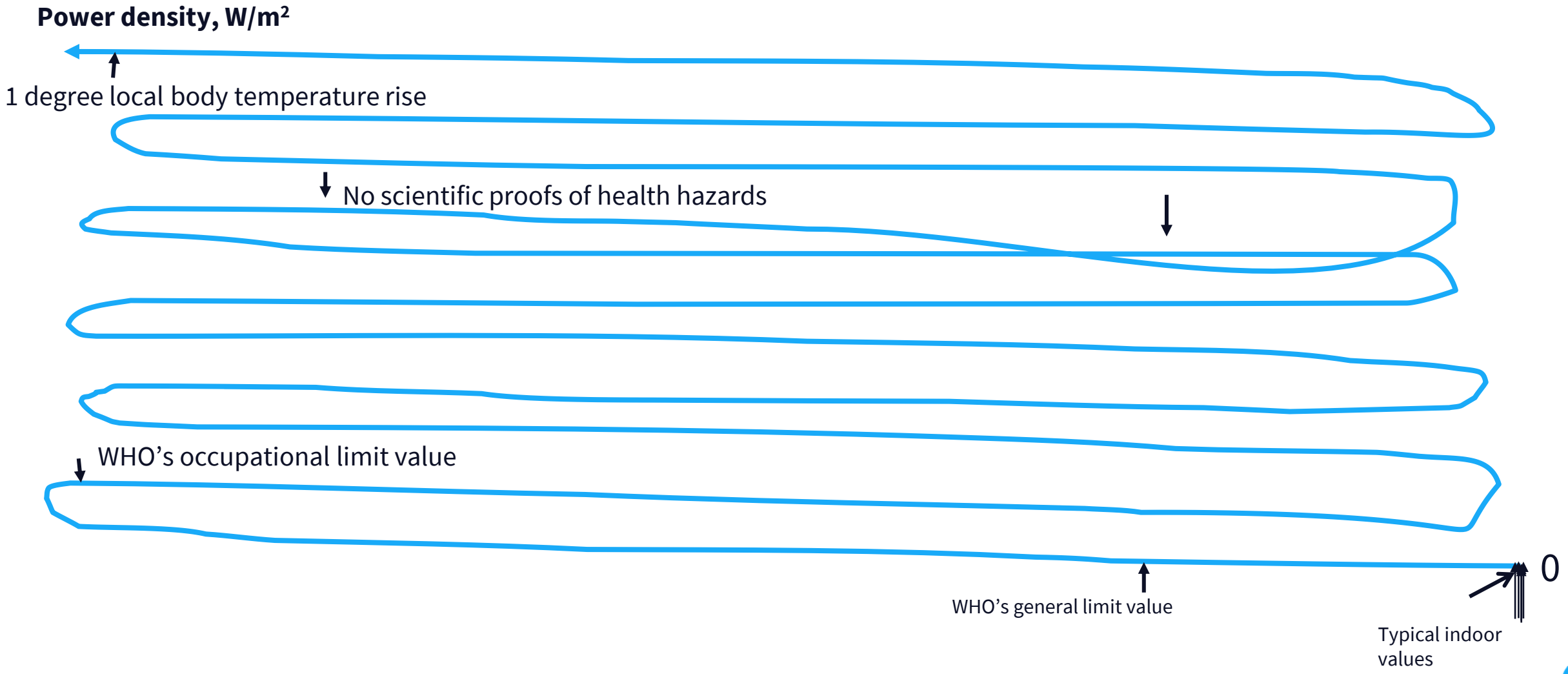
Limits are defined for whole body exposure and local exposure.

What are actual exposure levels?

- Surveys have shown that the RF exposures from base stations range from 0.002% to 2% of the levels of international exposure guidelines (Source: WHO)
  - Depending on a variety of factors such as the proximity to the antenna and the surrounding environment
- A UK test survey done by Ofcom in 2019 shows highest observed levels of 1.5 %
  - (https://www.ofcom.org.uk/__data/assets/pdf_file/0015/190005/emf-test-summary.pdf)

- **How far away from the base station do you need to be?**
- A typical 4G macro cell has the following parameters:
  - Power amplifier: 43 dBm = 20 W
  - Sector antenna gain: 18 dBi = 63x
  - EIRP: 61 dBm = 1.26 kW (!)
- The radiated power is distributed over the full sphere: $A(r) = 4\pi r^2$
  - Power density, Pd = EIRP/A(r):
    - R=1 m; Pd = 100 W/m^2
    - R=10 m; Pd = 1 W/m^2
    - R=100 m; Pd = 10 mW/m^2
    - R = 1 km; Pd = 0.1 mW/m^2

Safety margins into the right perspective



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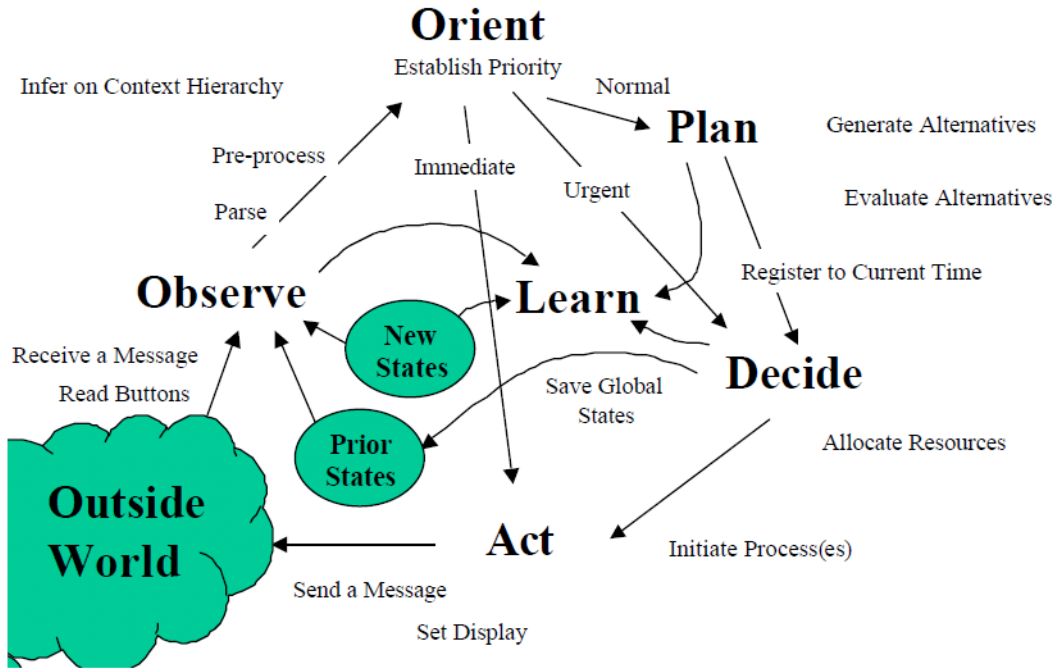
Cognitive Radio – an enabler for new spectrum sharing and trading

Update needed

- "**a really smart radio** that would be self-aware, RF-aware, user-aware, and that would include language technology and machine vision along with a lot of high-fidelity knowledge of the radio environment"
  - J. Mitola in: EETimes. The inventor of cognitive radio. EETimes, News & Analysis. 28th Nov 2005: http://www.eetimes.com/electronics-news/4056921/The-inventor-of-cognitive-radio.



- **Cognitive radio according to ITU-R:**
  - "A radio system employing technology that allows the system to obtain *knowledge* of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously *adjust* its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to *learn* from the results obtained."

Cognitive Radio becomes AI-enabled Radio and Networks

- Cognitive Radio (CR) was proposed to utilize the spectrum efficiently in an opportunistic way
  - Cognitive capability to *sense and gather* information from the surrounding environment and with *reconfigurability* to rapidly adapt the operational parameters according to the sensed information
  - Any user perceives its environment and takes actions that maximize its chance of successfully achieving its goals
- *Artificial Intelligence* (AI) methods, such as Machine Learning (ML) is brought to use in radio networks, named AI-enabled Radio and Networks
  - Example: Optimizing spectrum use in Non-Orthogonal Multiple Access (NOMA) by grouping users using "Object Migration Automata" (OMA)
    - OMA is a Machine-Learning (ML) method learning through Agent-Environment interaction where advantageous behavior is rewarded, and disadvantageous behavior is penalized (Source: Rebekka Olsson Omslandseter: "*On the Theory and Application of Hierarchical Learning Automata and Object Migration Automata*". Doctoral Dissertation ate the University of Agder, Norway,2023. https://uia.brage.unit.no/uia-xmlui/handle/11250/3105545

Spectrum management - summary

- Spectrum management became neccesary to avoid interference and regulate competition
- Spectrum management is done on three levels: global, regional and national
- Global spectrum management is handled by the ITU – a UN body
- Regional spectrum management is in Europe handled by the CEPT
- National spectrum management is done by the regulators

- Mobile spectrum is usually granted using spectrum auctions
- Certain parts of the spectrum are «commons», which requires no license to use, only conformance to certain rules on emission
  - Wi-Fi and Bluetooth uses commons in the 2.45 GHz band, Wi-Fi also in the 5 GHz band
- New trends are spectrum sharing
- Cognitive radio using AI and ML will enable new, dynamic methods of sharing spectrum

Spectrum resources and other readings

- R. Struzak and T. Tjelta, "Spectrum management trends to satisfy the growing mobile data traffic," *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*, Beijing, China, 2014, pp. 1-4, doi: 10.1109/URSIGASS.2014.6929588.
- M. Matinmikko-Blue, S. Yrjölä and P. Ahokangas, "Spectrum Management in the 6G Era: The Role of Regulation and Spectrum Sharing," *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020, pp. 1-5, doi: 10.1109/6GSUMMIT49458.2020.9083851.
- GSMA. Mobile spectrum handbooks – everything you need to know. https://www.gsma.com/spectrum/resources/learn-mobile-spectrum/
- GSMA Mobile Policy Handbook, Spectrum Management and Licensing: https://www.gsma.com/publicpolicy/mobilepolicyhandbook/spectrum-management-and-licensing
- GSMA Spectrum Policy Trends 24: https://www.gsma.com/spectrum/resources/spectrum-policy-trends-2024/)
- ITU-R Reports on Spectrum Management: https://www.itu.int/pub/R-REP-SM
- ITU-R World Radio Conference 2023, Final Acts: http://handle.itu.int/11.1002/pub/8225d4fb-en
- OECD iLibrary. OECD Digital Economy Papers, «New Approaches to Spectrum Management». https://www.oecd-ilibrary.org/science-and-technology/new-approaches-to-spectrum-management_5jz44fnq066c-en

Thank you

Per Hjalmar Lehne; Telenor R&I, Fornebu, Norway

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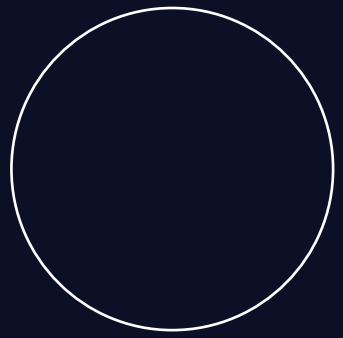


Extras

Frequency band designations

IEEE Standard Radar Band Nomenclature

(*IEEE Std. 521-2002, IEEE Standard Letter Designations for Radar-Frequency Bands)

Designation	Frequency	Wavelength
HF	3 - 30 MHz	100 m - 10 m
VHF	30 - 300 MHz	10 m - 1 m
UHF	300 - 1000 MHz	100 cm - 30 cm
L Band	1 - 2 GHz	30 cm - 15 cm
S Band	2 - 4 GHz	15 cm - 7.5 cm
C Band	4 - 8 GHz	7.5 cm - 3.75 cm
X Band	8 - 12 GHz	3.75 cm - 2.50 cm
Ku Band	12 - 18 GHz	2.50 cm - 1.67 cm
K Band	18 - 27 GHz	1.67 cm - 1.11 cm
Ka Band	27 - 40 GHz	1.11 cm - .75 cm
V Band	40 - 75 GHz	7.5 mm - 4.0 mm
W Band	75 - 110 GHz	4.0 mm - 2.7 mm
mm Band	110 - 300 GHz	2.7 mm - 1.0 mm

ITU Frequency Band Nomenclature

ITU Band	Designation	Frequency	Wavelength
1	ELF	3 - 30 Hz	100,000 km - 10,000 km
2	SLF	30 - 300 Hz	10,000 km - 1000 km
3	ULF	300 - 3000 Hz	1000 km - 100 km
4	VLF	3 - 30 kHz	100 km - 10 km
5	LF	30 - 300 kHz	10 km - 1 km
6	MF	300 - 3000 kHz	1 km - 100 m
7	HF	3 - 30 MHz	100 m - 10 m
8	VHF	30 - 300 MHz	10 m - 1 m
9	UHF	300 - 3000 MHz	1 m - 10 cm
10	SHF	3 - 30 GHz	10 cm - 1 cm
11	EHF	30 - 300 GHz	1 cm - 1 mm

Band Designation Acronyms
Extremely Low Frequency (ELF) Super Low Frequency (SLF) Ultra Low Frequency (ULF) Very Low Frequency (VLF) Low Frequency (LF) Medium Frequency (MF) High Frequency (HF) Very High Frequency (VHF) Ultra High frequency (UHF) Super High Frequency (SHF) Extremely High Frequency (EHF)

Spectrum for 5G: Pioneer bands to enable an early start

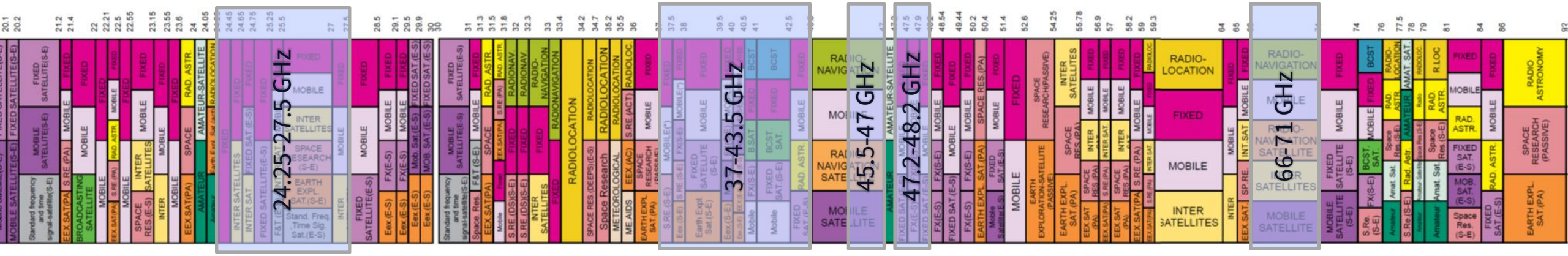
	US	EU	CJK*
Low band: To enable nationwide and indoor 5G coverage	600 MHz	700 MHz	
Middle band: Up to 400 MHz of continuous spectrum enabling wide channel bandwidth	2.6 GHz 3.55 – 3.7 GHz	3.4 – 3.8 GHz	3.3 – 4.2 GHz 4.4 – 4.9 GHz
High band: To ensure all the performance targets of 5G, for example multi gigabit per second data rates.	28, 37, 39 GHz 57 – 71 GHz (unlicensed)	24.25 – 27.5 GHz	28, 39 GHz

* China-Japan-Korea

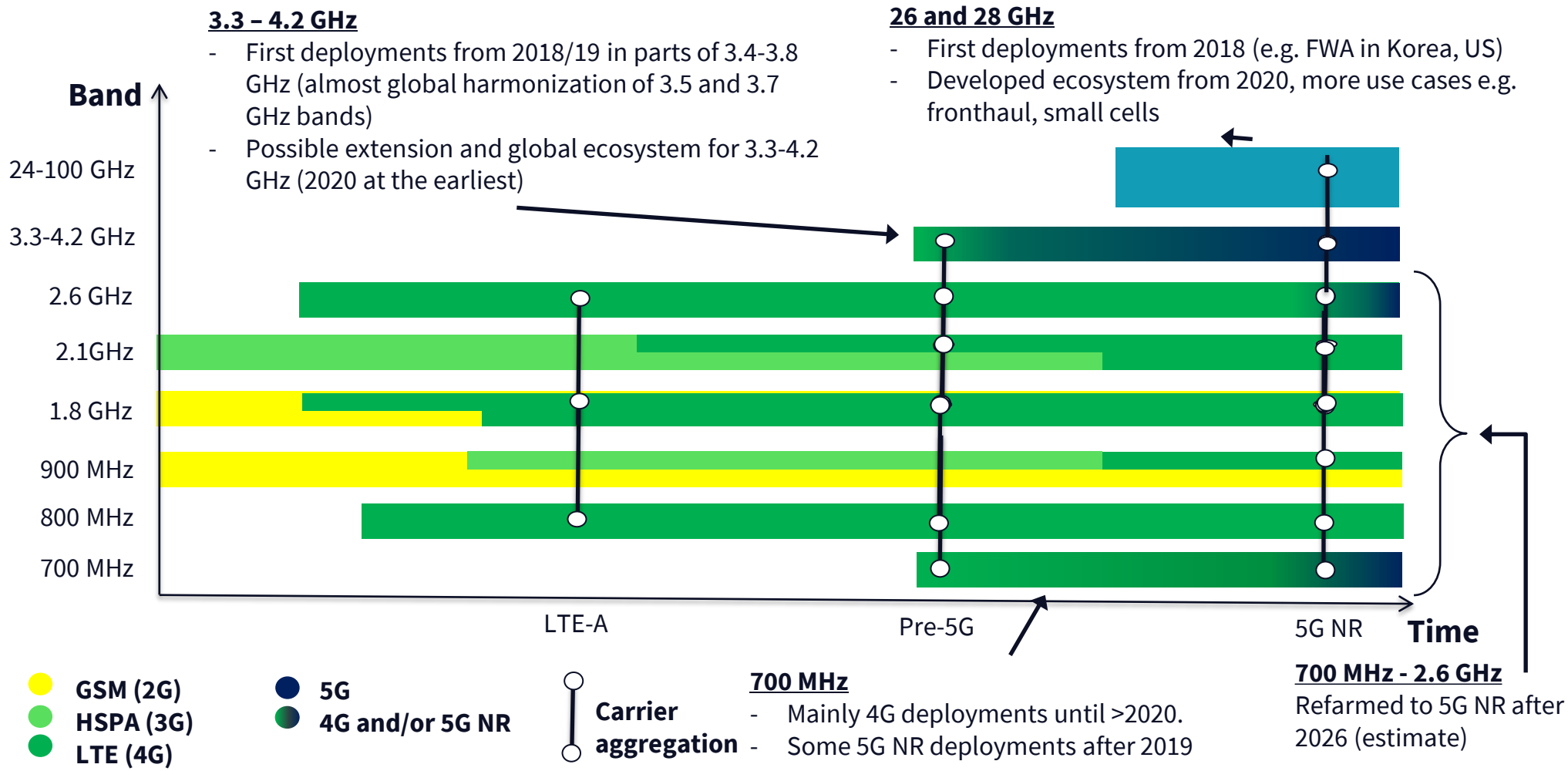
Source:
- GSMA Intelligence: Global Mobile Trends 2017
- RSPG16-032 FINAL. http://rspg-spectrum.eu/wp-content/uploads/2013/05/RPSG16-032-Opinion_5G.pdf

Spectrum for 5G on higher bands

- A total of 17.25 GHz bandwidth in FR2



Eventually, all current mobile bands will be available for 5G



3.3 – 4.2 GHz

- First deployments from 2018/19 in parts of 3.4-3.8 GHz (almost global harmonization of 3.5 and 3.7 GHz bands)
- Possible extension and global ecosystem for 3.3-4.2 GHz (2020 at the earliest)

26 and 28 GHz

- First deployments from 2018 (e.g. FWA in Korea, US)
- Developed ecosystem from 2020, more use cases e.g. fronthaul, small cells

700 MHz

- Mainly 4G deployments until >2020.
- Some 5G NR deployments after 2019

700 MHz - 2.6 GHz

Refarmed to 5G NR after 2026 (estimate)

Mobile frequency licenses in Norway (frekvens.nkom.no, 25.03.2019)

FDD band	Frequency band	Total available bandwidth	Use/expected use in Norway	Operators	Until
450 MHz	452.5-457.5 462.5-467.5	2 x 4 MHz	?	ICE Norge AS (2x4 MHz)	31.12.19
800 MHz	791-821 832-862	2 x 30 MHz	LTE	ICE Norge AS (2x10 MHz) TeliaSonera Norge AS (2x10 MHz) Telenor Norge AS (2x10 MHz)	31.12.33
900 MHz	880-915 925-960	2 x 35 MHz	GSM, UMTS, LTE	ICE Norge AS (2x5.1 MHz) TeliaSonera Norge AS (2x14.8 MHz) Telenor Norge AS (2x15.1 MHz)	31.12.33,
1800 MHz	1710-1785 1805-1880	2 x 75 MHz	GSM, LTE	Telenor Norge AS (2x20 MHz) TeliaSonera Norge AS (2x20 MHz) ICE (2x20 MHz)	31.12.33, 31.12.28
2100 MHz	1920-1980 2110-2170	2 x 60 MHz	UMTS, LTE	TeliaSonera Norge AS (2x19.8 MHz) Telenor Norge AS (2x19.8 MHz) Mobile Norway (2x19.8 MHz)	31.12.32, 31.12.19
2600 MHz	2500-2570 2620-2690	2 x 70 MHz	LTE	TeliaSonera Norge AS (2x20 MHz) Telenor Norge AS (2x40 MHz) NextNet (2x10 MHz)	31.12.22
3500 MHz	3400-3600	200 MHz	FWA 5G	NextGenTel, Broadnet, Ceragon Networks, Vestlink, Telenor, Get	31.12.22

Mobile frequency licenses in Sweden (www.pts.se, 3.4.2018)

Band	Frequency band	Total available bandwidth	Use/expected use in Sweden	Operators	Until
450 MHz	452.5-457.5 462.5-467.5	2 x 4 MHz	LTE	Net1 Sverige AB	5 mars 2020 till och med den 31 december 2044
800 MHz	791-821 832-862	2 x 30 MHz	LTE	791-801/832-842: Hi3G (2x10 MHz) 801-811/842-852: TeliaSonera (2x10 MHz) 811-821/852-862: Net4Mobility (Telenor+Tele2) (2x10 MHz)	
900 MHz	880-915 925-960	2 x 35 MHz	GSM+UMTS+LTE	925-930/880-885: Hi3G (2x5 MHz) 930-936/885-891: Net4Mobility (Telenor+Tele2) (2x6 MHz) 936-945/891-900: Tele2 (2x9 MHz) 945-950/900-905: Telenor (2x5 MHz) 950-960/905-915: Telia (2x10 MHz)	
1800 MHz	1710-1785 1805-1880	2 x 75 MHz	LTE	1805-1840/1710-1745 Telia (2x35 MHz) 1840-1870/1745-1775 Net4Mobility (Telenor+Tele2) (2x30 MHz) 1870-1875/1775-1780 Hi3G (2x5 MHz)	
2100 MHz	1920-1980 2110-2170	2 x 60 MHz	UMTS	1905-1910 (TDD): SULAB (Telia+Tele2) (5 MHz) 1910-1915 (TDD): Hi3G (5 MHz) 1915-1920 (TDD): Telenor (5 MHz) 1920,3-1940,1/2110,3-2130,1: Telenor (2x19,8 MHz) 1940,1-1959,9/2130,1-2149,9: Hi3G (2x19,8 MHz) 1959,9-1979,7/2149,9-2169,7: SULAB (Telia+Tele2) (2x19,8 MHz)	
2600 MHz	2500-2570 2620-2690	2 x 70 MHz	LTE	2500-2520/2620-2640: Net4Mobility (2x20 MHz) 2520-2530/2640-2650: Hi3G (2x10 MHz) 2530-2550/2650-2670: TeliaSonera (2x20 MHz) 2550-2570/2670-2690: Net4Mobility (2x20 MHz)	

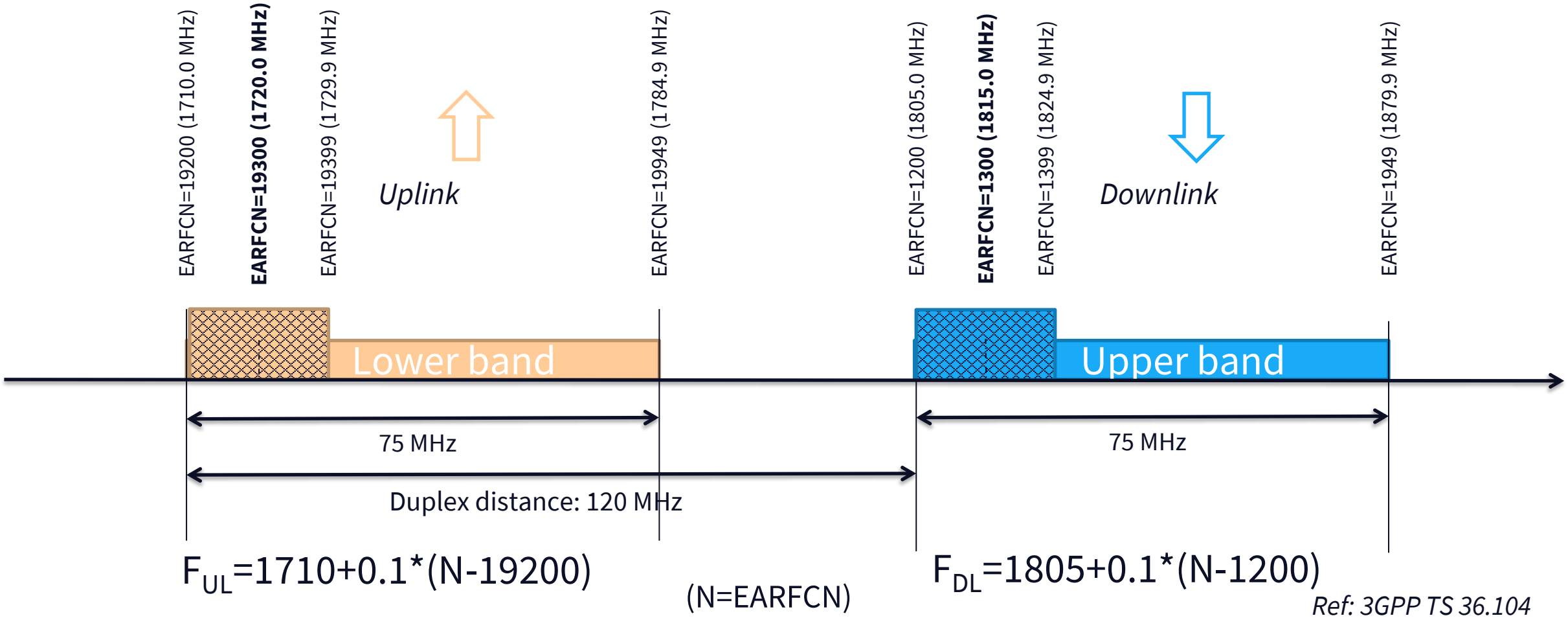
From channel number (ARFCN/UARFCN/EARFCN) to frequency – Downlink

Band	Channel number range (N_{DL})	Formula	Frequency range, DL (MHz)
GSM (GPRS, EDGE)			
Band 8: **«900 GSM»**	0 – 124; 975 - 1023	F_{DL}=890+0.2*N+45 F_{DL}= 890+0.2*(N-1024)+45	**935.0 – 959.8 MHz** **925.2 – 934.8 MHz**
Band 3: **«1800 DCS»**	512 - 885	F_{DL} = 1710.2+0.2*(N-512)+95	**1805.2 – 1879.8 MHz**
UMTS (HSPA, HSUPA, HSDPA, HSPA+)			
Band 1: **«2.1 GHz»**	10562 – 10838	F_{DL} = 0.2*N	**2112.4 – 2167.6 MHz**
Band 8: **«900 GSM»**	2937 – 3088	F_{DL} = 0.2*N+340	**927.4 – 957.6**
LTE			
Band 7: **«2.6 GHz»**	2750 – 3449	F_{DL}=2620+0.1*(N-2750)	**2620.0 – 2689.9 MHz**
Band 3: **«1800 DCS»**	1200 – 1949	F_{DL}=1805+0.1*(N-1200)	**1805.0 – 1879.9 MHz**
Band 8: **«900 GSM»**	3450 - 3799	F_{DL} = 925+0.1*(N-3450)	**925.0 – 959.9 MHz**

From channel number (ARFCN/UARFCN/EARFCN) to frequency – Uplink

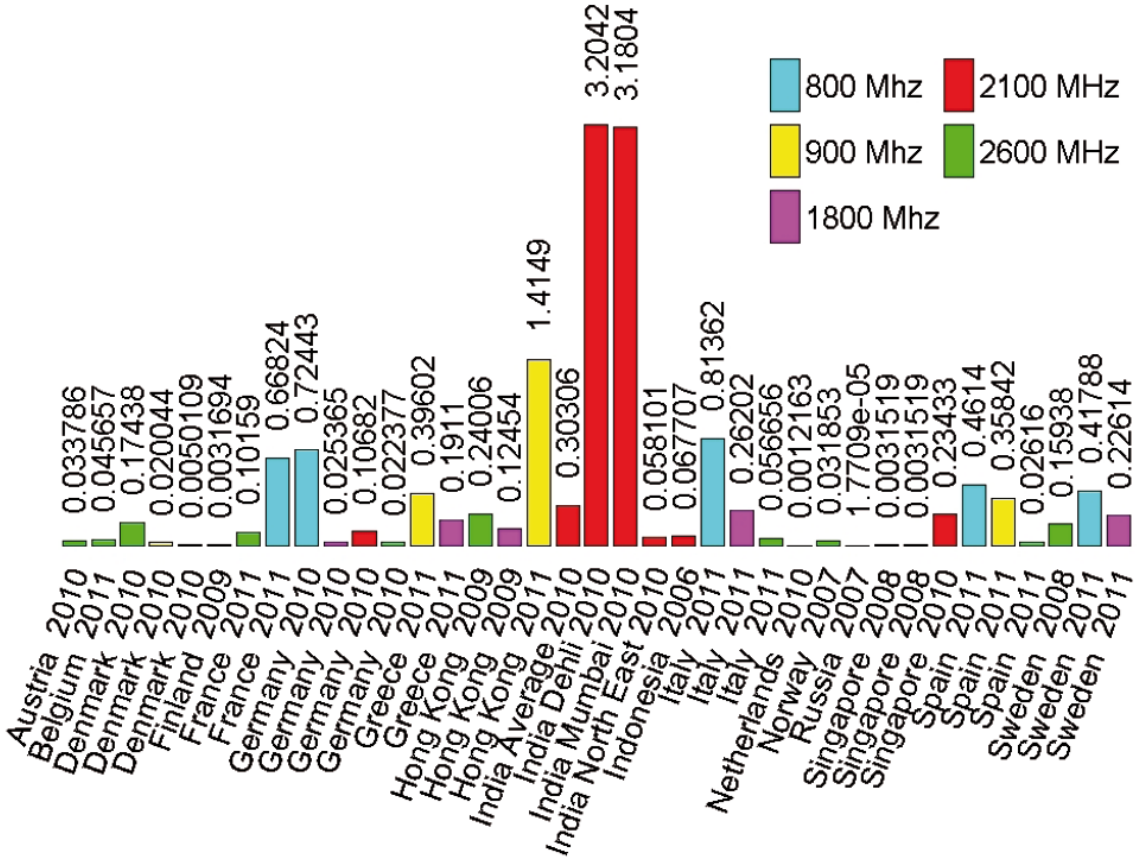
Band	Channel number range (N_{UL})	Formula	Frequency range, UL (MHz)
GSM (GPRS, EDGE)			
Band 8: **«900 GSM»**	0 – 124; 975 - 1023	F_{UL}=890+0.2*N F_{UL}= 890+0.2*(N-1024)	**890.0 – 914.8 MHz** **880.2 – 889.8 MHz**
Band 3: **«1800 DCS»**	512 - 885	F_{UL} = 1710.2+0.2*(N-512)	**1710.2 – 1784.8 MHz**
UMTS (HSPA, HSUPA, HSDPA, HSPA+)			
Band 1: **«2.1 GHz»**	9612 – 9888	F_{UL} = 0.2*N	**1922.4 – 1977.6 MHz**
Band 8: **«900 GSM»**	2712 – 2863	F_{UL} = 0.2*N+340	**882.4 – 912.6**
LTE			
Band 7: **«2.6 GHz»**	20750 – 21449	F_{UL}=2500+0.1*(N-20750)	**2500.0 – 2569.9 MHz**
Band 3: **«1800 DCS»**	19200 – 19949	F_{UL}=1710+0.1*(N-19200)	**1710.0 – 1784.9 MHz**
Band 8: **«900 GSM»**	21450 – 21799	F_{UL} = 880+0.1*(N-21450)	**880.0 – 914.9 MHz**

Channel numbers LTE FDD
Example: Band 3, LTE 1800, BW=20 MHz



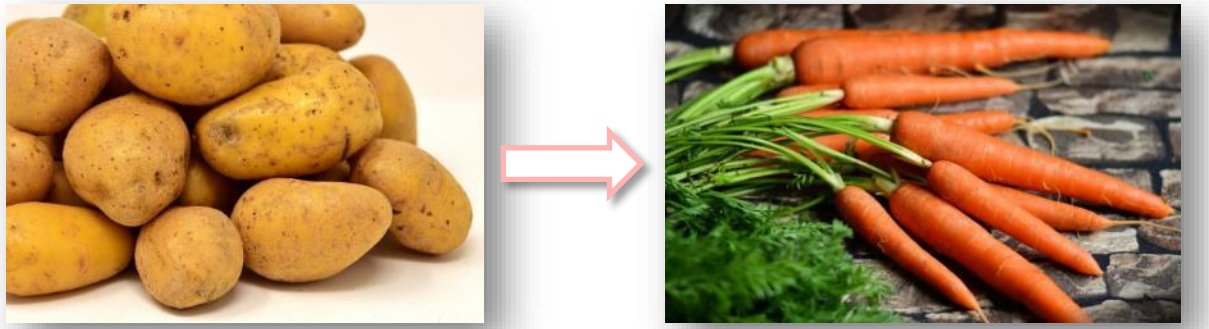
Ref: 3GPP TS 36.104

The common method for assigning spectrum to mobile operators is Auctions



Auction prices given in EUR/MHz/Pop for paired spectrum over a five year period (2006 – 2011)

Refarming of spectrum

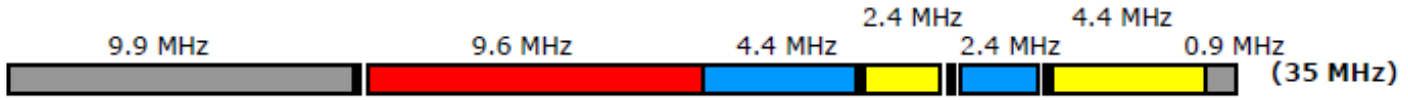


- In agriculture:
  - Switch from growing one type of product to another: E.g. from potato to carrot.
- In mobile communications:
  - Switch from one technology to another (in the same frequency band) – e.g. from GSM to GSM + UMTS

- Requirements:
  - Licenses are technology neutral
  - (Often) Spectrum holding is contiguous
  - Operators have a minimum amount of spectrum each

Refarming example 900 MHz

Before:



9.9 MHz + 0.9 MHz not allocated

Only red operator are able to refarm from GSM to GSM + UMTS (requires ~10 MHz and contiguous spectrum)

After

Government has:

- **Allocated the unassigned spectrum to the three operators**
- **Reshuffled the spectrum so that all operators have contiguous spectrum**
- **All operators can refarm from GSM to GSM + UMTS**

Refarming will sometimes be necessary in order to allow new technologies to be deployed and improve spectrum utlization.

Legends: **Red operator** | **Blue operator** | **Yellow operator** | **Unassigned**

Dynamic allocation of spectrum in TVWS

- Geolocation database approach is used for White Space Devices (WSD) to access the TVWS spectrum:

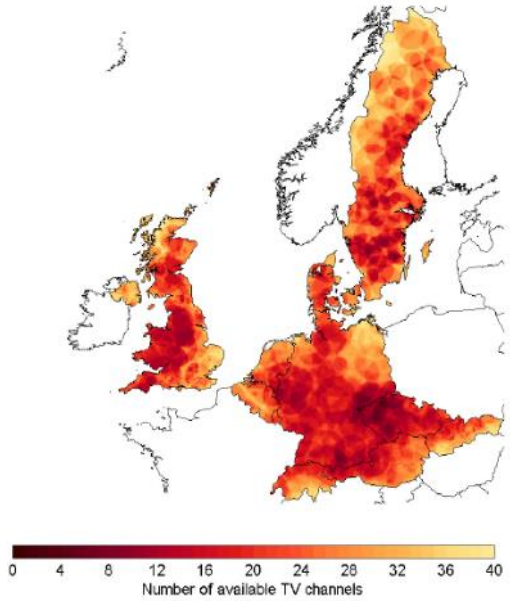
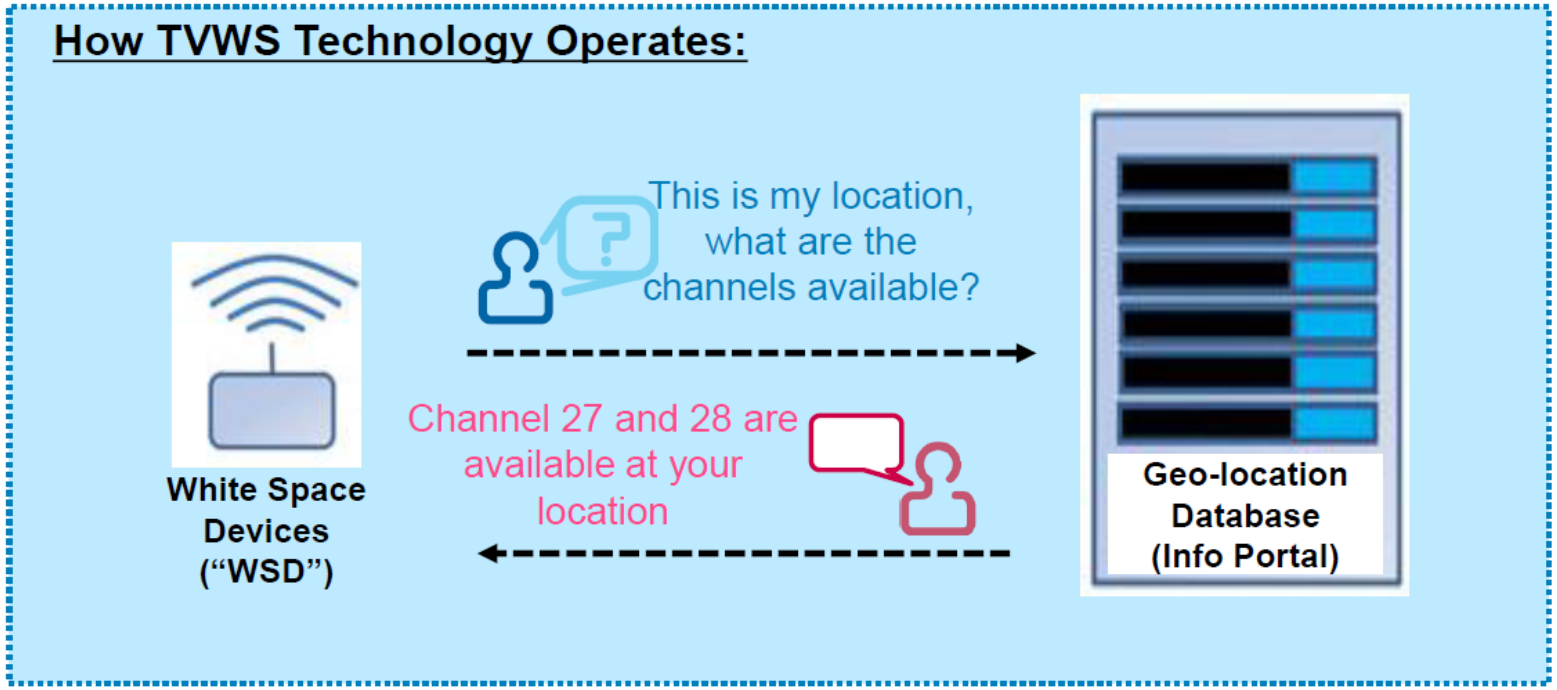


Fig. 2. White space map of $S(\mathbf{x})$ for 11 European countries.



Rules for using the TVWS

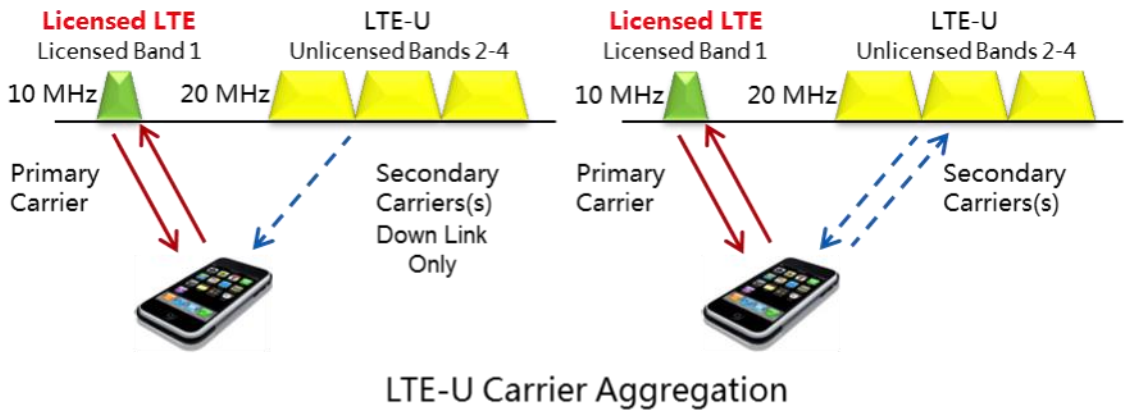
- **Primary system:**
  - DVB-T – digital terrestrial TV
    - 8 MHz channel width (Europe)
    - Tx power up to several kW
  - Also used for PMSE – program making and special events: wireless microphone systems and audio links
    - Narrow channels: 200 – 600 kHz
    - Tx power 0-17 dBm (handheld); 47 dBm for audio p2p links
- **Systems designed to use the TVWS:**
  - IEEE 802.11af – «White-Fi» - Wi-Fi in TVWS
  - IEEE 802.22 – Wireless Regional Area Network (WRAN) – Fixed Wireless Access
  - Weightless – Low Power Wide Area Network (LPWAN) standard developed by the Weightless SIG for IoT

As for sharing unlicensed spectrum, limiting transmitter power is the most important regulation

Parameter	FCC (US)	OFCOM (UK)
Power for FD in adjacent band	Not allowed	Not applicable
Power for FD in non-adjacent band with geo-location capability	30dBm (1W) (36dBm EIRP with 6dB gain antenna)	Not applicable
Power for PPD in adjacent band	16dBm (40mW) (Gain antenna not allowed)	4dBm
Power for PPD in non-adjacent band with geo-location capability	20dBm (100mW) (Gain antenna not allowed)	17dBm
Power for PPD in non-adjacent band without geo-location capability	17dBm (50mW)	

FD: Fixed Device; PPD: Personal Portable device

Combining Licensed and Unlicensed spectrum: Licensed Assisted Access – LAA Example: LTE-U



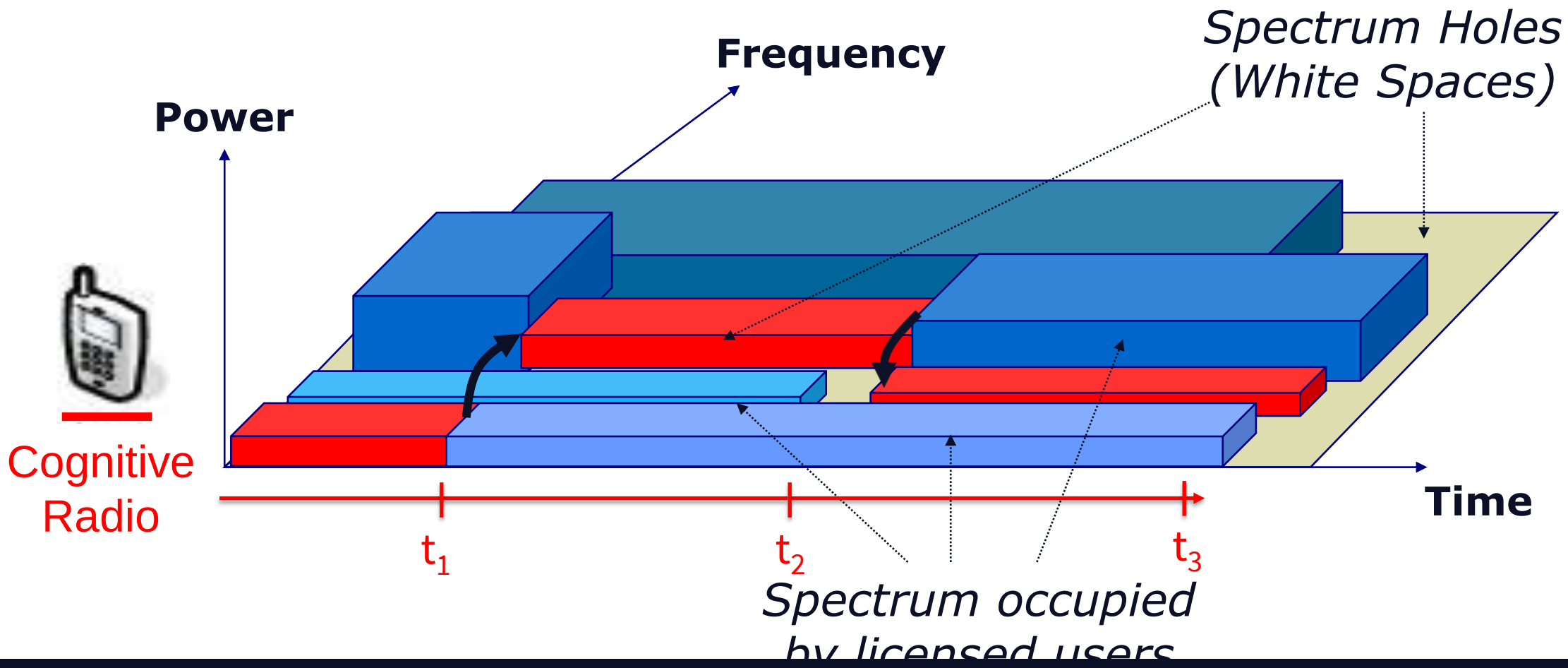
LTE-U Carrier Aggregation

SDL: Supplementary downlink

Spectrum for 5G

- NKOM, PTS:
- Se: https://www.insidetelecom.no/artikler/svenskene-frykter-5g-monopol/434219?utm_source=newsletter_2018-04-06
- http://www.pts.se/globalassets/startpage/dokument/icke-legala-dokument/remisser/2018/radio/20180405-pts-bemotande-konsultationssvar-700-mhz-tilldelning.pdf
- UK:
- https://www.ofcom.org.uk/about-ofcom/latest/features-and-news/results-auction-mobile-airwaves

Cognitive Radio can be used to dynamically access spectrum that is underutilized

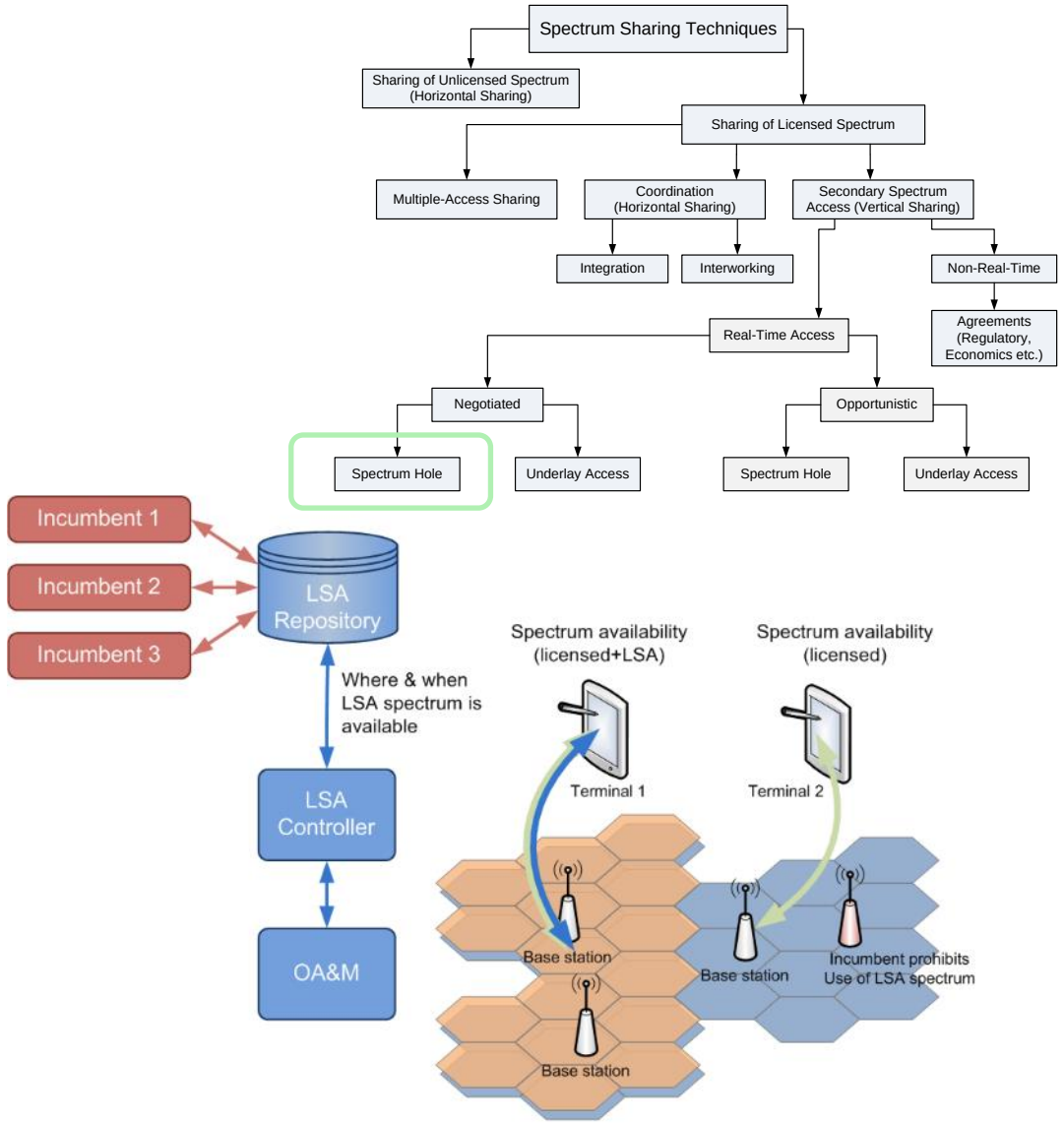


At WRC-15 and in preparation for WRC-19

- Discussion of new spectrum identified for IMT below and above 6 GHz
- New bands 3.4-3.6 GHz and 1.427-1.518 GHz for mobile broadband including, when appropriate, an IMT identification
- Resolution 238 (WRC-15) in preparation for WRC-19
  - determine the spectrum needs for the terrestrial component of IMT
    - in the frequency range between 24.25 GHz and 86 GHz
  - sharing and compatibility studies
    - 24.25-27.5 GHz, 37-40.5 GHz, 42.5-43.5 GHz, 45.5-47 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, 66-76 GHz and 81-86 GHz, which have allocations to the mobile service on a primary basis; and
    - 31.8-33.4 GHz, 40.5-42.5 GHz and 47-47.2 GHz, which may require additional
    -

Authorized Shared Access (Licensed Shared Access – LSA)

- **A framework to share spectrum between a limited amount of users**
  - The existing spectrum user(s) (“the incumbent(s)”) would share spectrum with one or several licensed LSA users (”LSA licensee(s)”) in accordance with a set of pre-defined conditions
- **The LSA repository**
  - A database containing relevant information on incumbent spectrum use
- **The LSA controller**
  - Computes LSA spectrum availability based on the rules built upon LSA rights of use and the incumbent’s use provided by the LSA repository.
- **The network Operation, Administration & Maintenance (OA&M)**
  - Corresponds to the OA&M of mobile broadband networks.
  - It takes care of the actual management of LSA licensed spectrum, practically translating spectrum availability information into radio resource management commands.



Future trend: Licensed Shared Access (LSA)

- Proposed in 2010 by Qualcomm and Nokia in an answer to a hearing on cognitive technologies by the EU

- LSA is a framework to share spectrum between a limited amount of users
  - Under this concept, the existing spectrum user(s) (“the incumbent(s)”) would share spectrum with one or several licensed LSA users (”LSA licensee(s)”) in accordance with a set of pre-defined conditions
  - the LSA concept is primarily about granting “individual authorisations” of the use of a frequency band which is already licensed to another incumbent usage(s), e.g. defence service, satellite service or wireless camera operation
- Two basic levels of spectrum access are foreseen:
  - *Incumbent user*, who is the current spectrum licensee. This could be an individual license holder or a governmental organisation with priority rights in order to deliver public services (defence, civil aviation, emergency communications,…)
  - *The LSA licensee*, who must not interfere with the incumbent spectrum user. There will also be imposed emission and power limits by the regulator. A spectrum guarantee may also be defined reflecting the rights of the incumbent user.
- A key feature of LSA is to ensure a predictable QoS for all spectrum rights of use holders, network operators and consumers.