Dynamic Spectrum Sharing (DSS) – The solution to the radio spectrum shortage

CWTe Research Retreat, October 20, 2022

Ignas G. Niemegeers
i.g.m.m.niemegeers@tue.nl

Center for Wireless Technology Eindhoven - Department of Electrical Engineering

Overview

- **What is DSS and why will we need it?**
- **Overview existing DSS systems and what they apply to**
- **Basic technologies for future DSS**
- **Concluding remarks**

Topics we do not cover:

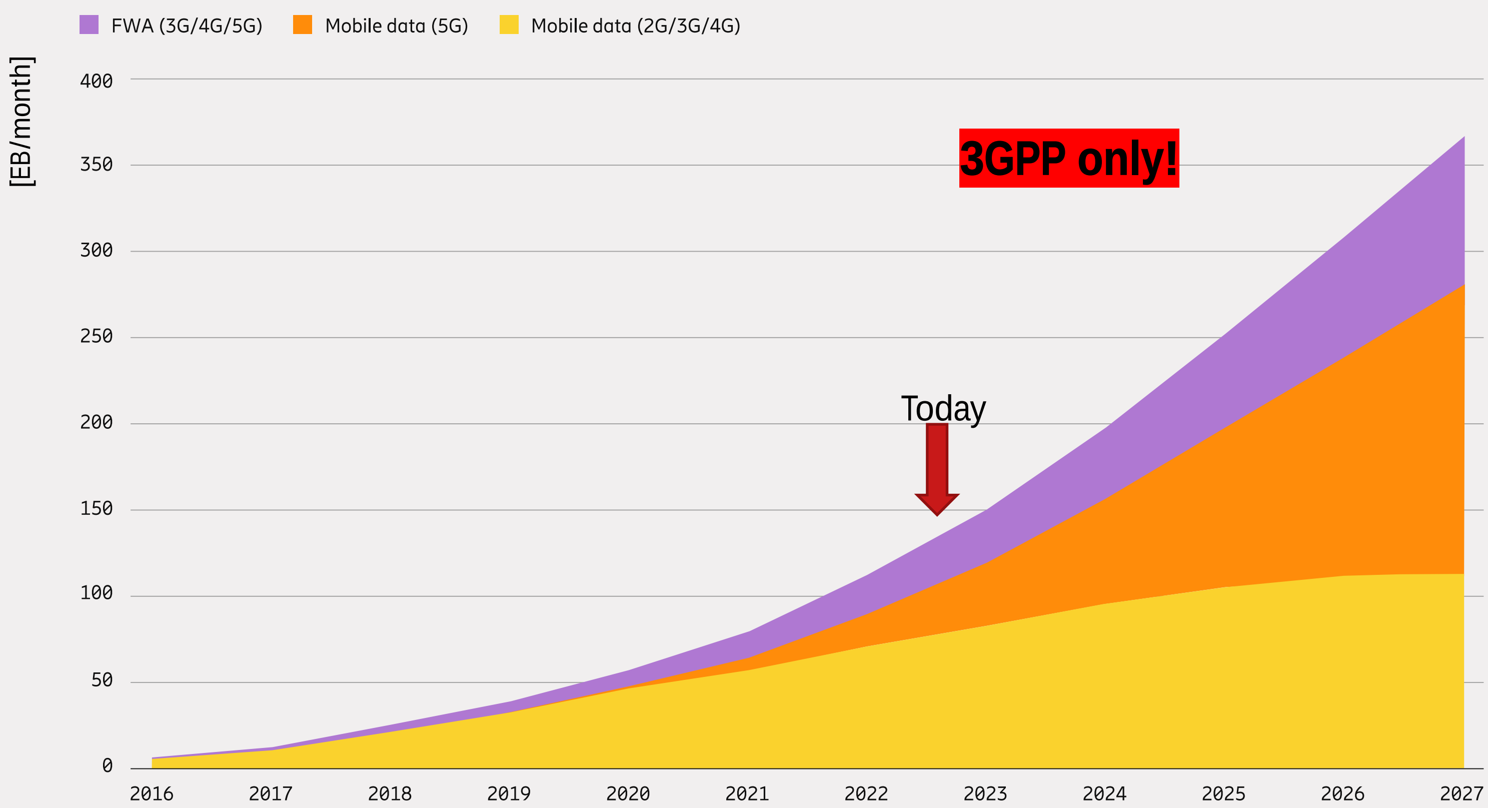
- Economical and policy issues
- Standardization
- Sharing within a single operator, e.g., 5G and 4G sharing => see 3GPP

Acknowledgement: The survey activity this presentation is based on was partly funded by Stratix B.V., see also [Stratix, 2021], a study commissioned by Radiocommunications Agency Netherlands, Ministry of Economic Affairs and Climate, July 2021.

Overview

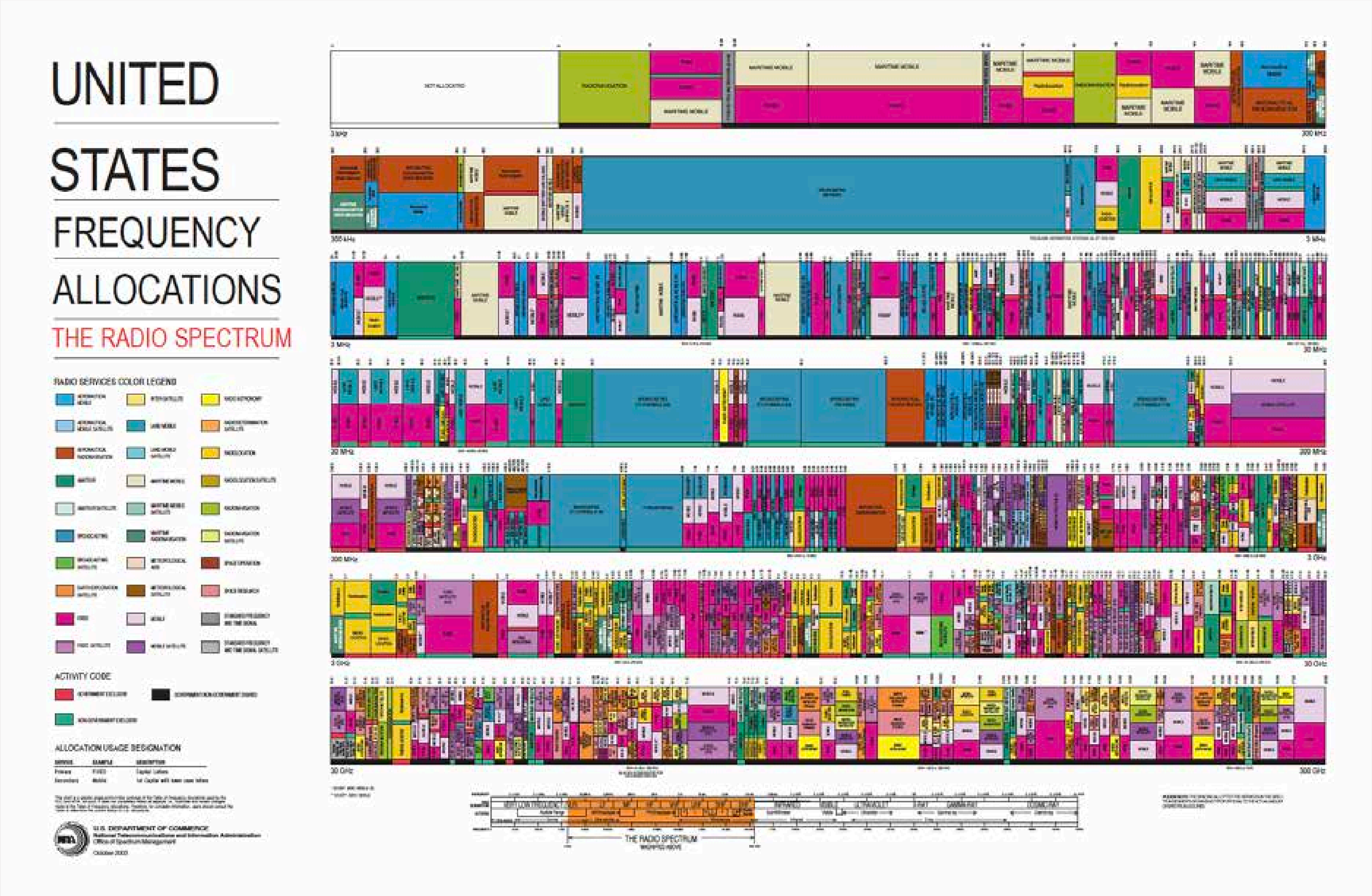
- **What is DSS and why we need it?**
- Overview existing DSS systems and what they apply to
- Basic technologies for future DSS
- Concluding remarks

How to deal with wireless data traffic growth?



Source: Ericsson Mobility Report 2022

FWA = Fixed-wireless access


UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
THE RADIO SPECTRUM

How to get more spectrum?

- New spectrum bands: mmWave, THz and optical:
  - Large bandwidth
  - Low coverage (propagation loss)

  => Only local usage, except when using beamforming
- Better usage of licensed and unlicensed bands through

  dynamic spectrum sharing (DSS)

Present situation and opportunities

- Many frequency bands are **little used in time or space**, e.g., bands allocated to particular radars, military, satellites, etc.
- Looking on a **“microscopic” time scale** (e.g., transmission times of frames or slots) a lot is unused

Need for Spectrum Access Control or SAC

- Required for DSS is a **“Spectrum Access Control or SAC”** across all spectrum users (MNOs, private networks, radars, broadcasters, satellites, airplanes, etc.)
- Analogous to **“Medium Access Control or MAC”** for a single network, which is about sharing a medium within a single network
- Similar principles apply as in MAC design, e.g.,
  - High efficiency under heavy load requires coordination/cooperation (like MAC scheduling)
  - Guaranteeing **Quality of Service**, requires, e.g., reservation of resources, preventing resource hogging, priorities or preemption
- A **control and/or management plane** might be needed for coordination between parties

Overview

- What is DSS and why we need it?
- **Overview existing DSS systems and what they apply to**
- Basic technologies for future DSS
- Concluding remarks

Categories of existing and projected DSS systems

- **Licensed spectrum sharing**, where an authorization is required to use the spectrum

  e.g., TVWS, LSA and eLSA

- **Unlicensed spectrum sharing**, where spectrum can be used without license, provided certain technical requirements are met

  e.g., LAA, eLAA, FeLAA, MulteFire, 5G NR-U

- **Mixed licensed and unlicensed**

  e.g., CBRS (US only)

- **Beyond-5G methods**, comprising both licensed and unlicensed access: research stage

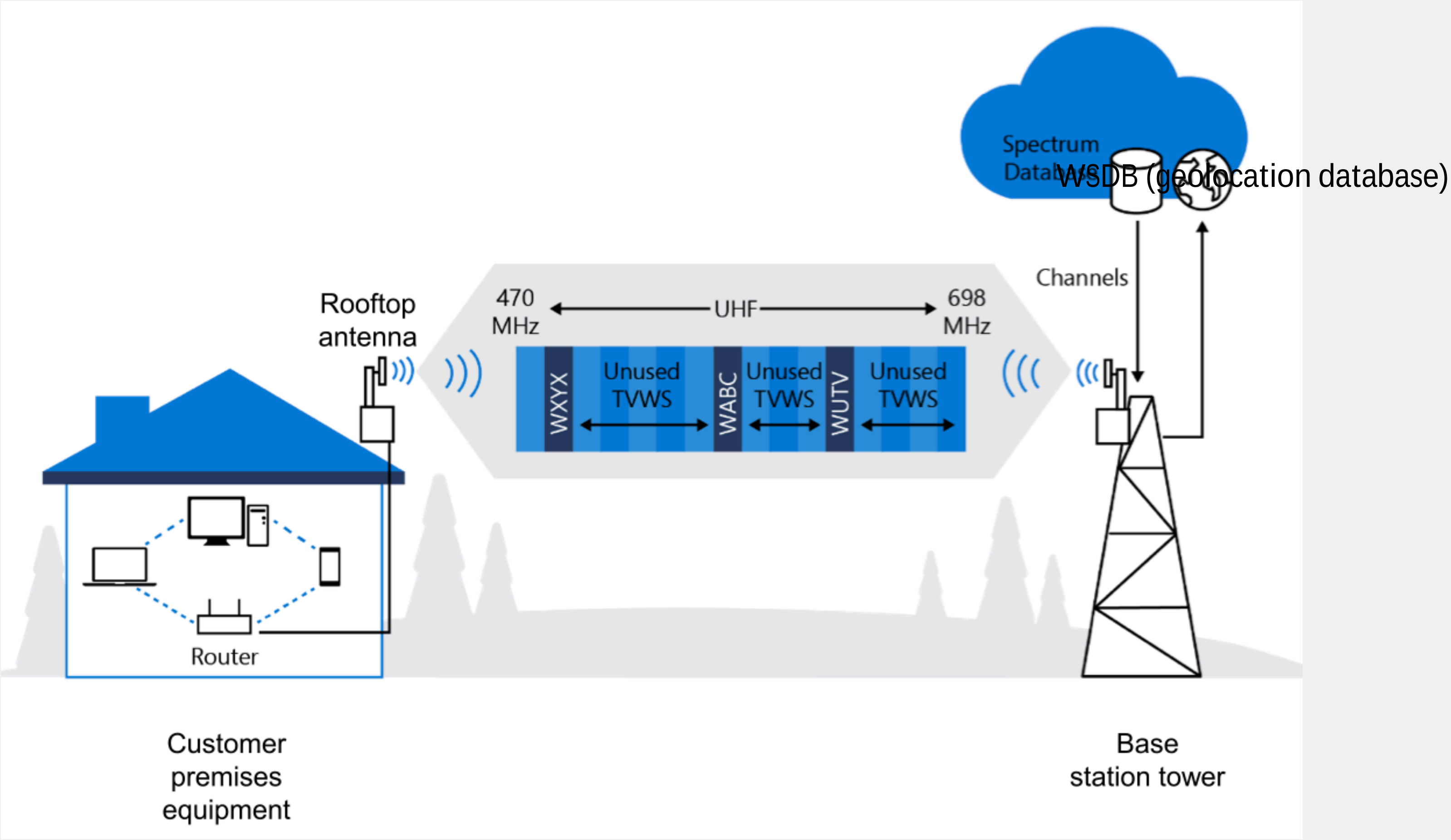
  e.g., CSS, DARPA SC2, etc.

TU/e

TV White Space (TVWS) - Concept

- TVWS = "*portion of (UHF or VHF) spectrum allocated and used for TV broadcasting that is identified by an administration as available for wireless communication at a given time in a given geographical area on a non-interfering and non-protected basis with regard to other services with a higher priority on a national basis*" (ITU)
- Primary users (PU): licensed TV broadcasters with higher priority to transmit and protected against interference
- Secondary users (SU): low-power White Space Devices (WSD) with lower priority to transmit and not protected from interference by PU or other SUs

Example: TVWS FWA service in rural areas



Source: [Dynamic Spectrum Alliance (DSA), 2020]

TVWS Geo-database Mechanism

- WSD queries WSDB, providing device location, device information, antenna height, etc. => WSDB indicates as a function of time and location of WSD, which channels could be used.
- WSDB regularly updated to reflect spectrum usage by the PUs
- WSDB information on what channels are available and where, is based on (theoretical) propagation models not on real propagation conditions from the WSD to PU => over-conservative (e.g., indoor 40% usable spectrum missed in Hong Kong measurements)
- Could, in principle, be improved by feeding WSDB by spectrum sensing, but there are issues, e.g., hidden terminal problem

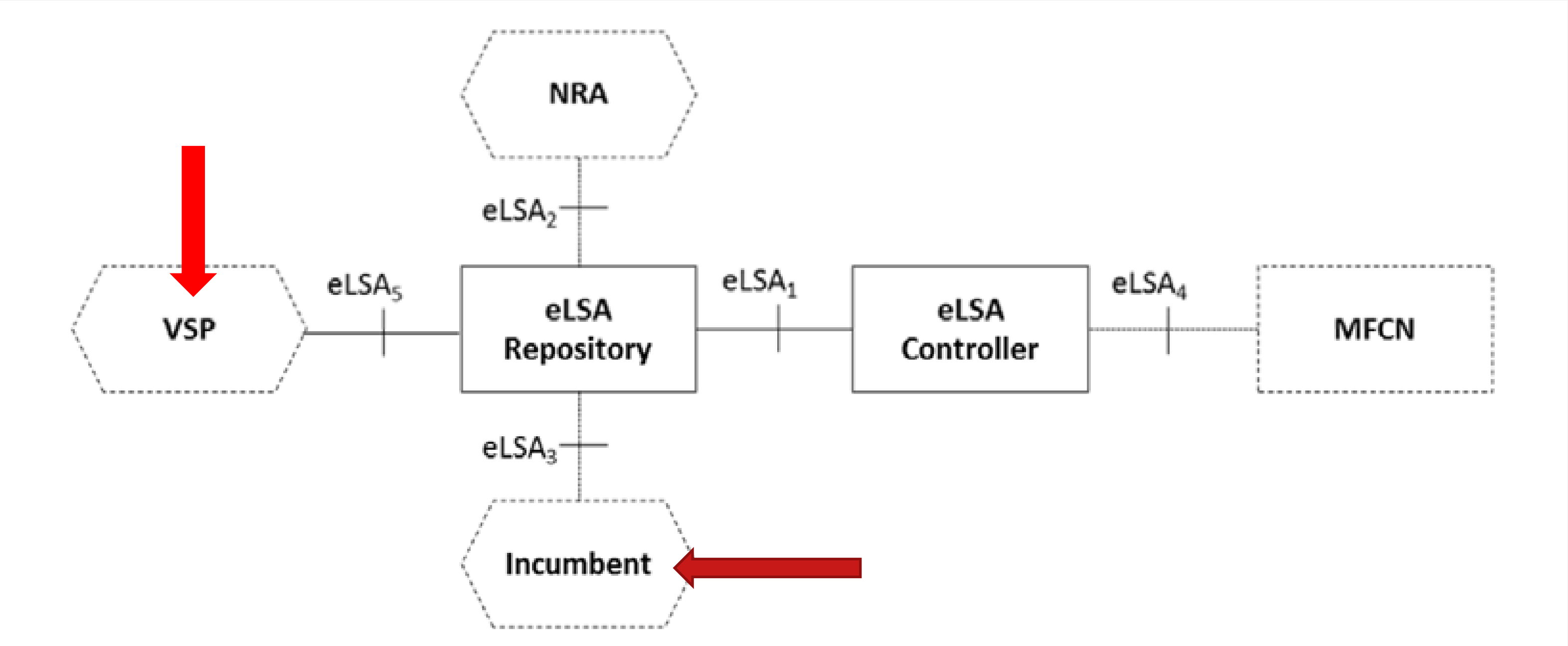
Licensed spectrum sharing – Licensed Shared Access (LSA)

- Extend cellular capacity below 6 GHz by enabling 3GPP LTE MNOs (licensees) to share the 2.3-2.4 GHz band with incumbents (e.g., telemetry, military, MNOs)
- Extended by Agentschap Telecom (NL) to other frequency bands and an extension to Programme-Making and Special Events (PMSE), e.g., professional radio microphones, wireless audio distribution, talkback walkie-talkies, etc.
- ETSI specified

Evolved Licensed Shared Access (eLSA)

- Aimed at providing spectrum for local environments, e.g., factory, campus, events, festivals, PMSE, etc.
- Predictable QoS
- Dynamics of sharing: from short-term (days) to long-term deployment (years)
- Radio-technology agnostic except in spectrum-as-a-service where radio-technology of the MNO is used, e.g., 5G-NR
- ETSI specified

eLSA Architecture



Source: [ETSI eLSA, 2020] VSP = Vertical Sector Player MFCN = Mobile/Fixed Communication Network
NRA = National Regulatory Authority

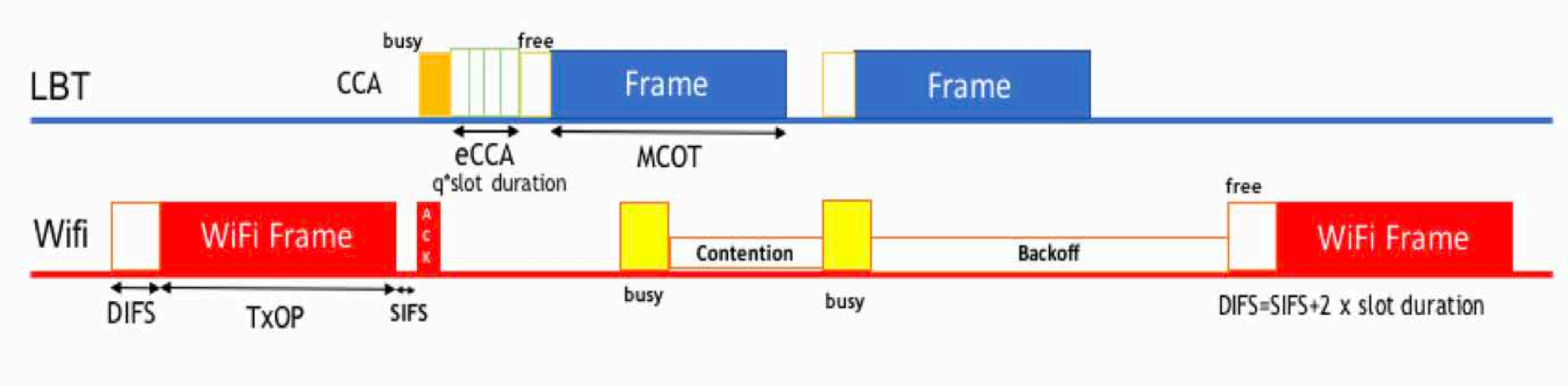
eLSA Architecture

- eLSA Repository:
  - description of shared spectrum resources
  - incumbent and VSP usage and protection requirements
  - convey spectrum resource information to eLSA Controllers.
  - provides means for the NRA to monitor the operation of the eLSA System and provide the eLSA System with information on local area licensing and leasing
- eLSA Controller:
  - obtain eLSA spectrum and availability information from eLSA Repository
  - interacts with the VSP network in order to support mapping spectrum resource and availability information into radio transmitter configurations and receive the respective confirmation from the MFCN.

Sharing Unlicensed Spectrum
Licensed-Assisted Access: LAA, eLAA and FeLAA

- Intended for cellular operators (4G technology LTE)
- Augment capacity through carrier aggregation of licensed spectrum + shared unlicensed spectrum in the 5 GHz band: LAA (DL only), ELAA (UL+DL), FeLAA (grant-free access)
- Fairness requirement: **license-exempt users should experience LAA/eLAA/FeLAA users as if they were other license-exempt users**
- Fully under control of eNB (“base station”), except for FeLAA
- Evolves into 5G NR-U

LAA achieving fairness:
Listen before talk (LBT) + Random backoff



CCA = Clear Channel Assessment MCOT = Maximum Channel Occupancy Time

DIFS = DCF Interframe Space SIFS = Short Interframe Space

Source: [Baena et al.,2020]

Drawbacks of LAA, eLAA and FeLAA

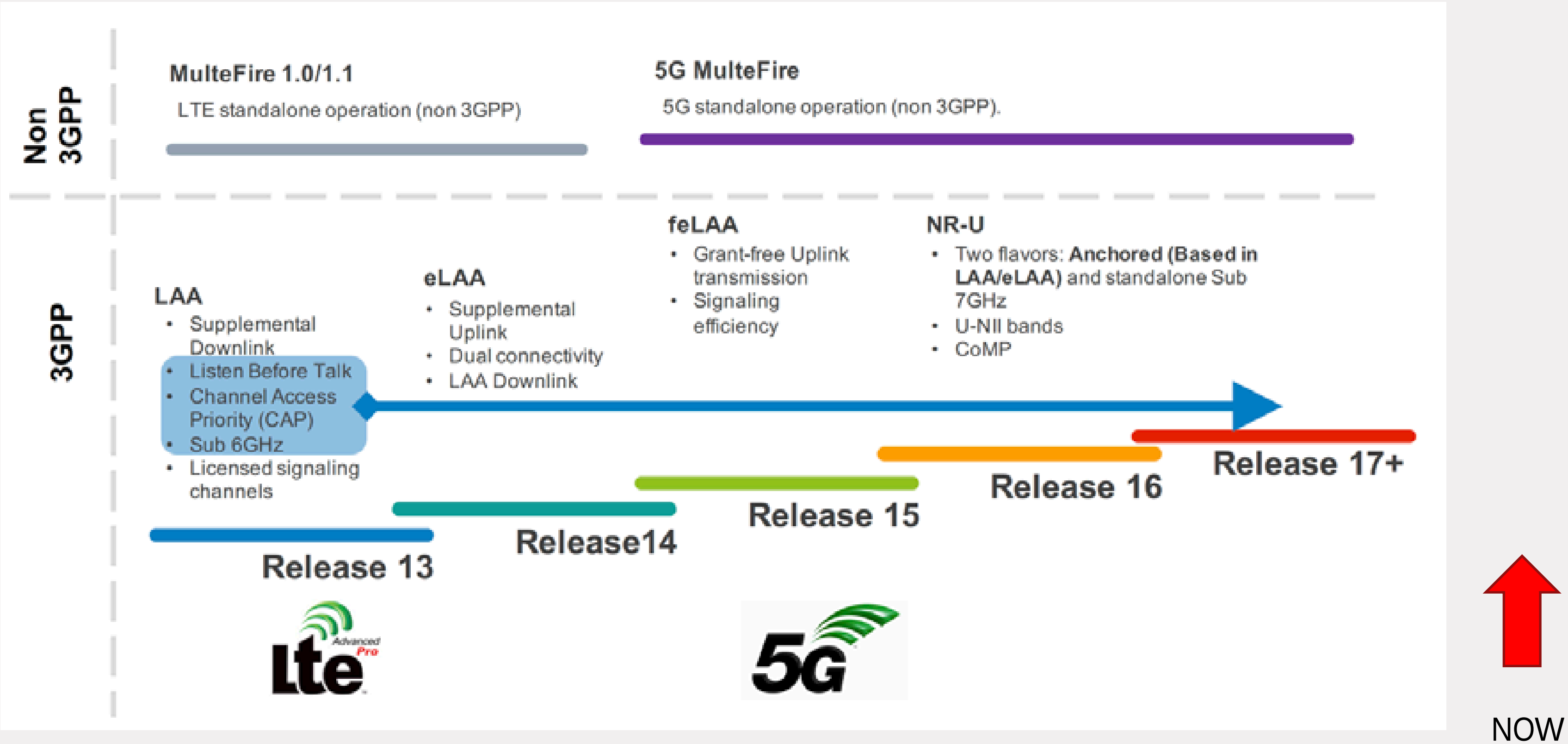
- No QoS guarantees, because it is difficult to predict upcoming access opportunities
- Potentially long delays in accessing the channel if it is in use by neighbouring devices
- No possibility of explicit cooperation and coordination between devices

Unlicensed spectrum sharing – 5G NR-U (Release 16) Use cases?

- Private cellular networks for enterprises, vertical industries, and indoor networks
- Neutral-host infrastructure
- Mobile network densification (adding small cells for MNOs),
- Fixed wireless access (FWA) (US mainly)
- Integration with wired Time Sensitive Networks (IEEE 802.3 TSN) for industrial control

Replaces all 3GPP and non-3GPP unlicensed spectrum sharing schemes

Evolution into 5G NR-U



Source: 3GPP

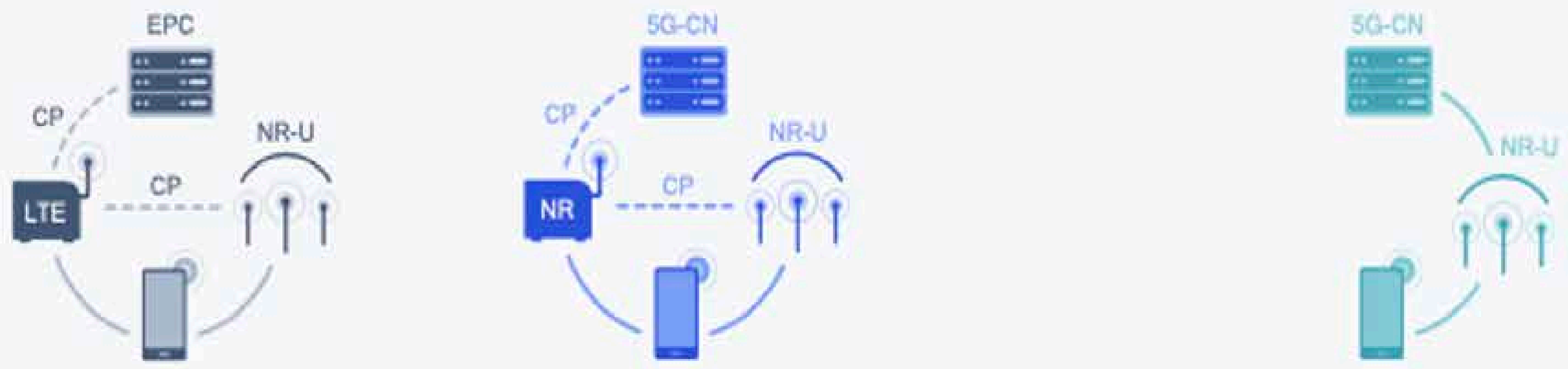
5G NR-U Capabilities

- Wideband carriers
- Flexible numerologies
- Beamforming
- Dynamic TDD: uplink-downlink allocation may change over time to adapt to traffic conditions
- Wide range of unlicensed and shared licensed bands, such as the 2.4, 3.5, 5, 6 GHz (Release 16) and 60 GHz (Release 17) bands

NR-U deployment scenarios

Anchored NR-U

Standalone NR-U



Scenario A
Dual connectivity
LTE with EPC[1] and NR-U

Scenario B
Carrier aggregation
NR with 5G-CN[2] and NR-U

Scenario C
Standalone
NR-U with 5G-CN

CP = Control Plane   EPC = Evolved Packet Core   CN = Core Network

Source: Qualcomm

TU/e

Access mechanism for networks sharing the same channel (1)

- Dynamic Frequency Selection and Transmit Power Control (like in WiFi).

- Asynchronous, using LBT (like LTE-LAA):
  - Short access delays if channel is lightly loaded
  - Access delays up and throughput down for high loads

==> inefficient spectrum sharing

Access mechanism for networks sharing the same channel (2)

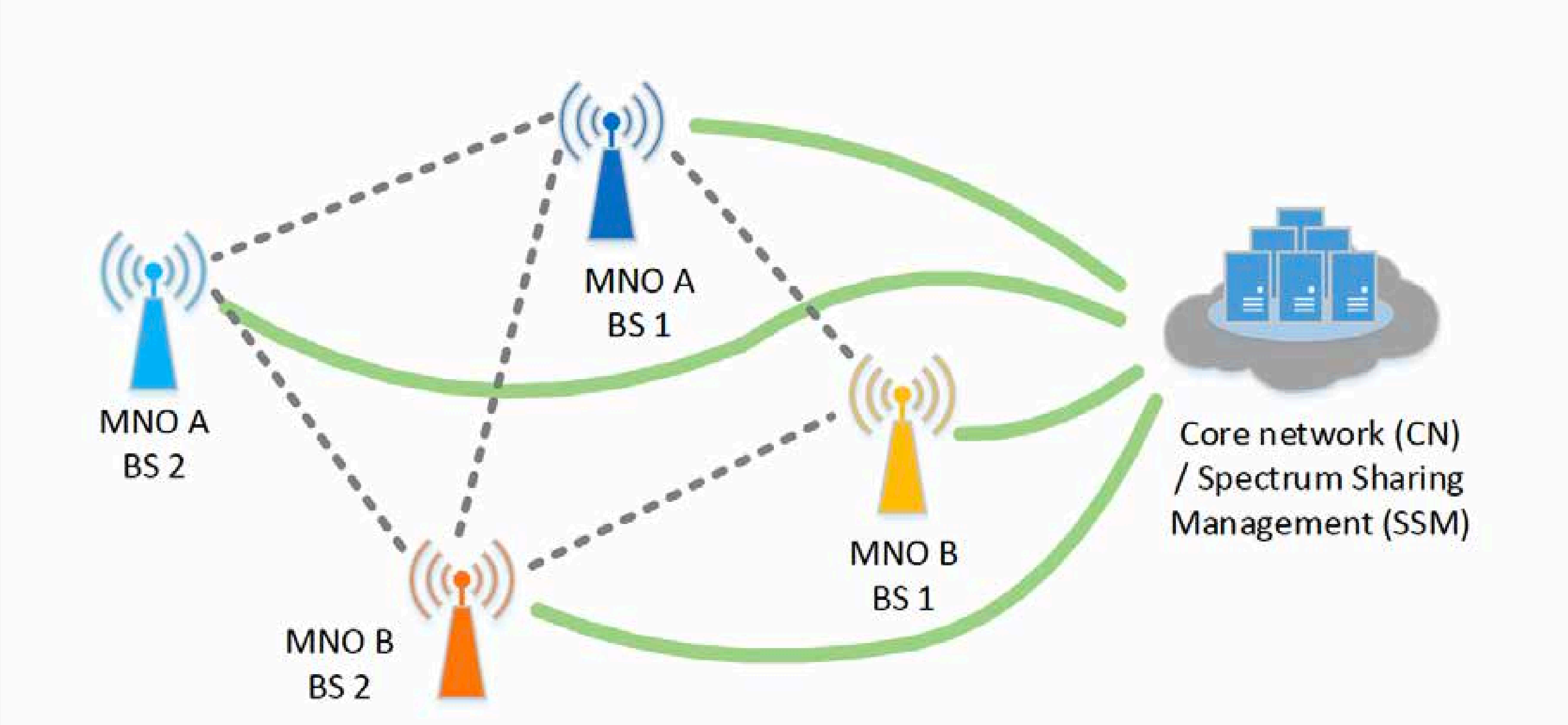
- Synchronous access, using Coordinated Multi-Point transmission (CoMP): synchronized geographically distributed radio-heads jointly transmit signals to each UE in a coordinated way
  - Multiple networks sharing the same channel monitor each other's transmission (spectrum sensing) to avoid conflicts
  - Separate networks are not allowed to exchange synchronization and coordination messages because (legal restrictions) è information only from spectrum sensing.

Compared with LBT, sharing efficiency can be dramatically increased, e.g., with 2 networks and depending on the type of traffic, data throughput x 3 (Qualcomm at MWC 2019).

Beyond-5G DSS

- Coordinated Spectrum Sharing (CSS)
- DARPA Spectrum Collaboration Challenge (SC2) – SCATTER solution

Coordinated Spectrum Sharing (CSS)



Source: [Jeon et al., 2019]

Developed by Samsung Research

CSS Premises

- Spectrum most needed in urban areas and for human/smart-phone communications

  è diurnal pattern, linked to human activity

  è traffic demands of MNOs strongly correlated in time and space

  è little to be gained by sharing?

- Answer: **NO!**
  - On a small time scale traffic patterns are bursty
  - Future traffic demands will shift towards machine-to-machine communication, which does not necessarily have a diurnal pattern.

CSS Characteristics

- For new unlicensed spectrum bands without incumbents, e.g.,
  - CBRS 3.5 GHz band
  - new up to 3 THz bands è total of 95 GHz unlicensed spectrum foreseen (FCC ‘s Spectrum Horizon project)
- Intended for “dense” urban networks
- No coexistence with LAA nor WiFi

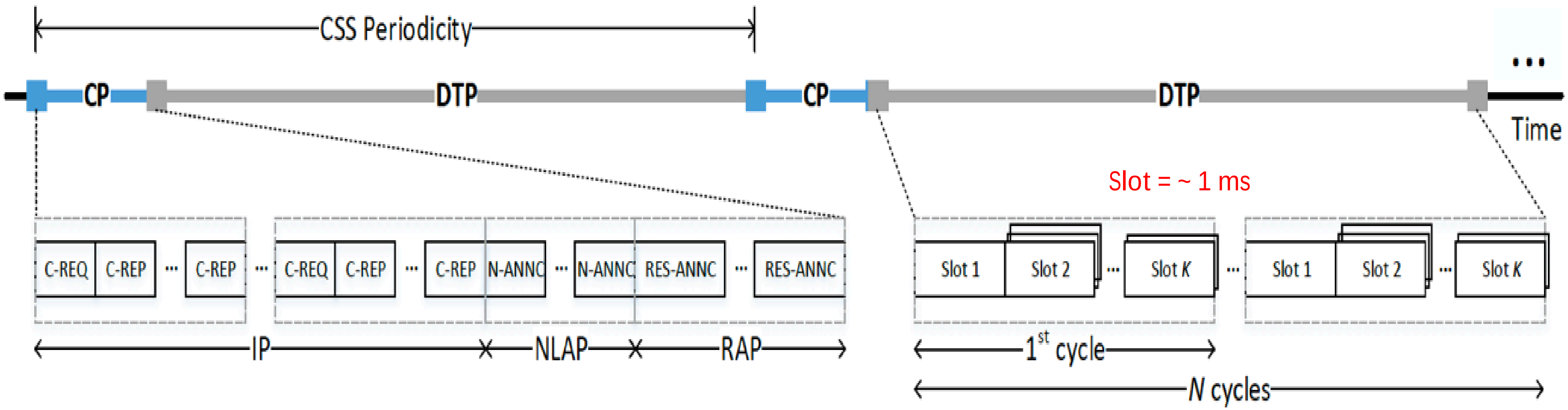
CSS - Principles

- Dynamic coordination between base stations belonging to different MNOs
- Sharing at the level of transmission bursts: ms time scale
- Scheduling of BSs by Spectrum Sharing Manager (SSM)
- “Soft” prioritization between sharing entities: from rigid hard prioritization to equal sharing.
- Opportunistic uncoordinated access, using CSMA/CD, still possible under particular circumstances.

CSS – Spectrum Sharing Management (SSM)

- SSM resides in the core network.
- Operated by neutral party.
- Resource reservation and allocation on request of BSs, based on coordination info from BSs:
    - Sensing-based mutual interference relationships between BSs
    - Intention of other BSs to access the spectrum.
- SSM operates on a per frame basis/ BSs operate on a per slot basis
- Could also be distributed: BSs exchange info among themselves over the air

CSS –Frame Structure



CP = Coordination Phase DTP = Data Transfer Phase IP = Interaction Period
NLAP = Neighbor List Announcement Period
RAP = Reservation Announcement Period

Source: [Jeon et al., 2019]

CSS – Simulation results (1)

- Energy (signal) detection threshold to estimate whether BSs are interfering or not, has a big influence on the performance (throughput as well as access delay) and needs to be determined empirically.
- Compared to LAA with WiFi: a very significant increase in mean throughput (40% to 143% depending on the traffic scenario) and a dramatic improvement at the (small cell) edges (60% to 413%, depending on traffic scenario).
- Compared to LAA with WiFi: significant improvements in access delay are observed, e.g., from 12 ms for LAA sharing with WiFi, to less than 1 ms for CSS for heavy loads.

CSS – Simulation results (2)

- Compared to LAA with WiFi: fairness of access to spectrum, as measured by Jain's fairness (index value between 0 and 1, where 1 is the highest degree of fairness) also improves (e.g., for a dense-BS scenario: 0.81 vs 0.47 for LAA users and 0.39 for WiFi).
- Compared to CBRS: significant increase in mean throughput (40% to 243%depending on the traffic scenario) and dramatic improvement at the (micro)cell edges (up to 576%, for a low load traffic scenario).
- Compared to CBRS: access delay and resource fairness are always better for CBRS, since resources are always reserved.

DARPA Spectrum Collaboration Challenge (SC2) – Premises (1)

- Demand for spectrum for commercial and military use is ever increasing
- To satisfy this demand sharing of spectrum will be a necessity.
- Present spectrum sharing mechanisms are not sufficient:
  - Exclusive licenses are inefficient because licensees underutilize the spectrum.
  - Spectrum access in unlicensed bands is both suboptimal and not consistent enough for users that require a guaranteed QoS.

DARPA Spectrum Collaboration Challenge (SC2) - Premises (2)

- Spectrum can be shared much better, while satisfying the diverse user needs, by having collaborative joint optimization by all involved parties.
- No central authority: all sharing parties operate autonomously.
- **There is a (low-rate) communication channel between all sharing networks**
- AI techniques and advanced optimization techniques for robust optimization for any desired ensemble state
- No longer a distinction between licensed and unlicensed spectrum
- No knowledge of which network technologies are being used

SC2 - Goals

Fairness and coexistence in any possible spectrum range.

DARPA SC2 Paradigm Shift

- Standardization of technologies => standardization of a simple coordination protocol.
- Exclusive spectrum access => coordinated and collaborative spectrum sharing.
- Intra-technology centralized scheduling => cross-technology distributed coordination.
- Domain expertise (knowledge of technologies present) => machine learning approaches.

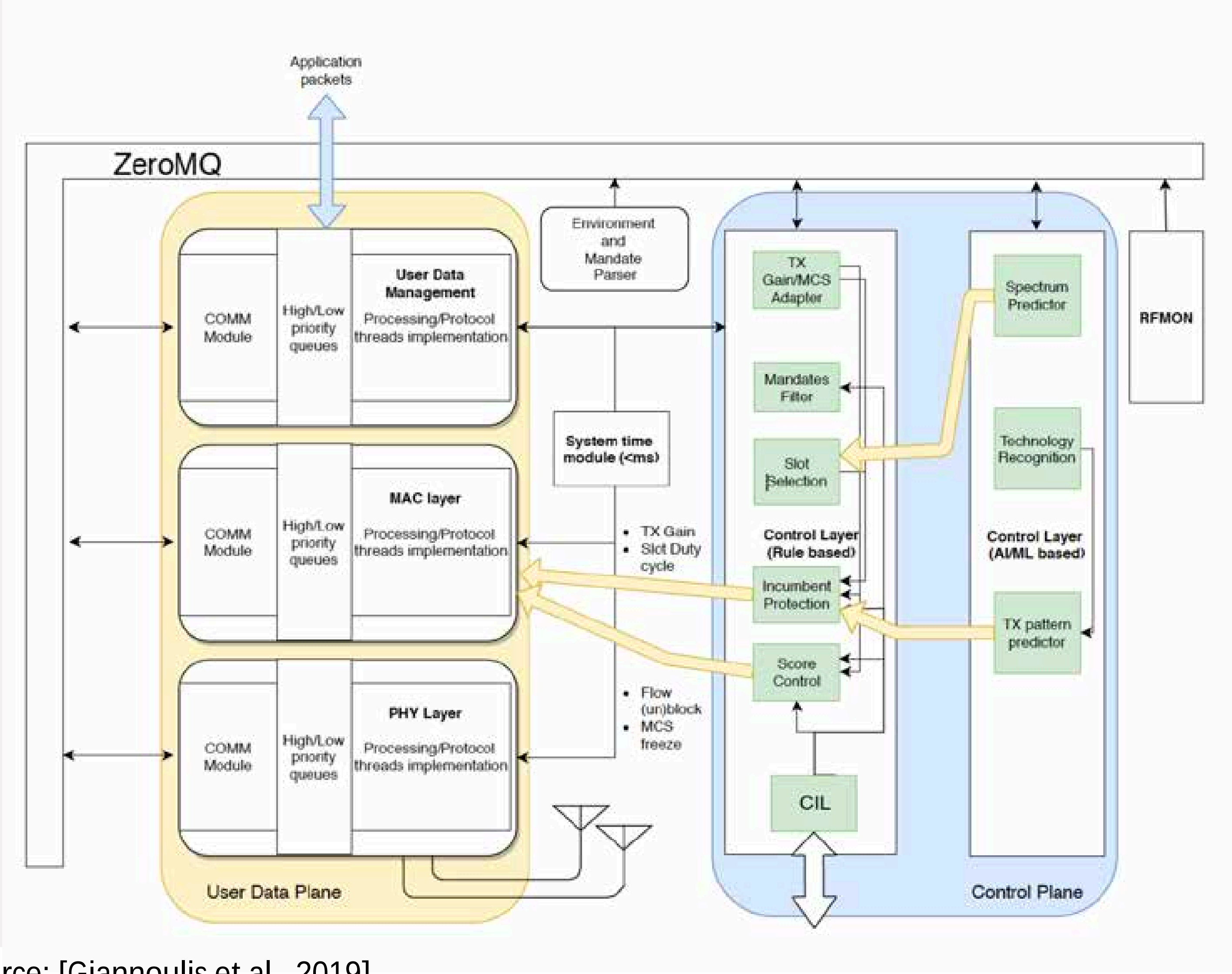
SC2 Testing and Evaluation

- World's largest RF emulation testbed: Colosseum (Johns Hopkins University).
- Colosseum capabilities [Barcklow et al., 2019]:
  - > 65,000 simultaneous interactions, e.g., text messages, video streams, etc., between 128 two-channel radios
  - Emulated area of ~ 1km x 1km
- Measures of success of proposed methods:
  - Number of tasks (data transmitted of different types and QoS) accomplished for its own benefit
  - How much capability was left for its collaborating competitors, to achieve their goals.
- Competition band: 40 MHz

SCATTER SC2 Solution: Universiteit Gent/IMEC & Rutgers University

- Slotted system: discovery and prediction of (slot) holes in the spectrum by a Deep Convolutional Neural Network (CNN).
- Offline training plus online training model using RFMON data: to quickly learn, recognize, adapt and predict the behavior of other networks.
- Goal: avoid interference with other transmissions.
- Output CNN: matrix of values with the superframe shape, used as a filter into the slot selection module for to selecting, negotiating, and allocating slots.
- Shared control channel: WiFi (CSMA/CA broadcast).
- SCATTER data transmission: LTE (TDMA and FDMA) or WiFi.
- SCATTER recognizes 5 different RF technologies: radar, jammer, SCATTER, other networks and noise.

Scatter SC2 System



Source: [Giannoulis et al., 2019]

Overview

- What is DSS and why we need it?
- Overview existing DSS systems and what they apply to
- **Basic technologies for future DSS**
- Concluding remarks

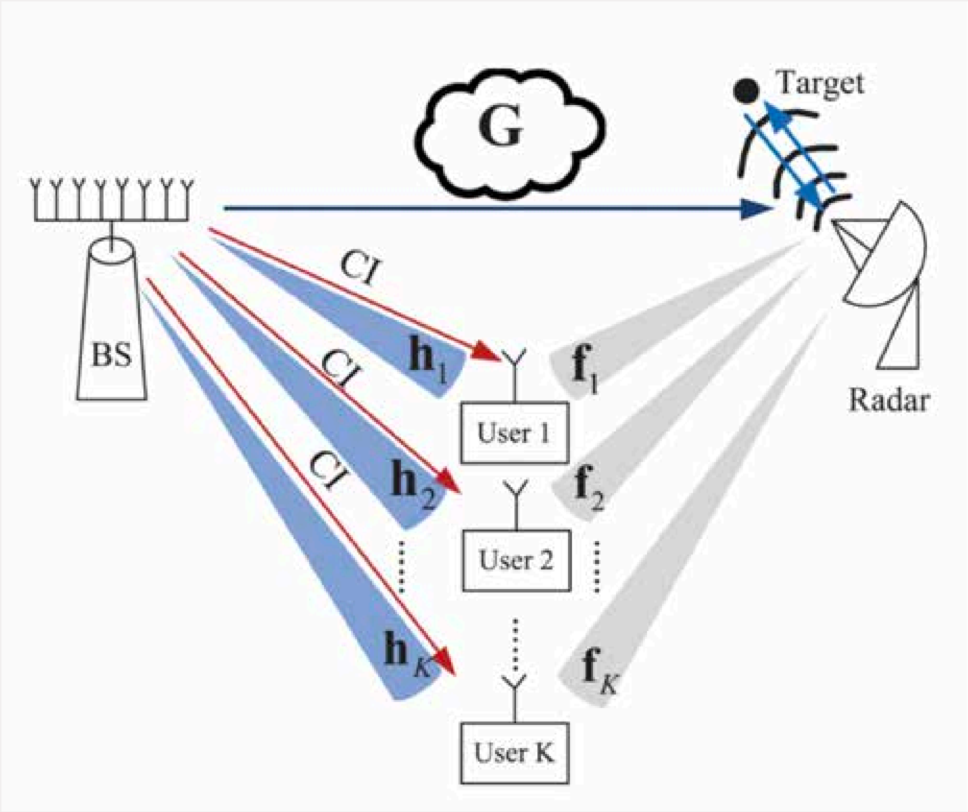
TU/e

Selected Technologies and their role in dynamic spectrum sharing (research)

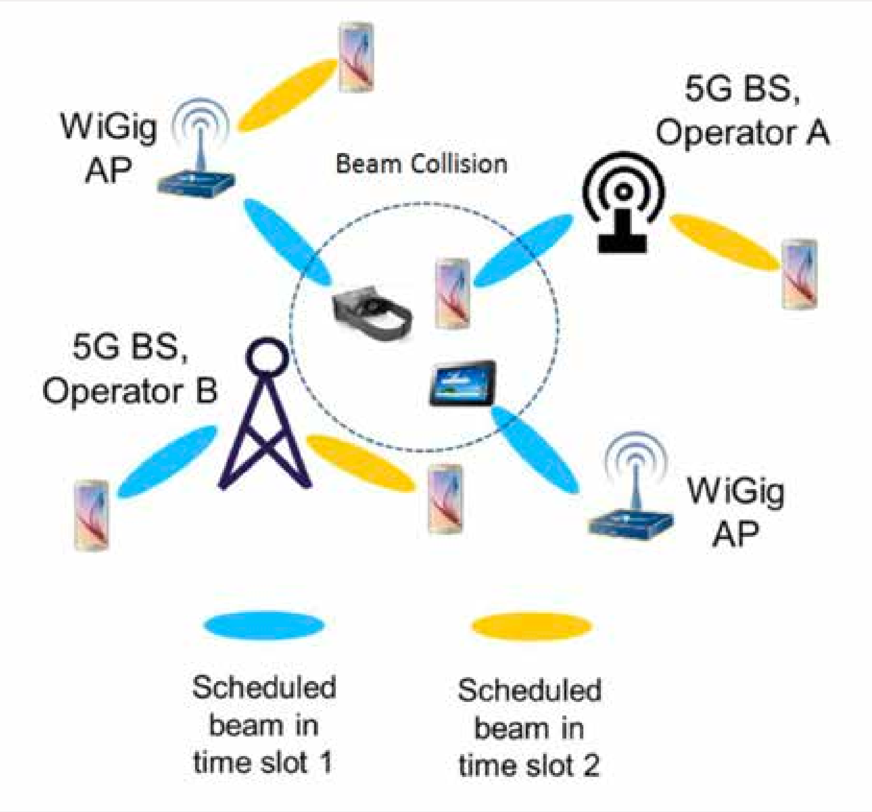
- Spatial spectrum sharing
- AI Techniques: Machine Learning (ML)
- FDX Radio
- Radio Virtualization and Infrastructure Sharing

Spatial spectrum sharing

- Facilitated by beamforming and massive-MIMO



Source: [Liu et al.,2018]



Source: [Nekovee, 2018]

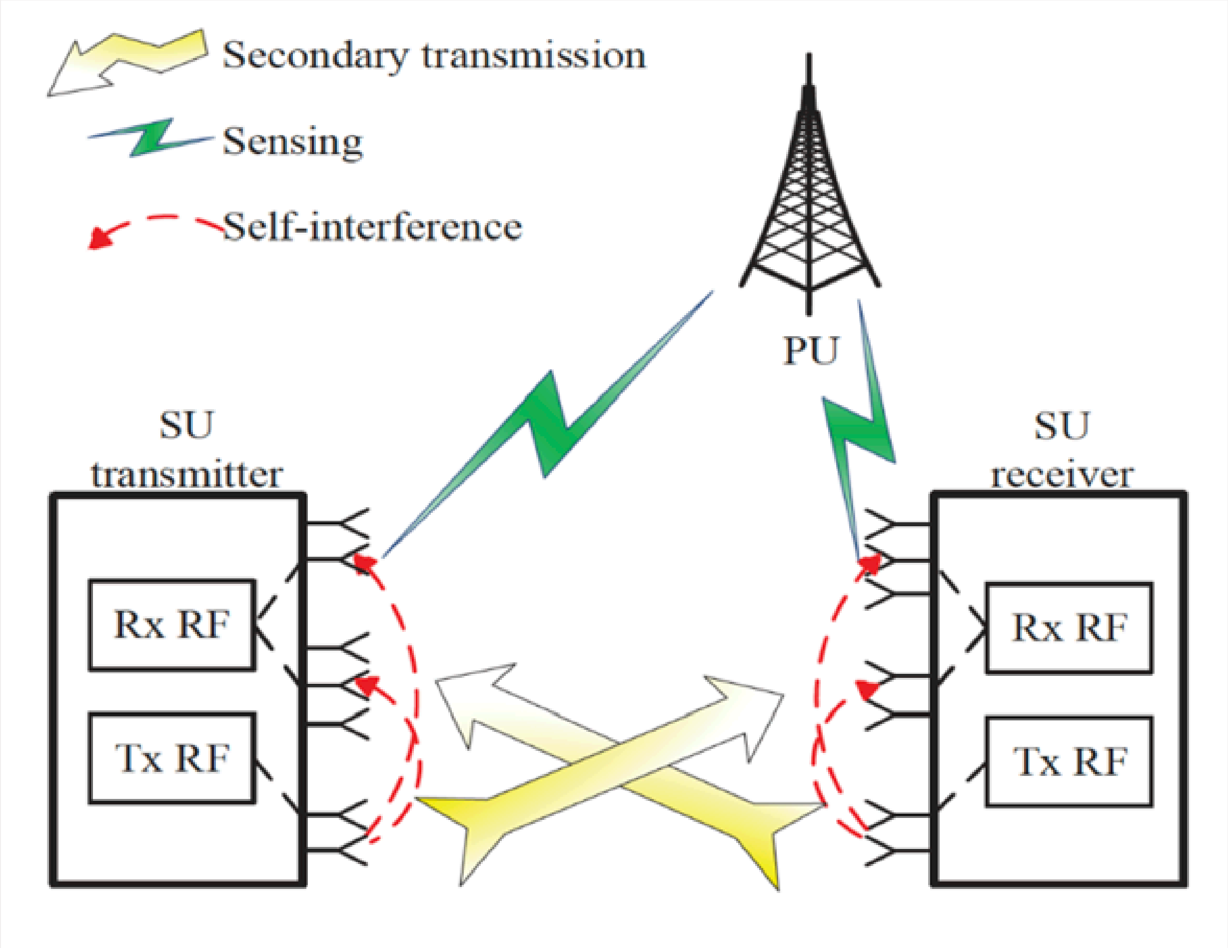
AI Techniques: Machine Learning (ML) (1)

- Example application domains in DSS
  - Cooperative spectrum sensing.
  - Signal classification and traffic recognition.
  - Dynamic spectrum access based on local decision making
- Why?
  - Does not require domain knowledge.
  - Computationally less complex and hence faster and more energy-efficient than classical solutions. This implies that certain functions can be performed in real-time that previously could not.
  - Often more robust (i.e., still work) when the operational circumstances deviate from what an original design was assuming.

AI Techniques: Machine Learning (ML) (2)

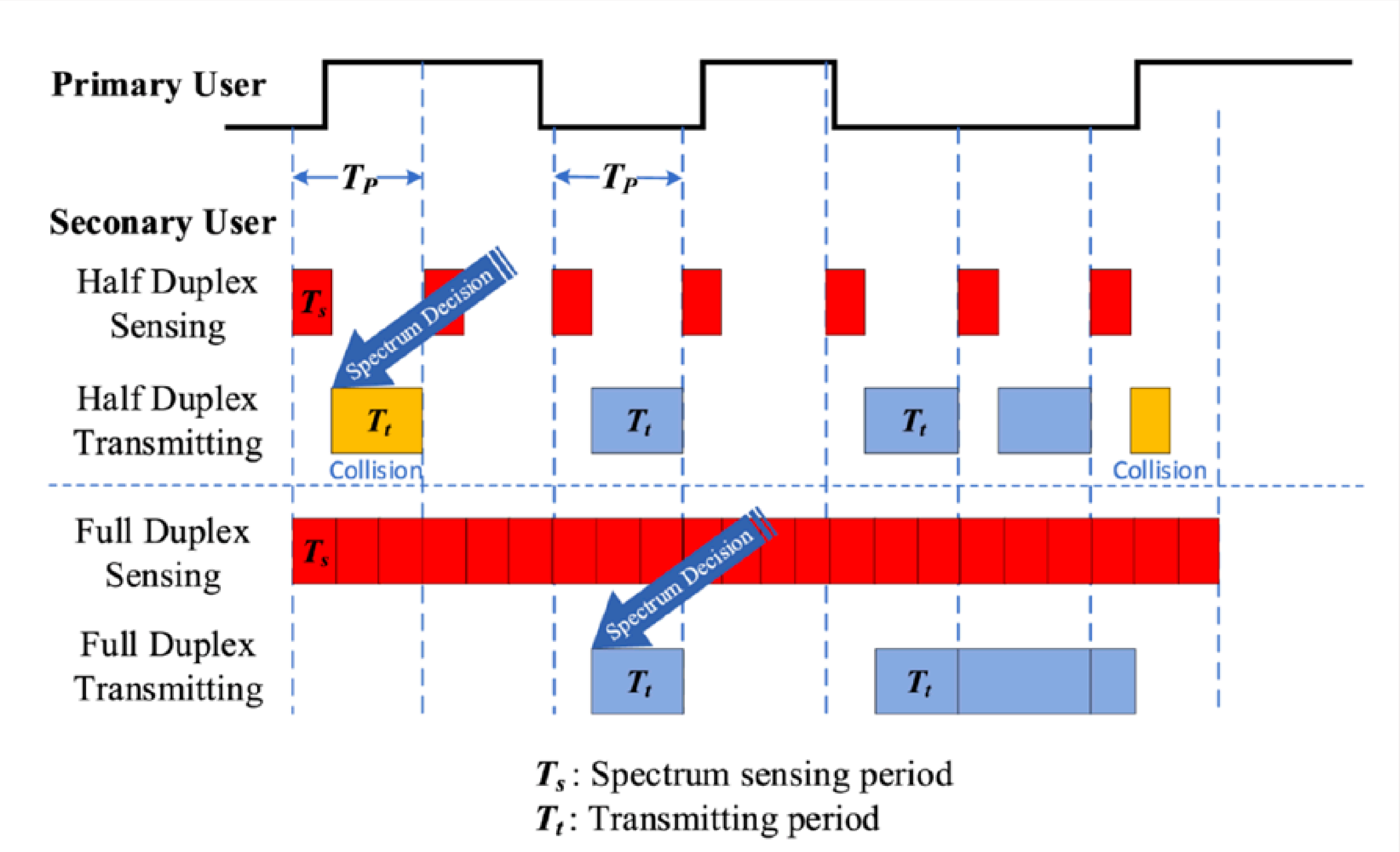
- The initial offline training can be costly (lengthy), and appropriate training data must be generated through simulations or measurement campaigns. Some of the problem can sometimes be alleviated by an online-learning neural network.

FDX Radio



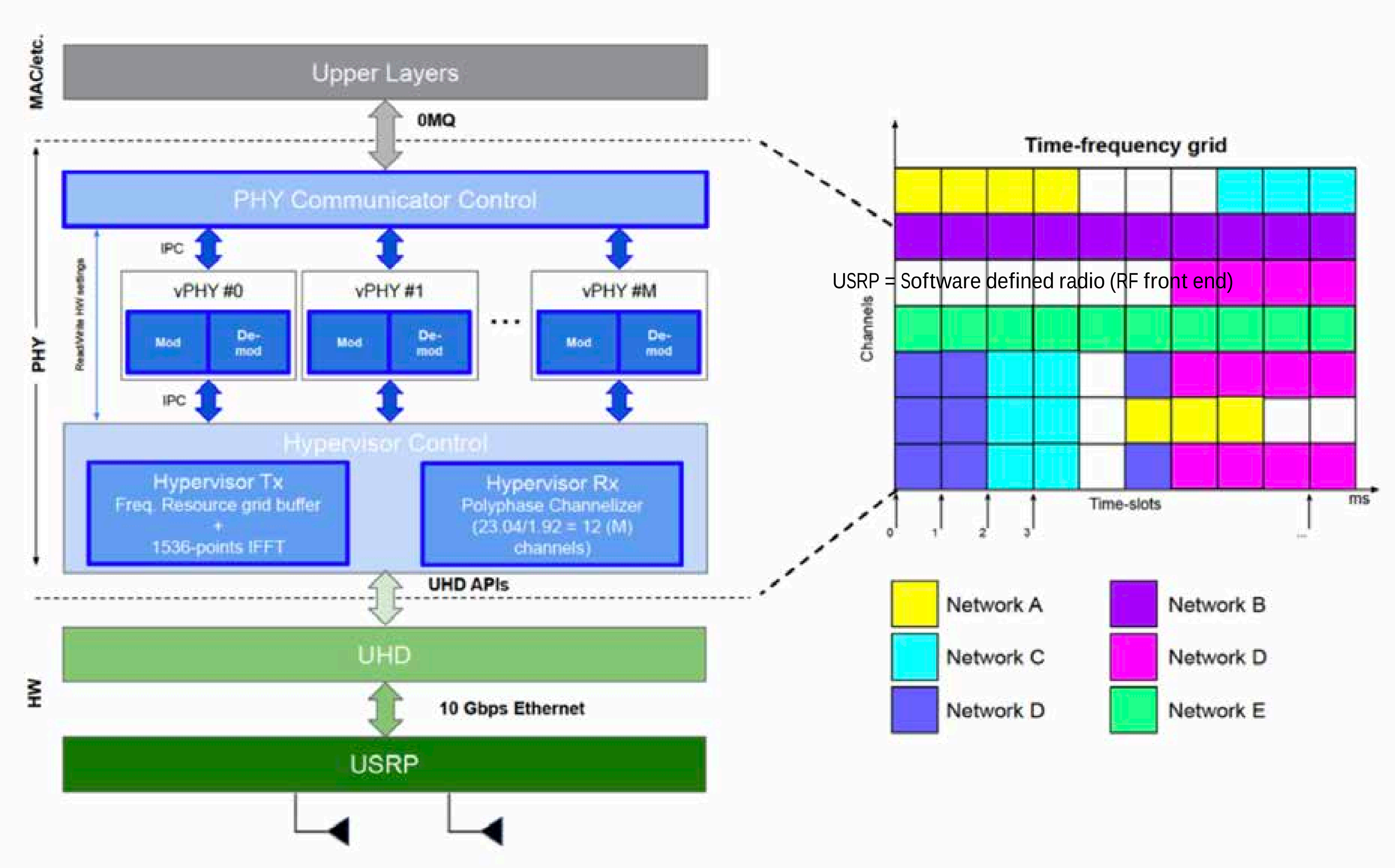
Source: [Liao et al., 2015]

FDX Radio: FDX Sensing



Source: [Hu et al., 2018]

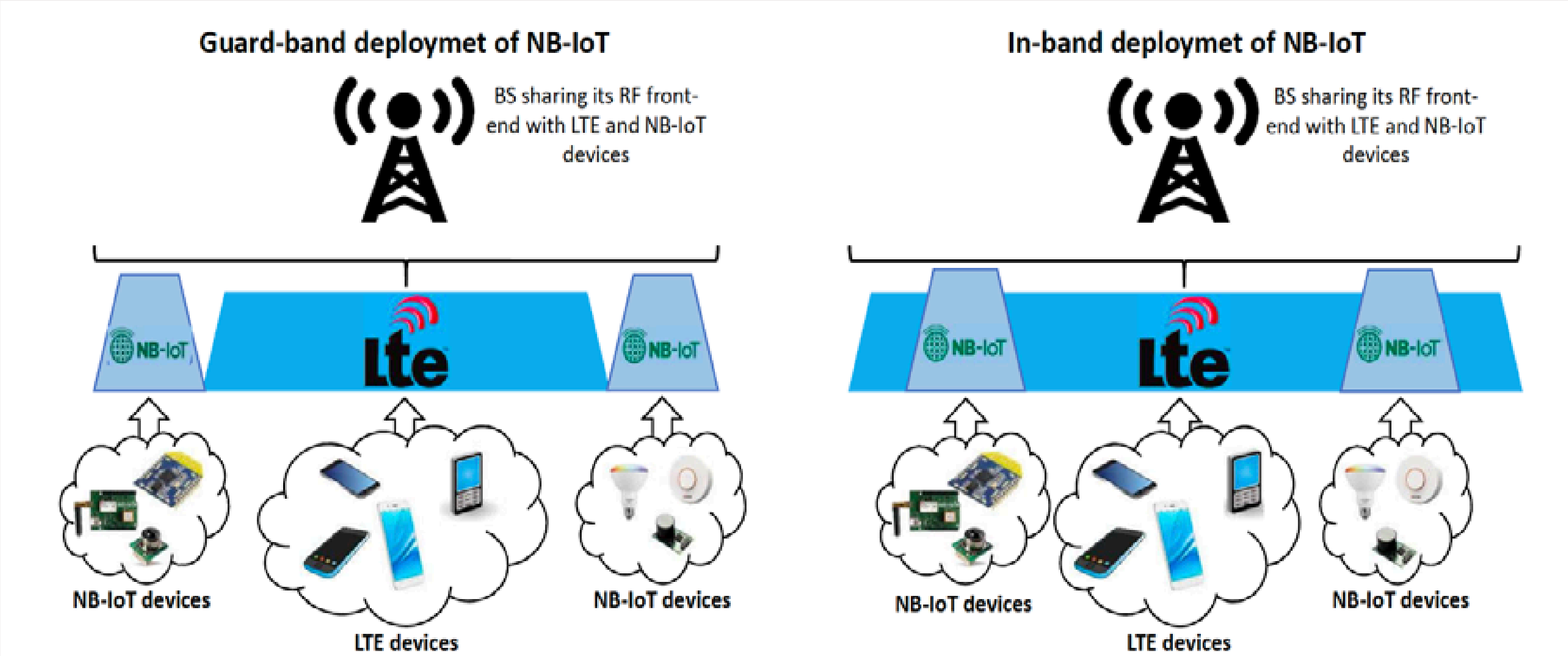
Radio Virtualization and Infrastructure Sharing



USRP = Software defined radio (RF front end)

Source: [de Figueiredo et al., 2020]

Radio Virtualization and Infrastructure Sharing - Example



Overview

- What is DSS and why we need it?
- Overview existing DSS systems and what they apply to
- Basic technologies for future DSS
- **Concluding remarks**

Concluding remarks

- Need for spectrum is real and increases rapidly
- Spectrum resource is finite è we need to share it
- A range of standardized techniques and technologies are available for sharing between networks:
  - Most are rather “coarse” and static, i.e., not very efficient
  - Most address specific use cases and are not “flexible”.
- More advanced and “fine-grain” methods, enabled by advanced hardware/software technologies will squeeze more out of existing spectrum through dynamic sharing.
- DSS applied to new spectrum bands is an opportunity! Easier to introduce than in “legacy” systems.

References (1)

- [Ericsson Mobility Report, 2022], https://www.ericsson.com/49d3a0/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-june-2022.pdf
- [Dynamic Spectrum Alliance, 2020] Dynamic Spectrum Alliance (DSA), "Latest Advances On Regulatory Frameworks, Ecosystem, Commercial Development Status And Social Impact" http://dynamicspectrumalliance.org/wp-content/uploads/2020/08/DSA, TVWS Workshop, July 2020.
- [ETSI eLSA, 2020] ETSI, "Reconfigurable Radio Systems (RRS); evolved Licensed Shared Access (eLSA); Part 2: System architecture and high-level procedures", ETSI TS 103 652-2 V1.1.1 (2020-01).
- [Baena et al.,2020] Baena et al., "KQI Performance Evaluation of 3GPP LBT Priorities for Indoor Unlicensed Coexistence Scenarios", Electronics MDPI, October 2020.
- [Jeon et al., 2019] Jeon et al., "Coördinated Dynamic Spectrum Sharing for 5G and Beyond Cellular Networks", IEEE Access, August 2019.

References (2)

- [Giannoulis et al., 2019] Giannoulis et al., “Dynamic and Collaborative Spectrum Sharing: The SCATTER Approach”, Conference Proceedings DySPAN Conference 2019.
- [Barcklow et al.,2019] Daniel R. Barcklow et al., “Radio Frequency Emulation System for the Defense Advanced Research Projects Agency Spectrum Collaboration Challenge”, Johns Hopkins APL Technical Digest, Volume 35, Number 1, 2019.
- [Liu et al., 2018] Liu et al., “MIMO Radar and Cellular Coexistence: A Power-Efficient Approach Enabled by Interference Exploitation”, IEEE Transactions on Signal Processing, Volume 66, Issue: 14, 2018.
- [Nekovee, 2018] Nekovee M., “Opportunities and Enabling Technologies for 5G Spectrum Sharing”, Book chapter, “Handbook of Cognitive Radio”, Springer, 2018.
- [Liao et al., 2015] Liao et al., “Full-Duplex Cognitive Radio: A New Design Paradigm for Enhancing Spectrum Usage”, IEEE Communications Magazine, vol. 53, no. 5, May 2015.

References (3)

- [Hu et al., 2018] Hu et al., “Robust Modulation Classification Under Uncertain Noise Condition Using Recurrent Neural Network”, Proceedings of the IEEE Global Communications Conference (GLOBECOM’18), 2018.

- [de Figueiredo et al., 2020] de Figueiredo et al., “A Baseband Wireless Spectrum Hypervisor for Multiplexing Concurrent OFDM Signals”, Sensors, February 2020.

Further reading:

- [Stratix, 2021] Stratix, “Dynamic Spectrum Management & Sharing”, Study commissioned by Radiocommunications Agency Netherlands, Ministry of Economic Affairs and Climate, July 2021.

- [Niemegeers, 2021] Niemegeers I.G., “State of the Art of Dynamic Spectrum Sharing”, CWTe Technical Report, CWTe TU/e, 2021.*

- This report has served as input to [Stratix, 2021] and contains numerous references to DSS literature and research projects.

Centre for Wireless Technology, Eindhoven