INSPIRED BY…

Orca

Orchestration and Reconfiguration Control Architecture

WiSHFUL

Wireless Software and Hardware platforms for Flexible and Unified radio and network controL

eWINE

Elastic Wireless Networking Experimentation

imec IDLab GHENT UNIVERSITY Universiteit Antwerpen

SC2

Spectrum Collaboration Challenge

TEAM SCATTER

imec +
Rutgers University

MOTIVATION

SPECTRUM IS GETTING OVERLOADED

Wi-Fi traffic has a 30%+ CAGR

Source: Cisco VNI Forecast

BLE traffic: 22% CAGR

Source: https://truthtoday24.com/bluetooth-beacon-market-to-expand-with-a-cagr-of-22-0-from-2017-2025/:

Wireless sensor traffic: 18.55% CAGR

https://www.marketsandmarkets.com/PressReleases/wireless-sensor-network.asp

Private LTE market: 32.3% CAGR

Source: https://www.multefire.org/wp-content/uploads/HRI_Paper_Private-LTE-Network-Paper_20-July-2017_Final.pdf

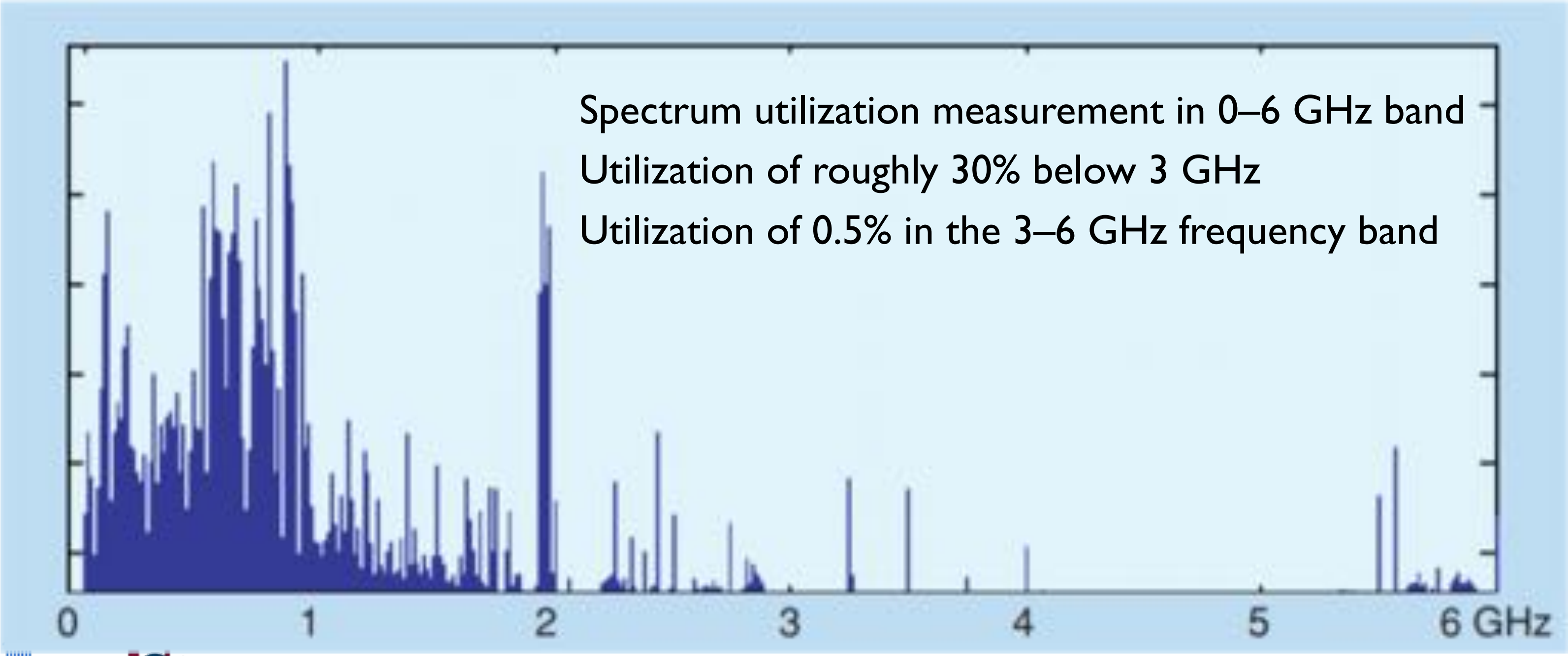
LTE traffic: 41% CAGR

Source: https://www.ericsson.com/assets/local/mobility-report/documents/2017/ericsson-mobility-report-november-2017-central-and-eastern-europe.pdf

Extremely challenging deployments

A LOT OF SPECTRUM IS WASTED!

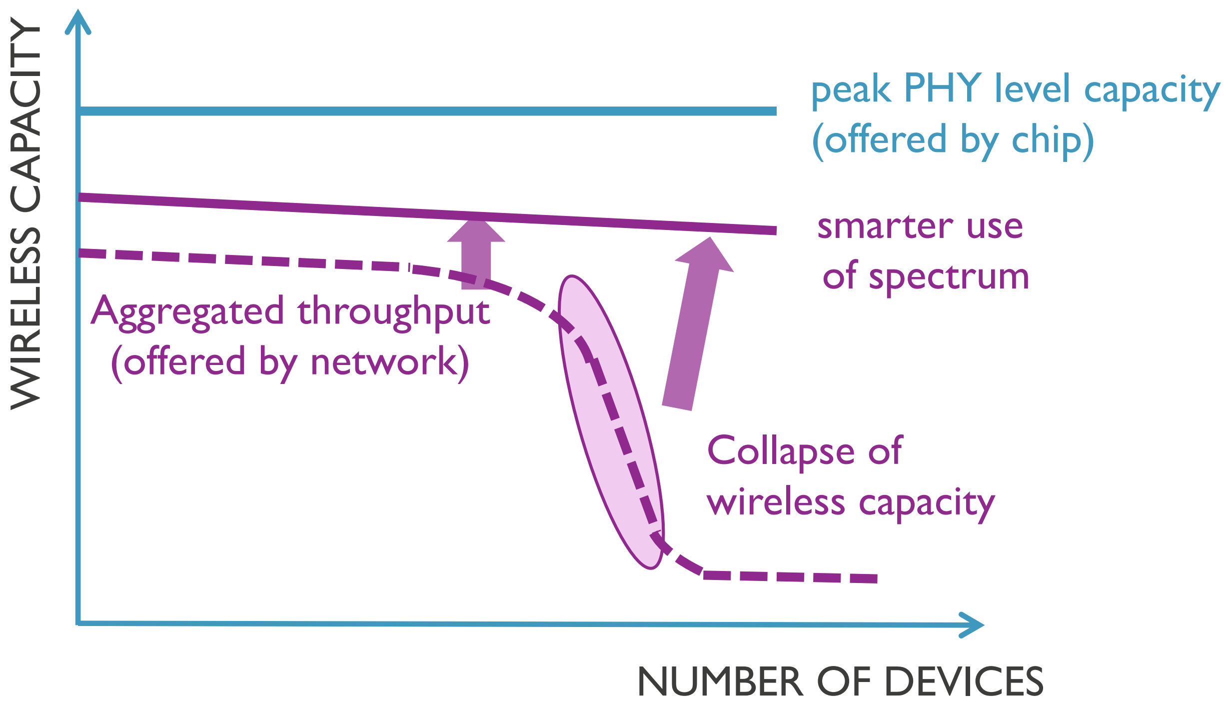
- Unlicensed bands: waste of spectrum due to CCA (mandatory), contention, collisions, interference
- Licensed technologies: designed for maximum capacity, most of time underutilized
- **Spectrum is a scarce resource (like water, energy) and should NOT be wasted!**



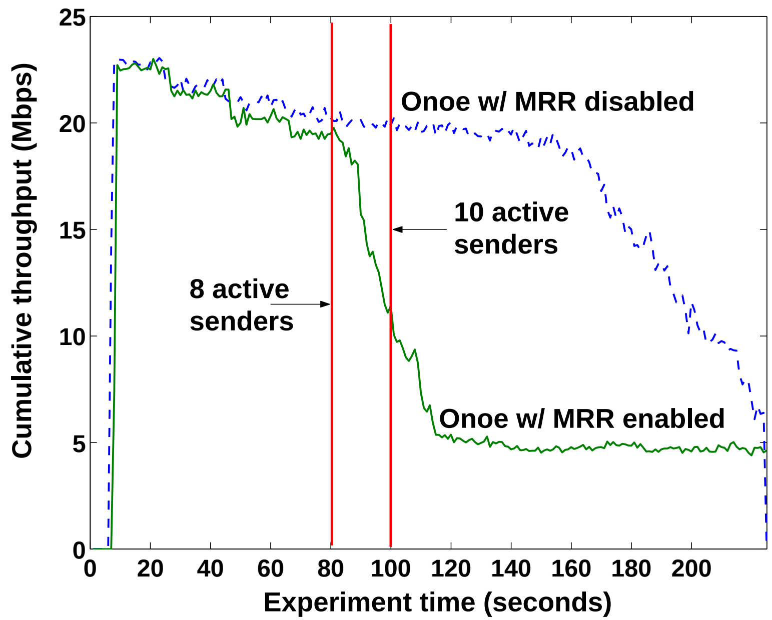
SPECTRUM SHARING IN UNLICENSED BANDS

THE WIRELESS CAPACITY BOTTLENECK: LIMITED THROUGHPUT & SCALABILITY

- Today, capacity of **WIRELESS TECHNOLOGIES COLLAPSES** when usage is high



Scalability analysis at Rutgers University



SPECTRUM USAGE MODELS

DIFFERENT MODELS EXIST TO WORK (OR NOT) TOGETHER

TODAY

Model	Description	Deployment	Technologies
Licensed access	Exclusive assignment of frequency band	Single mobile operator	Traditional cellular networks (e.g. GSM, UMTS, LTE, 5G)
Unlicensed shared access	License-free operation according to regional regulation	Many providers	Uncoordinated operation of many technologies (short range: IEEE802.11, IEEE802.15.4, Bluetooth, MulteFire,...,

SPECTRUM DOES NOT SCALE WITH NEED FOR HIGHER DATA RATES

UPCOMING

Model	Description	Deployment	Technologies
Licensed Spectrum Sharing	Frequency band assigned to multiple providers based (loca	Authorized provider (micro-operators) +	Private LTE/5G networks (e.g. CBRS) Directive from FCC (US) : SAS Directive from RSC (EC) : LSA
Licensed assisted access (LAA)	Use of unlicensed band(s) in addition to	Mobile operator + unlicensed network	Coexistence of cellular + unlicensed technologies (e.g. LTE-LAA)
Sharing in application-specific bands	Frequency band assigned to specific applications	Multiple providers	DSRC 5.9 GHz for ITS: IEEE802.11p + LTE V2X

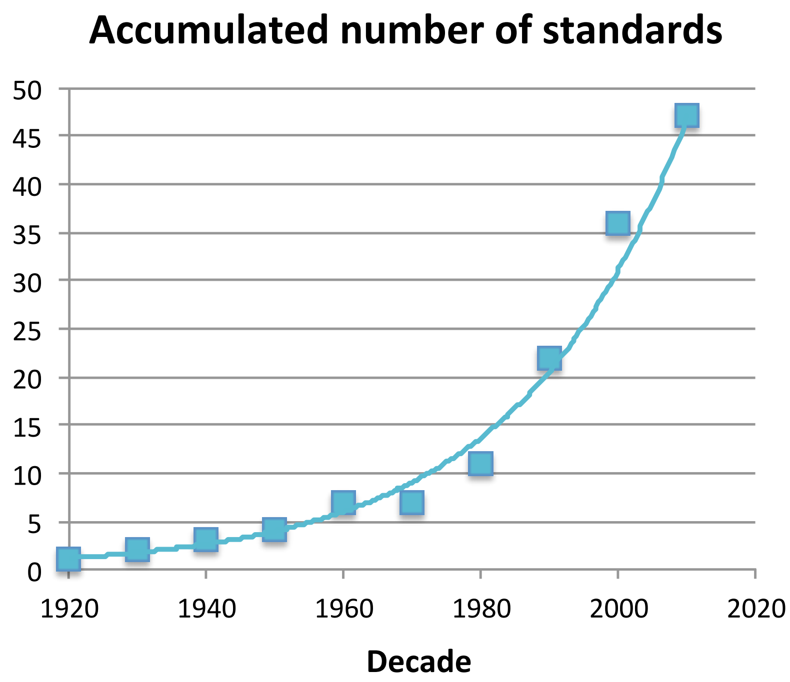
EXCLUSIVE SPECTRUM IS LIMITED

MORE SPECTRUM SHARING IS UNAVOIDABLE!

WIRELESS NETWORKS ARE COMPLEX SYSTEMS

- INCREASING
  - number of devices
  - density of devices
  - number of applications
  - data rates
  - diversity of QoS requirements
  - number of heterogeneous technologies & standards

THE EXPLOSION OF WIRELESS STANDARDS



	Terrestrial broadcasting	Two-way radio	Mobile Telecom	Wireless internet	IoT/peripheral
1920s	AM				
1930s	FM				
1940s			AT&T MTS		
1950s	NTSC				
1960s	PAL SECAM		AT&T IMTS		
1970s					
1980s	FM-RDS		AMPS, NTT, NMT		
1990s	DAB, DVB-T, ATSC	TETRA, P25	D-AMPS, GSM, IS-95	802.11 a/b	Bluetooth
2000s	DRM, DVB-T2, ISDB-T, DTMB	DMR. NXDN	CDMA-2000, WCDMA, TD-SCDMA, WiMAX, LTE	802.11n	ANT, 802.15.4
2010s			LTE-A, 5G-NR	802.11 ac/ad/ah/ax /p	NB-IoT, BTLE, LoRa, SigFox…

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WIRELESS NETWORKS ARE COMPLEX SYSTEMS

- INCREASING
  - number of devices
  - density of devices
  - number of applications
  - data rates
  - diversity of QoS requirements
  - number of heterogeneous technologies & standards
  - flexibility & number of reconfigurable parameters
  - …

- centralized scheduling schemes and algorithms based on domain-expertise only cannot cope anymore with increasing complexity

Need for more distributed and intelligent control in shared spectrum environments

Need for smart monitoring schemes to support network decisions

EXAMPLE: LTE-LAA

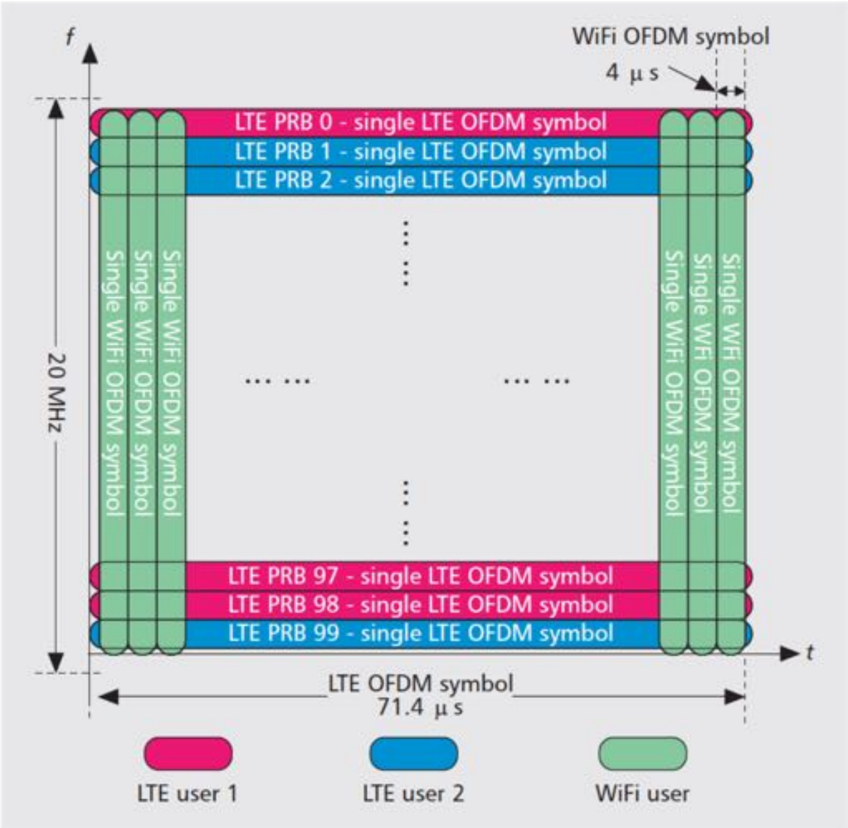
CURRENT LTE AND Wi-Fi STANDARDS

SIMILARITIES AND DIFFERENCES

	LTE	Wi-Fi
Same PHY design	Modulation: QPSK, 16/64/256 QAM OFDM	
Different PHY parameters	**Long range, outdoor (large fading)** • Long symbols (66.7µs) • Narrow subcarriers (15 kHz)	**Short range, indoor (limited fading)** • Short symbols (4µs) • Wide subcarriers (312.5 kHz)
MAC design	**MF-TDMA (OFDMA):** allocation of time slots and subcarriers to multiple users **No LBT** (Listen Before Talk) **Tight frequency & time synchronisation** **Continuous bit stream** (also if no data)	**CSMA:** contention based random access All subcarriers allocated to single user **LBT:** Clear Channel Assessment (CCA) **Only frequency synchronisation** **Packet-based transmission** (only if date)
Coordination	Centralised resource allocation	Distributed coordination (DCF)

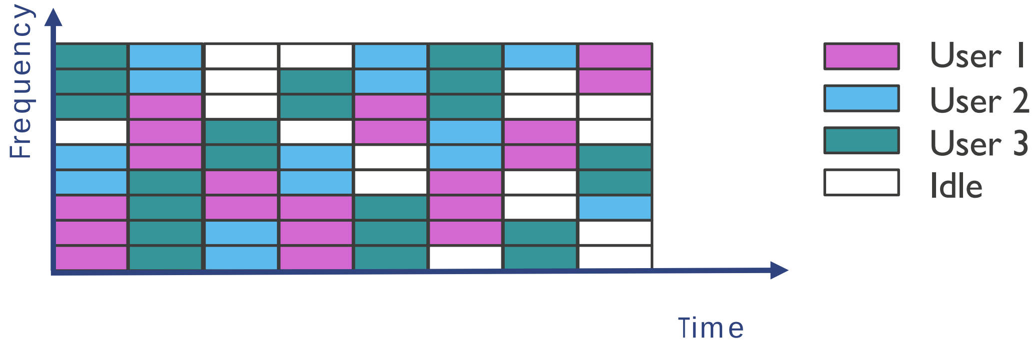
LTE AND Wi-Fi ARE NOT DESIGNED TO WORK TOGETHER!

Different PHY design parameters

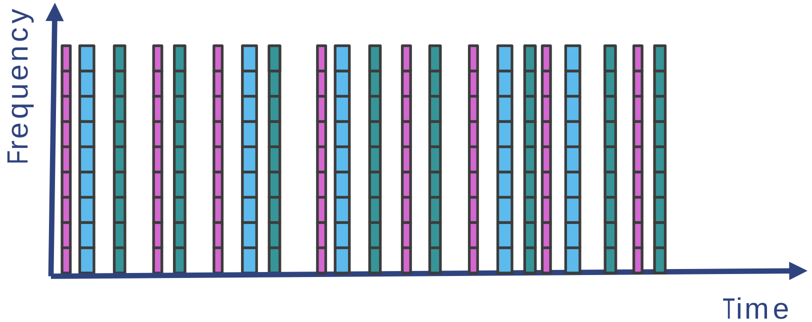


Different MAC, transport streams & timings

LTE: OFDMA + stream of transport blocks



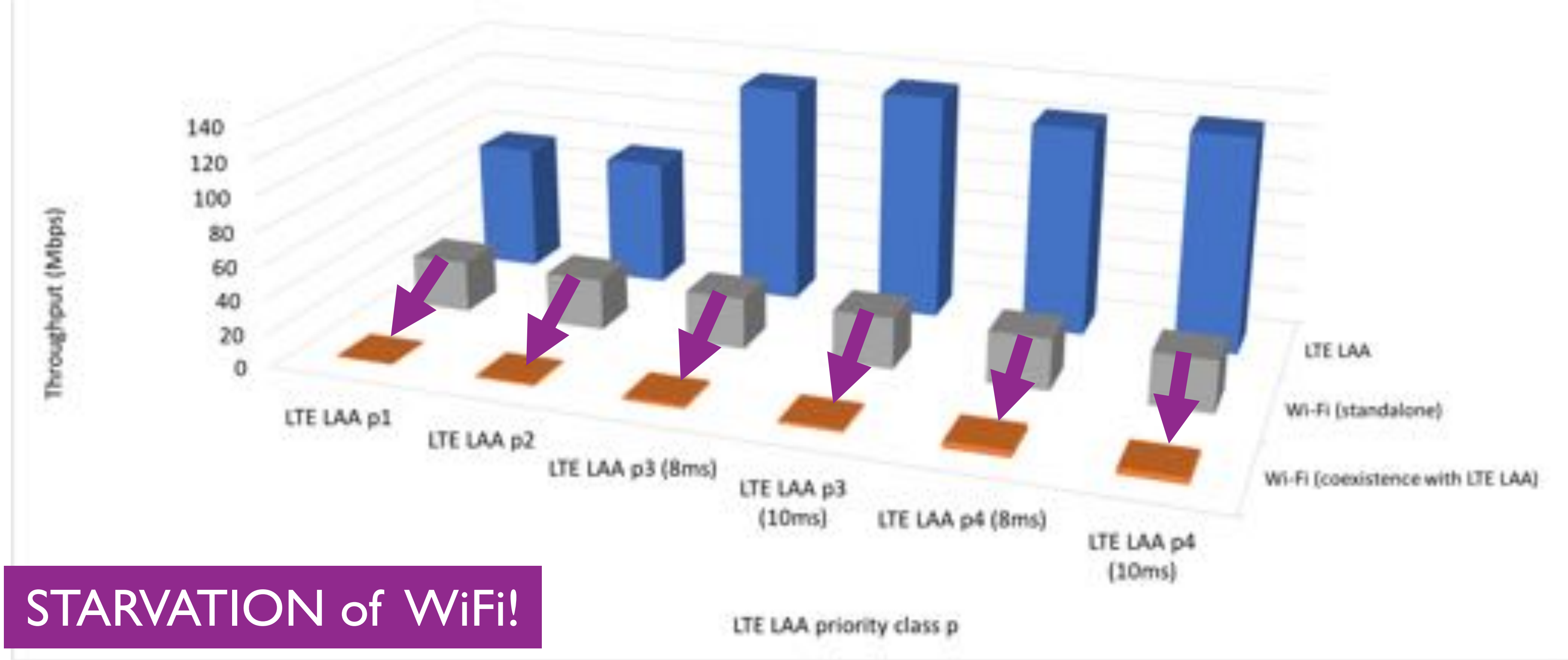
Wi-Fi: OFDM + random packet access



LTE-LAA (LICENSE ASSISTED ACCESS)

PROBLEM: LTE IS NOT DESIGNED FOR COEXISTENCE

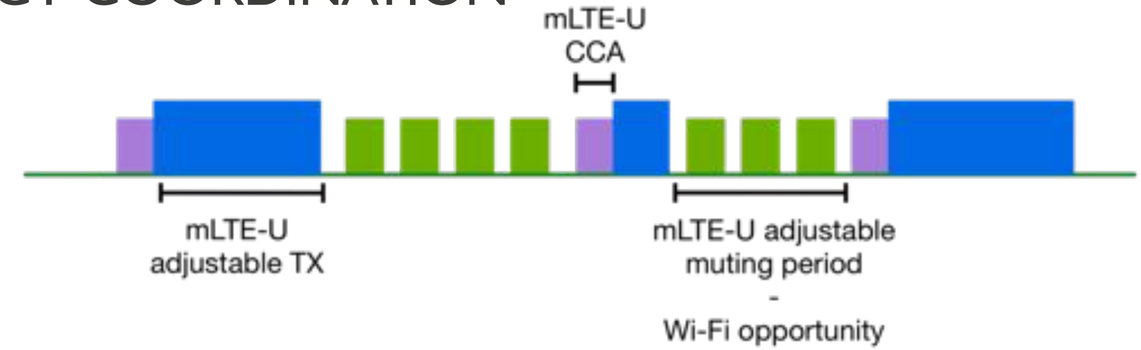
- contention of short Wi-Fi packets and large LTE TX opportunities



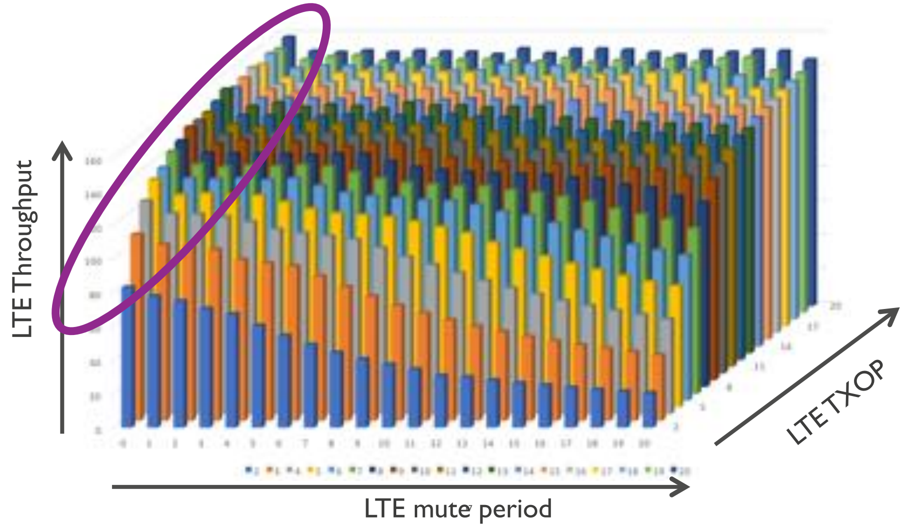
COEXISTENCE OF LTE AND WI-FI

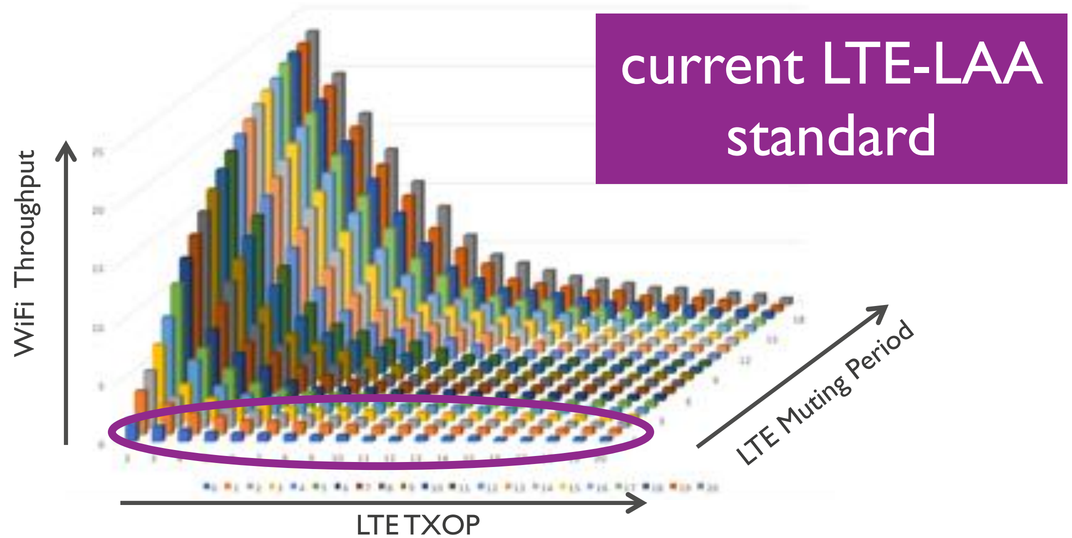
IMEC SOLUTION: CROSS-TECHNOLOGY COORDINATION

- Adjustable muting period + adjustable TXOP
- Cross-technology monitoring of load
- Cross-technology management (load-balancing)
  - adjust LTE muting period and TXOP based on load



- Example of 4 LTE + 4 Wi-Fi networks





TECHNOLOGY RECOGNITION

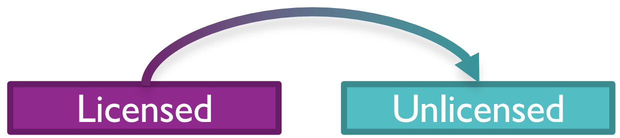
PUBLIC

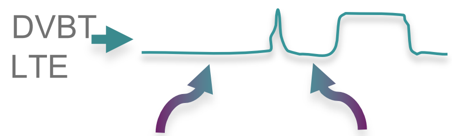
FROM DOMAIN EXPERTISE TO MACHINE LEARNING APPROACHES

MOTIVATION AND CONCEPT

Co-existing environments need intelligent decision making

- Offloading licensed to unlicensed bands
  - LTE co-existing with legacy Wi-Fi
- Sharing licensed bands e.g. DVB-T / LTE
  - White space reuse if no active transmission
- Identifying technologies for intelligent decision making
  - Maintaining quality of service for users
- Technology, interference, and traffic identification using machine learning
  - Flexible and robust way of identification
  - Requires no domain expertise

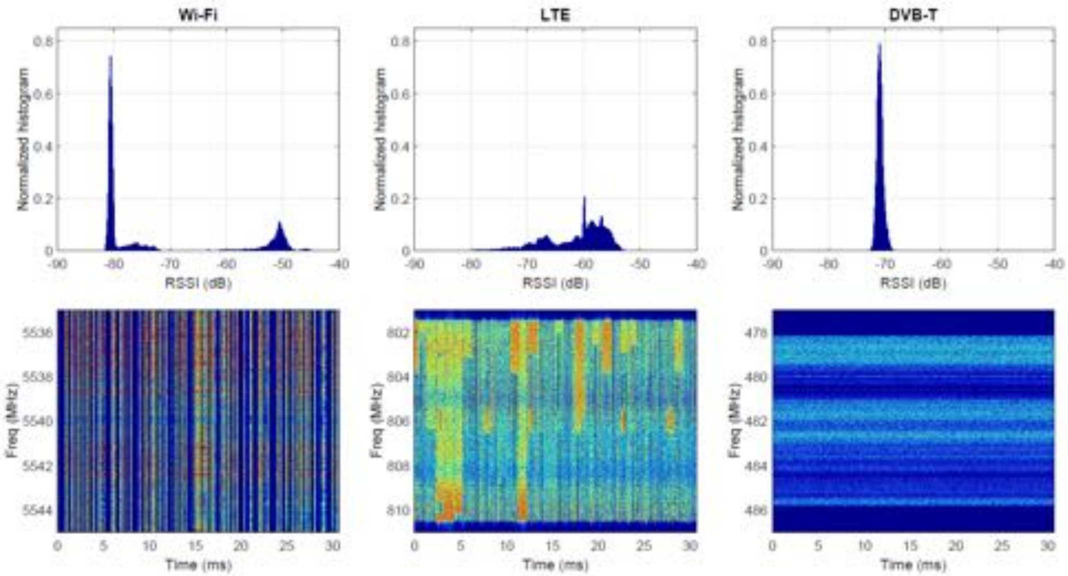




Windows of opportunity for cognitive radios

FROM DOMAIN EXPERTISE TO MACHINE LEARNING APPROACHES

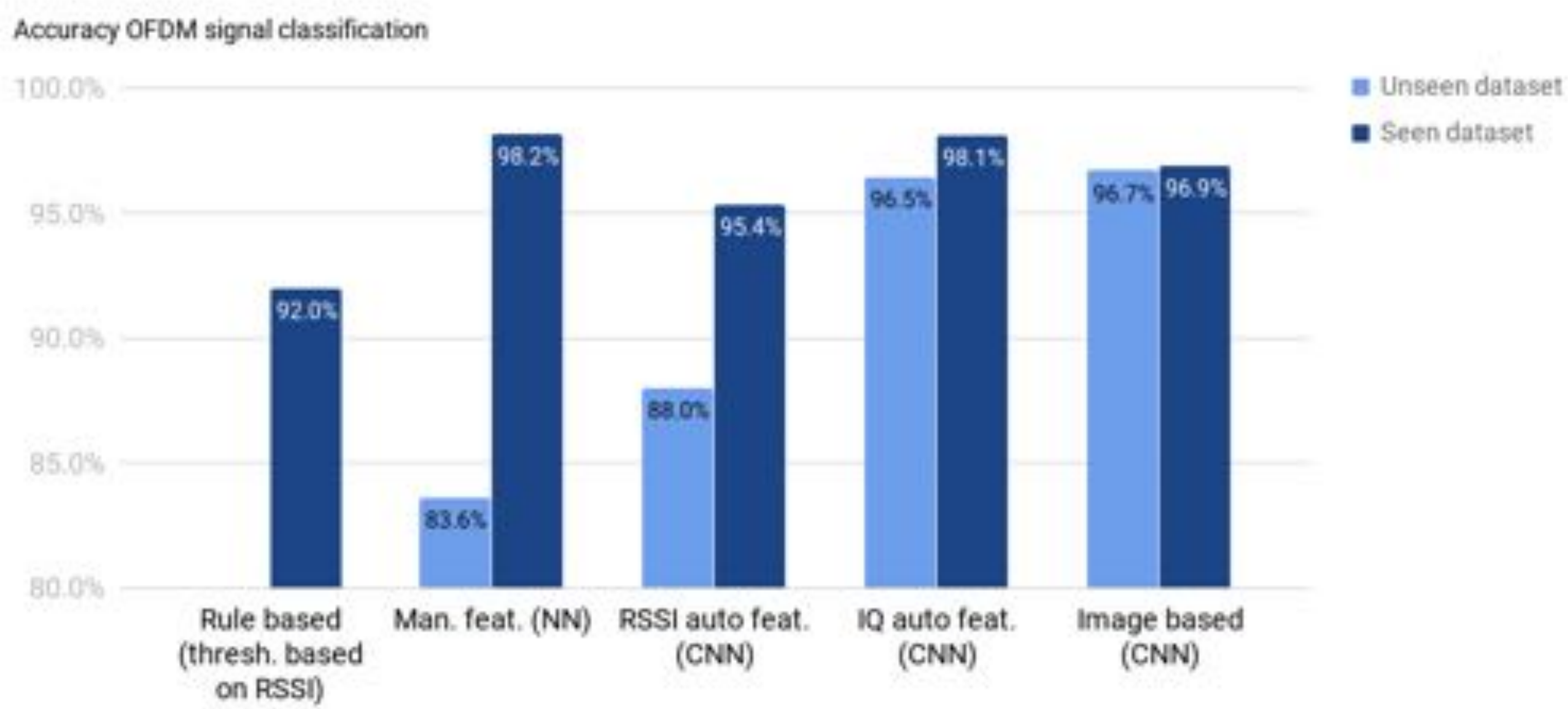
OFDM CLASSIFICATION OF WI-FI, LTE AND DVB-T



Classification using:

- manual extracted features from RSSI distributions [domain expertise]
- automatic extracted features from raw RSSI data using deep learning techniques
- automatic extracted features from spectrogram using deep learning techniques
- automatic extracted features from raw I/Q samples using deep learning techniques

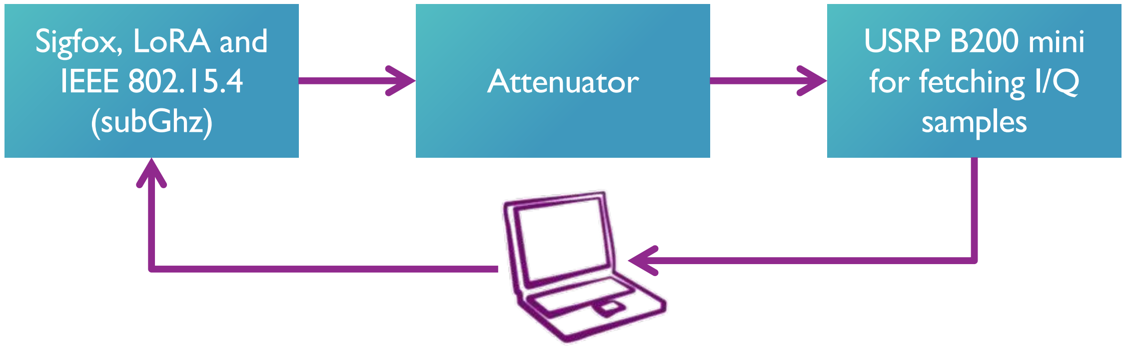
OFDM CLASSIFICATION OF WI-FI, LTE AND DVB-T



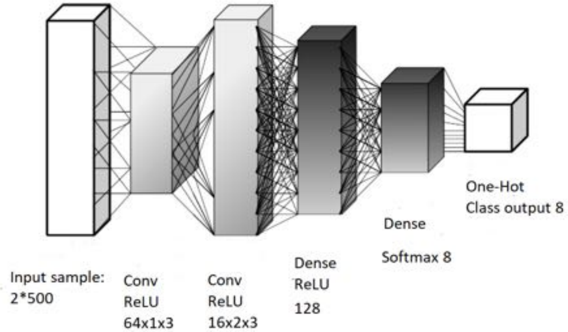
TECHNOLOGY RECOGNITION

FAST CLASSIFICATION OF LPWAN TECHNOLOGIES: SIGFOX, LORA AND IEEE 802.15.4 (SUBGHZ)

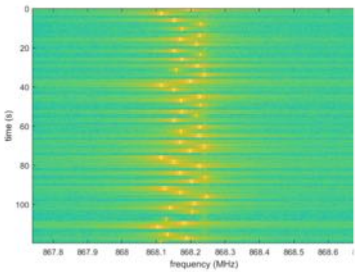
1) Data generation



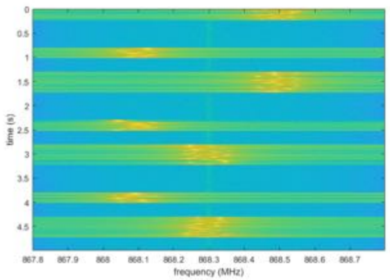
3) Implementation of CNN using Keras machine learning library with Tensorflow as a backend



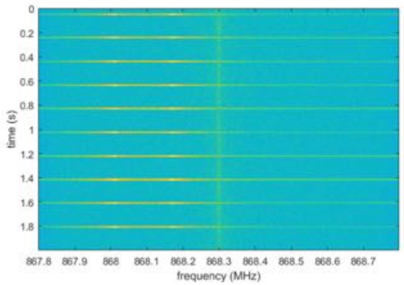
2) Signal classes visualization



Sigfox

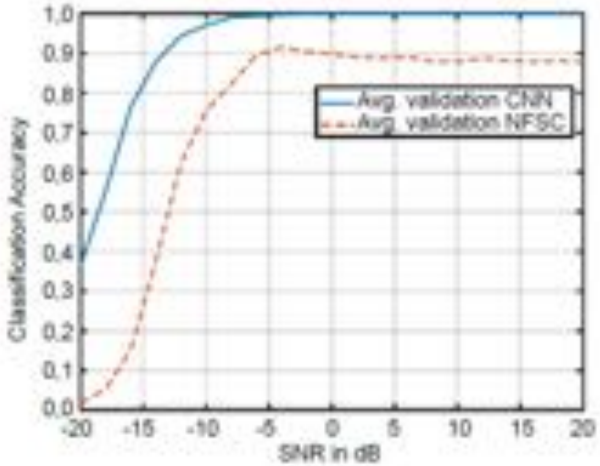


LoRA



IEEE 802.15.4 (subGHz)

4) Classification accuracy of CNN versus SotA (NFSC - Neuro-fuzzy signal classifier)



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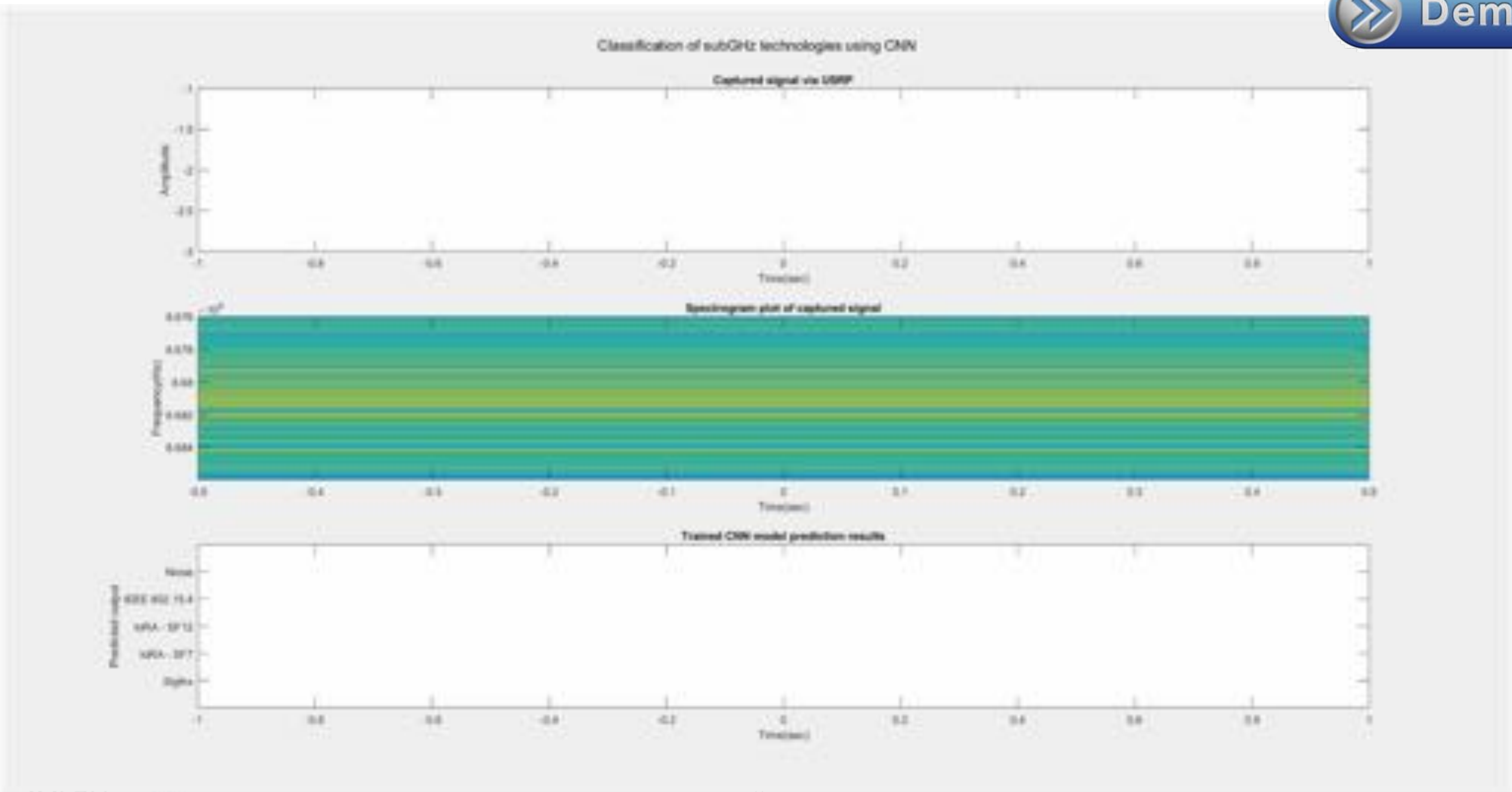
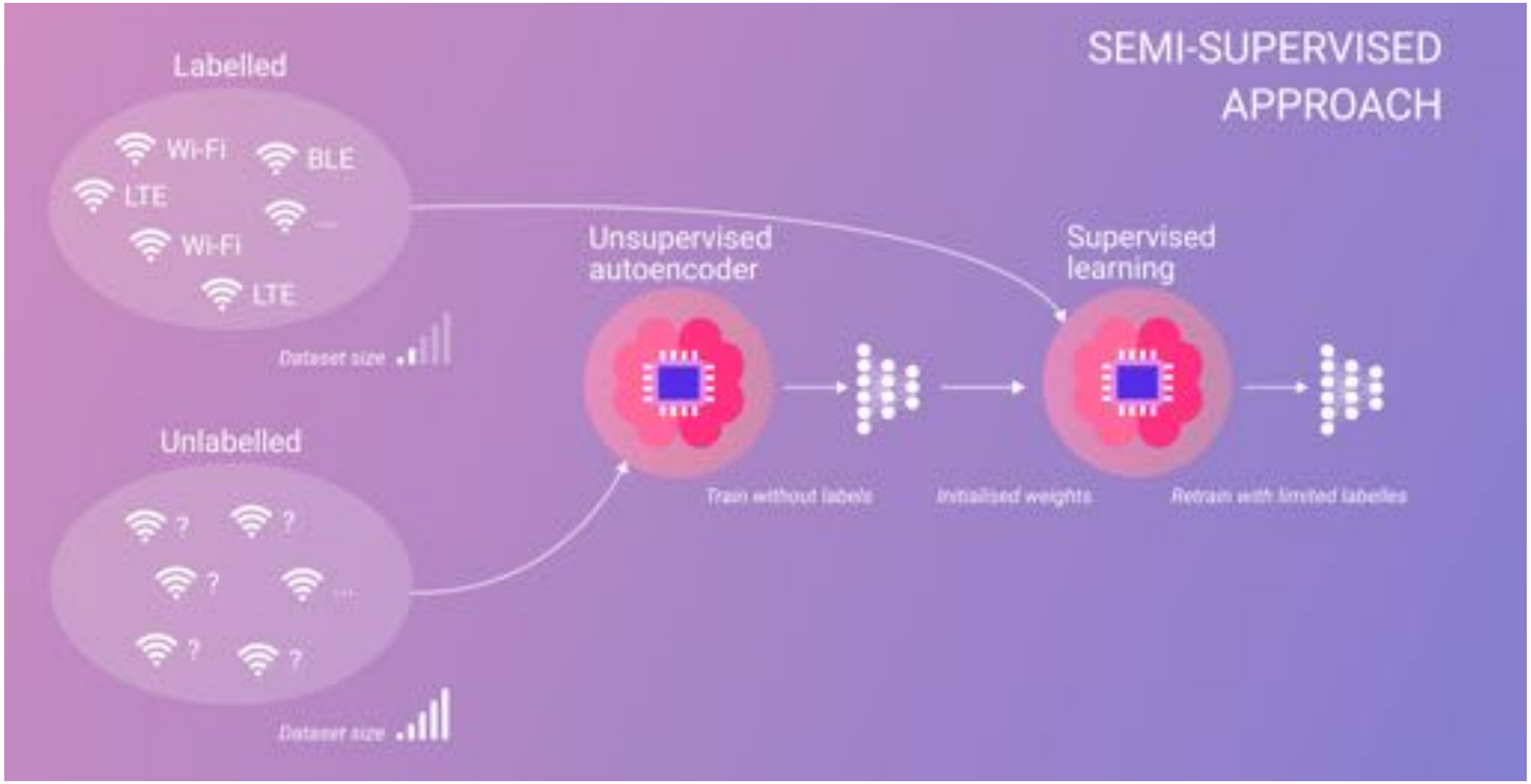
CLASSIFICATION OF SUB-GHz TECHNOLOGIES: SIGFOX, LORA, IEEE 802.15.4, NOISE

Demo



FUTURE WORK: SEMI-SUPERVISED APPROACH

USING BOTH LABELLED AND UNLABELED DATA



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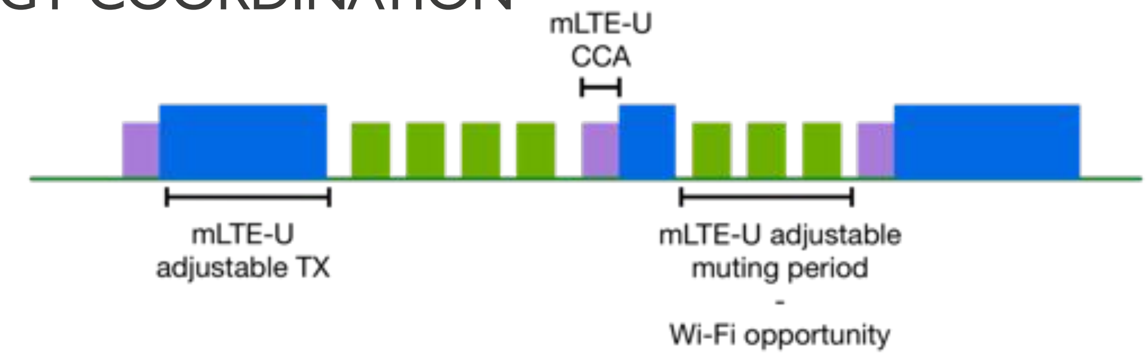
TECHNOLOGY RECOGNITION APPLIED TO LTE-LAA

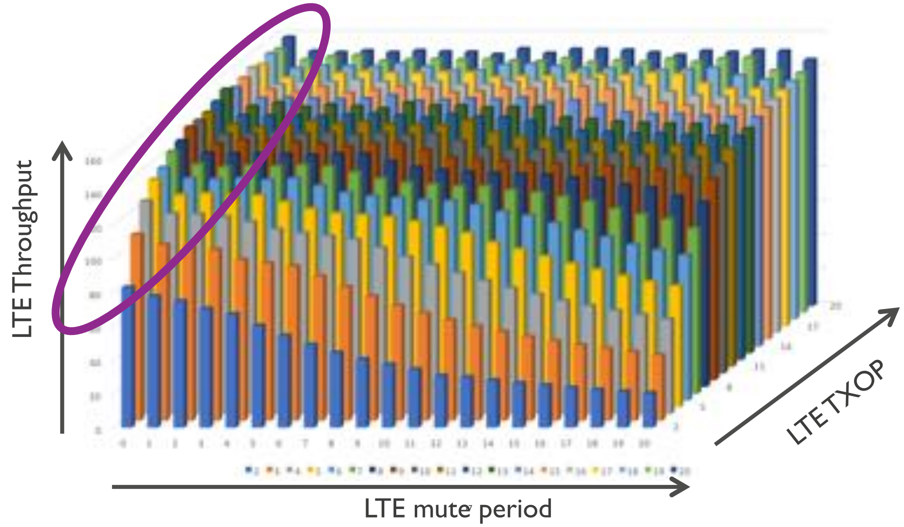
COEXISTENCE OF LTE AND WI-FI

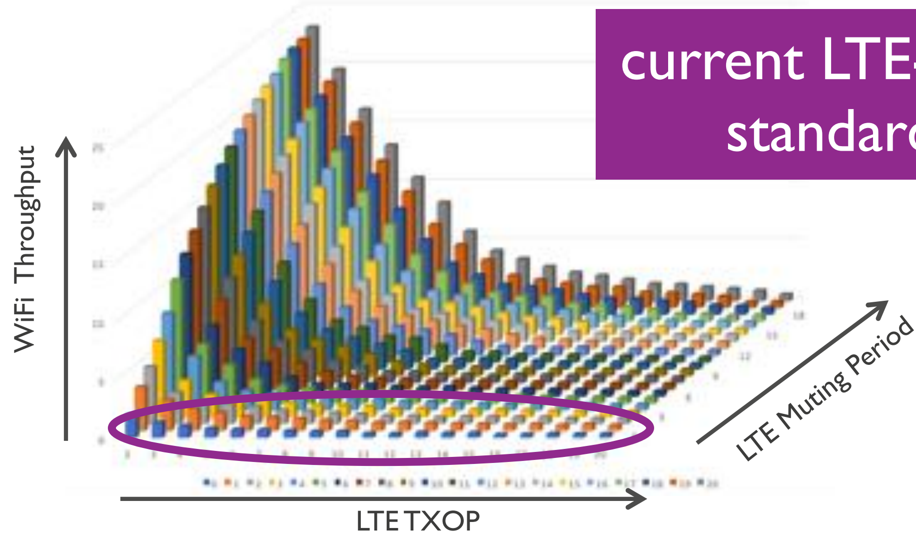
IMEC SOLUTION: CROSS-TECHNOLOGY COORDINATION

- Adjustable muting period + adjustable TXOP
- Cross-technology monitoring of load
- Cross-technology management (load-balancing)
  - adjust LTE muting period and TXOP based on load



- Example of 4 LTE + 4 Wi-Fi networks

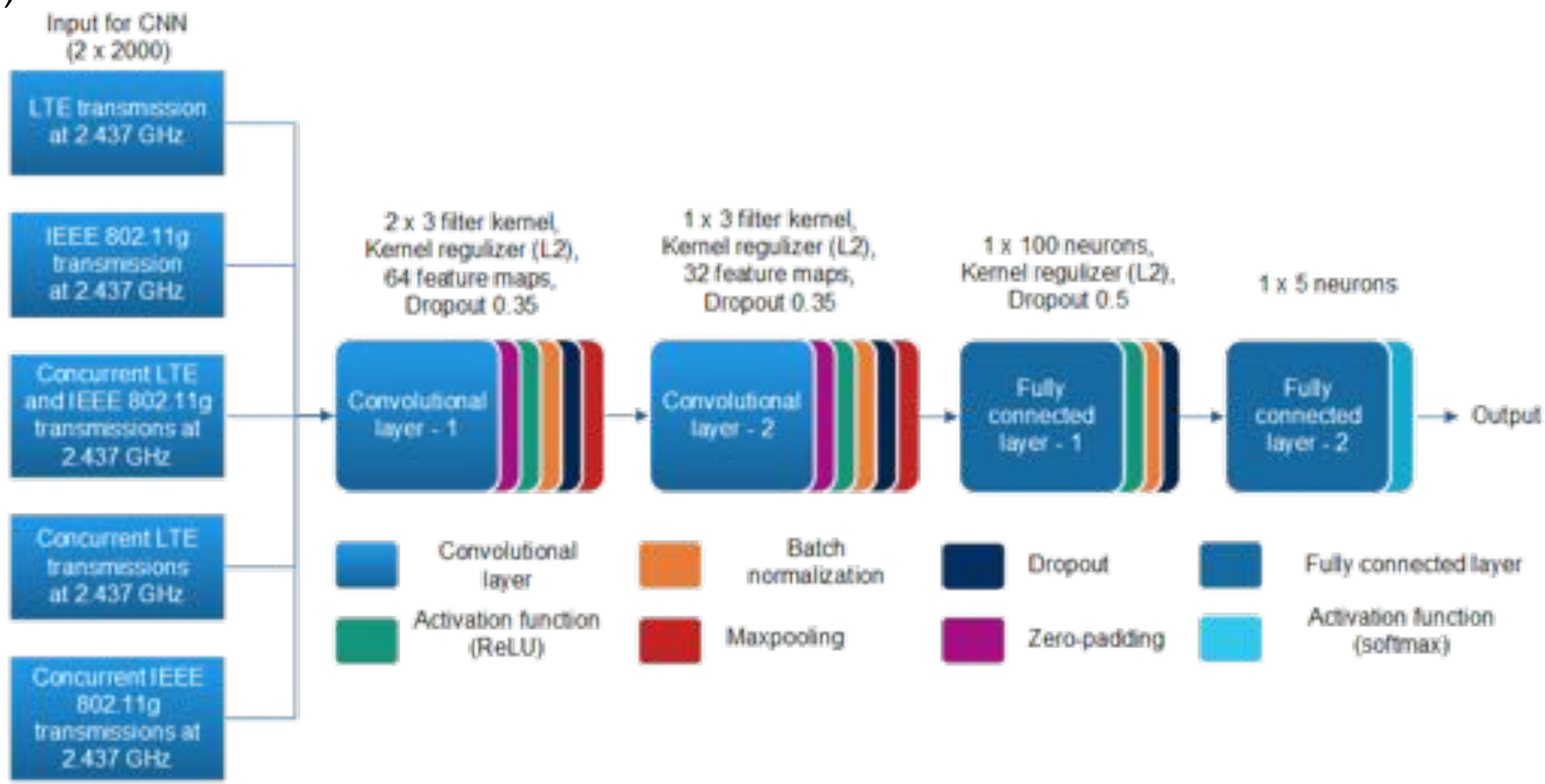




current LTE-LAA standard

COEXISTENCE OF LTE AND WI-FI
IMEC SOLUTION: CROSS-TECHNOLOGY COORDINATION

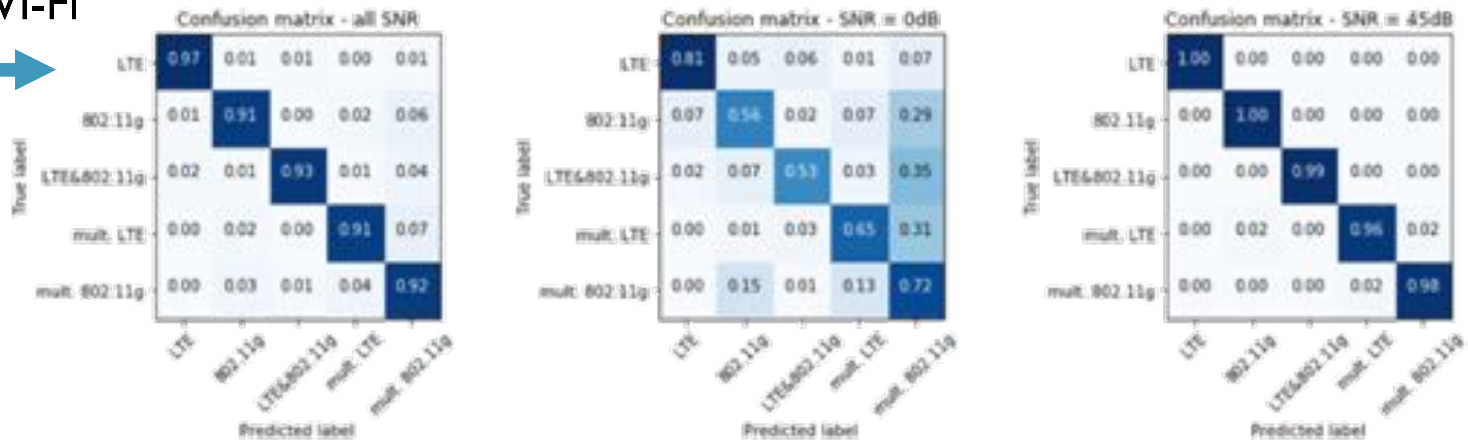
- Classification of LTE and Wi-Fi for load estimation
  - deep learning (CNN)



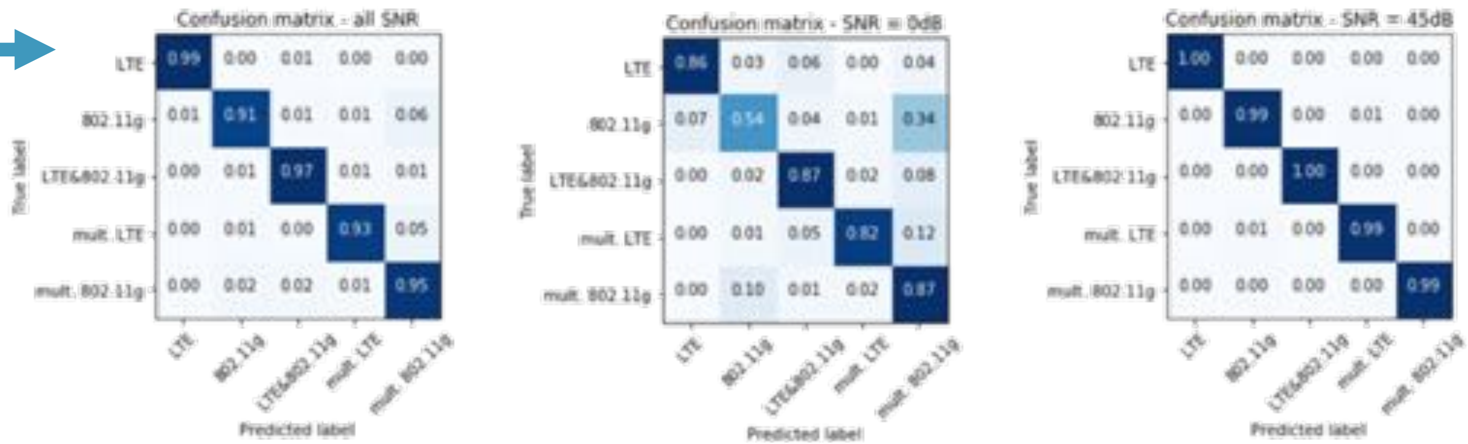
COEXISTENCE OF LTE AND WI-FI

IMEC SOLUTION: CROSS-TECHNOLOGY COORDINATION

- Classification of LTE and Wi-Fi
  - I/Q samples



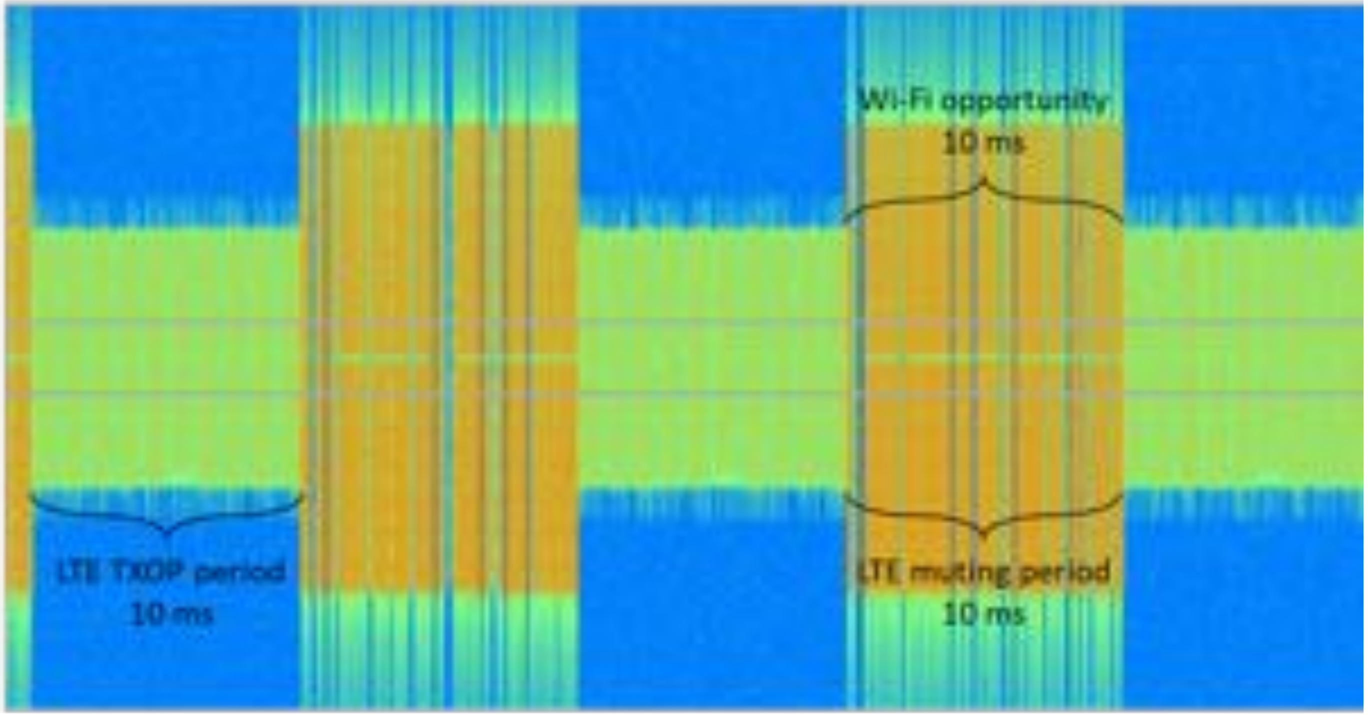
  - FFT of I/Q samples



COEXISTENCE OF LTE AND WI-FI

IMEC SOLUTION: CROSS-TECHNOLOGY COORDINATION

Balanced spectrum access through use of CNN (experimental PoC validation) to identify the channel occupancy of each technology



EXAMPLE: DARPA SPECTRUM COLLABORATION CHALLENGE

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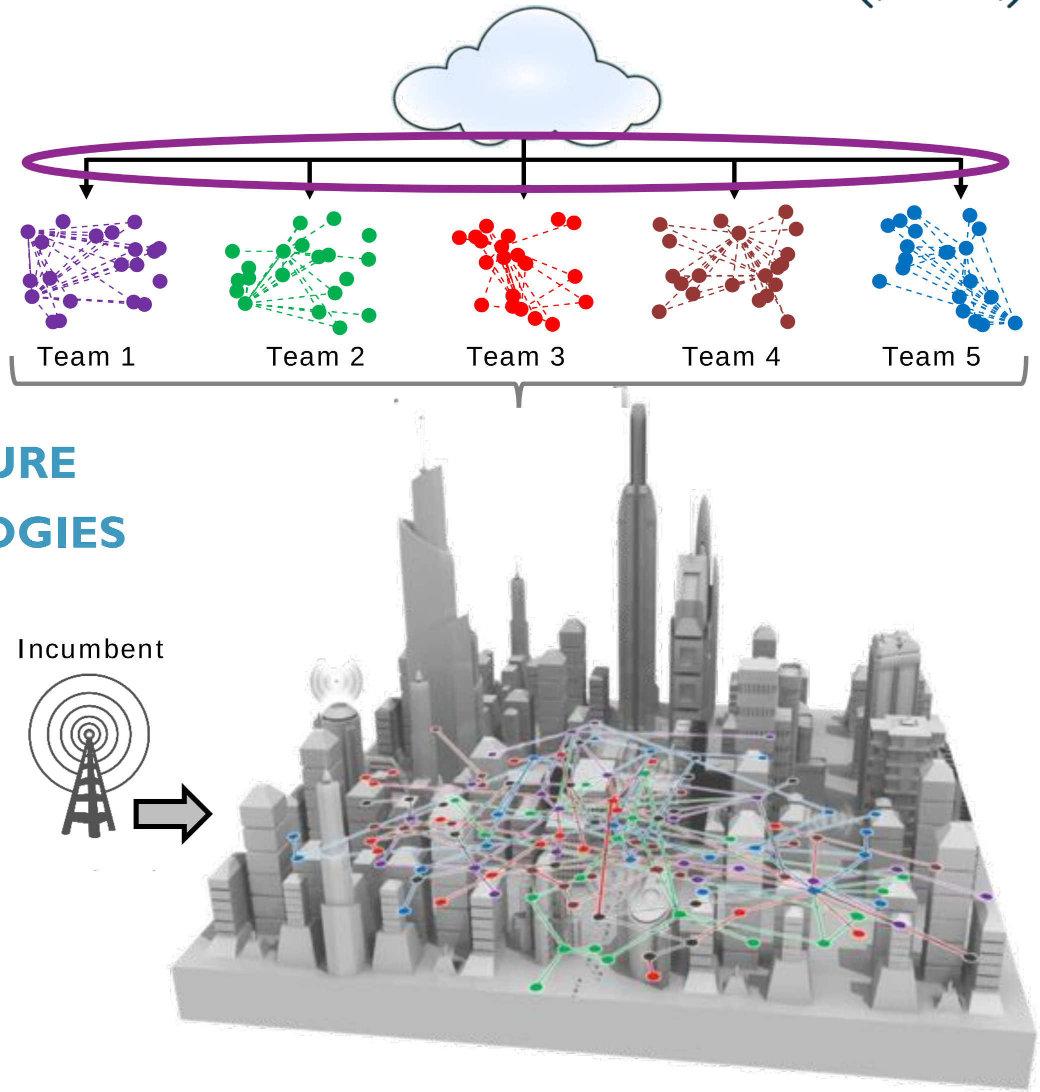
SPECTRUM COLLABORATION CHALLENGE

OPEN COMPETITION
WIRELESS NETWORKS
SPECTRUM SHARING

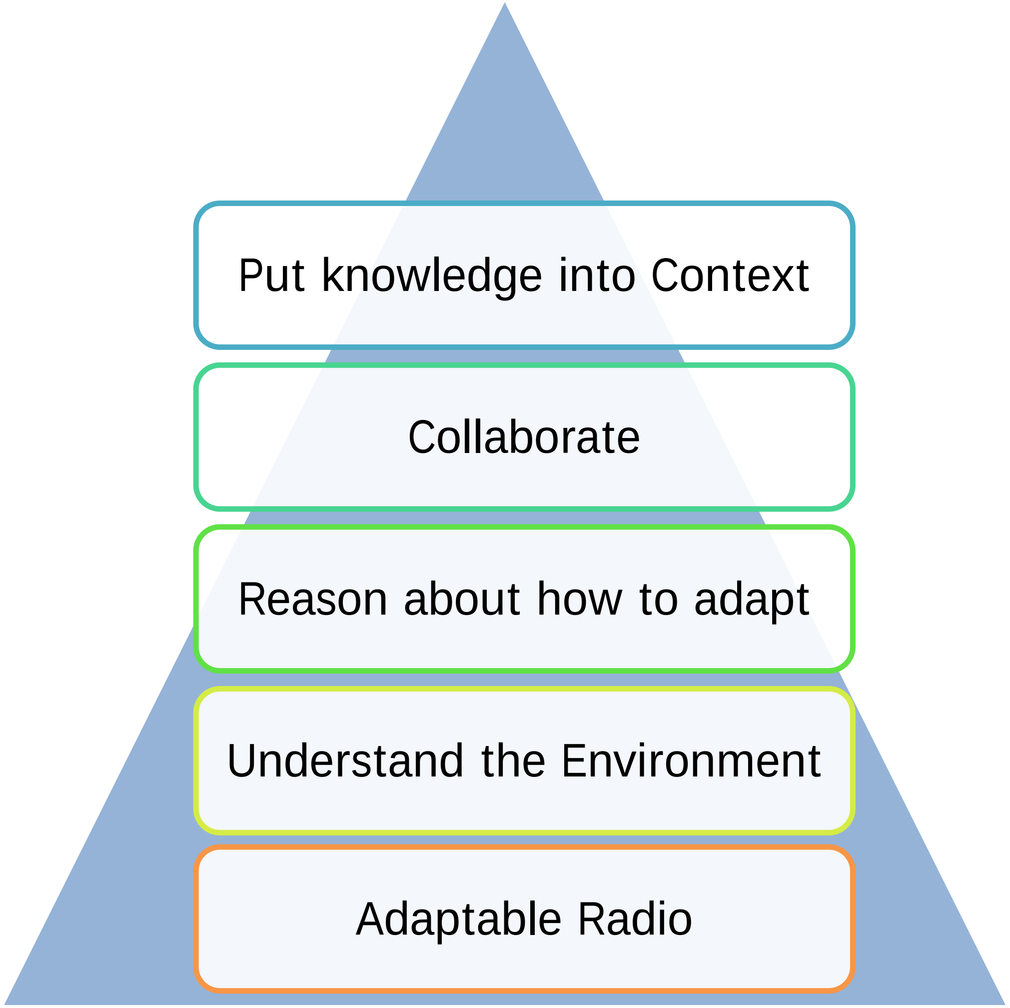
NO
PLANNING
COMMUNICATION INFRASTRUCTURE
STANDARDISED RADIO TECHNOLOGIES

INTELLIGENCE
LEARN TO ADAPT

COLLABORATION
OPTIMIZE SPECTRUM CAPACITY



BUILDING THE COLLABORATIVE INTELLIGENT RADIO NETWORK



Contextualize existing knowledge to rapidly overcome changes and new challenges

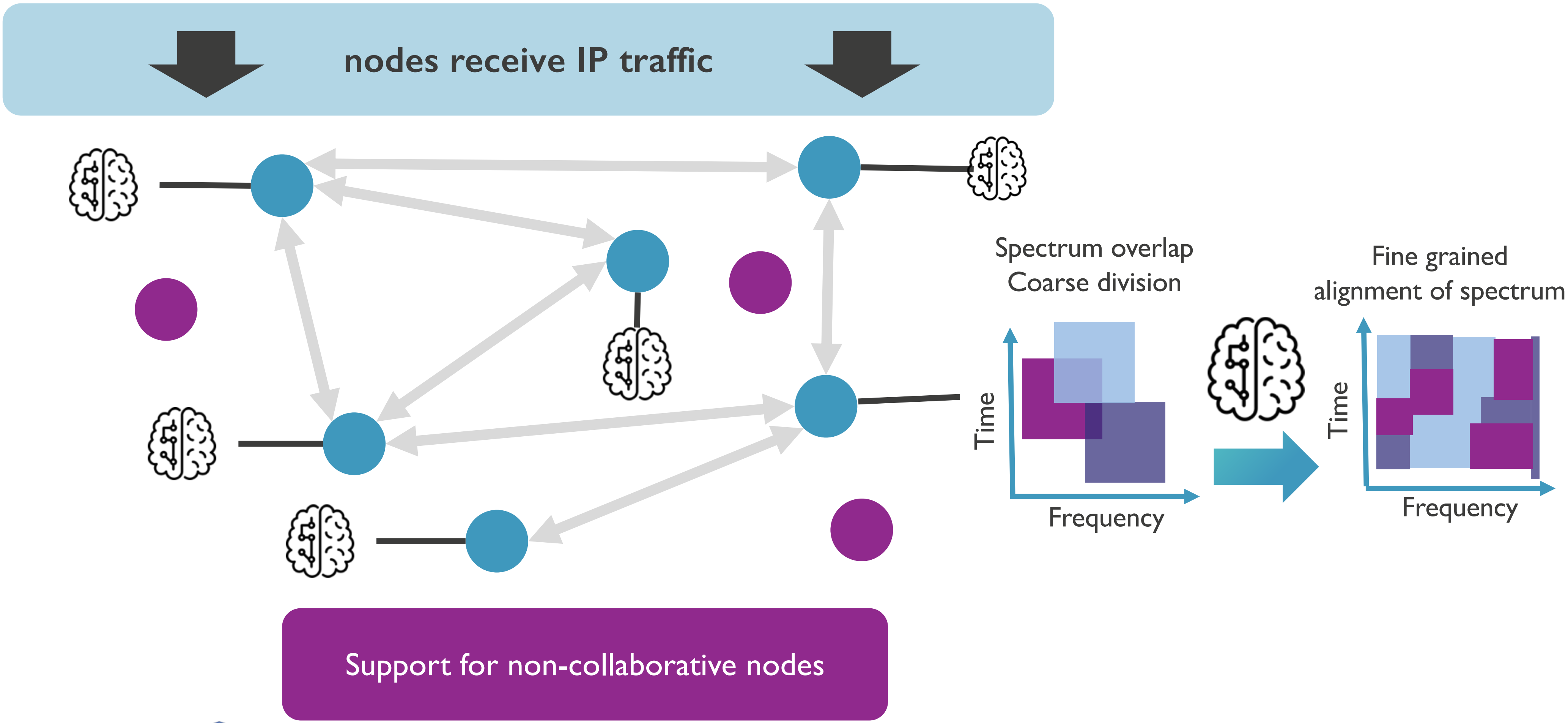
Collaborate with previously unknown radio systems, discover the value of information and optimize the overall joint utility

Reason about how to take actions to result in successful communication, taking into account the effect the action may have on others

Understand and characterize signals to infer the conditions of the local RF environment through noisy observations

Adaptability in time, frequency, space, code, waveform, MAC scheme, network, etc.

SPECTRUM COLLABORATION THROUGH MULTI-AGENT LEARNING

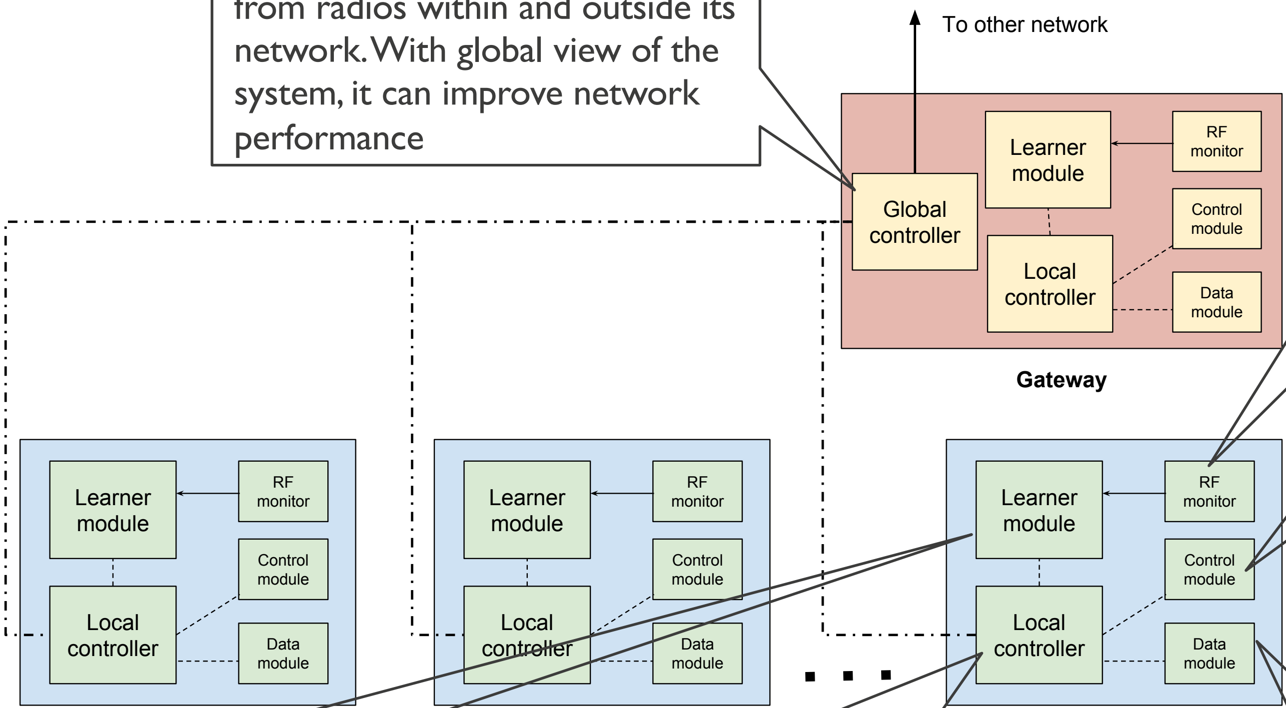


APPROACH – END-TO-END MODULAR SYSTEM

Receives control information from radios within and outside its network. With global view of the system, it can improve network performance

Channel condition monitoring, and feature identification

Enables resilient control communication among all radios in the network



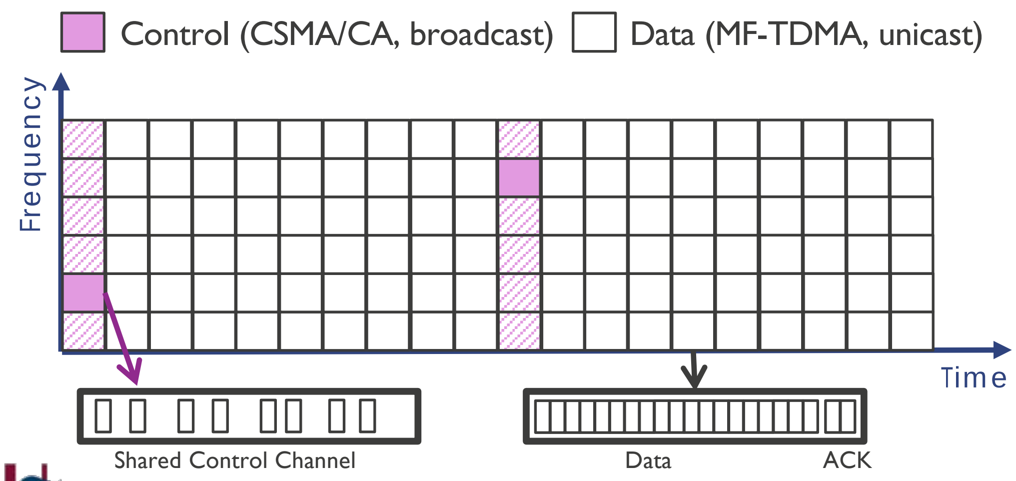
Enables configurable optimum data transfer according to QoS demands among radios in the network

Predicts channel environment and/or incumbent users' behavior using AI/machine learning fed with data collected by the RF monitor

Provides appropriate transmission parameters to the radios based on information provided by RF monitor and learner module

APPROACH – END-TO-END MODULAR SYSTEM

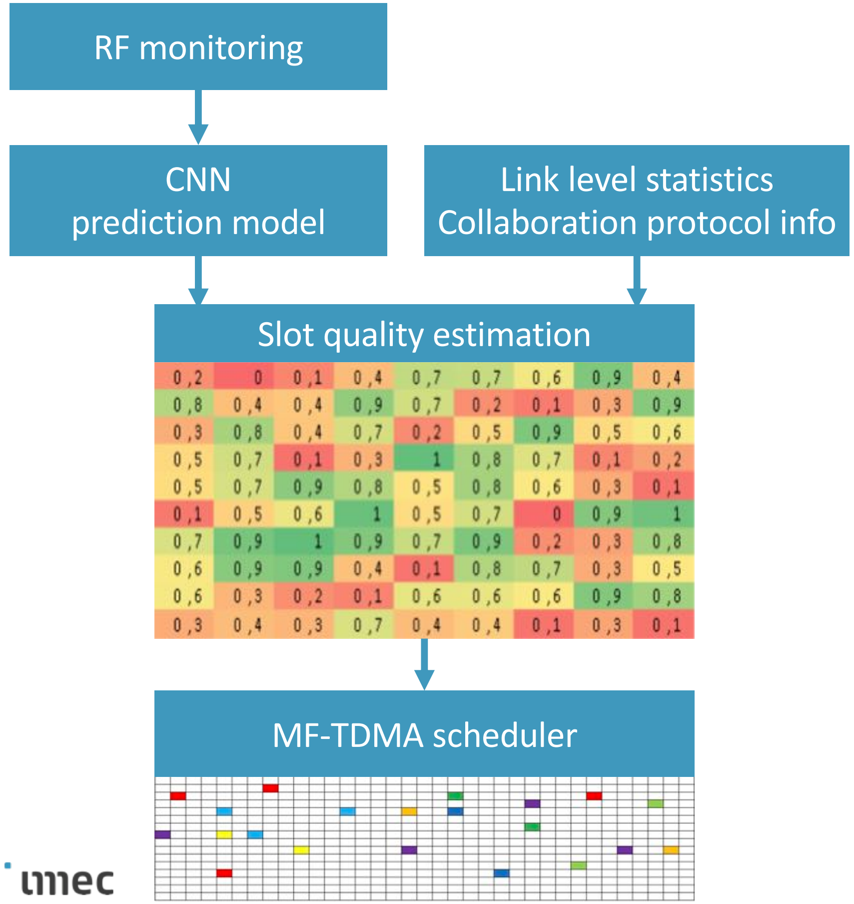
- LTE/Wi-Fi co-design: combine the best of 2 worlds
  - Packet-based LTE (self-contained packet, no need for synchronisation)
  - MF-TDMA (= combination of TDMA/FDMA) + CSMA/CA
- AI-based control of MAC and PHY
  - Adding and deleting slots based on link statistics and channel sensing
  - Using AI (deep learning) for predicting future network state based on other nodes' behaviour



COLLABORATIVE SPECTRUM SHARING

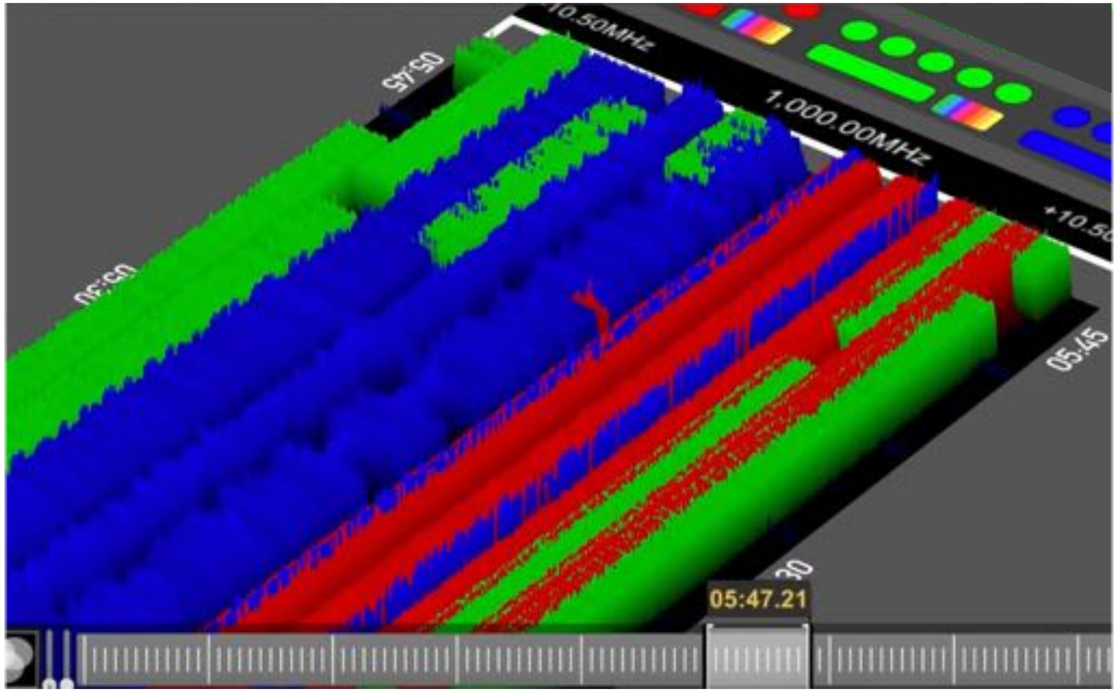
APPLY MACHINE LEARNING TO PREDICT FUTURE SPECTRUM OCCUPATION

Distributed intelligent slot allocation



0,2	0	0,1	0,4	0,7	0,7	0,6	0,9	0,4
0,8	0,4	0,4	0,9	0,7	0,2	0,1	0,3	0,9
0,3	0,8	0,4	0,7	0,2	0,5	0,9	0,5	0,6
0,5	0,7	0,1	0,3	1	0,8	0,7	0,1	0,2
0,5	0,7	0,9	0,8	0,5	0,8	0,6	0,3	0,1
0,1	0,5	0,6	1	0,5	0,7	0	0,9	1
0,7	0,9	1	0,9	0,7	0,9	0,2	0,3	0,8
0,6	0,9	0,9	0,4	0,1	0,8	0,7	0,3	0,5
0,6	0,3	0,2	0,1	0,6	0,6	0,6	0,9	0,8
0,3	0,4	0,3	0,7	0,4	0,4	0,1	0,3	0,1

Efficient spectrum sharing without central coordination



Preliminary Round of DARPA Spectrum Collaboration Challenge Awards Ten Teams

Top teams introduce various methods to collaborate autonomously and overcome spectrum scarcity

For the preliminary event, 475 fully autonomous matches were run with the 19 qualified teams' radio designs in SC2's custom testbed environment, known as Colosseum. The final matches for the first event were carried out across six different communications scenarios designed to mirror real-world congested EM environments, but with more complexity than existing commercial radios are equipped to handle. The competing teams faced fluctuating bandwidths and interference from other competitors as well as DARPA designed bots that tested and challenged their radio designs. Each team's radio performance was scored based on its collaborative spectrum sharing abilities.

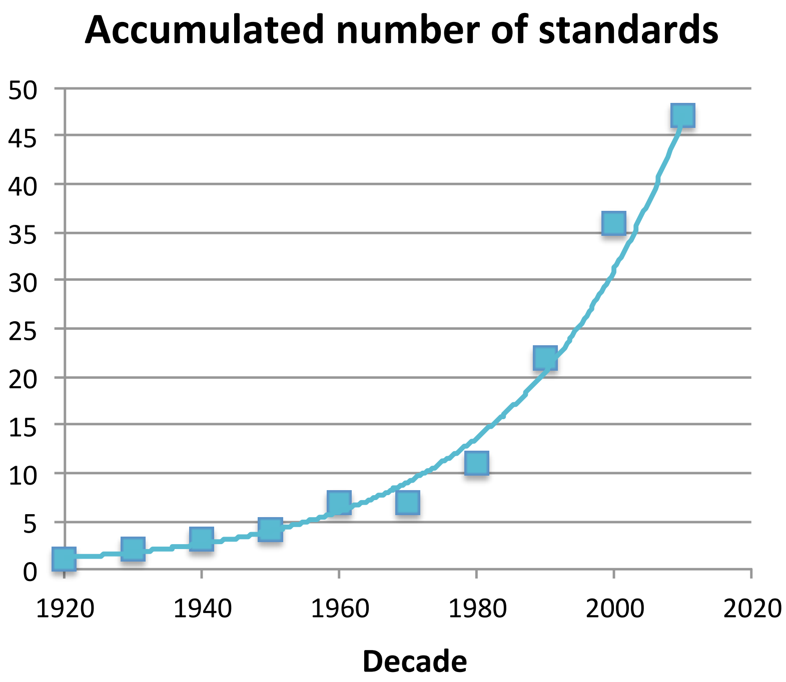
At the event's conclusion, the 10 highest scoring teams were:

- MarmotE from Vanderbilt University
- SHARE THE PIE from BAE Systems with Eigen LLC
- Zylinium from a Maryland-based startup
- Erebus, consisting of three independent engineers and software developers
- SCATTER from IDLab, an imec research group at Ghent University and University of Antwerp, and Rutgers University
- GatorWings from University of Florida
- Sprite from Northeastern University
- Strawberry Jammer from Northrop Grumman
- Optical Spectrum, consisting of two independent LIDAR engineers
- BAM! Wireless from Purdue University and Texas A&M University

https://www.darpa.mil/news-events/2017-12-21a

THE ROLE OF STANDARDISATION

THE ROLE OF STANDARDISATION



	Terrestrial broadcasting	Two-way radio	Mobile Telecom	Wireless internet	IoT/peripheral
1920s	AM				
1930s	FM				
1940s			AT&T MTS		
1950s	NTSC				
1960s	PAL SECAM		AT&T IMTS		
1970s					
1980s	FM-RDS		AMPS, NTT, NMT		
1990s	DAB, DVB-T, ATSC	TETRA, P25	D-AMPS, GSM, IS-95	802.11 a/b	Bluetooth
2000s	DRM, DVB-T2, ISDB-T, DTMB	DMR. NXDN	CDMA-2000, WCDMA, TD-SCDMA, WiMAX, LTE	802.11n	ANT, 802.15.4
2010s			LTE-A, 5G-NR	802.11 ac/ad/ah/ax /p	NB-IoT, BTLE, LoRa, SigFox…

EXPLOSION OF STANDARDS!

PUBLIC

RETHINKING THE ROLE OF STANDARDISATION

- Number, complexity, time and hence costs for standardisation increases
  - e.g. 24 documents for GSM ↔ 279 documents for LTE
- Despite huge standardisation efforts, wireless world is getting more and more fragmented

↕

- DARPA spectrum collaboration challenge
  - smart spectrum sharing between heterogeneous networks without standardisation and central coordination
  - collaboration protocol for low data rate exchange of spectrum usage & system performance

PARADIGM SHIFT

- from standardisation of technologies to standardisation of coordination protocol
- from exclusive spectrum access to coordinated/collaborative spectrum sharing
- from intra-technology centralized scheduling to cross-technology intelligent distributed coordination
- from domain expertise to machine learning approaches

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