From Cognition to Intelligence in Communications Networks

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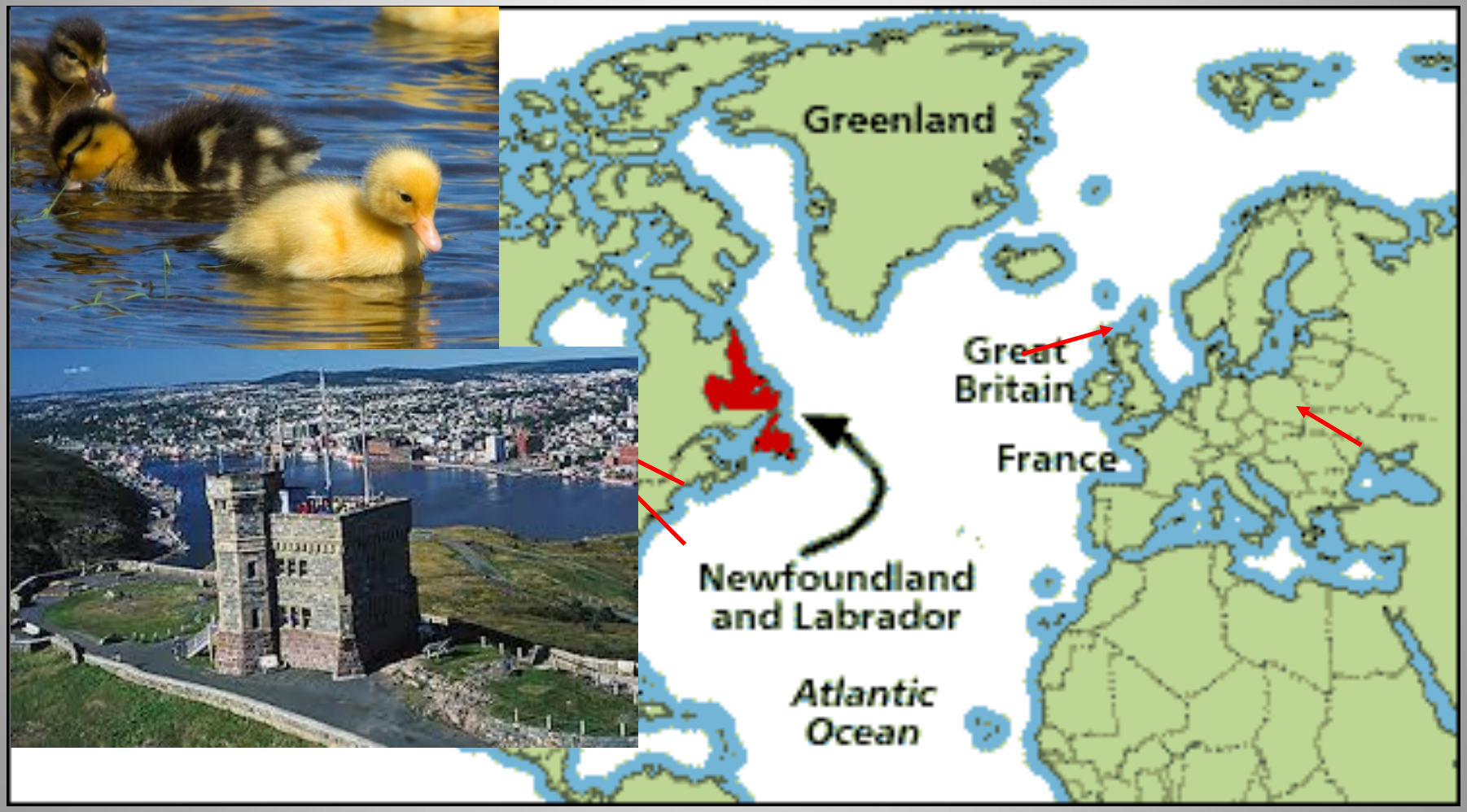
MEMORIAL UNIVERSITY – ST. JOHN'S, CANADA



Advanced Communications Research Lab

Main research areas:

Wireless: NOMA, full duplex, resource allocation, edge computing, machine learning for PHY & MAC, signal intelligence, and cognitive radio.

Optical: technologies for Tbps optical transport networks

Underwater: acoustic wireless communications

Research funded by:

NSERC, CFI, MITACS, CRC, DRDC, DTA Systems, Allen Vanguard, ThinkRF, Huawei Wireless & Optical, Equinor

HS: 3 postdoctoral fellows and 12 students

MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

Cognition To Intelligence: Ideas Whose Time Have Come

Cognitive Radio Technology: Roadmap

How/When did it start?

70's	90's		1999	2000
First attempts: progr. radios	Software-defined radio	Military applications	First papers (Mitola)	PhD Thesis (Mitola)

What has been achieved in about 20 years?

2003	2004	2005		2006	2006-2007
FCC releases Cognitive Radio Tech. Proc.	First plenary meeting IEEE 802.22	IEEE P1900 SC	DySPAN-SC (pred.)	Haykin: cognitive radar	Prototypes & proof-of-concepts

2009	2011	2015	2016	2018	+2020	2030
3GPP first femtocell standard	3GPP R10 CA (DL) 40 MHz	3GPP R12 CA (UL/DL; TDD/FDD); dual connectivity	3GPP R13 Licensed Assisted Access (DL)	3GPP R15 NR CA (mmWave, sub-6 GHz); dual connectivity	B5G Intelli gence (AI)	6G Mitola's radio ?

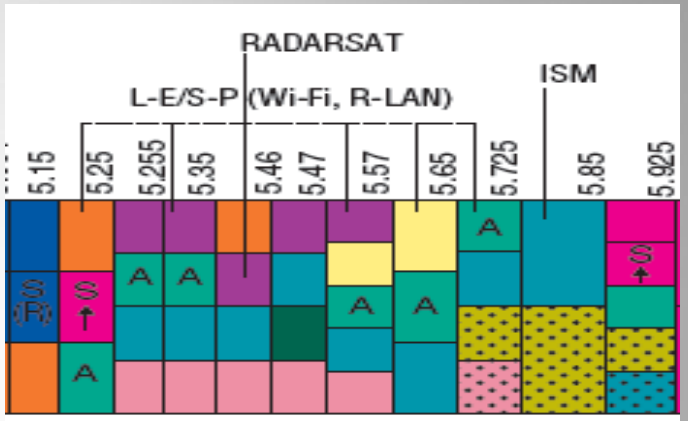
Spectrum Aggregation Essential to 5G NR Deployments

- CA across spectrum bands: tight CA between 5G NR mmWave and sub-6 GHz to address mmWave coverage gaps
- CA across spectrum types: licensed and unlicensed with 5G NR Licensed Assisted Access
- CA across FDD and TDD bands: sub-1 GHz and mid/high band aggregation, supplemental uplink for better coverage, supplemental downlink for capacity
- Dual connectivity across LTE and NR: leverages LTE investments and coverage

Source: Qualcomm Making 5G NR a Reality.

Spectrum below 6 GHz

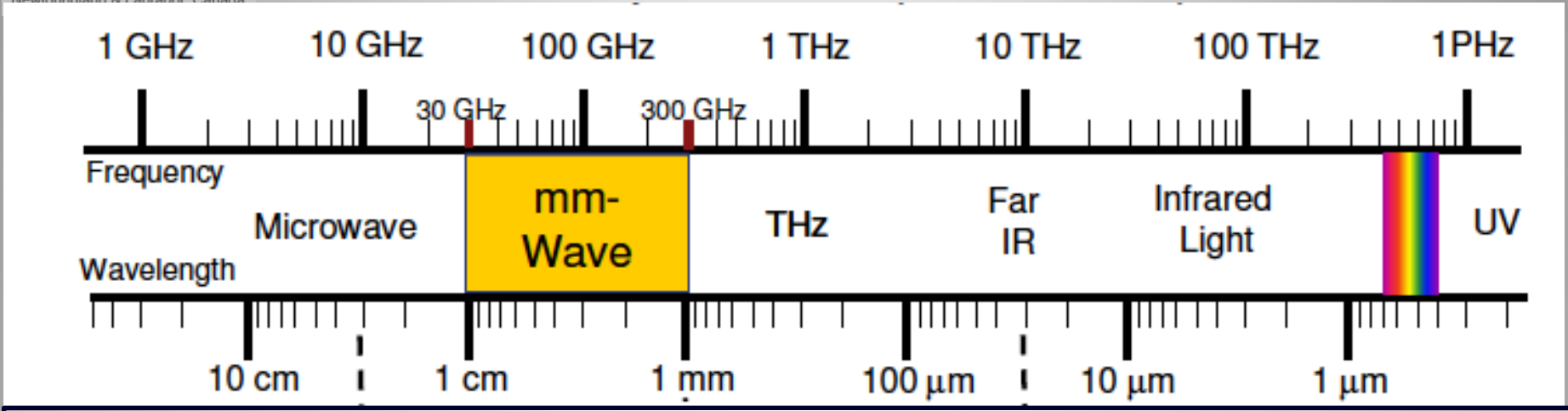
5 GHz ISM band–underused today–access to new 580 MHz spectrum (non-contiguous)
3GPP: Licensed Assisted Access (LAA)
Co-existence with itself and WiFi
Carrier aggregation (CA): also in 5G NR



Industry Canada: http://www.ic.gc.ca

Germany: 420 MHz in 2 GHz and 3.5 GHz bands (2019)
Spain: 200 MHz in 3.6-3.8 GHz
Austria: 400 MHz in 3.4-3.8 GHz
Italy: 700 MHz, 3.6-3.8 GHz
Canada: 600 MHz (2019); 3.5 GHz band in 2020, delayed to 2021
USA: 600 MHz; 3.5 GHz (auction started July 2020)
South Korea: 280 MHz in 3.5 GHz (June 2018)
China: 2.5-2.6 GHz, 3.5 GHz, 4.8-4.9 GHz (Dec. 2018)
Japan: 3.6-4.2 GHz & 4.4-4.9 GHz

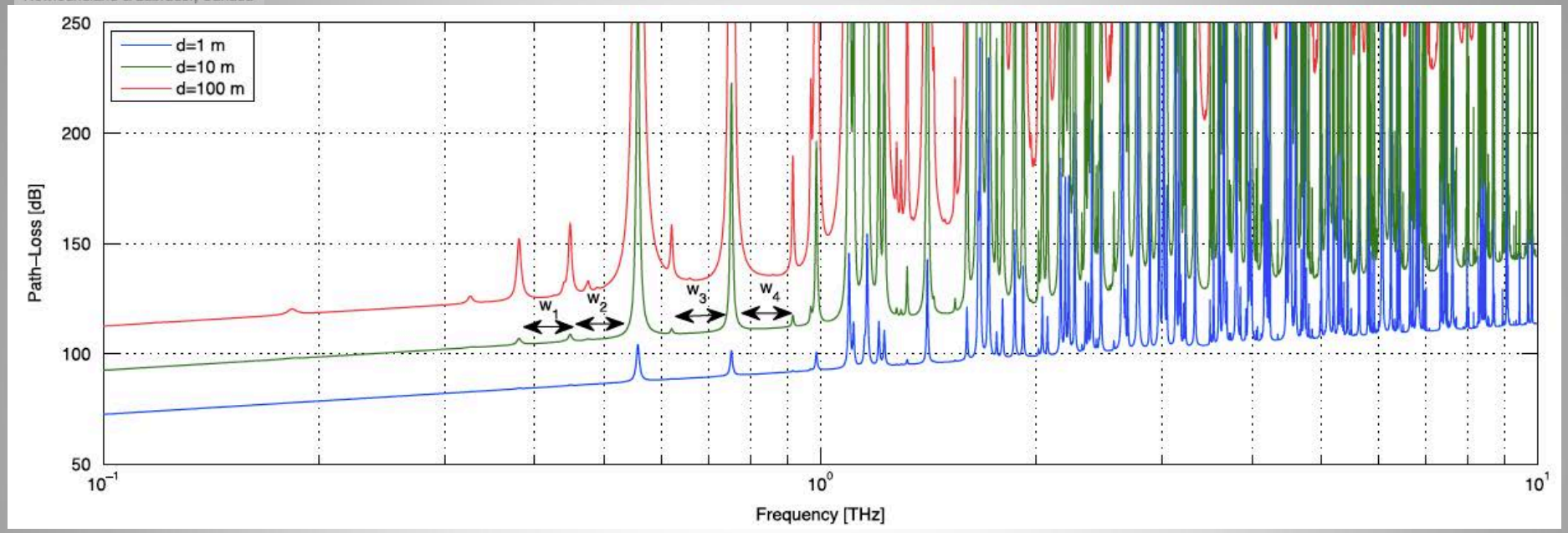
Spectrum above 6 GHz



Increased capacity:
a) frequency bandwidth b) mMIMO (sp. efficiency) c) network densification

Verizon Pre-5G: 28 GHz and 39 GHz
FCC: 24.75-25.25 GHz; 27.5-28.35 GHz; 37, 39, 47 GHz (Dec. 2019)
South Korea: 28 GHz (2018); Japan: 27.5-29.5 GHz; China: 24.75-27.5 GHz, 37-42.5 GHz (2018)
Italy: 26 GHz (2018)
WRC-19 (Oct.-Nov. 2019): 24.25; 37; 47; 48; 66-71 GHz (17.25 GHz BW; 85% global)
60 GHz ISM band (8.64 GHz; 59.4 GHz to 63.72 GHz−around 4 GHz contiguous spectrum across the world; learn from the experience with IEEE 802.11 ad).

THz Spectrum



Source: Akyldiz et al., "THz band: Next frontier for wireless communications," PHYCOM.

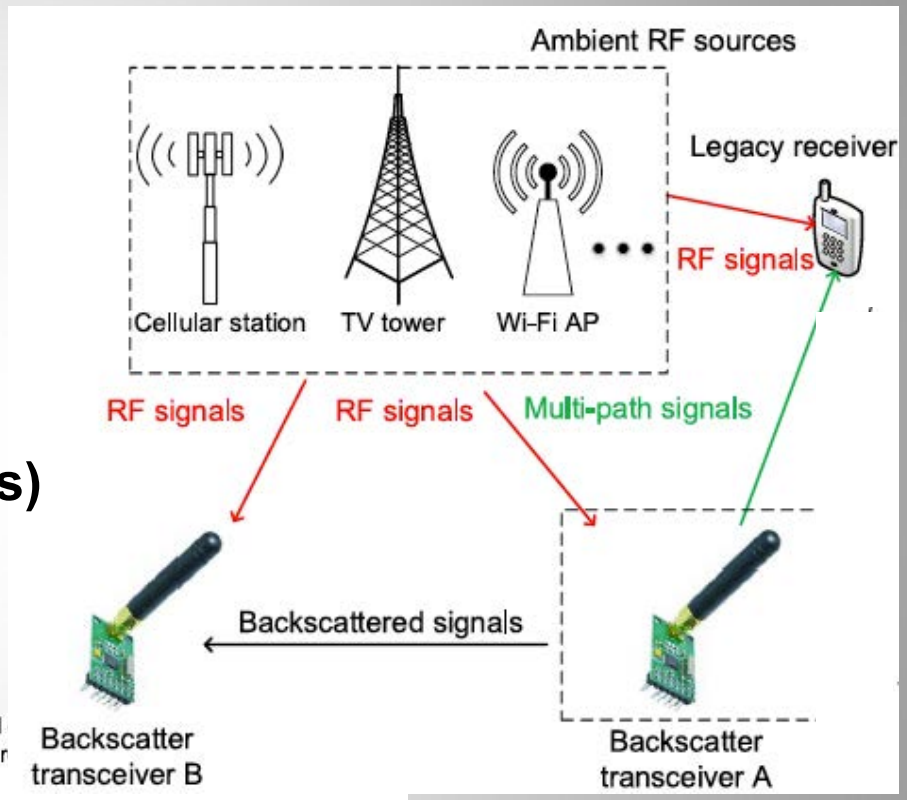
Challenges

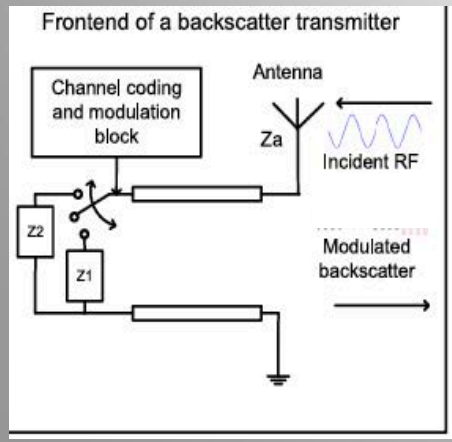
- **THz band transceivers and antennas**
- **Communication networks: channel modeling, noise sources; modulation (dependence on the Tx window); coding (decoding power vs. Tx power); dynamic mMIMO: CSI, multi-band Tx; synchronization; medium access control (low probability of collisions; low MUI; user acquisition vs. data transmissions; ; optimal packet size; ARQ: coding time vs. retransmission); handover (speed); relays; routing (Bw in Tx window as a metric).**

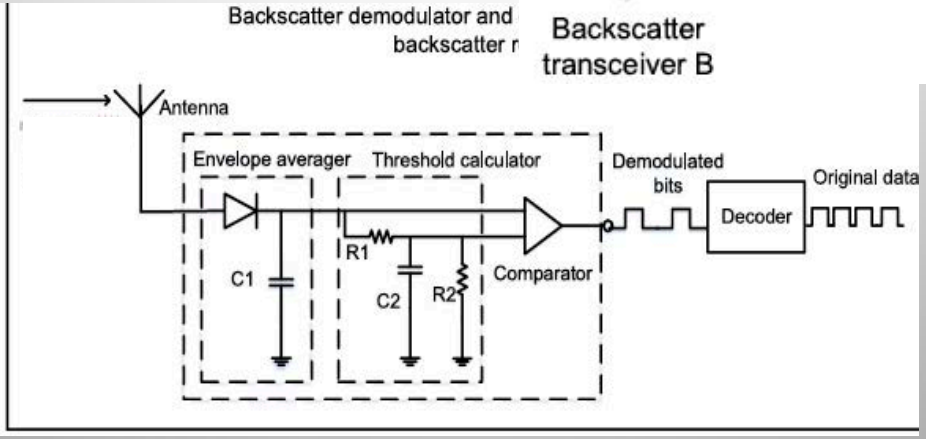
Ambient Backscatter Communications

Characteristics:

- **Very low power consumption (μW)**
- **Allows direct D2D and multi-hop commun.**
- **Do not require dedicated spectrum**
- **Not possible to control ambient RF sources (transmit power, frequencies)**
- **Security issues (simple devices)**
- **Limited bit rate and range**

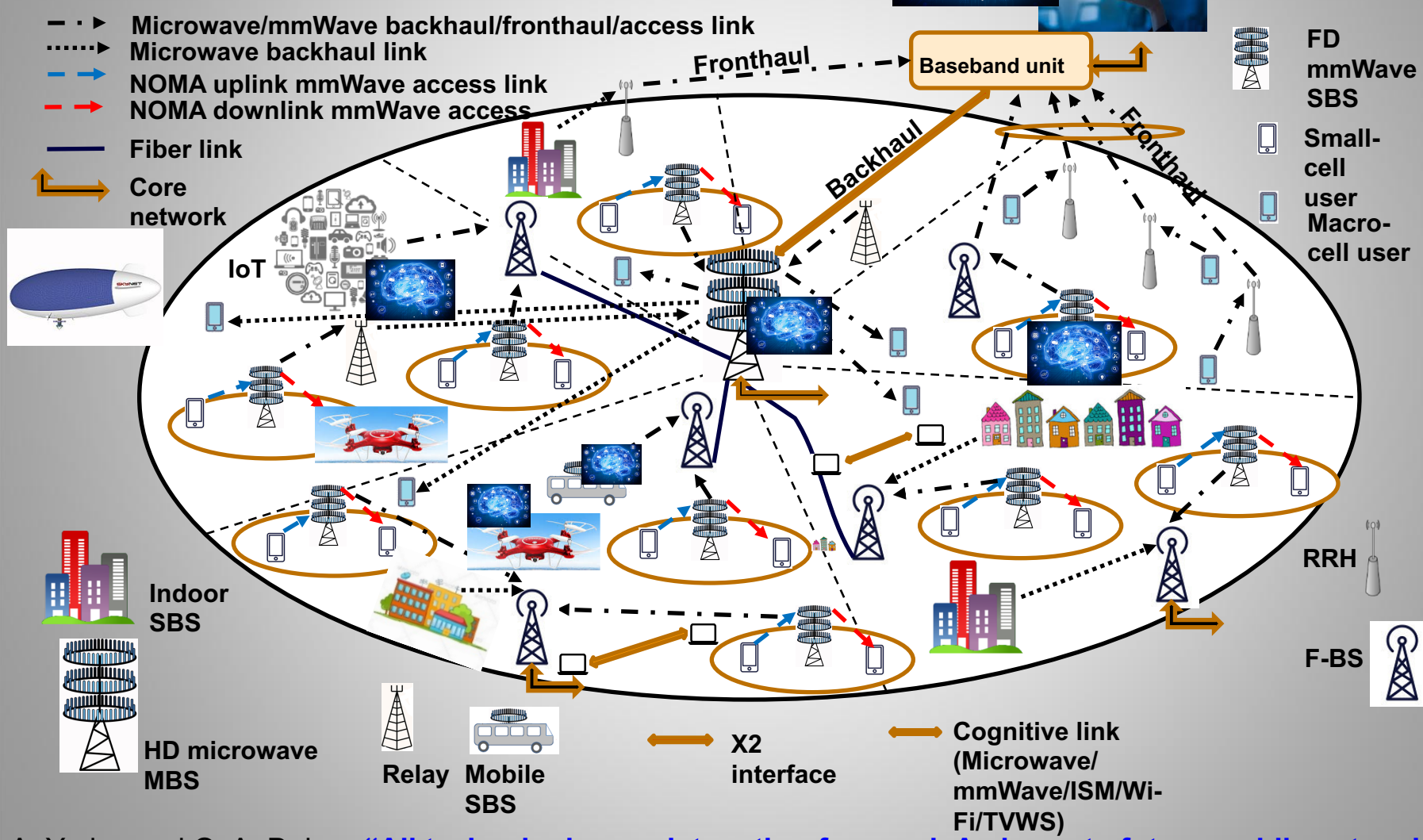






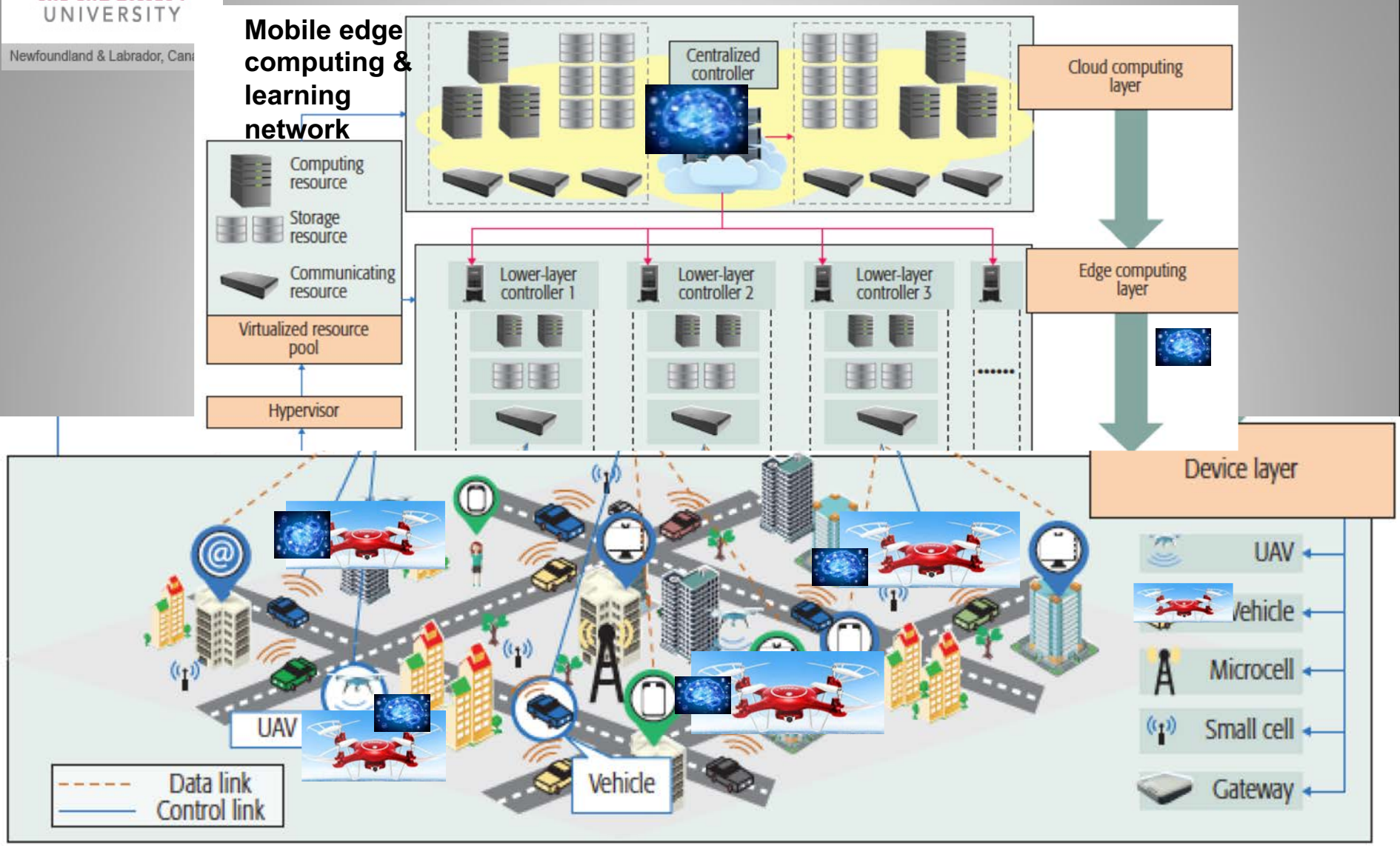
N. Van Huynh et al., "**Ambient backscatter communications: A contemporary survey**," IEEE Commun. Surveys & Tuts., 2018.

B5G: All Technologies Should Work Together



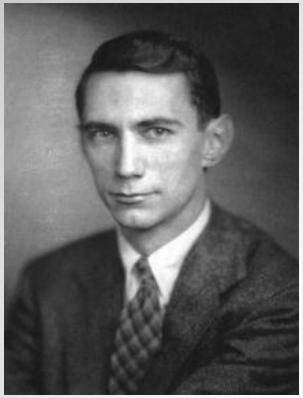
A. Yadav and O. A. Dobre, **"All technologies work together for good: A glance to future mobile networks,"** *IEEE Wireless Communications*, 2018.

B5G: Air-Ground Integrated Approach



Z. Zhou et al, "An ait-ground integrated approach for mobile edge computing in IoT," IEEE Commun. Magazine.

Communications & Computing & Artificial Intelligence



Claude Shannon

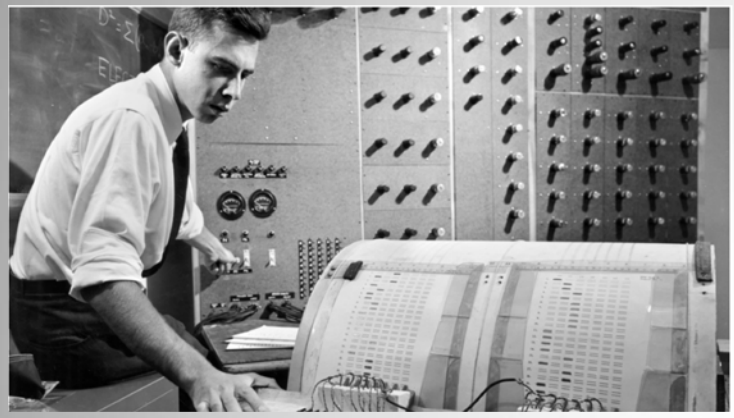
1916 – 2001

Alan Turing

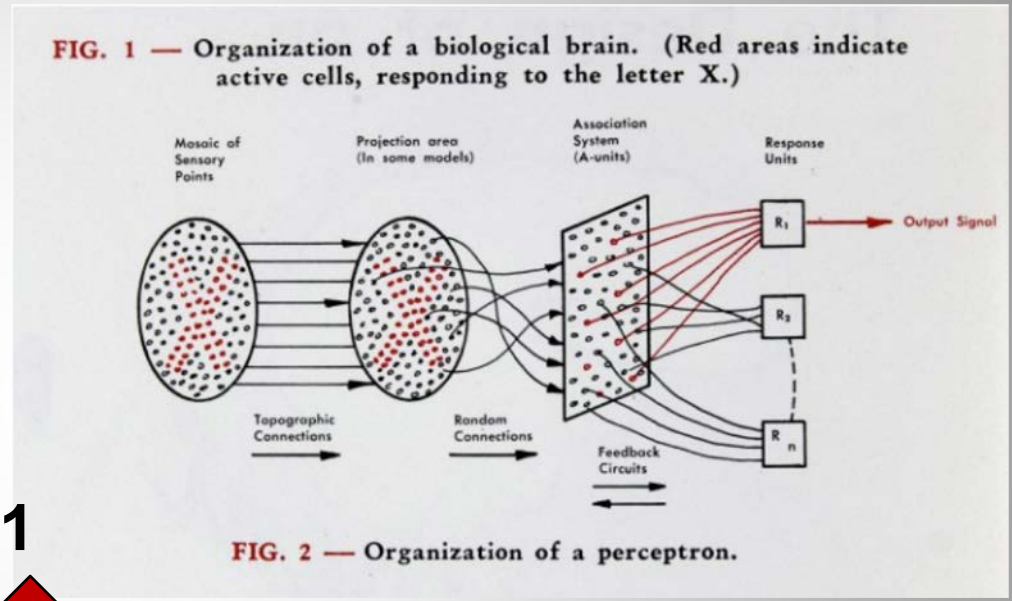
1912 – 1954

1950: "Theseus (1950) was a mechanical mouse controlled by an electromechanical relay circuit that enabled it to move around a labyrinth of 25 squares. The mouse was designed to search through the corridors until it found the target. Having travelled through the maze, the mouse could then be placed anywhere it had been before, and because of its prior experience it could go directly to the target." [Wikipedia]

Communications & Computing & Artificial Intelligence



Frank Rosenblatt, 1928-1971

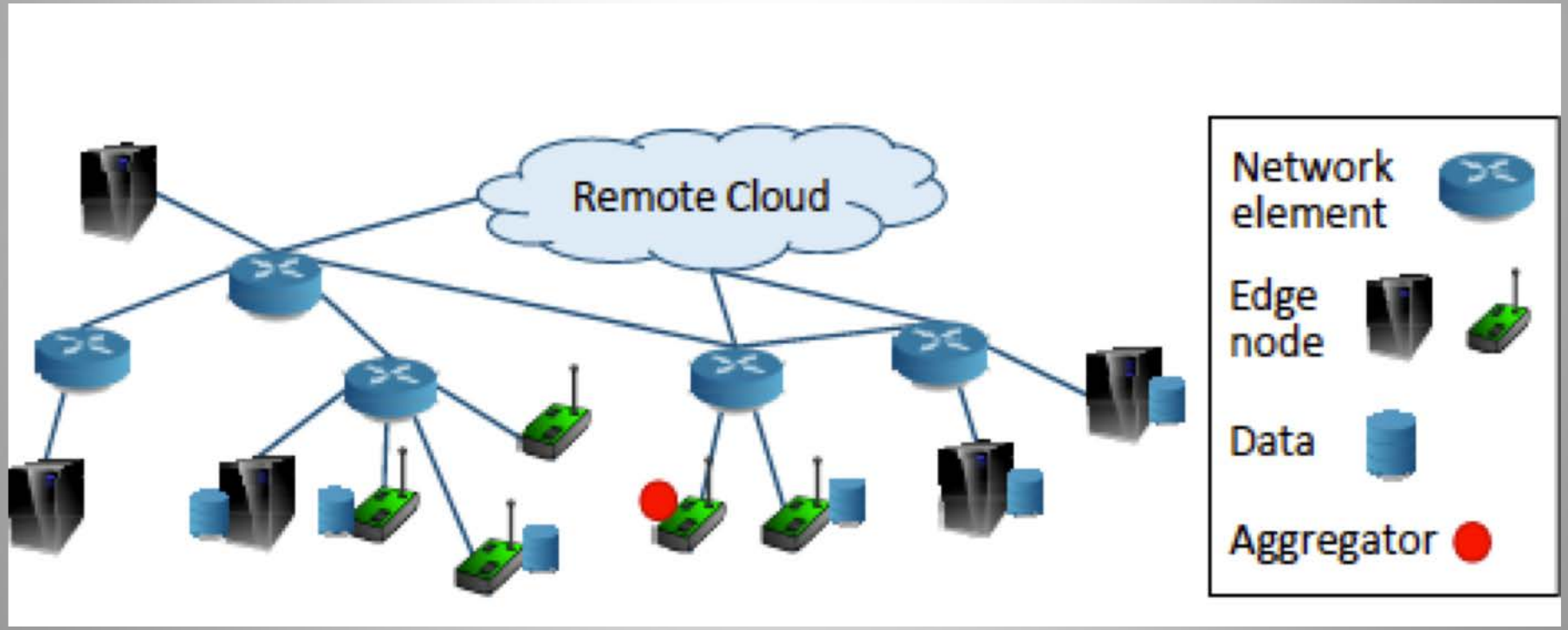


Claude Shannon

Alan Turing

Integrating the Intelligence

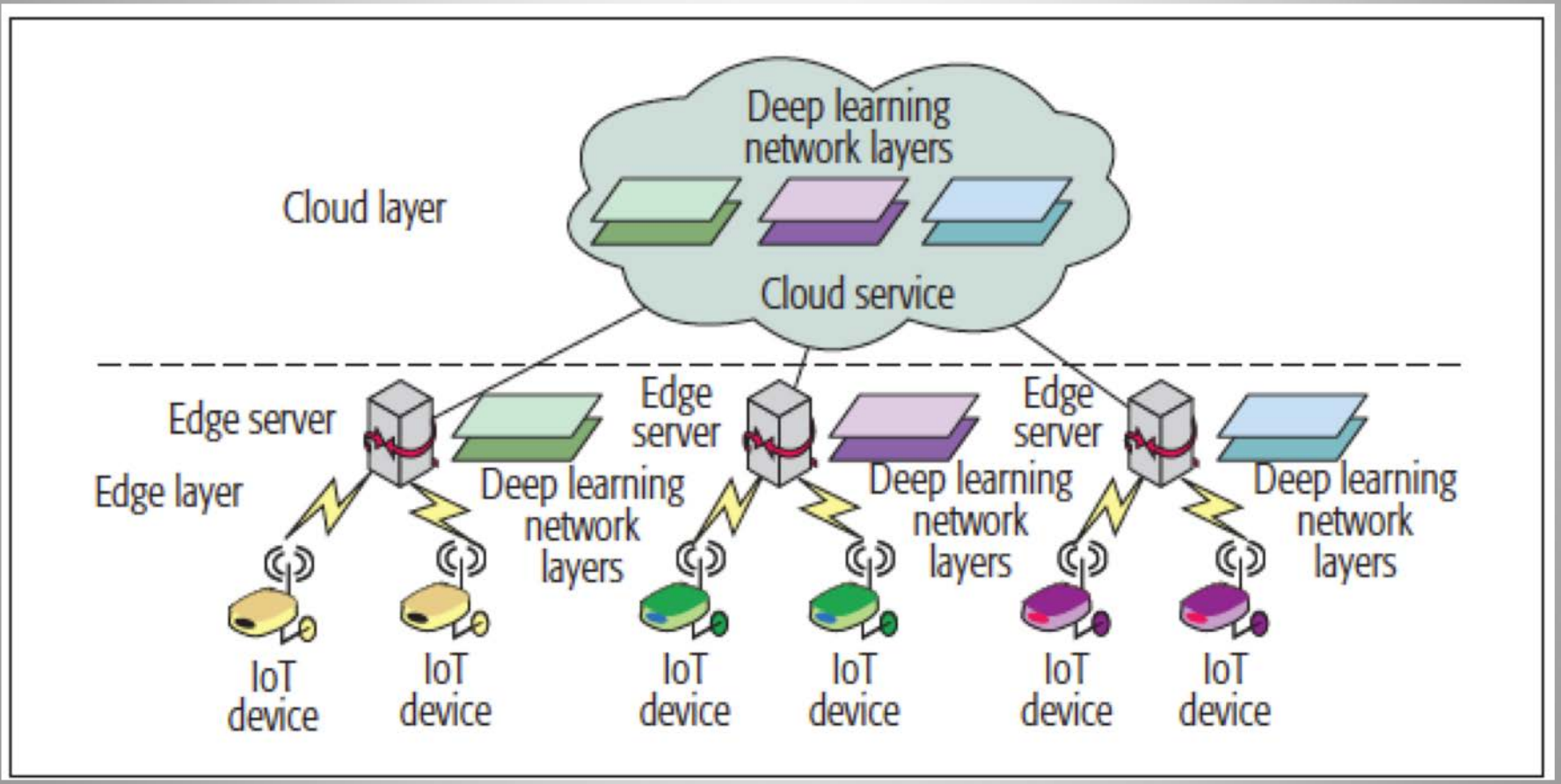
- Distributed machine learning (model training) from a federation of edge nodes (federated learning)
- Local updates & global aggregation (frequency of global aggregation to most efficiently used available resources).



S. Wang et al., "Adaptive federated learning in resource constrained edge computing systems," IEEE JSAC.

Integrating the Intelligence: IoT in Edge

Deep learning network (DLN)

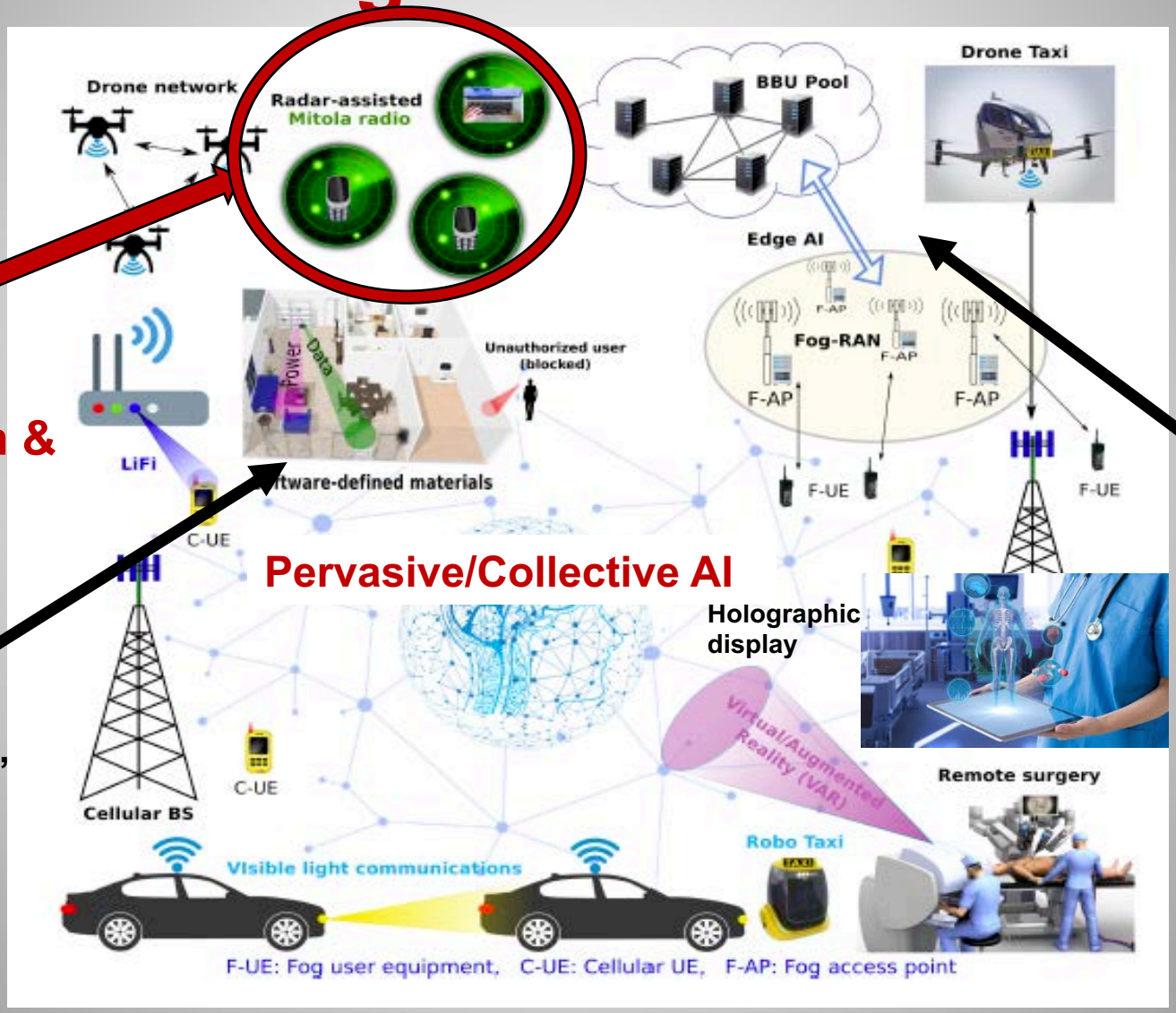


Question: How to divide the DLN?

H. Li et al, "Learning IoT in edge: Deep learning for the Internet-of-Things with edge computing," IEEE Network.

6G: All Technologies Should Work Together & New Use Cases

Integrated sensing, localization & commun.

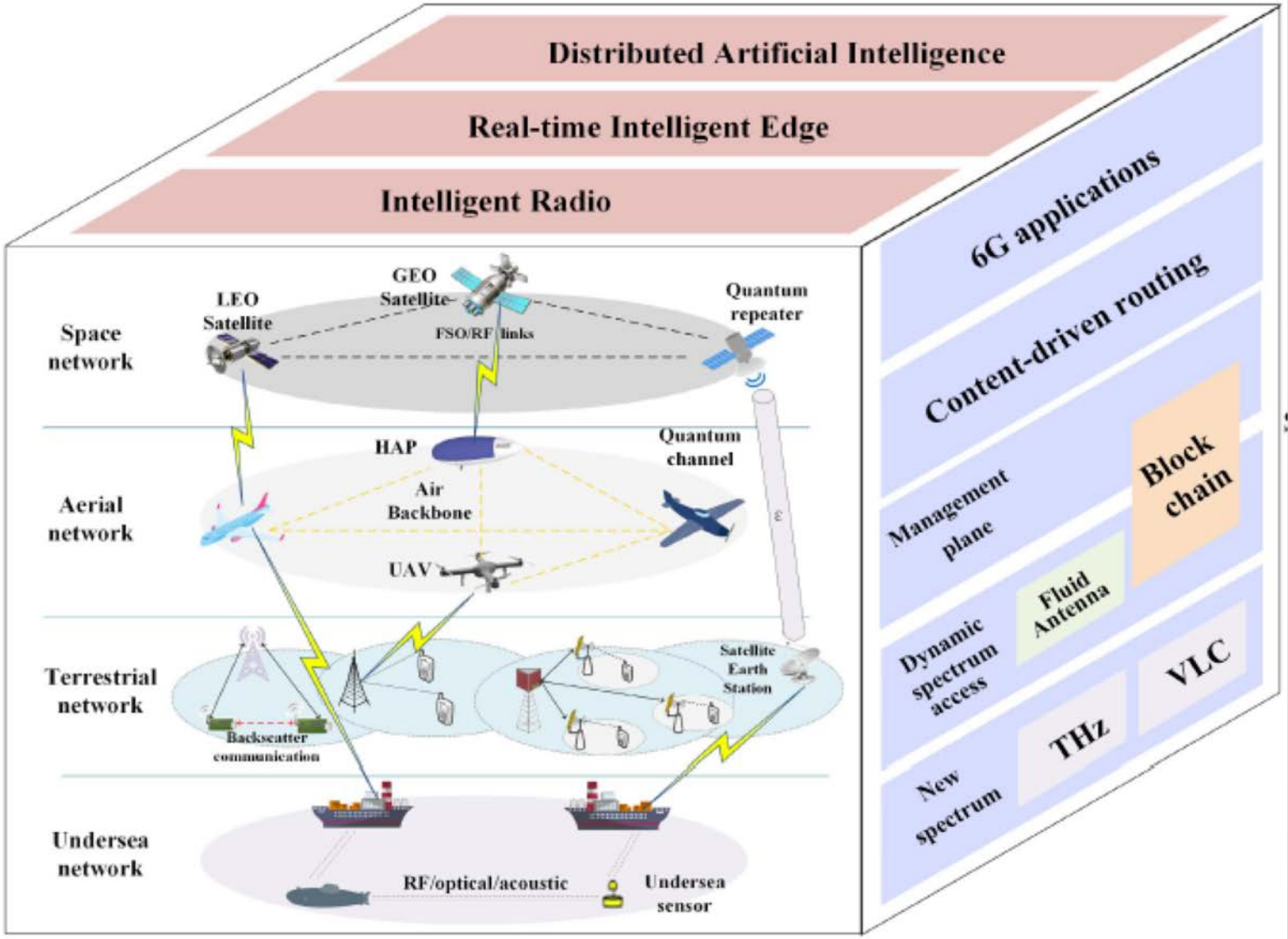


AI-assisted joint commun., sensing & localization

IRS-assisted joint commun., sensing & localization

"A Speculative Study on 6G," https://arxiv.org/abs/1902.06700.

6G: All Technologies Should Work Together & New Use Cases



T. Huang et al., "A Survey on Green 6G Network: Architecture and Technologies," IEEE Access.

Selected Work: 5G, B5G, 6G

[J1] "A prospective look: Key enabling technologies, applications and open research topics in 6G networks," *IEEE Access*, 2020.

[J2] "An outlook on the interplay of AI and software-defined metasurfaces," *IEEE Open Access of the Vehicular Society Journal*, 2020 (Invited Paper).

[J3] "Intelligent reflecting surface enhanced millimeter-wave NOMA systems," *IEEE Communications Letters*, 2020.

[J4] "Graph neural network based channel tracking for massive MIMO networks," *IEEE Communications Letters*, 2020.

[J5] "Large intelligent surface assisted wireless communications with receive spatial modulation and antenna selection," *IEEE Journal on Selected Areas in Communications*, 2020.

[J6] "Energy-constrained UAV-assisted secure communications with position optimization and cooperative jamming," *IEEE Transactions on Communications*, 2020.

[J7] "Delay minimization for massive MIMO assisted mobile edge computing," *IEEE Transactions on Vehicular Technology*, 2020.

[J8] "Massive MIMO-assisted mobile edge computing: Exciting possibilities for computation offloading," *IEEE Vehicular Communications Magazine*, 2020.

[J9] "Task scheduling for mobile edge computing using genetic algorithm and conflict graphs," *IEEE Transactions on Vehicular Technology*, 2020.

[J10] "Power minimization for multi-cell uplink NOMA with imperfect SIC," *IEEE Wireless Communications Letters*, 2020.

[J11] "Semi-blind interference aligned NOMA for downlink MU-MISO systems," *IEEE Transactions on Communications*, 2020.

Signal Identification: Wireless and Optical Communications

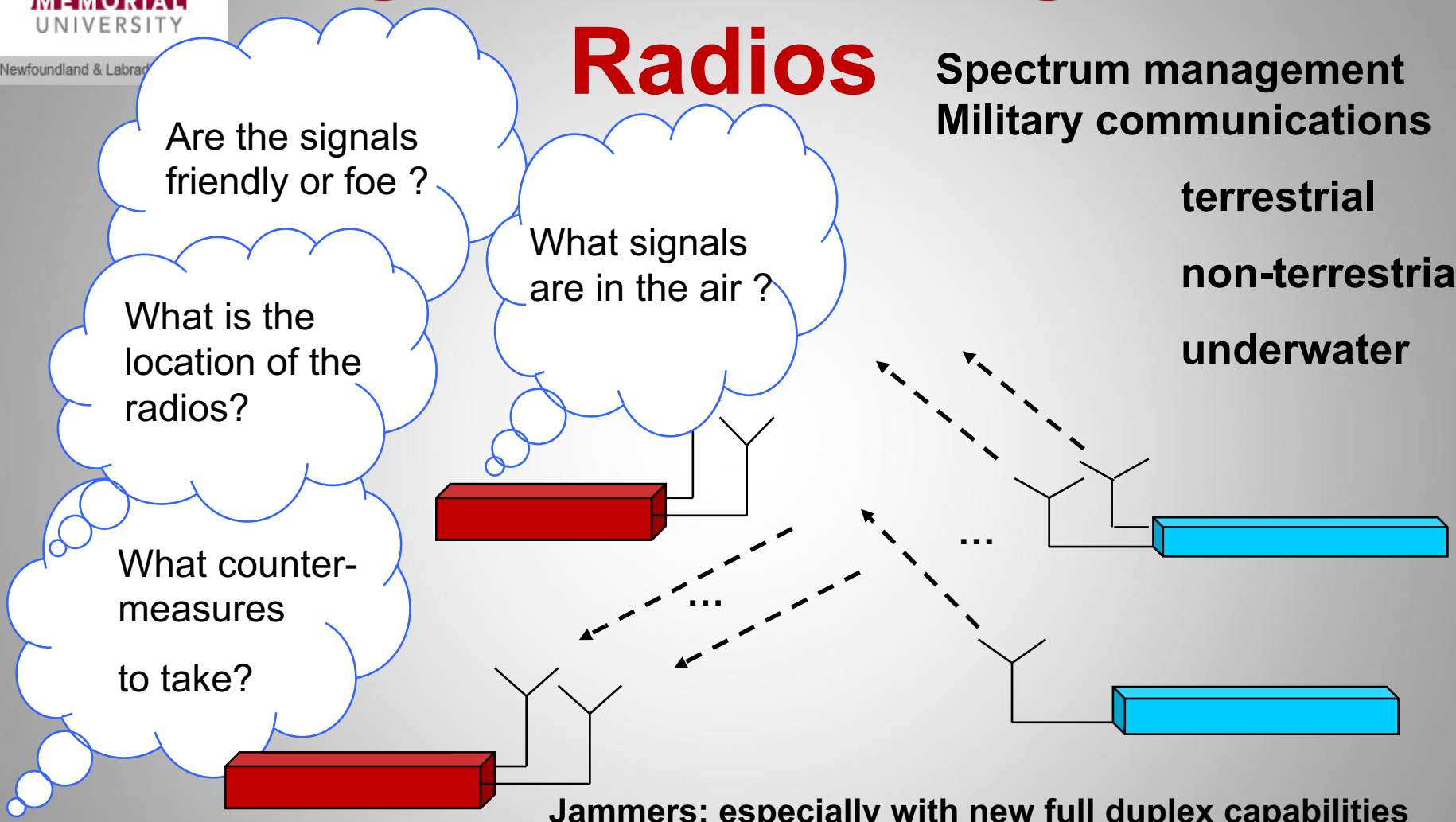
Cognitive & Intelligent Radios

Spectrum management
Military communications

terrestrial

non-terrestrial

underwater



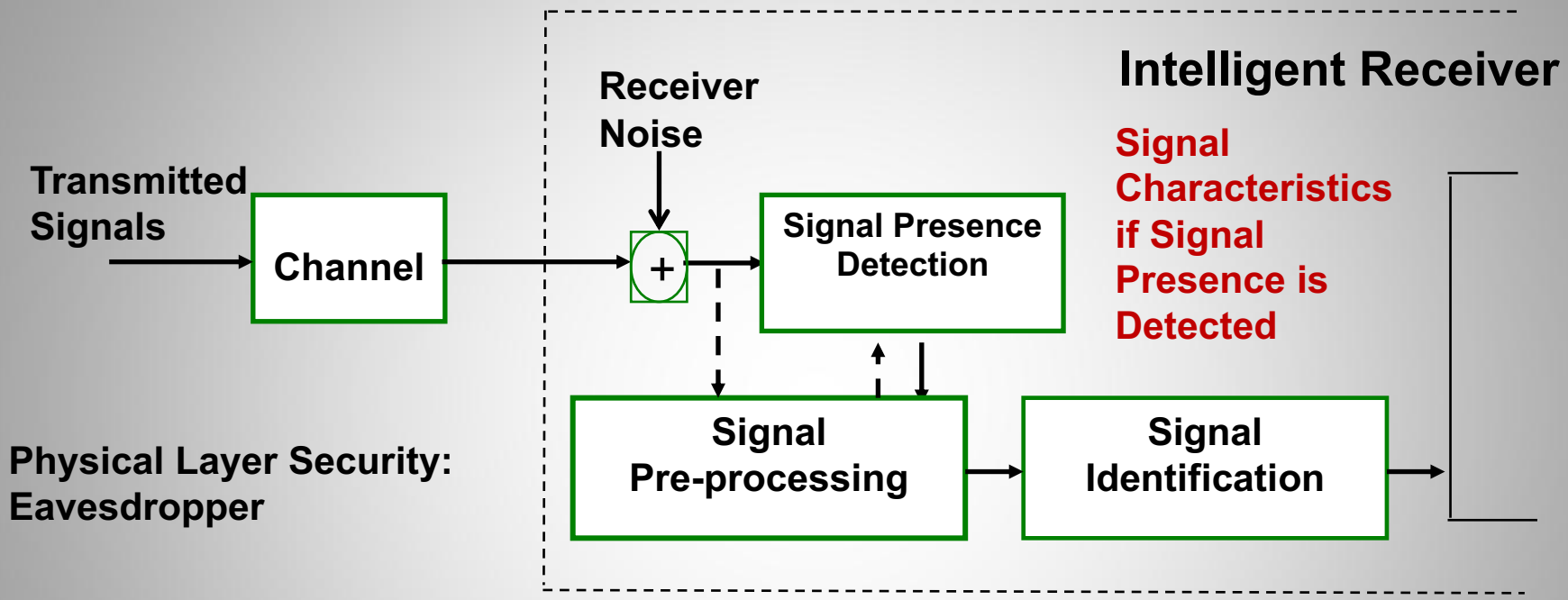
Jammers: especially with new full duplex capabilities

Intelligent radio

Y. Eldemerdash, O. A. Dobre, and M. Oner, "**Signal identification for multiple-antenna wireless systems: Achievements and challenges**," IEEE Communications Surveys & Tutorials.

O. A. Dobre, "**Signal identification for emerging intelligent radios: Classical problems and new challenges**," IEEE Instrumentation Measurement Magazine.

Blind Signal Identification



Physical Layer Security: Eavesdropper

Examples:

- antenna enumeration, identification of the transmission scheme, modulation format and FEC, identification of a standard signal

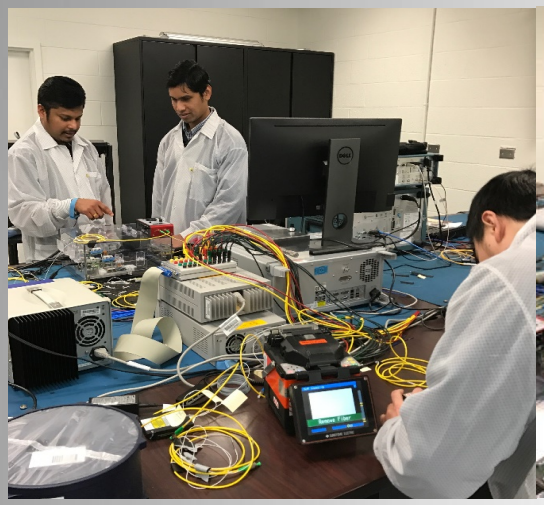
- it can exploit the pilot contamination phenomenon, hijacking the reciprocity-based beamforming mechanism.

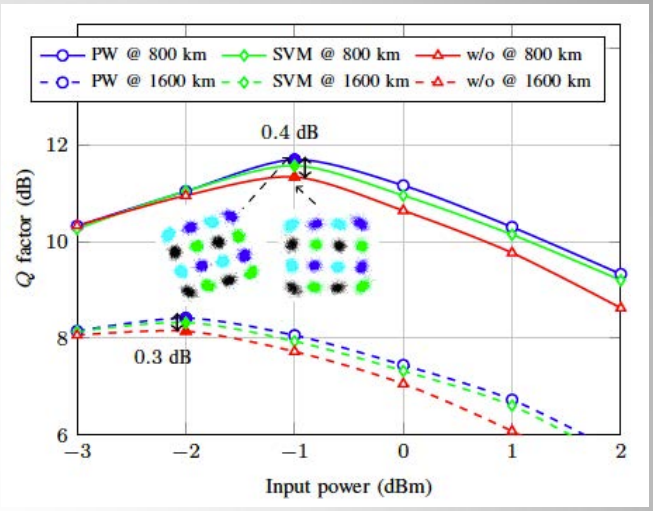
Y. Eldemerdash, O. A. Dobre, and M. Oner, "**Signal identification for multiple-antenna wireless systems: Achievements and challenges**," IEEE Communications Surveys & Tutorials.

O. A. Dobre, "**Signal identification for emerging intelligent radios: Classical problems and new challenges**," IEEE Instrumentation Measurement Magazine.

Optical Communications

http://www.engr.mun.ca/~omoptics/



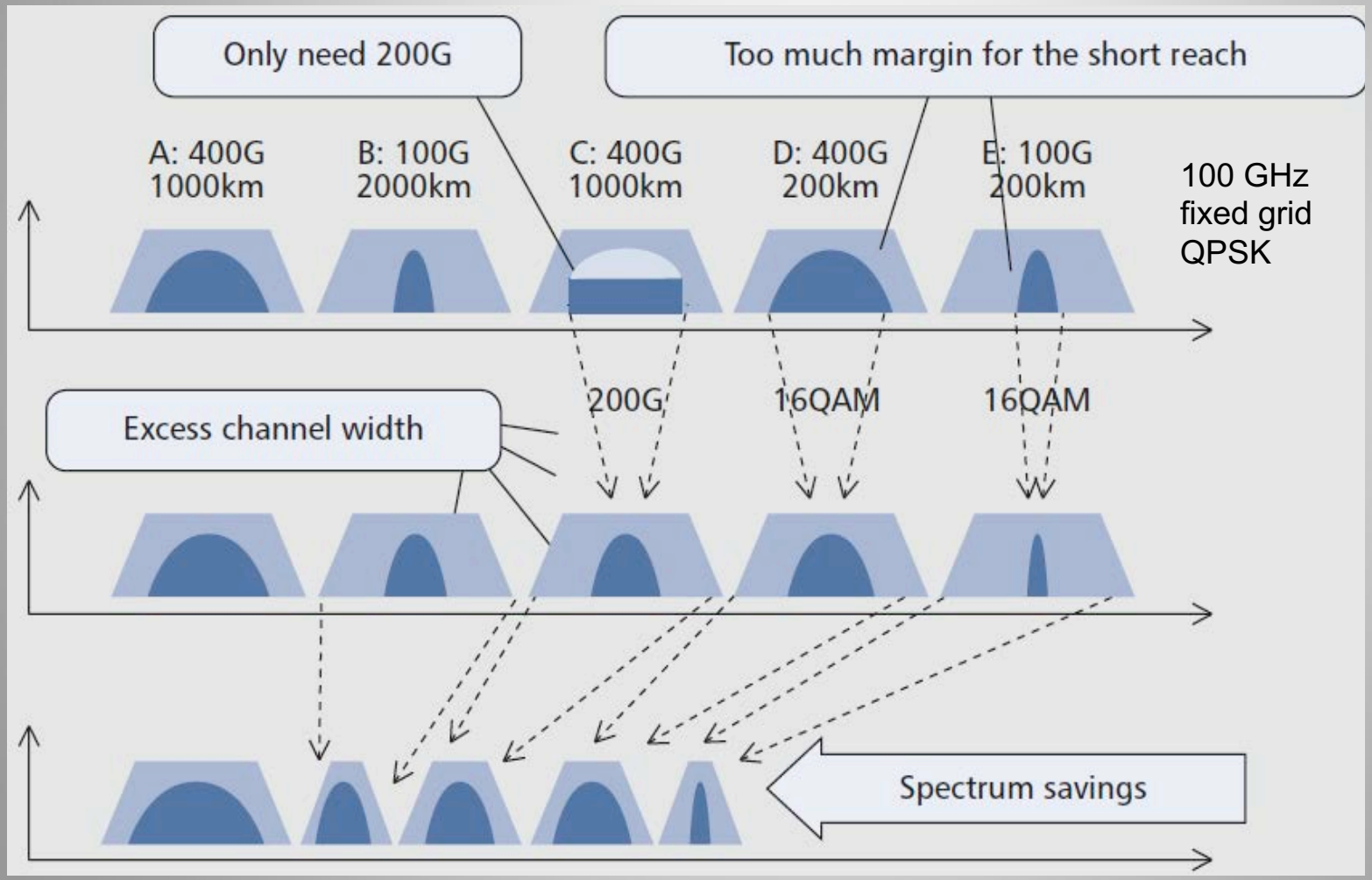


Technology Development for Terabit Optical Transport Networks

A. Amari, X. Lin, O. A. Dobre, R. Venkatesan, and A. Alvarado, "**A machine learning-based detection technique for optical fiber nonlinearity mitigation**," *IEEE Photonics Letters*, Feb. 2019.

Elastic Optical Network (EON)

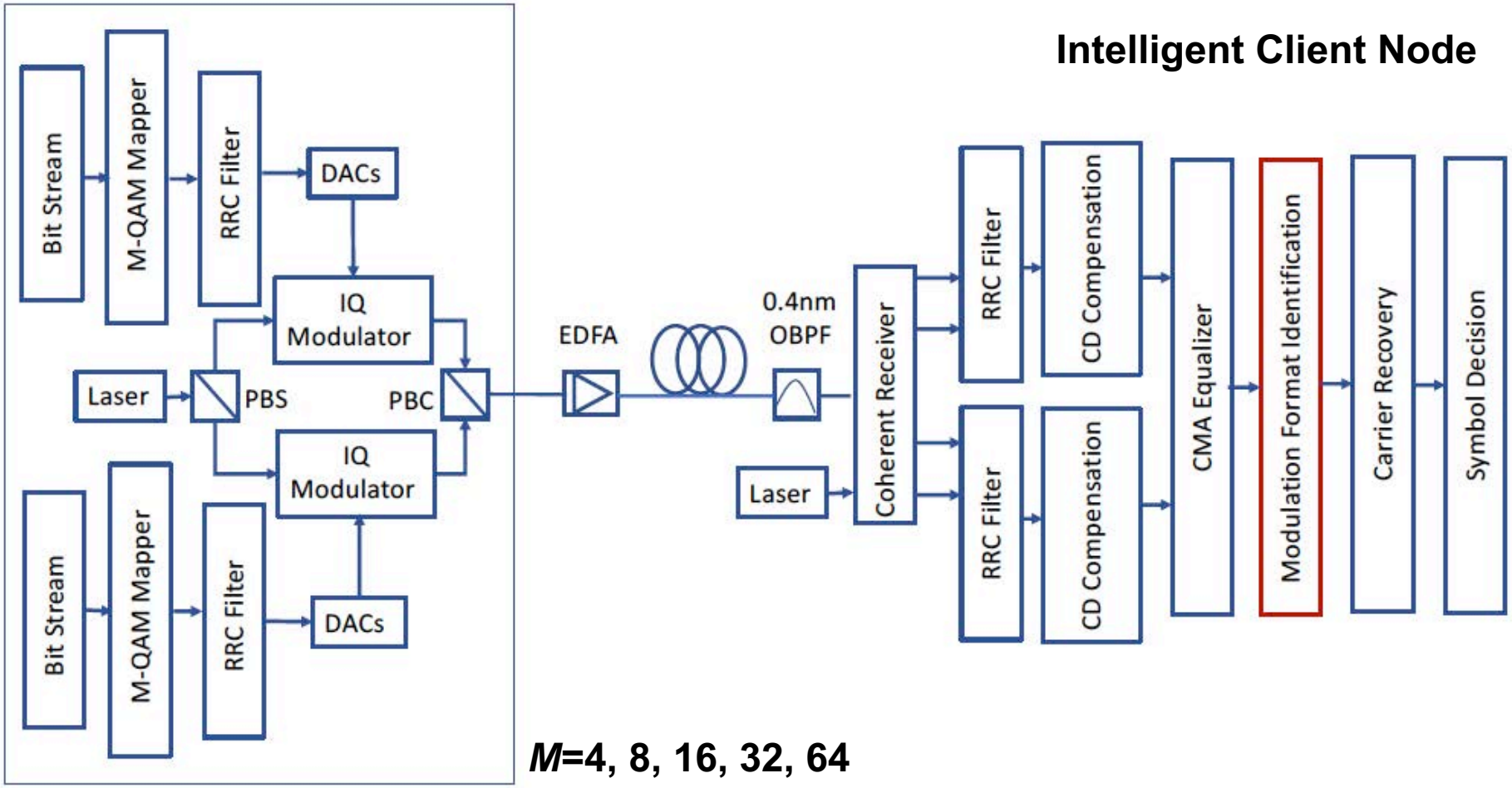
Flexible and adaptive networks equipped with flexible transceivers and network elements that can adapt to the actual traffic needs.



Best implementation of the request – modulation, FEC and spectrum - with lowest-cost solution

O. Gerstel et al, **"Elastic optical networking: A new dawn for the optical layer?,"** IEEE Commun. Mag.

EON: Modulation Identification



X. Lin, O. A. Dobre, Y. Eldemerdash, T. Ngatched, and C. Li, "**Joint modulation classification and OSNR estimation enabled by support vector machine**," IEEE Photonics Technology Letters.

X. Lin, Y. Eldemerdash, O. A. Dobre, S. Zhang, and C. Li, "**Modulation classification using received signal's amplitude distribution for coherent receivers**," IEEE Photonics Technology Letters.

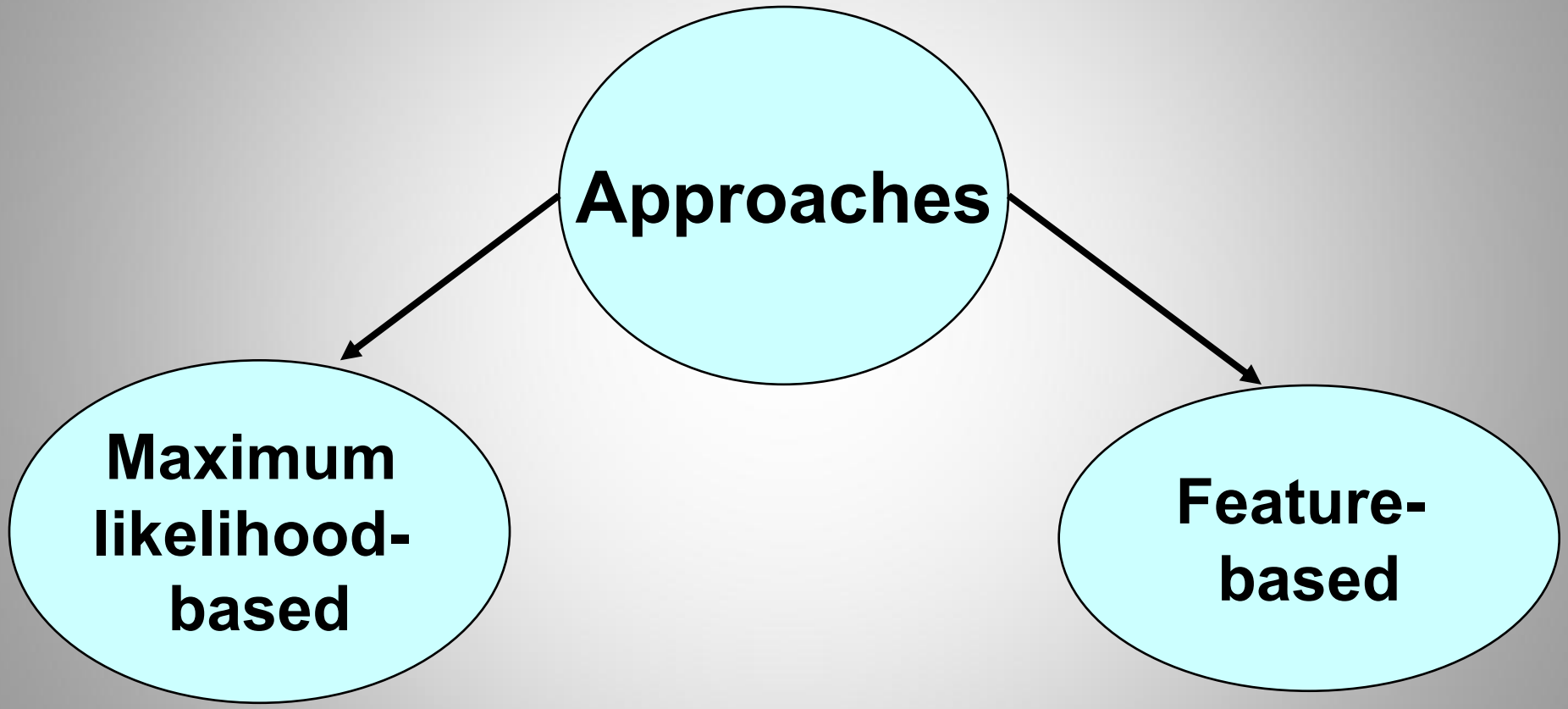
Signal Identification

Requirements

- *High* degree of *flexibility* in terms of sensing different signal types under diverse conditions.
- *High identification performance* for low SNR in a short observation interval.
- *Reduced pre-processing requirements*, e.g., timing and carrier recovery, are not required.
- *Robustness* to non-ideal conditions, such as frequency and timing offsets.
- *Low complexity*.

O. A. Dobre et al., "**Cyclostationarity-based robust algorithms for QAM signal identification**," IEEE Communications Letters.
M. Muhlaus et al., "**A low complexity modulation classification algorithm for MIMO systems**," IEEE Communications Letters.

Signal Identification



O. A. Dobre et al., "**Survey of automatic modulation classification techniques: classical approaches and new trends**," IET Communications.

Average LRT: Examples

▪ ***Complexity***

- **Unknowns** $\mathbf{u}_i = [\{s_k^{(i)}\}_{k=1}^K]$**, AWGN**

$$\Lambda_{A-AWGN}^{(i)}[\mathbf{r}] = \prod_{k=1}^{K} E_{s_k^{(i)}}\left[\exp\left\{\frac{2\alpha}{N_0}\mathrm{Re}[e^{-j\varphi}R_k^{(i)}] - \frac{\alpha^2 T}{N_0}|s_k^{(i)}|^2\right\}\right]$$

$\boxed{\mathrm{O}(M_i K)}$

- **Unknowns** $\mathbf{u}_i = [\varphi\ \{s_k^{(i)}\}_{k=1}^K]^\dagger$**, AWGN**

The phase φ is uniformly distributed over $[-\pi, \pi)$.

$$\Lambda_{A-CP}^{(i)}[\mathbf{r}] = E_{\{s_k^{(i)}\}_{k=1}^K}\left[I_0\left(\frac{2\alpha}{N_0}|\Psi_K^{(i)}|\right)\exp\left\{-\frac{\alpha^2 T}{N_0}\eta_K^{(i)}\right\}\right]$$

$\boxed{\mathrm{O}(M_i^K)}$

F. Hameed, O. A. Dobre, and D. Poepscu, "**On the likelihood-based approach to modulation classification**," IEEE Transactions on Communications.

Feature-based Approach

Feature Extraction → **Decision-Making**

- ✓ ***Features:*** unique characteristics for each signal

  Examples: instantaneous amplitude, phase, frequency, their CDFs or statistics; signal statistics and cyclic statistics, different transforms (e.g., wavelet)

- ✓ ***Decision-making:*** based on feature differences

  Examples: correlations, distances, decision tree classifiers, neural networks, support vector machine

MACHINE LEARNING-BASED ALGORITHMS

O. A. Dobre et al., "**Survey of automatic modulation classification techniques: classical approaches and new trends**," IET Communications.

Example: General Cyclostationarity-based Algorithm

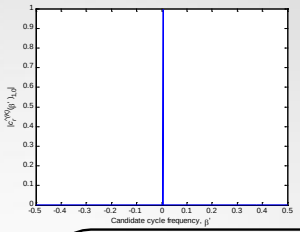
SCLD: Single Carrier Linear Digital Modulation

CP-SCLD or SC-FDMA: Cyclically Prefixed SCLD or SC-Frequency Division Multiple Access

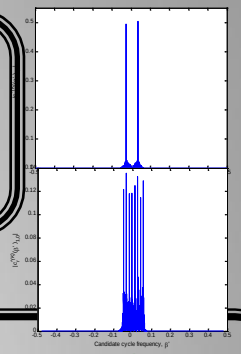
OFDM: Orthogonal Frequency Division Multiplexing

FSK: Frequency Shift Keying

AM: Amplitude Modulation



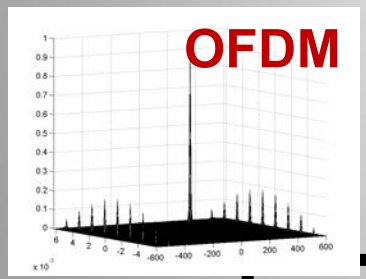
Exploitation of first-order cyclostationarity



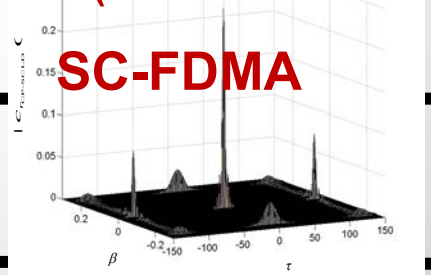
AM (detection of a single CF)

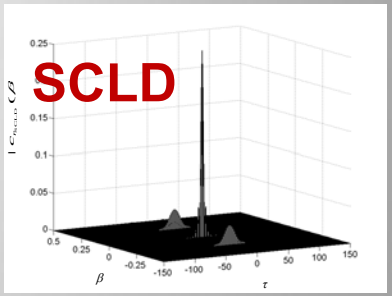
***M*-ary FSK (detection of *M* CFs)**

OFDM, CP-SCLD, SCLD, Noise (no first-order CFs)



Exploitation of second-order cyclostationarity





Preamble, reference-signal induced

OFDM-based standards

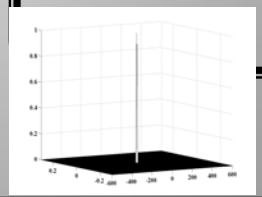
Exploitation of higher-order cyclostationarity

Modulation Type

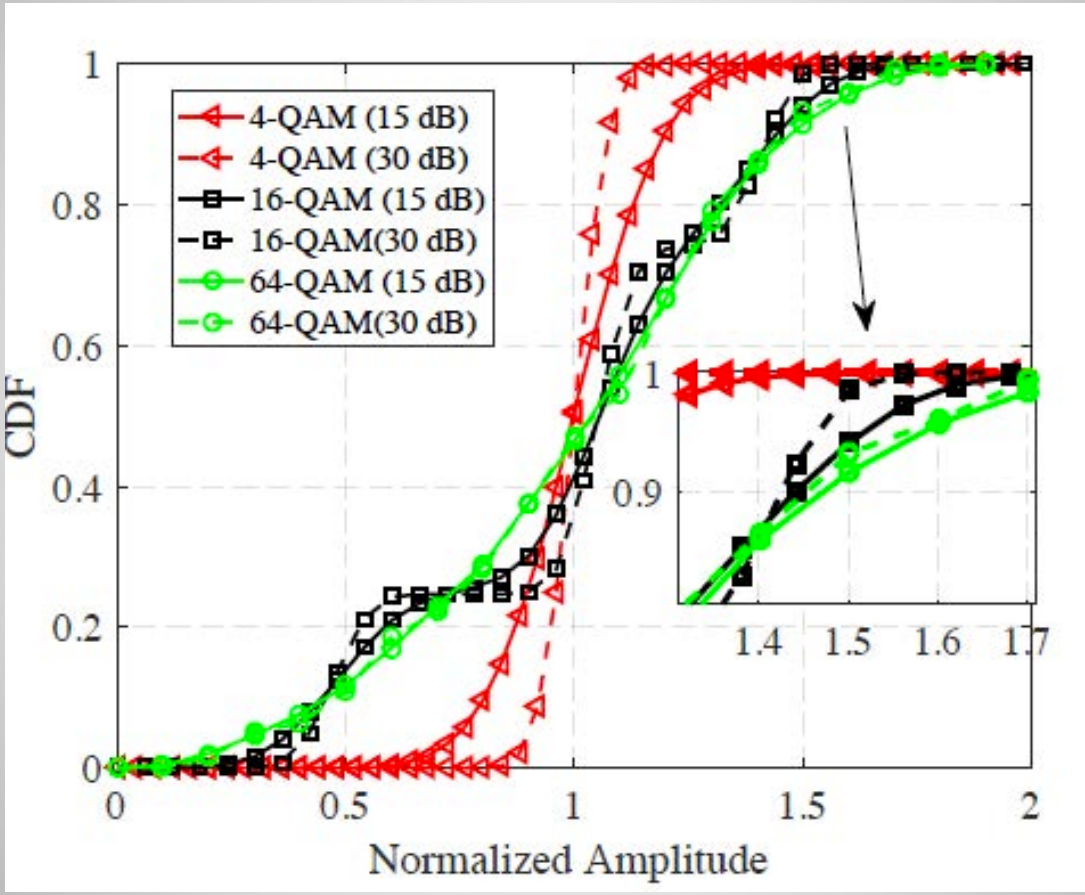
Exploitation of higher-order cyclostationarity

Modulation Type

Noise

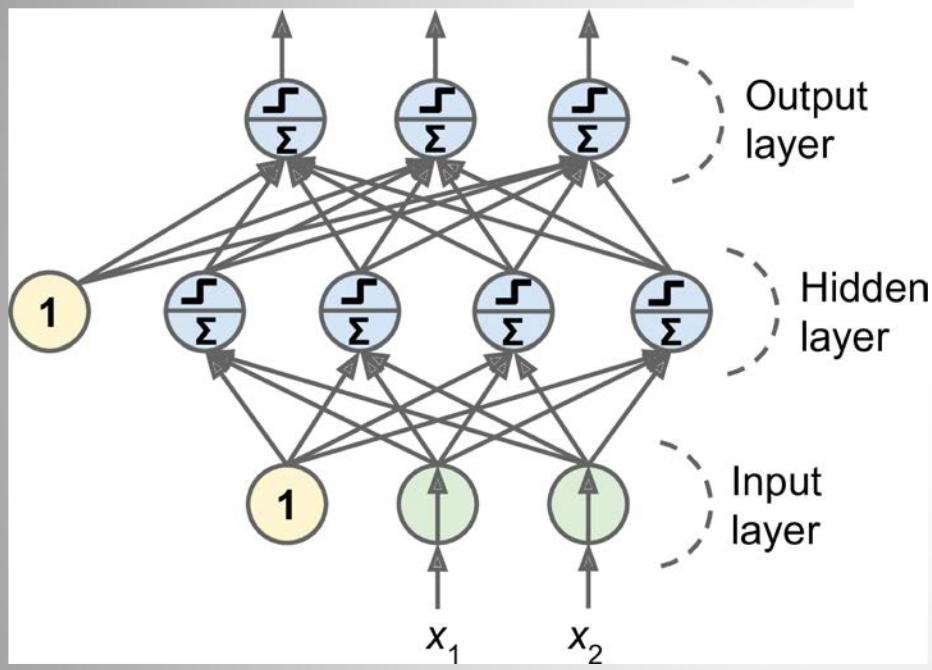


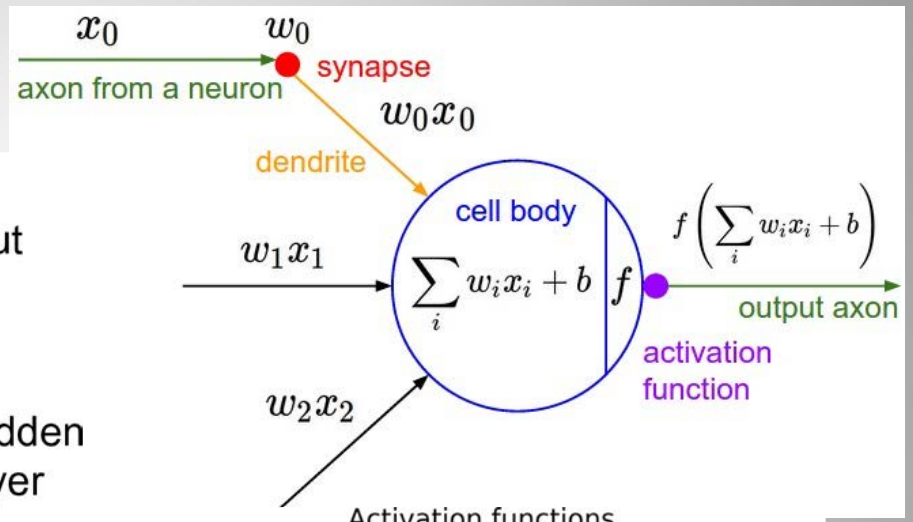
Example: Amplitude Cumulative Distribution Function (CDF)

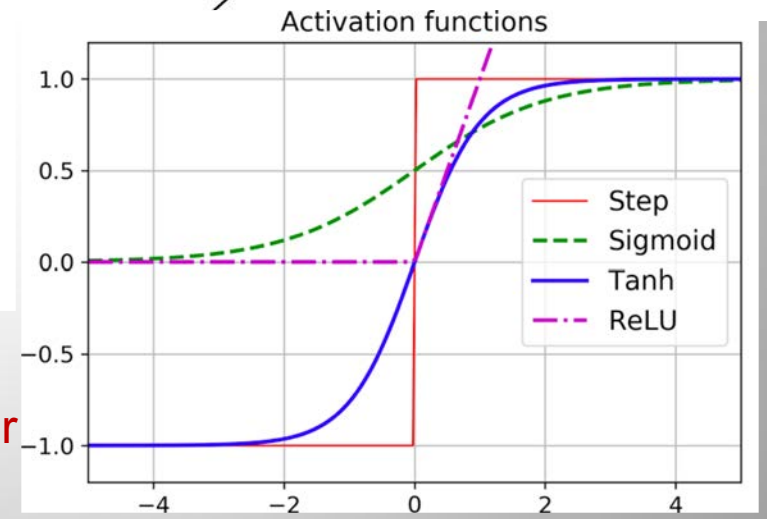


X. Lin, O. A. Dobre, Y. Eldemerdash, T. M. N. Ngatched, and C. Li, "**Joint modulation classification and OSNR estimation enabled by support vector machine**," *IEEE Photonics Technology Letters*, 2018.

Neural Networks



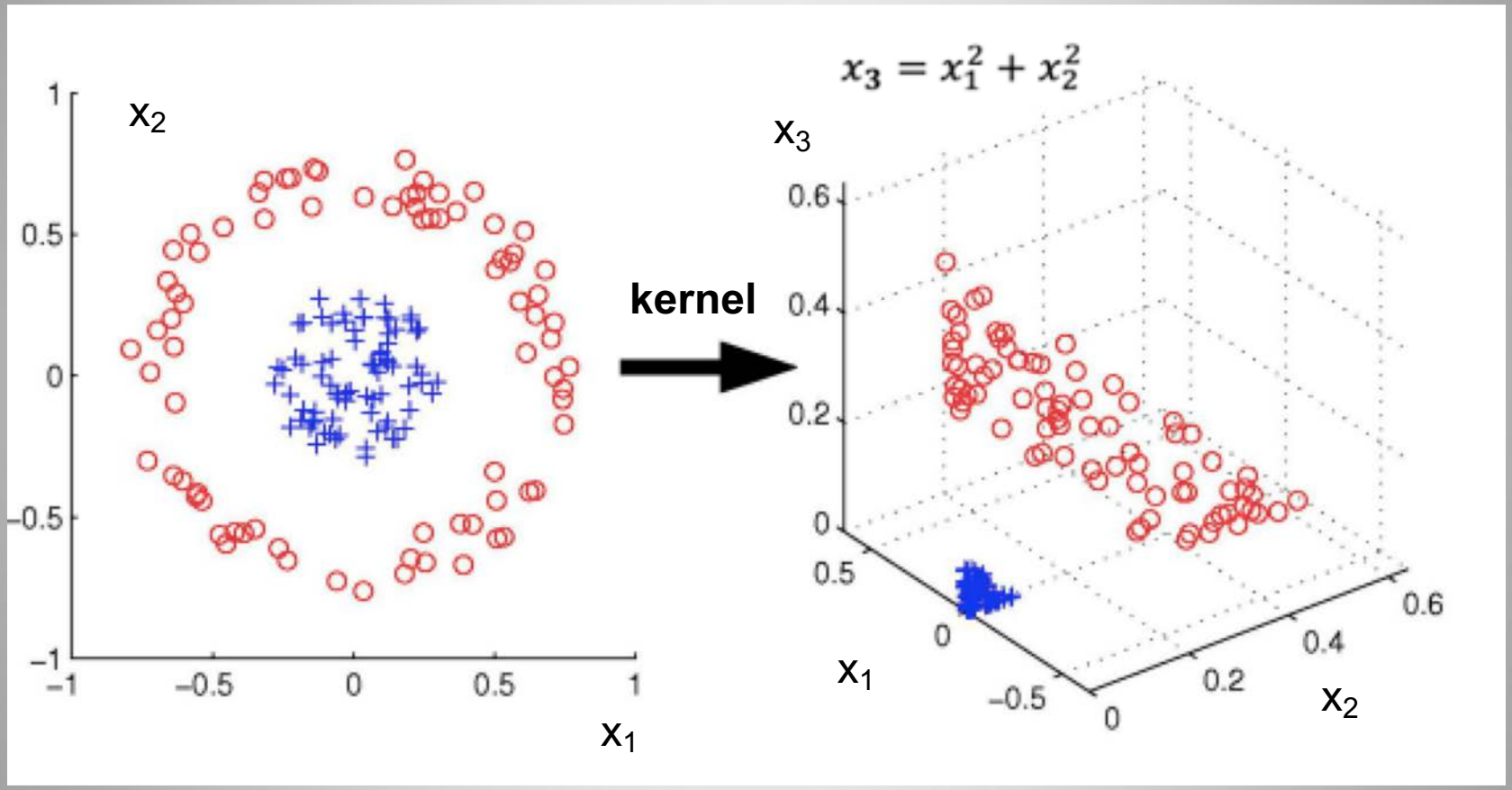




Example of cost function: mean square error

A. P. Tao Lau et al., Applications of Machine Learning in Optical Communications and Networks, OFC 2020.
A. Geron, Hands-on Machine Learning with Scikit-Learn, Keras & TensorFlow, O'Reilley, 2019.

Support Vector Machine

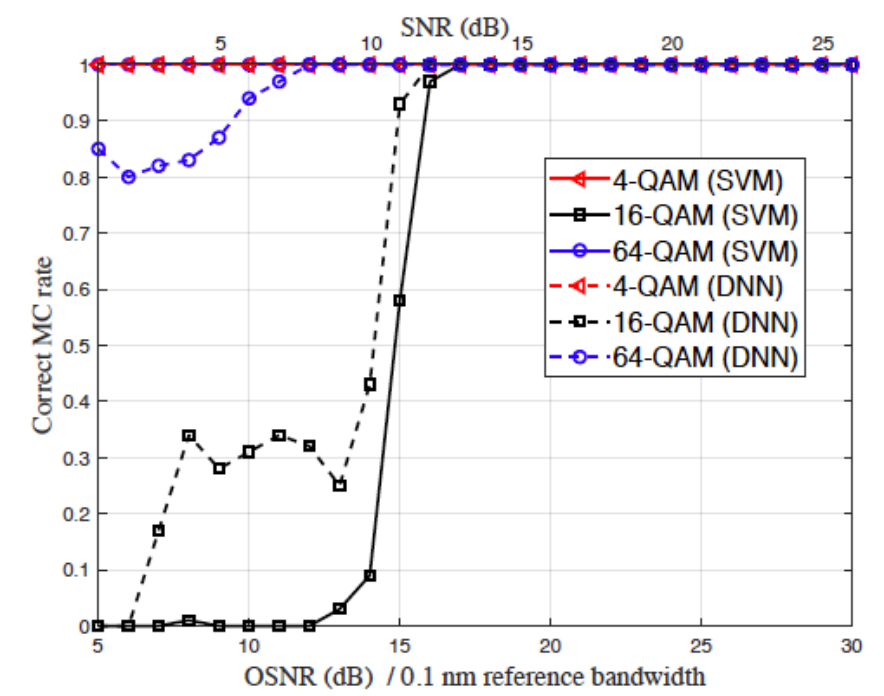


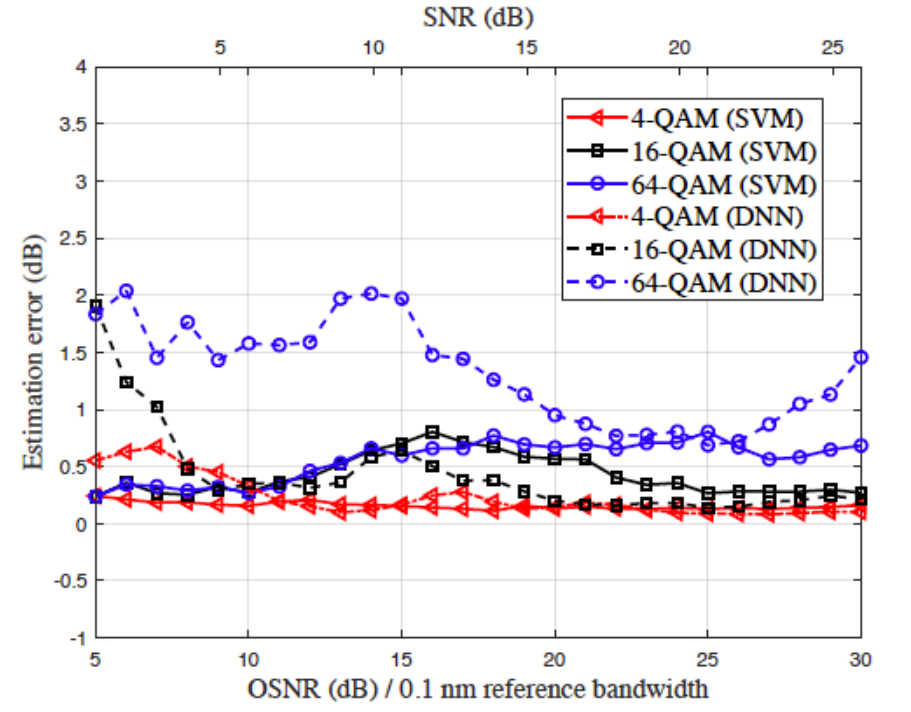
Example of kernel: Gaussian radial basis function

$$K\big(\mathbf{x}(i), \mathbf{x}(j)\big) = \exp(-\gamma \|\mathbf{x}(i) - \mathbf{x}(j)\|^2)$$

A. Geron, Hands-on Machine Learning with Scikit-Learn, Keras & TensorFlow, O'Reilley, 2019.

Joint Modulation Classification & OSNR Estimation based on CDF





32 Gbaud PDM, with CD and PMD; 800 km SSMF; 1GHz freq. offset, 100 kHz linewidth laser; 10,000 samples to create the CDF.

DNN: 2 hidden layers; 10/30 neurons/layer for MC; Adam optimizer; sigmoid activation function.

SVM: Gaussian radial basis function kernel, $\gamma = 0.1$; $\varepsilon = 0.01$

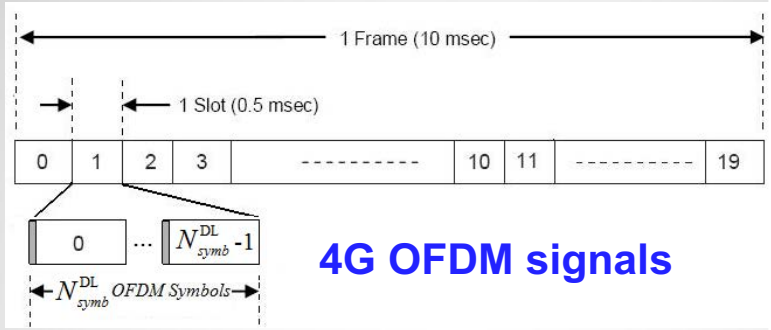
Training data: 78 CDFs (3 modulation formats and 26 OSNRs); Testing data: 7800 CDFs

Complexity: linear with the number of input samples

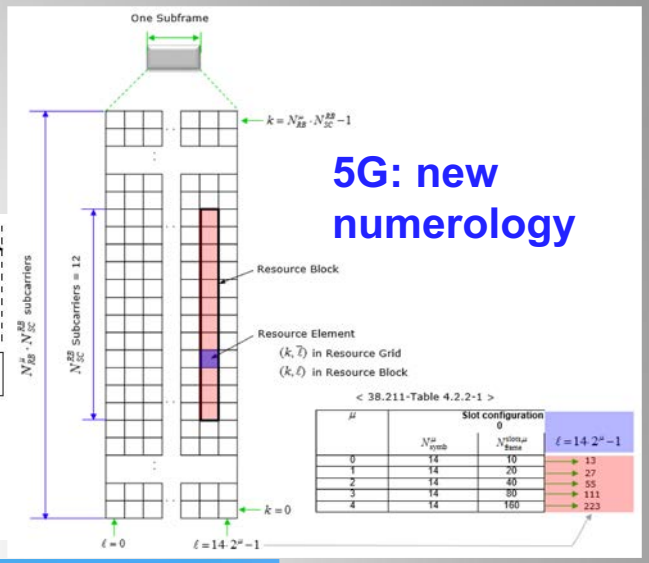
X. Lin, O. A. Dobre, Y. Eldemerdash, T. M. N. Ngatched, and C. Li, "**Joint modulation classification and OSNR estimation enabled by support vector machine**," *IEEE Photonics Technology Letters*, 2018.

Signal Identification: New Trends

- ✓ **Identification of *new standard signals*: 5G NR**



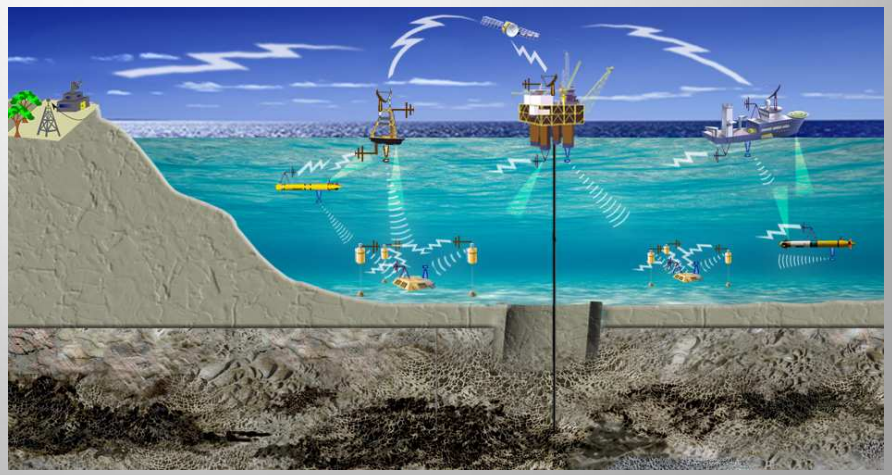
4G OFDM signals



5G: new numerology

- ✓ ***Drone* detection & identification**

- ✓ **Identification of *underwater systems* (*signals* & *noises*)**



Selected Work: Blind Signal Identification

[J1] Y. Eldemerdash, O. A. Dobre, O. Ureten, and T. Yensen, "**A robust modulation classification method for PSK signals using random graphs**," *IEEE Transactions on Instrumentation and Measurement*, 2019.

[J2] X. Lin, O. A. Dobre, Y. Eldemerdash, T. M. N. Ngatched, and C. Li, "**Joint modulation classification and OSNR estimation enabled by support vector machine**," *IEEE Photonics Technology Letters*, 2018.

[J3] M. Gao, Y. Li, O. A. Dobre, and N. Al-Dhahir, "**Joint blind identification of the number of transmit antennas and MIMO schemes using Gerschgorin radii and FNN**," *IEEE Transactions on Wireless Communications*, 2018.

[J4] M. Gao, Y. Li, O. A. Dobre, and N. Al-Dhahir, "**Blind identification of SFBC-OFDM signals using subspace decompositions and random matrix theory**," *IEEE Trans. on Vehicular Technology*, 2018.

[J5] R. Gupta, S. Majhi, and O. A. Dobre, "**Design and implementation of a tree-based blind modulation classification algorithm for multiple-antenna system**s," *IEEE Transactions on Instrumemntation and Measurement*, 2018.

[J6] Y. Eldemerdash, O. A. Dobre, O. Ureten, and T. Yensen, "**Identification of cellular networks for intelligent radio measurements**," *IEEE Transactions in Instrumentation and Measurement*, 2017.

[J7] M. Mohammadkarimi, O. A. Dobre, and M. Win, "**Number of transmit antennas detection using time-diversity of the fading channel**," *IEEE Transactions on Signal Processing*, 2017.

[J8] L. Han, F. Gao, Z. Li, and O. A. Dobre, "**Low complexity automatic modulation classification based on order statistics**," *IEEE Transactions on Wireless Communications*, 2017.

[J9] Y. A. Eldemerdash, O. A. Dobre, and M. Oner, "**Signal identification for multiple-antenna wireless systems: Achievements and challenges**," *IEEE Communications Surveys and Tutorials*, 2016.

[J10] Y. A. Eldemerdash and O. A. Dobre, "**On the identification of SM and Alamouti-coded SC-FDMA signals: A statistical-based approach**," *IEEE Transactions on Vehicular Communications,* 2016.

[J11] F. Wang, O. A. Dobre, C. Chan, and J. Zhang, "**Novel fold-based Kolmogorov-Smirnov modulation classifier**," *IEEE Signal Processing Letters*, 2016.

[J12] O. A. Dobre, "**Signal identification for emerging intelligent radios: Classical problems and new challenges**," *IEEE Instrumentation and Measurement Magazine*, 2015.

Summary

- **Communications and computing synergy:** allows implementation of distributed AI
- **B5G**: Native-AI systems & sensing – AI enables enhanced sensing –
- **Cellular network as a sensor –** sensed data + AI = the basis of many applications
- It is important to understand how to **incorporate the intelligence** in the network
- **Wireless** communication: major paradigm shifts towards “intelligently connecting intelligent things”
- **Optical** communication networks: paradigm shift towards flexibility and intelligence
- **Non-terrestrial networks:** co-exist & complement terrestrial networks
- **Signal identification**: from pure military to commercial optical and wireless applications