FROM COGNITION TO INTELLIGENCE IN COMMUNICATIONS NETWORKS

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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

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HS: 3 postdoctoral fellows and 12 students
COGNITION TO INTELLIGENCE: IDEAS WHOSE TIME HAVE COME
## Cognitive Radio Technology: Roadmap

### How/When did it start?

<table>
<thead>
<tr>
<th>First attempts: progr. radios</th>
<th>Software-defined radio</th>
<th>Military applications</th>
<th>First papers (Mitola)</th>
<th>PhD Thesis (Mitola)</th>
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</thead>
<tbody>
<tr>
<td>70's</td>
<td>90's</td>
<td>1999</td>
<td>2000</td>
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</table>

### What has been achieved in about 20 years?

|----------------------------------------|-----------------------------------|----------------|------------------|------------------------|-------------------------------|

<table>
<thead>
<tr>
<th>3GPP first femtocell standard</th>
<th>3GPP R10 CA (DL) 40 MHz</th>
<th>3GPP R12 CA (UL/DL; TDD/FDD); dual connectivity</th>
<th>3GPP R13 Licensed Assisted Access (DL)</th>
<th>3GPP R15 NR CA (mmWave, sub-6 GHz); dual connectivity</th>
<th>B5G Intelligence (AI)</th>
<th>6G Mitola’s radio ?</th>
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</table>
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

<table>
<thead>
<tr>
<th>Country</th>
<th>Spectrum Range</th>
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<tbody>
<tr>
<td>Germany</td>
<td>420 MHz in 2 GHz and 3.5 GHz bands (2019)</td>
</tr>
<tr>
<td>Spain</td>
<td>200 MHz in 3.6-3.8 GHz</td>
</tr>
<tr>
<td>Austria</td>
<td>400 MHz in 3.4-3.8 GHz</td>
</tr>
<tr>
<td>Italy</td>
<td>700 MHz, 3.6-3.8 GHz</td>
</tr>
<tr>
<td>Canada</td>
<td>600 MHz (2019); 3.5 GHz band in 2020, delayed to 2021</td>
</tr>
<tr>
<td>USA</td>
<td>600 MHz; 3.5 GHz (auction started July 2020)</td>
</tr>
<tr>
<td>South Korea</td>
<td>280 MHz in 3.5 GHz (June 2018)</td>
</tr>
<tr>
<td>China</td>
<td>2.5-2.6 GHz, 3.5 GHz, 4.8-4.9 GHz (Dec. 2018)</td>
</tr>
<tr>
<td>Japan</td>
<td>3.6-4.2 GHz &amp; 4.4-4.9 GHz</td>
</tr>
</tbody>
</table>


![Spectrum diagram](image-url)
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

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).

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

B5G: Air-Ground Integrated Approach

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.
Question: How to divide the DLN?

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

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

Selected Work: 5G, B5G, 6G


SIGNAL IDENTIFICATION: WIRELESS AND OPTICAL COMMUNICATIONS
Cognitive & Intelligent Radios

Are the signals friendly or foe?

What signals are in the air?

What is the location of the radios?

What countermeasures to take?

Spectrum management
Military communications
terrestrial
non-terrestrial
underwater

Jammers: especially with new full duplex capabilities


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.

Technology Development for Terabit Optical Transport Networks

Elastic Optical Network (EON)

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

EON: Modulation Identification

$M=4, 8, 16, 32, 64$


Signal Identification

- **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**.

Signal Identification

Approaches

Maximum likelihood-based

Feature-based

Average LRT: Examples

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

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

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

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

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

Feature-based Approach

**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**

Exploitation of first-order cyclostationarity

Exploitation of second-order cyclostationarity

Exploitation of higher-order cyclostationarity

Exploitation of higher-order cyclostationarity

Exploitation of higher-order cyclostationarity

Exploitation of higher-order cyclostationarity

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

**OFDM**

**SC-FDMA**

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

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

**SCLD**

**Noise**
Example: Amplitude Cumulative Distribution Function (CDF)

Neural Networks

Example of cost function: mean square error

Support Vector Machine

Example of kernel: Gaussian radial basis function

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

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

Signal Identification: New Trends

✓ Identification of new standard signals:
  5G NR

✓ Drone detection & identification

✓ Identification of underwater systems (signals & noises)
Selected Work: Blind Signal Identification


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