NETWORLD EUROPE

Strategic Research and Innovation Agenda Webinar
12,13th January 2023

RADIO TECHNOLOGY AND SIGNAL PROCESSING

Wen Xu

SRIA 2022 Webinar, Jan. 13, 2023

OVERVIEW ON SRIA 2022

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2. System Services and Their Description
3. System Architecture
4. Network and Service Security
5. Software Technologies for Telecommunications
6. Radio Technology and Signal Processing (Editor: Wen Xu)
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Technical Annex

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1. VISION AND REQUIREMENTS (1)

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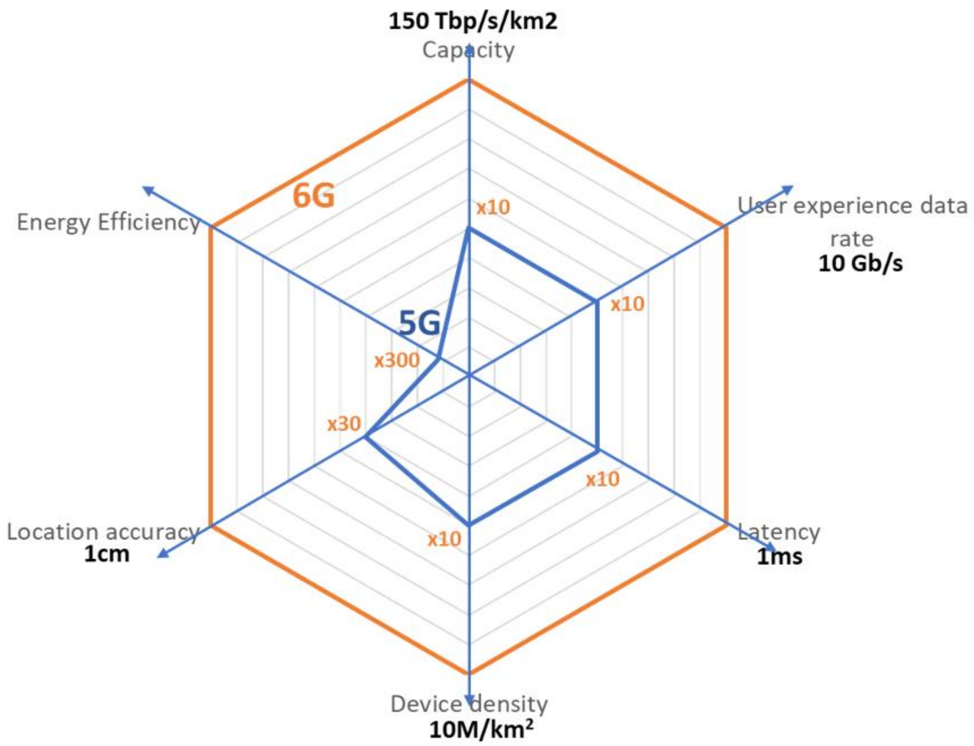
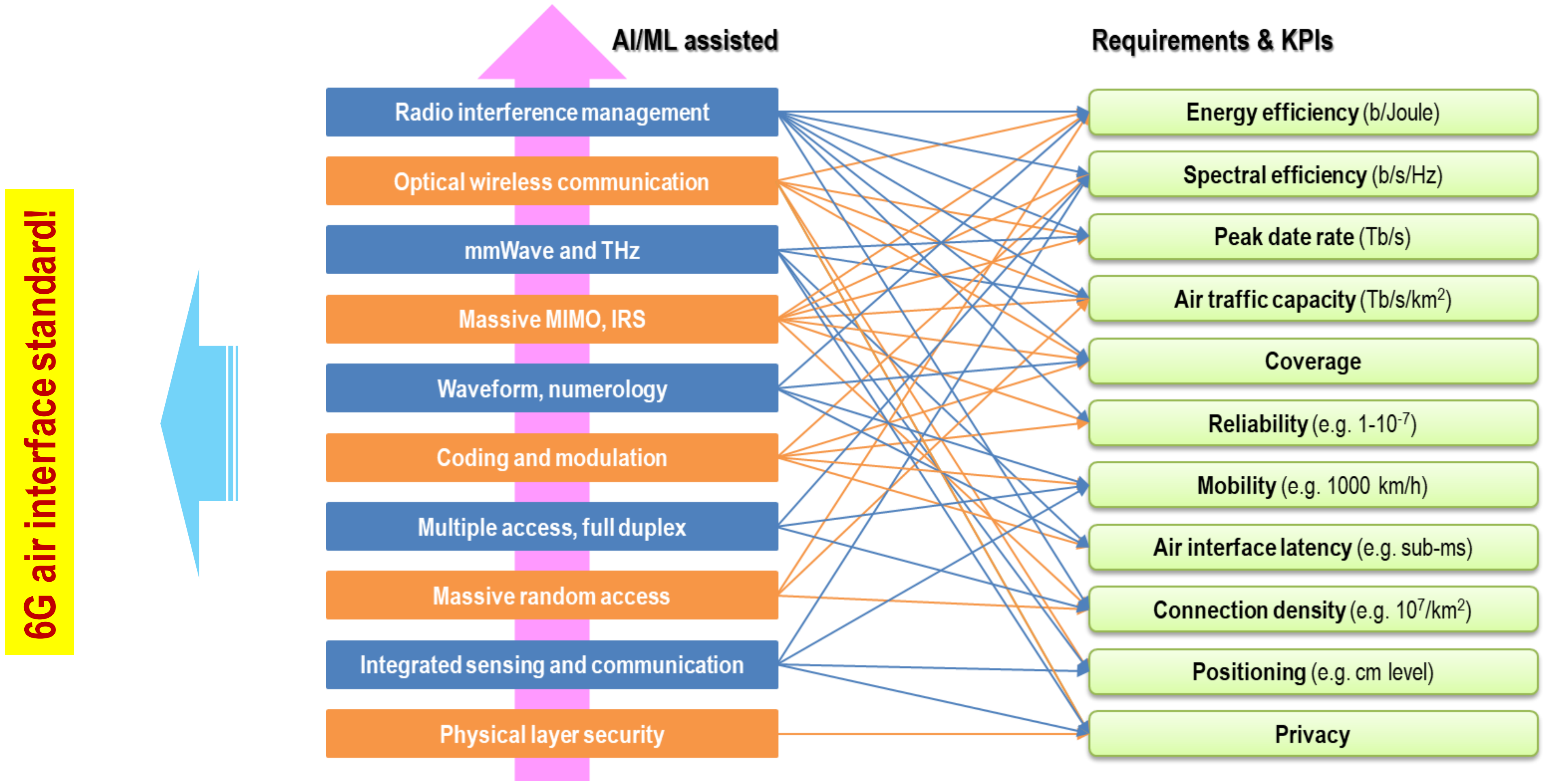
Selected KPIs forecast from 5G to 6G air interface



Target KPI	5G	6G
Bandwidth	<0.5 GHz	10 GHz
Energy efficiency (NW, UE)	Qualitative	>100% gain vs IMT-2020
Experienced spectral efficiency	0.3 b/s/Hz	3 b/s/Hz
Peak data rate	20 Gb/s	1 Tb/s
User data rate	0.1 Gb/s	10 Gb/s
Area traffic capacity	10 Mb/s/m^2	1 Gb/s/m^2
Reliability	URLLC: >1-10^{-5}	>1-10^{-8}
Mobility	<500 Km/h	<1000 Km/h
U-plane latency	URLLC: <1 ms	<0.1 ms
C-plane latency	<20 ms	<2 ms
Connection density	>1 device/m^2	10 device/m^2
Positioning accuracy	<1 m	<1 cm

Source: *5G-IA White Paper* "European vision for the 6G network ecosystem," 2021.

1. VISION AND REQUIREMENTS (2)



Enabling technologies relevant to 6G air interface standard and with main contributions to different 6G KPIs.

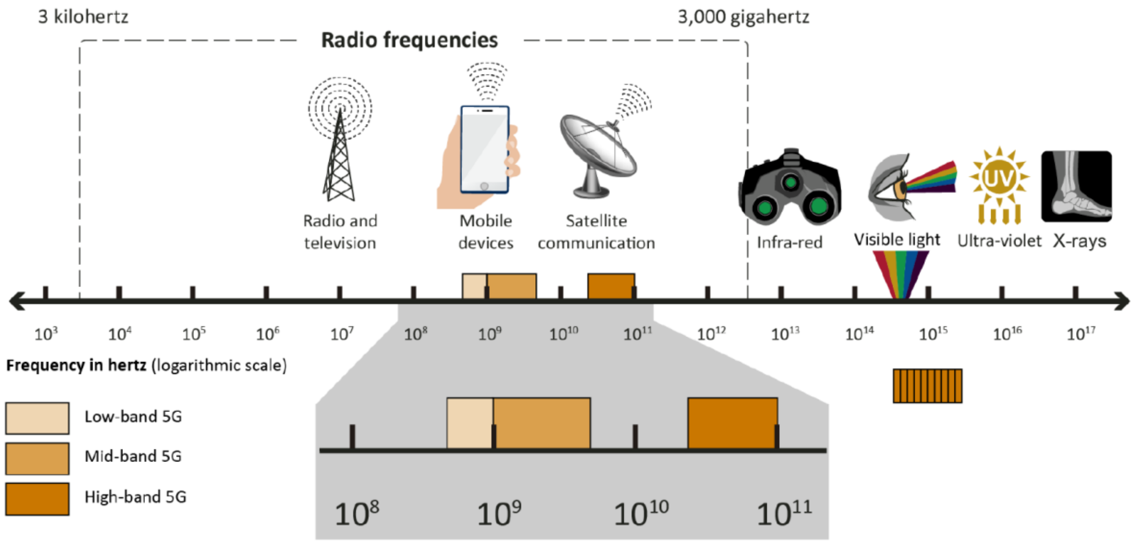
2. RADIO INTERFERENCE MANAGEMENT:
SPECTRUM RE-FARMING AND SHARING

MOTIVATION

- Radio spectrum is a very scarce resource (see Figure below). The lower frequency bands are especially precious and tightly regulated.
- Traditionally, dedicated spectrum allocated to each radio access technology (RAT).
- Spectrum reutilization between RATs (spectrum sharing) offers an efficient utilization of resources and great flexibility, e.g. for load-balancing.

RESEARCH CHALLENGE

- Advanced methods and protocols to efficiently re-utilize the existing spectrum resources, improve spectral efficiency, availability, ...
- Jointly utilize licensed and unlicensed spectra.
- Spectrum usage supported by multi-RAT connectivity, e.g. using cognitive radio based solutions. UE can choose the best RAT depending on link qualities.



Source: "5G wireless: Capabilities and challenges for an evolving network" (*GAO-21-26SP*), Nov. 2020. https://www.gao.gov/assets/gao-21-26sp.pdf.

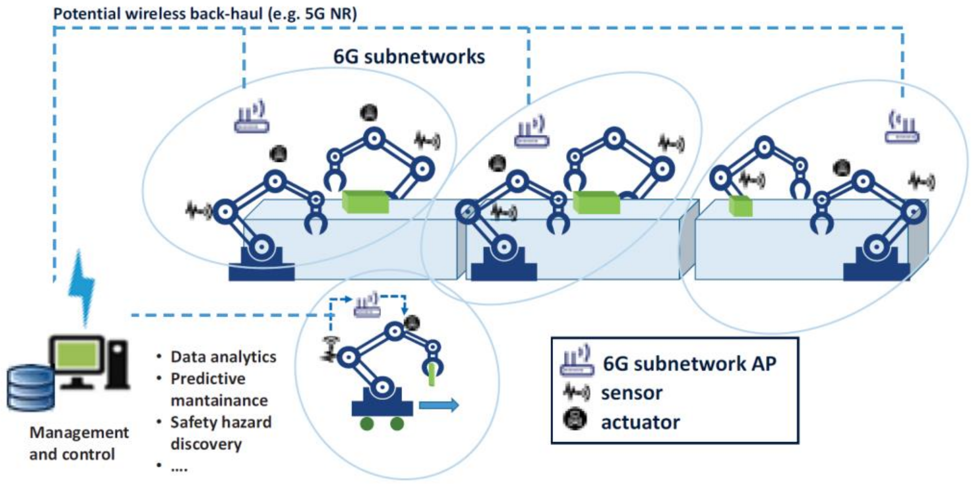
2. RADIO INTERFERENCE MANAGEMENT:
SUBNETWORKS AND COEXISTENCE

MOTIVATION

- Different scenarios may need different (extreme) KPIs, but not necessarily concurrently, e.g. in-robot, in-car, in-body, communications demand sub-ms latency, 1-10^{-7} reliability, whereas holographic communication requires Gbps ~ Tbps throughput.
- Subnetworks are required to deal with different scenarios.
- A subnetwork needs to run autonomously even when the connection to the overlay network is lost (e.g. a car in tunnel).
- Individual subnetworks may be non-mobile or mobile.

RESEARCH CHALLENGE

- From radio perspective, the new radio access node setting up a subnetwork serving local nodes
  - Vertical use cases (e.g. inside a car or robot).
  - Consumer use cases (smart wearables).
  - Very low latency, very high reliability, extreme data rates, reduced energy consumption.



Source: G. Berardinelli et al, "6G subnetworks for life-critical communication," *2nd 6G Wireless Summit (6G SUMMIT)*, 2020.

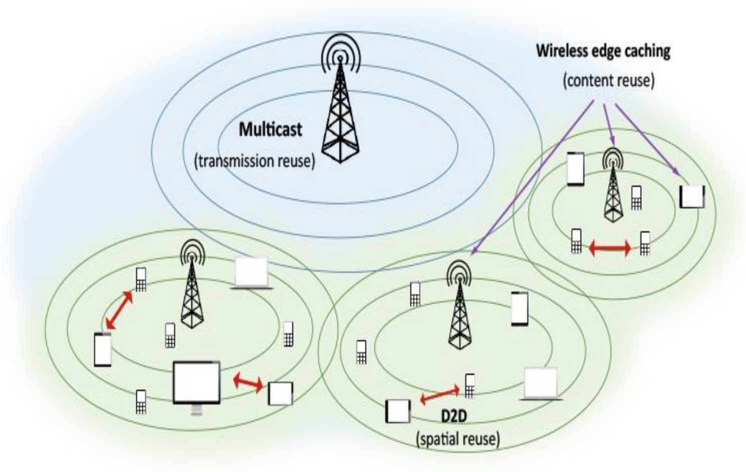
2. RADIO INTERFERENCE MANAGEMENT:
WIRELESS EDGE CACHING

MOTIVATION

- On-demand video streaming and Internet browsing
  - Asynchronous content reuse
  - Highly predictable demand distribution
  - Delay tolerant, variable quality
- Some issues
  - The wireless capacity of macro-cells is not sufficient.
  - Wired backhaul to small cells is weak or expensive.
- Caching can reduce network load and interferences, and consequently increase spectral and energy efficiency (due to efficient reuse of resources), and decrease latency (due to smaller distance between content and user).

RESEARCH CHALLENGE

- Caching is usually implemented in the core network, how to efficiently implement it for wireless?
- Challenges include
  - Coding, e.g., combining edge caching with modern multiuser MIMO physical layer schemes.
  - Protocol architectures, e.g., combining edge caching with schemes for video quality adaptation.
  - Machine learning based content popularity prediction can be used to efficiently update the cached content.



Source: https://wireless.engineering.nyu.edu/cache-aided-wireless-networks/.

3. OPTICAL WIRELESS COMMUNICATION (OWC)

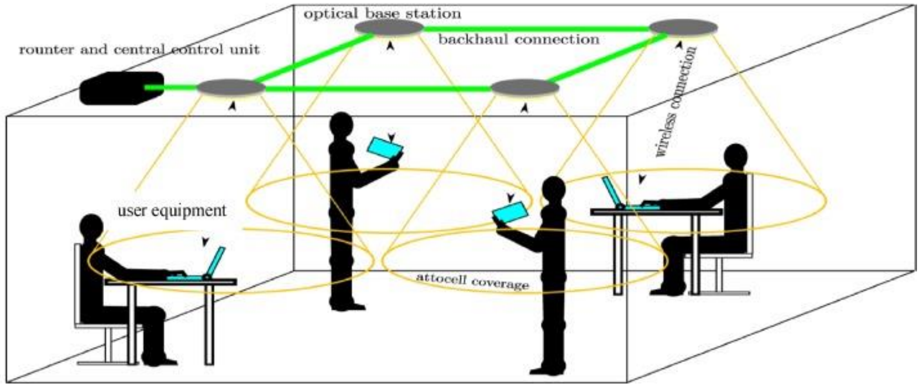
MOTIVATION

- OWC (usually based on intensity modulation and direct detection) consists of infrared and visible light spectrum, which is ~2600 times the size of the entire RF spectrum of 300 GHz.
- It complements RF communications to fulfill the ever-increasing demand in data traffic.
- It can combine illumination and data communication.
- Using ‘solar cell’ can achieve simultaneous energy harvesting and high-speed data communication.
- Off-the-shelf optical devices can be used.
- No need of beamforming to direct beams.
- MIMO structures can be implemented at chip-level, due to extremely small wavelength.
- No multipath fading, as detector sizes >> wavelength.
- There are, e.g., IEEE standards 802.11, 802.15.13, etc.

RESEARCH CHALLENGE

- Advanced transmitter and detector technology including solar cell data detectors acting as simultaneous energy harvesting devices.
- Optimized multiuser access and interference management.
- Better support optical wireless backhaul, e.g. > 2 Tbps throughput.
- Bespoke RIS technology for OWC to support mobility in indoor and outdoor scenarios.
- OWC integration into the 6G system to guarantee a seamless connection.

LiFi Networking



Source: H. Haas, “LiFi is a paradigm-shifting 5G technology,” *Reviews in Physics*, vol. 3, 2018.

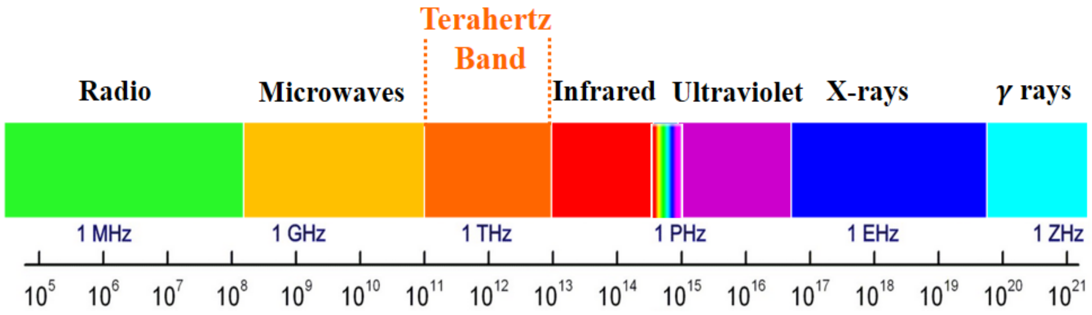
4. MILLIMETER-WAVE AND TERAHERTZ COMMUNICATION

MOTIVATION

- THz means the 0.1–10 THz band, between microwave and infrared bands, where 100–300 GHz are also considered as upper mmWave band.
- < 1 m range possible at ~10 THz carrier.
- > tens m range possible at tens or hundreds GHz.
- While the total consecutive bandwidth of mmWave systems is less than 10 GHz, the one in THz communication is in the order of multiple THz.

RESEARCH CHALLENGE

- New channel models for THz band: spreading loss, molecular absorption loss, scattering loss, etc.
- New experimental platforms and testbeds that can operate at THz frequencies.
- New congestion control at the transport layer to accommodate traffic in the order of Tbps.
- THz transceiver design, incl. high directional antenna systems (e.g., lens arrays and IRSs), new modulation schemes, waveforms, synchronization and channel coding that take into account the THz band characteristics.
- Regulation and standardization of THz bands, …



Source: https://bwn.ece.gatech.edu/projects/teranets/index.html.

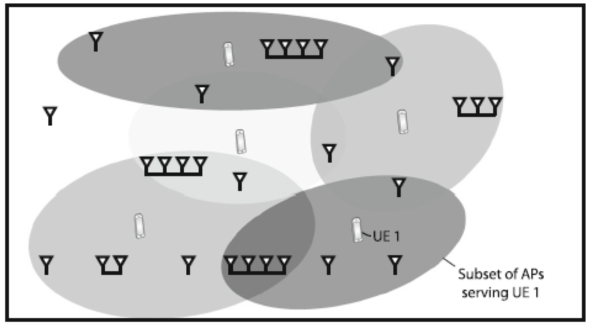
5. MASSIVE MIMO

MOTIVATION

- *Ultra-massive MIMO (um-MIMO):* Antenna arrays in the order of thousands of elements, e.g. to be employed in THz bands. Highly directional antenna elements can achieve very high array/BF gains and combat the very large path loss.
- *Intelligent reflecting surfaces (IRSs):* A new way to improve wireless communications is to change propagation characteristics of wireless channel, e.g. through IRSs or reconfigurable intelligent surfaces (RISs). IRSs can be employed to improve coverage, to increase physical layer security, positioning accuracy and support wireless power transfer.
- *Cell-free massive MIMO (mMIMO):* To achieve almost uniform services across the network, the current network centric architecture needs to be transformed into the cell-free mMIMO.

RESEARCH CHALLENGE

- Construction of graphene-based antenna arrays, considering physical constraints of semiconductor and packaging technologies; implementable digital predistortion for wideband massive arrays.
- Implementation of large IRS arrays, incl. low complexity techniques for signal separation; advanced feeding/control (activation) schemes for IRS antenna elements/panels.
- Cell-free mMIMO technologies, e.g. the relevant initial access, power control, distributed processing considering encoding/decoding, resource allocation, channel modelling, compliance with existing cellular standards, prototype design, etc.
- Real-time estimation and feedback of a large number of channels, … to enable mMIMO operation, etc.



Source: G. Interdonato et al., "Ubiquitous cell-free massive MIMO communications," *EURASIP JWCN*, 2019.

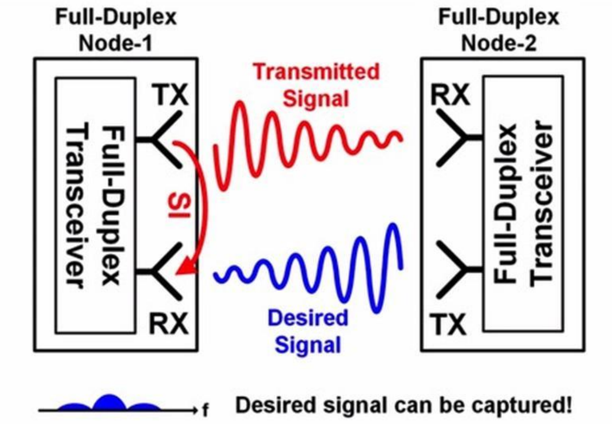
6. WAVEFORM, MULTIPLE ACCESS AND FULL-DUPLEX

MOTIVATION

- CP-OFDM waveform has been adopted in several wireline and wireless standards such as xDSL, Wi-Fi, 4G and 5G. Strict synchronization is required for CP-OFDM to maintain orthogonality.
- Relaxing the orthogonality constraint leads to a more efficient and flexible use of the wireless channel. Non-orthogonal multiple access (NOMA) can result in larger achievable rates and provide means for grant-free access.
- Advanced self-interference cancellation (SIC) techniques are needed to enable full-duplex transceivers.

RESEARCH CHALLENGE

- Optimize and develop advanced waveform, NOMA schemes, etc, for mmWave, THz, OWC and ISAC applications, under the new requirements and KPIs, e.g. Tbps throughput, extreme URLLC, asynchronous mMTC, extremely low power consumption, …
- Enhanced NOMA including code design, resource allocation, and receiver algorithms.
- Develop broadband full-duplex schemes, incl. RF frontends, esp. for MIMO and mMIMO.



Source: https://www.techrepublic.com/article/researchers-accomplish-full-duplex-radio-communications-using-an-ic/.

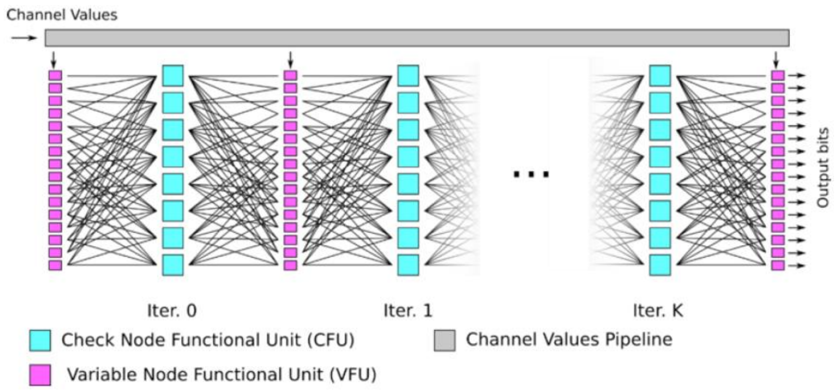
7. CODING AND MODULATION

MOTIVATION

- Channel coding aims to correct transmission errors, and is vital for reliable mobile communications. Modern channel coding schemes such as Turbo, LDPC and Polar codes with excellent performance made their way into 2G, 3G, 4G, 5G and other standards.
- Channel decoder is often considered as the most complex and power-consuming component in the baseband transceiver chain (see Figure below).
- New KPIs like Tbps throughput, extreme URLLC and low-energy consumption pose new requirements on designing coding & modulation schemes.
- Current mobile systems generate uniformly distributed channel input symbols, resulting in a signal shaping loss of up to 1.53 dB for higher order modulations.

RESEARCH CHALLENGE

- Channel codec for 1) extremely high throughput or/and, 2) extremely high reliability or/and, 3) extremely low latency or/and, 4) extremely low power consumption, e.g. to support the ultra-high data rate ranging from 100–1000 Gbps, reliability of $1\text{-}10^{-7}$, etc.
- Design extreme low-power consumption coding and modulation schemes, esp. for extreme mMTC.
- Develop advanced coded modulation schemes which remove signal shaping loss and close the gap between Shannon limit and practical implementations.



Example LDPC decoder architecture

Source: https://epic-h2020.eu/downloads/Epic_Poster_MWC2020_LDPC_169.pdf, 2020.

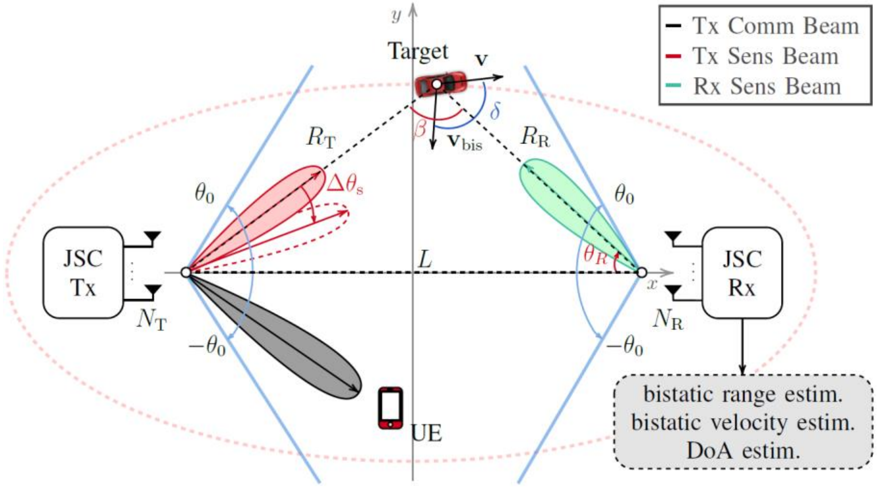
8. INTEGRATED SENSING AND COMMUNICATION

MOTIVATION

- Accurate positioning has been identified as a key enabler for many applications, e.g. autonomous driving for connected cars, local collaboration of unmanned aerial vehicles, etc.
- For smart factory, V2X vulnerable road user discovery, etc, a cm-level positioning accuracy may be required.
- Cooperation can greatly improve positioning accuracy. Future wireless systems will have higher bandwidth, more antennas, densed network and D2D links, which may enable a radio positioning with cm-level accuracy.
- Radar can sense the environment and hence increase communication efficiency (sensing aided communication).
- Similarly, communication links can be used to improve sensing capability (communication aided sensing).
- With integrated sensing and communication (ISAC), improved spectral/energy efficiency and reduced latency will become possible.

RESEARCH CHALLENGE

- Distributed and cooperative sensing.
- Sensing aided communication.
- Communication aided sensing.
- Design of integrated waveform flexible for joint (mono- and multi-static) sensing and communication (JSC); optimal resource allocation/trade-off for JSC.
- Multi-band sensing technology, e.g. for THz, mmWave, … bands.

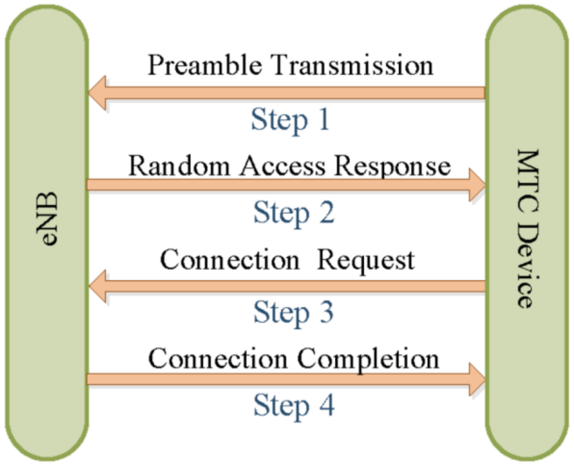


Source: L. Pucci et al, "Performance analysis of a bistatic joint sensing and communication system," *IEEE ICC Workshops*, pp. 73-78, 2022.

9. MASSIVE RANDOM ACCESS

MOTIVATION

- The future vision of IoT envisages a very large number of connected devices, generating and transmitting very sporadic data (mMTC).
- How to coordinate such a network without spending the whole network resource and node energy in protocol overhead?



RESEARCH CHALLENGE

- Code design and NOMA: Design new random access codes for which the superposition of a large number of distinct codewords can be uniquely decoded; advanced receivers to resolve packet collisions for contention-based access.
- Synchronization, channel estimation, and beamforming for random access.
- User activity detection: Algorithms to determine the set of active users based on group testing or compressed sensing; joint activity and data detection, etc.
- Low complexity/energy protocols, low-cost devices.
- Massive number of devices with low overhead, and potentially with energy and latency constraints.

Source: Y. Kishiyama et al, "Standardization status towards the introduction of 5G in 2020," *NTT Technical Review*, vol. 15, 2017.

10. MACHINE LEARNING EMPOWERED PHYSICAL LAYER

MOTIVATION

- Machine learning (ML) has shown the potential to redefine the classical approach in communication system design to achieve global optimization or performance improvement.
- 6G will be a large-scale and self-organized system that integrates terrestrial and non-terrestrial networks to provide seamless wireless connectivity everywhere.
- ML can potentially improve the physical layer design and performances, e.g. for adoption of new frequency bands (THz), introduction of new network elements (like IRSs), beamforming in um-MIMO, non-identified interference sources, etc.
  - Specific ML algorithm applied to optimize individual physical layer components, e.g. channel estimation, selection of modulation and coding scheme (MCS), etc.
  - ML approach used for E2E communication system deign and optimization.

RESEARCH CHALLENGE

- ML can be employed to enable, e.g.,
  - *Overall physical layer* where the entire Tx-Rx chain can be considered as an E2E auto-encoder;
  - *Channel learning* which leads to more accurately predicted time, frequency and spatial properties of the channel, and to overhead reduction;
  - *Radio interface design* where ML can assist the design of channel coding and decoding, modulation schemes beyond QAM, and new (e.g. fully pilotless) signal waveforms;
  - *Multi-antenna systems* where ML can optimize MIMO precoders, esp. in case of a large number of antenna elements, imperfect RF, and hardware impairments;
  - *In-radio network AI computing* where ML can improve the efficiency or reliability of the computing tasks.
  - ML can be used to enhance the *physical layer security* by exploiting spectral and signal analysis to detect radio attacks, etc.
  - Research is needed on *hardware architectures and solutions*, e.g. for implementing real-time physical layer ML algorithms.

CONCLUSION

- **Future 6G wireless networks need to address challenging use cases/KPIs, e.g.**
  - ✓ Tbps throughput
  - ✓ sub-ms latency
  - ✓ Gbps availability
  - ✓ Extreme reliability (e.g. with packet error rate < 10^{-8})
  - ✓ Extreme energy efficiency
  - ✓ cm-level radio positioning accuracy
  - ✓ etc

- **NetWorld Europe identified the research areas to be addressed in Radio Technology and Signal Processing, also aided by AI/ML, for potential 6G use cases/KPIs, incl.**
  1. Spectrum reutilization, interference management, subnetworks and wireless edge caching
  2. Optical wireless communication, esp. VLC
  3. Millimeter-wave and terahertz communication, incl. new materials (graphene)
  4. Massive and ultra-massive MIMO, including IRSs, cell-free massive MIMO, etc
  5. Improved waveform, non-orthogonal multiple access and full-duplex
  6. Enhanced coding and modulation
  7. Integrated sensing and communication
  8. Random access for massive connections
  9. Machine learning empowered physical layer

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THANK YOU FOR YOUR ATTENTION

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