From NR to 6G in Unlicensed Spectrum: the RAT for Wireless Private Networks in Industry 4.0

Sandra Lagén and Lorenza Giupponi

Centre Tecnològic de Telecomunicacions de Catalunya
(CTTC/CERCA), Barcelona, Spain

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Motivation

- **Industry 4.0**: integrate IoT and cyber-physical systems to the connected industries and automation domain...
  - Stringent requirements: availability, reliability, latency, security, integrity, maintainability, and, in some cases, accuracy positioning
  - Flexibility: mobile robots, automated guided vehicles, and head mounted displays with advanced mobile applications for workers (e.g., XR devices)
  - Opportunity for the cellular industry to conform a privately-owned and wirelessly-connected network (WPN) for the future smart factories
- **Unlicensed spectrum**:
  - Cellular expansion: beyond the usual licensed paradigm (recent trend through LTE-LAA, MulteFire, NR-U)
  - Interest for industrial WPNs: due to its relatively ease of access, large global availability, and non-dependency on public networks

Analyze the applicability of NR and 6G-based access to unlicensed spectrum (NR-U and 6G-U) as the RAT for Industry 4.0 scenarios

Outline

- Industry 4.0 requirements
- Challenges for future cellular networks
- NR-U
- Evolution towards beyond NR-U and 6G-U
  - frequency bands
  - operational modes
  - regulatory requirements
- NR-U and 6G-U applicability to future smart factories
  - pillars
  - integration

Industry 4.0 Requirements

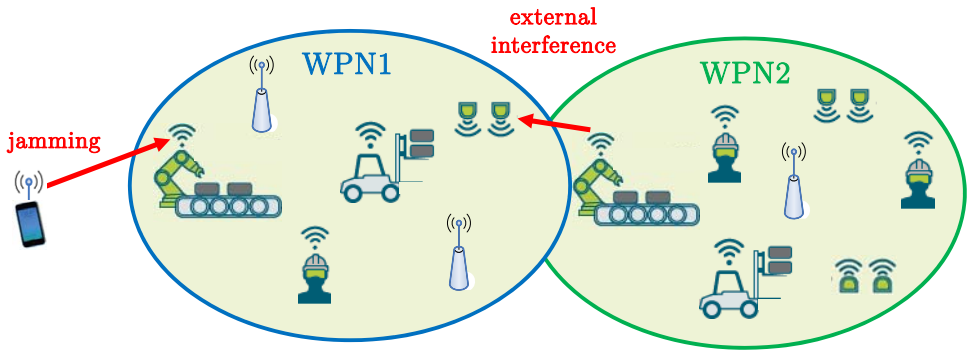
- Requirements of selected Industry 4.0 devices:

Industrial devices	latency	availability	throughput	number
Industrial robot (control)	<1 ms	>99.9999%	kbps	>100
Mobile robot (control, XR)	<1 ms	>99.9999%	Mbps	>100
Sensor (monitoring)	∼100 ms	>99.99%	kbps	>200
Head mounted display (XR)	<10 ms	>99.9999%	G-Mbps	>50
Handheld terminal (safety)	<10 ms	>99.9999%	M-kbps	>50
Automated guided vehicle	<10 ms	>99.9999%	Mbps	>10
Security camera	∼100 ms	>99.99%	G-Mbps	>10

  - Industry 4.0 devices can be classified as combinations of: latency-critical, availability-critical, throughput-critical, and massive-critical
  - 5G promises to fulfill some of the requirements, such as high reliability and low latency, as well as to support mobility for robotics and machines
    - URLLC, eMBB, mMTC → separate URC and LLC, more slice categories
    - latency-guarantee: TSN
    - WPN: Ethernet replacement, standalone operation in unlicensed

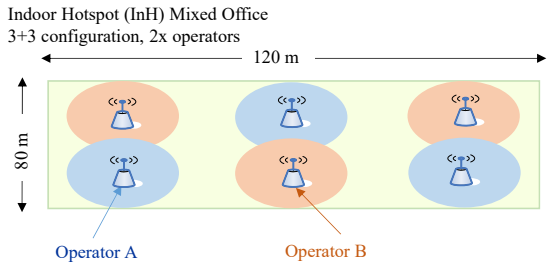
Challenges for Future Cellular Networks

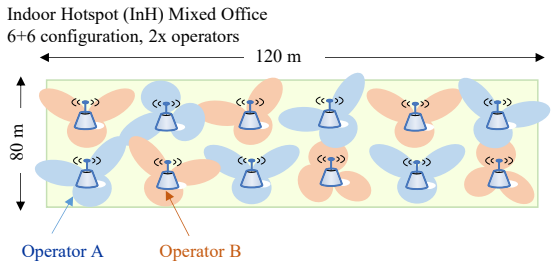
- Key challenge for future smart factories:
  - provide connectivity for industrial control and automation systems by addressing simultaneously the variety of devices with diverse requirements
- Some critical aspects of industrial WPNs are not addressed in 5G yet, and will need to be revisited in 6G...
  - security and privacy
  - latency below 1 ms
  - resilience for massive deployments
    - deployment and management of multiple spatially-collocated WPNs,
    - resilience against external unintentional interference,
    - resilience against external intentional jamming

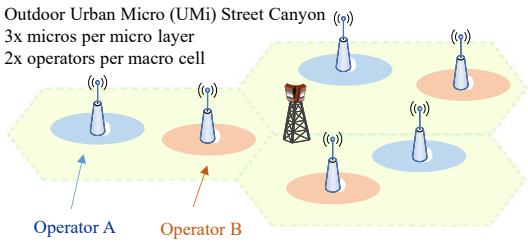


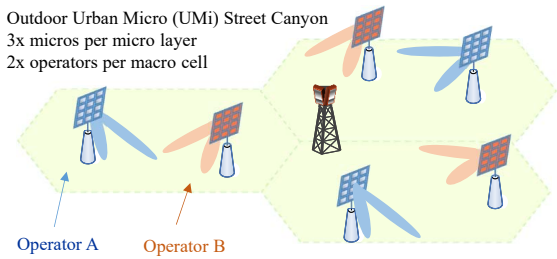
NR-U

- NR-U has been investigated in a 3GPP Rel-16 SI, and a recently approved 3GPP Rel-16 WI will enable its inclusion in future NR specifications...
  - **objective**: extend the applicability of NR to unlicensed spectrum bands as a general purpose technology through a design that allows fair coexistence across different RATs
  - **target**: sub 7 GHz bands (2.4, 3.5, 5, and 6 GHz bands)
  - **layout scenarios**: indoor sub 7 GHz, outdoor sub 7 GHz



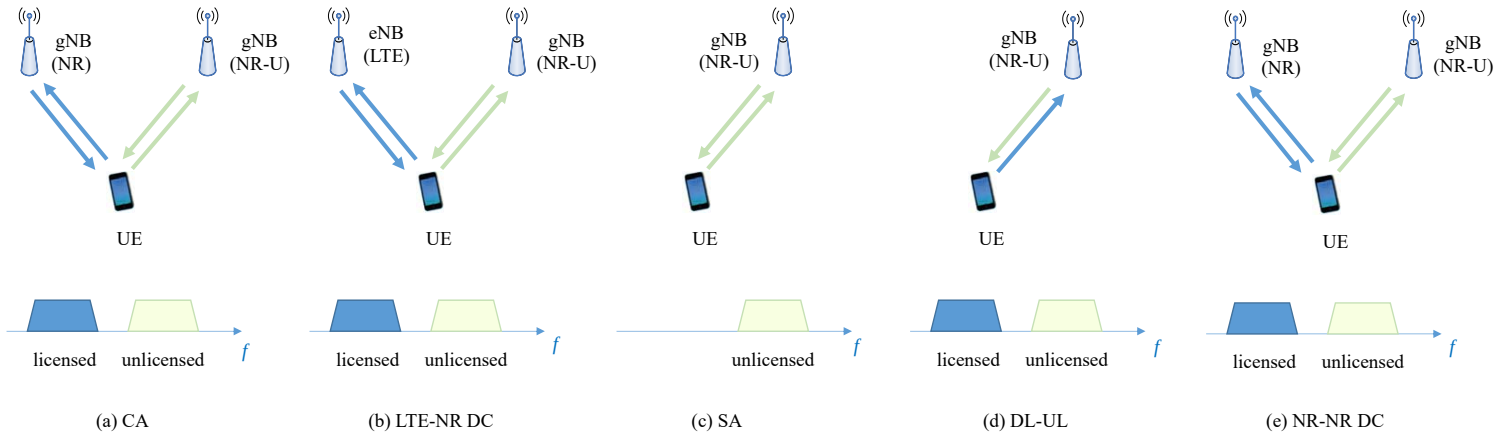






NR-U

- **deployment scenarios**: carrier aggregation, dual connectivity, standalone



- **coexistence requirement**: NR-U devices should not impact deployed Wi-Fi services (data, video, and voice services) more than an additional Wi-Fi network would do on the same carrier
- **regulatory requirements**: channel access (LBT, MCOT), power limits (EIRP and PSD), bandwidth constraints (OCB), functionalities (DFS, FR)

Evolution towards beyond NR-U and 6G-U

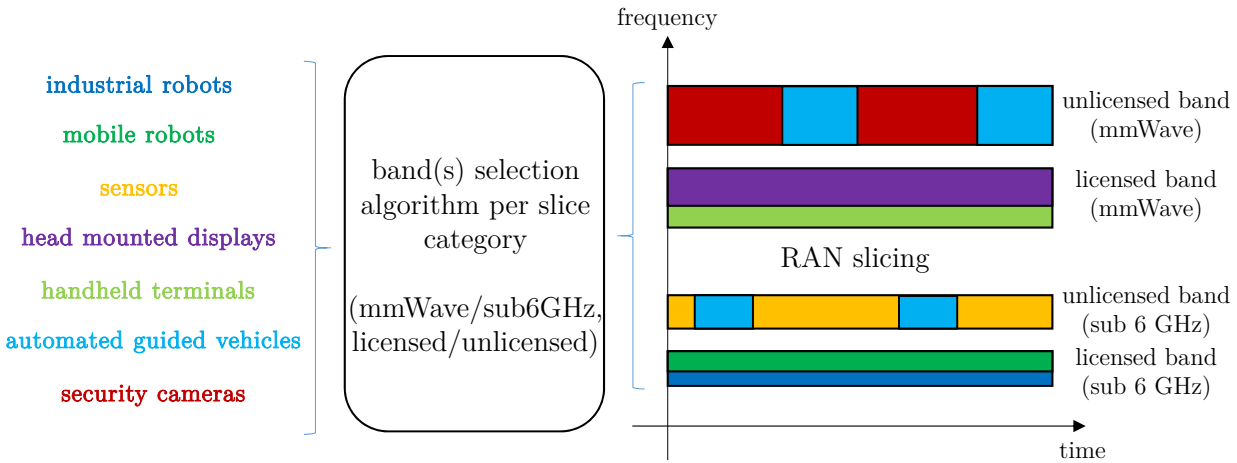
- **Frequency bands**:
  - LAA and MulteFire: 5 GHz band
  - NR-U: sub 7 GHz bands
  - Beyond NR-U and 6G-U:
    - consider multiple bands, including recently opened spectrum for unlicensed operations (6 GHz), mmWave bands (37 GHz, 60 GHz), even higher bandwidth (90-100 GHz bands) and the THz level
- **Operational modes**:
  - LAA: carrier aggregation, MulteFire: standalone mode
  - NR-U: carrier aggregation, dual connectivity, and standalone modes
  - Beyond NR-U and 6G-U:
    - expand deployment scenarios by considering >2 bands for CA and DC
    - aggregation/connectivity with multiple unlicensed bands (sub 6 GHz, mmWave, and THz) to enable a new multi-band standalone mode uniquely in unlicensed
- **Regulatory requirements**:
  - LBT usage partially covers the challenges of WPNs. As a downside, it may increase the access delay, and so the total latency...
  - Critical: analyze the impact of LBT on the E2E latency, to enable NR-U and beyond to be used in industrial WPNs

NR-U and 6G-U Applicability to Future Smart Factories

- **Pillars**:
  - multi-band operation and multi-spectrum sharing paradigms through the integration of sub 6 GHz, mmWave, and THz bands, licensed and unlicensed, at the RAN to improve reliability, availability, and resilience
  - network slicing to meet simultaneously the requirements of latency-critical, availability-critical, throughput-critical, and massive-critical devices
  - distributed computing and network control to increase the quality, accuracy and precision of industrial processes
  - enhanced URLLC to address low-latency, high-secure and high-reliable communications, including TSN, packet duplication, and multi-connectivity
- All these pillars require the support for a **ML-assisted network control** in charge of managing, through software-based platforms, the complexity of the network in an autonomous manner...
  - data-centric approach: information collection through sensors, distributed actuators to execute actions, taken by controllers

NR-U and 6G-U Applicability to Future Smart Factories

- ML-assisted network control to **integrate** RAN slicing, multi-band operation, and multi-spectrum sharing paradigms in Industry 4.0.:



- Challenges:
  - automatic selection of the most appropriate band and/or technology
  - stability of multiple distributed learning controllers making decisions
  - timeliness of the autonomous decisions and learning processes

Refs

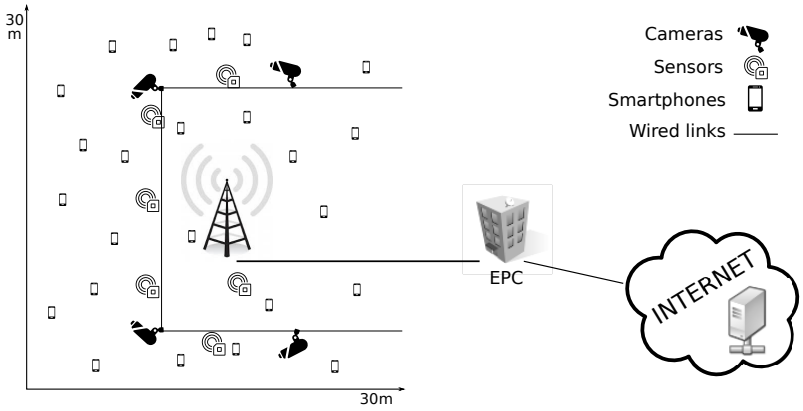
- **NR-U for mmWave bands:**
  - investigate how the coexistence framework in the unlicensed context changes under directional transmissions/receptions
    - S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojovic, A. Demir, M. Beluri, "5G NR in Unlicensed Spectrum: Design Challenges and Solutions", under review, available at: https://arxiv.org/abs/1809.10443
    - S. Lagen, L. Giupponi, N. Patriciello, "LBT Switching Procedures for New Radio-based Access to Unlicensed Spectrum", IEEE GLOBECOM, Dec. 2018.
    - S. Lagen, L. Giupponi, B. Bojovic, A. Demir, M. Beluri, "Paired Listen Before Talk for multi-RAT Coexistence in Unlicensed mmWave Bands", IEEE ICC - WS, May 2018.
    - S. Lagen, L. Giupponi, "Listen Before Receive for Coexistence in Unlicensed mmWave Bands", IEEE WCNC, Apr. 2018.

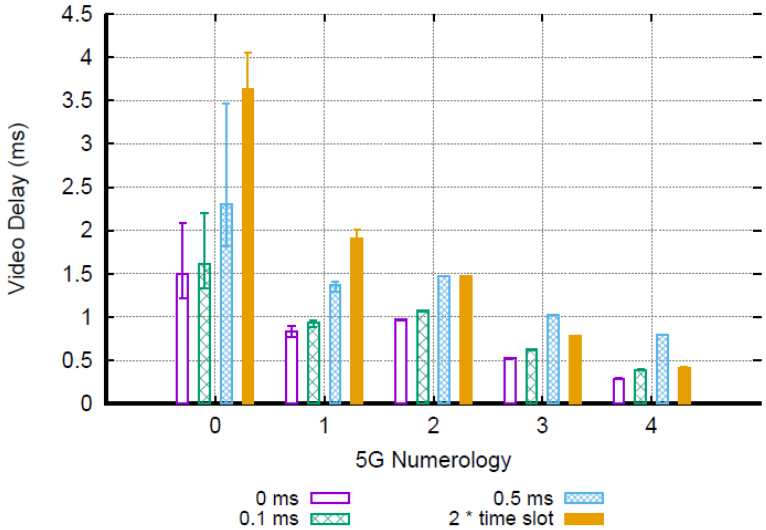
Refs

- **5G-LENA https://5g-lena.cttc.es/**
  - end-to-end, standard-compliant, full-stack NR network simulator
  - open source, designed as a pluggable module to ns-3, emulation capabilities
  - NR Rel-15 features (numerologies, BWPs, dynamic TDD, beamforming, 3GPP MIMO channel model, OFDMA/TDMA), calibrated
    - N. Patriciello, S. Lagen, L. Giupponi, B. Bojovic, "An Improved MAC Layer for the 5G NR ns-3 module", Workshop on ns-3, June 2019.
    - N. Patriciello, S. Lagen, L. Giupponi, B. Bojovic, "5G New Radio Numerologies and their Impact on the End-To-End Latency", IEEE CAMAD, Sep. 2018.
    - B. Bojovic, S. Lagen, L. Giupponi, "Implementation and Evaluation of Frequency Division Multiplexing of Numerologies for 5G New Radio in ns-3", Workshop on ns-3, June 2018.
  - next release by Sept. 2019:
    - beyond 5G extensions to the NR module for its use in unlicensed spectrum (NR-U), and coexistence studies with WiGig
    - NR-compliant PHY abstraction including LDPC and 256-QAM

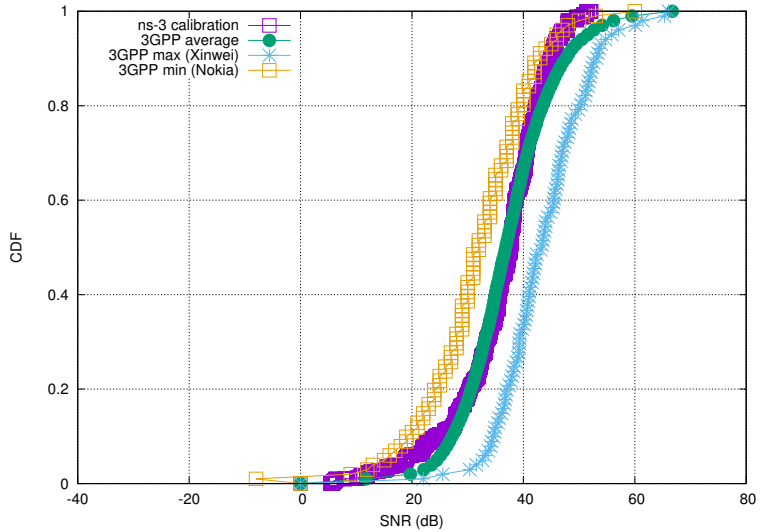
Refs

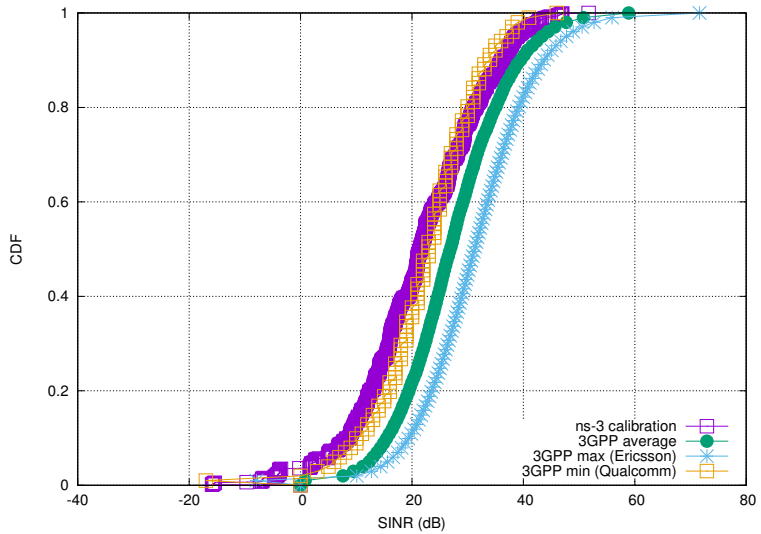
NR end-to-end delay analysis





calibration in mmWave InH





Thank you for your attention!
Questions?

sandra.lagen@cttc.es