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:

<table>
<thead>
<tr>
<th>Industrial devices</th>
<th>latency</th>
<th>availability</th>
<th>throughput</th>
<th>number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial robot (control)</td>
<td>&lt;1 ms</td>
<td>&gt;99.9999%</td>
<td>kbps</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Mobile robot (control, XR)</td>
<td>&lt;1 ms</td>
<td>&gt;99.9999%</td>
<td>Mbps</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Sensor (monitoring)</td>
<td>~100 ms</td>
<td>&gt;99.99%</td>
<td>kbps</td>
<td>&gt;200</td>
</tr>
<tr>
<td>Head mounted display (XR)</td>
<td>&lt;10 ms</td>
<td>&gt;99.9999%</td>
<td>G-Mbps</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Handheld terminal (safety)</td>
<td>&lt;10 ms</td>
<td>&gt;99.9999%</td>
<td>M-kbps</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Automated guided vehicle</td>
<td>&lt;10 ms</td>
<td>&gt;99.9999%</td>
<td>Mbps</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Security camera</td>
<td>~100 ms</td>
<td>&gt;99.99%</td>
<td>G-Mbps</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

- 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 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

![Diagram showing deployment scenarios](image)

- **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
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:

  - **Industrial robots**
  - **Mobile robots**
  - **Sensors**
  - **Head mounted displays**
  - **Handheld terminals**
  - **Automated guided vehicles**
  - **Security cameras**

**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
NR-U for mmWave bands:

- investigate how the coexistence framework in the unlicensed context changes under directional transmissions/receptions


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
  - 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
NR end-to-end delay analysis

Calibration in mmWave InH

CDF
SNR (dB)
nS-3 calibration
3GPP average
3GPP max (Xinwei)
3GPP min (Nokia)

CDF
SINR (dB)
nS-3 calibration
3GPP average
3GPP max (Ericsson)
3GPP min (Qualcomm)
Thank you for your attention! Questions?

sandra.lagen@cttc.es