Can 5G NR-Light Operate at Millimeter Waves? Design Guidelines for Mid-Market IoT Use Cases

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Abstract—5th generation (5G) systems have been designed with three main objectives in mind: increasing throughput, reducing latency, and enabling reliable communications. To meet these (often conflicting) constraints, in 2019 the 3GPP released a set of specifications for 5G NR, one of the main innovations being the support for communications in the millimeter wave (mmWave) bands. However, how to implement lower complexity, energy efficient, mid-market Internet of Things (IoT) applications is still an ongoing investigation, currently led by the 3GPP which is extending the NR standard with NR-Light specifications to support devices with reduced capabilities (REDCAP). In this paper we investigate the feasibility of operating such devices at mmWaves, in view of the requirements and expectations for NR-Light applications in terms of cost and complexity, throughput, and latency. Contributions of this paper are threefold. First, we illustrate the potential of mmWave communication for mid-market IoT use cases. Then, we highlight and motivate the design of an NR-Light candidate interface derived from NR by a selection of features. Finally, we demonstrate the technical soundness of this interface in an industrial IoT setup via simulations.

Index Terms—NR-Light, REDCAP, Internet of Things (IoT), 3GPP, performance evaluation, use cases, technological enablers.

I. INTRODUCTION

The grand objective of 5th generation (5G) systems is to support three generic services with vastly heterogeneous requirements: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (URLLC). 5G guarantees very high data rates (up to 20 Gbps in ideal conditions), ultra-low latency (around 1 ms), and a 10× increase in energy efficiency with respect to previous wireless generations. To meet those requirements, the 3rd Generation Partnership Project (3GPP) has released a set of specifications for NR [1] which include, besides an updated/flexible radio access and core network design, the support for communications in the millimeter wave (mmWave) range up to 52.6 GHz for Release 15. On one hand, the vast amount of available spectrum at mmWaves makes it possible to achieve multi-Gbps transmission speeds, while also improving security and privacy thanks to directional transmissions [2]. On the other hand, exploiting mmWaves is challenging for mid-market Internet of Things (IoT) devices, such as wearables or industrial sensors, which are subject to cost, complexity, and battery lifetime constraints.

To address the above market use cases, NR specifications need to be extended to support a simpler and lighter version of NR, which is usually referred to as NR-Light (or “reduced-capability” REDCAP) NR devices” in 3GPP parlance). NR-Light needs to satisfy higher data rate, improved reliability, and lower latency than current LTE-based LTE-MTC and Narrowband-IoT (NB-IoT) technologies for IoT services, while guaranteeing lower cost/complexity, longer battery life, and wider coverage than Release 15 NR solutions. This new 5G air interface is the subject of a new Work Item in 3GPP Release 17 [3] that, among other features, considers the possibility for NR-Light users to operate at mmWaves to improve the network performance. However, while being attractive for private networks, e.g., to support high-end applications of low-cost devices in the industrial domain, the direct applicability of the mmWave technology to IoT-like use cases raises many challenges, including how to meet the low-cost/low-energy requirements of NR-Light devices while providing sufficient performance levels. Moreover, adequate discussion on whether and how standardization proposals will be able to overcome such limitations is still missing.

In this paper, we introduce the 3GPP vision on NR-Light, and review the current standardization status. Compared to prior work [4], we focus for the first time on those IoT use cases that will benefit the most from NR-Light at mmWaves, and characterize their Key Performance Indicators (KPIs). Also, we identify possible hardware/software simplifications in mmWave bands to fulfill NR-Light requirements while reducing energy consumption and costs compared to a baseline NR architecture. These include (i) narrower bandwidth for devices, (ii) simplified air interface procedures, protocol stack, and antenna configuration, and (iii) enhanced device power saving features, as summarized in Fig. 1. Finally, we provide guidelines, based on numerical simulations, towards an efficient set of simplifications for NR-Light devices, referred to as “NR-L-Mid,” in an indoor factory scenario (although we do not preclude other simplifications to be adopted too). Our simulations reveal that demanding Industrial IoT applications involving video streaming and periodic reporting of sensor readings can be advantageously supported by NR-L-Mid.

II. 3GPP NR-LIGHT IN MMWAVE BANDS

NR-Light is expected to support network operation in both FR1 (between 410 MHz and 7125 MHz) and FR2 (between 24.25 and 52.6 GHz, i.e., the lower part of the mmWave spectrum) [3]. In Sec. II-A we review the propagation char-
characteristics of mmWaves, while in Sec. II-B we discuss the potential of this technology for NR-Light systems.

A. Millimeter waves communication

Despite the undeniable potential, communication at mmWaves introduces new challenges for the whole protocol stack [2]. First, as described by Friis equation, the power loss of a signal in free space is proportional to the square of the frequency and of the distance between the transmitter and the receiver. As such, the severe attenuation experienced at mmWaves typically prevents devices from communicating at large distance. Certain mmWave bands, such as those around 22 and 60 GHz, are subject to even stronger attenuation due to water vapor and oxygen molecules in the air. Moreover, mmWave signals are sensitive to rain.

Second, mmWave links do not propagate well through most obstacles, including walls and windows. As a consequence, ensuring uniform coverage is challenging, and achieving seamless connectivity in indoor environments through outdoor base stations is generally not possible. Humans can also be a source of attenuation: this effect mainly depends on the “shape” of the occluding body and the antenna configuration, with just a weak dependence on the number of people in the environment. For moving terminals, the Doppler effect can lead to a dispersion of the signal in the frequency domain too: the spread experienced at mmWaves is 10 to 20 times higher than at 3 GHz.

Third, the vast amount of spectrum in the mmWave bands makes it possible to achieve multi-Gbps transmission speeds which, for mid-market devices generating asynchronous traffic bursts, may not be needed, and could actually degrade the network performance.

Finally, mmWave components, such as amplifiers, mixers and phase shifters, must support high-bandwidth operations and are very expensive. As such, a fully-operational mmWave module does not seem compatible with the cost objective of low-power NR-Light nodes. Large-scale antenna arrays, desirable at mmWaves, also consist of amplifiers and shifters, and further increase the power consumption of mmWave radios.

B. Millimeter waves for IoT Use Cases

Originally, many IoT use cases were characterized by three fundamental prerequisites, namely the support for (i) long-range links (in the orders of kilometers), (ii) bursty traffic with loose performance requirements, and (iii) low-energy-consuming low-complexity architectures and network functionalities. Given the limitations discussed in Sec. II-A, mmWave systems look incompatible with these prerequisites.

In light of this, we pose the following question: why are the standardization and industrial communities investigating NR-Light architectures operating at mmWaves? On one hand, future IoT use cases for NR-Light, as will be discussed in Sec. III, expose bolder requirements than in current IoT services in terms of data rate, reliability, and latency, for which the large bandwidth available at mmWave is an attractive option. At the same time, mmWave bands are cheaper with respect to more common sub-6 GHz bands (FR1), allowing operators to buy large chunks of continuous spectrum with limited investments. Also, the foreseen directionality of mmWave communications can provide limited interference and enable higher spectral efficiency through spatial diversity. Additionally, the limited propagation range and the inability to penetrate through walls make mmWaves suitable for the realization of private networks, such as in factories, where private cells can be placed in different areas without interfering with other stations and without propagating outside buildings. While current mmWave solutions for NR might have to be redesigned/simplified to promote energy efficiency, as illustrated in Sec. III, in Sec. V we will show that mmWave systems can effectively support NR-Light specifications.
TABLE I: Communication requirements for NR-Light use cases (“factory of the future” and “smart agriculture” in light and dark grey, respectively) [5].

| Use case                      | KPI       | Traffic flow | Data rate                  | Latency [ms] | Reliability [%] |
|------------------------------|-----------|--------------|-----------------------------|--------------|-----------------|
| **Industrial WSN**           |           | UL           | Depends on the sensors:     | 50–1000      | 99.9            |
| Sensors to monitor the behavior of an industrial process for safety purposes. The captured data are uploaded to a private cloud where a monitoring application is running. |           |              | • Environmental: 6 kbps    | 5–10         | 99.999999       |
|                              |           |              | • Acceleration: 192–384 kbps|              | Safety          |
|                              |           |              | • Audio (wav): 2.4–4.6 Mbps  |              | Non-safety      |
|                              |           |              | • Audio (MP3): 8–320 kbps   |              | Safety          |
|                              |           |              | • Vibration: 48–480 kbps    |              | Non-safety      |
|                              |           |              | • Video (1080p): 5–8 Mbps   |              | Safety          |
| **AGVs/MRs for factory logistics** | UL, DL   | Video stream | Commands                  | 10–100       | > 99.9999       |
| Mobile robots (assisted by a remote operator) move products in production sub-chains. | Video stream | Control commands | 5–10 Mbps | N/A (Estimate: 10–100 Mbps) | N/A (Not critical) |
|                              |           |              | 5–100 kbps                  |              | N/A (Estimate: High) |
| **Crop data collection**     |           | UL           | N/A (Estimate: 10–100 Mbps) | N/A          | N/A (Estimate: High) |
| Sensors on the field to monitor soil and crop parameters. Data is used to optimize/assist farmers’ decisions. Communication can be assisted by base stations mounted on a tractor. | UL        |              |               |               |                 |
| **UAVs for livestock monitoring** | UL, DL   | Video stream | Commands                  | 10–100       | > 99.9999       |
| Teleoperated UAVs are used to keep track of the health status of the livestock, for counting purposes or to prevent poaching. | Video stream | Control commands | 5–10 Mbps | N/A (Low to medium) | N/A (Estimate: 10-50) |
| **High-precision agriculture** |           | Sidelink among robots | N/A (Low to medium) | N/A          | > 99.9999       |

III. IOT USE CASES FOR NR-LIGHT AT MM WAVES

NR-Light at mmWaves targets vertical domains with an ongoing digitalization evolution which, in most cases, involves more powerful devices than in traditional IoT but, at the same time, cheaper and less power hungry than high-end NR terminals. Two examples of such domains are (i) the factory of the future (Sec. III-A), and (ii) smart agriculture (Sec. III-B). In Table I we collected the KPIs (based on 3GPP specifications in [5]) for a selection of use cases belonging to the above vertical domains.

A. Factory of the Future

Increasingly volatile/globalized markets are opening the way towards Industrial Internet of Things (IIoT) to support ubiquitous connectivity and powerful computing infrastructures in the industrial sector. Among the many use cases in this ecosystem we can identify some common characteristics [6]. For example, the signal propagation in factories may be very different from a typical cellular deployment, because these scenarios feature a much richer scattering environment and the presence of many blockers. Also, networks may be private and built to cover a limited area. Some critical use cases may have stringent requirements in terms of reliability and privacy. Finally, a longer lifetime of the communication infrastructure may be required compared to other wireless systems.

The role of NR-Light. NR-Light at mmWaves can play a key role to support the digitalization process of future factories. For example, non-time-critical Autonomous Ground Vehicles (AGVs) and Mobile Robots (MRs) are expected to improve the efficiency of logistics and warehousing, and to automate industrial operations. The traffic flow consists of video feeds from various sensors, either periodic (e.g., in case of teleoperated remote control) or aperiodic (e.g., in case of fully-automated robots). In both cases, the latency requirements go from 10 to 100 ms, and the packet error rate should be below 10^{-5} [6]. Therefore, the vast bandwidth available at mmWaves can support the exchange of sensors’ data at high speed. Moreover, AGVs/MRs are beneficial only if affordable: in [7], the authors estimate that the cost of mobile robots should be lower than 1000 USD/year to make this solution economically viable. In this context, NR-Light modules will be cheaper compared to 5G NR modems, and will then be preferable.

Another promising paradigm for the factories of the future is the adoption of Wireless Sensor Networks (WSNs), i.e., the deployment of a large number of sensors to monitor the state of an industrial process. As such, the directionality of mmWave links could reduce interference among different sensors, and maximize the spatial reuse of radio resources. Furthermore, the form factor of NR-Light modules shall be smaller with respect to 5G NR hardware, therefore limiting the size/cost of the sensors. The data generated by the sensors are then collected and exchanged at a centralized controller which can run specialized algorithms to detect anomalies and/or optimize the inputs. In this case, the traffic pattern depends on the
types of measurements: low-bandwidth (e.g., a few kbps for environmental signals) or high-bandwidth (e.g., in the order of Mbps for video/images) streams might be transmitted. In particular, each sensor may generate a small amount of (bursty) traffic, but the aggregate data rates might be high. In this perspective, the NR-Light architecture guarantees flexibility, and accommodates the different traffic patterns involved.

B. Smart Agriculture

The growth of human population, the consequent rising demand for agricultural products, and the need to protect the environment, triggered new innovations in the agricultural sector. Specifically, digital technologies will play a crucial role in maximizing the production chain output, optimizing the use of the available land resources, minimizing both inputs (water, fertilizers, pesticides) and waste, and reducing CO$_2$ emissions [8]. For example, the pervasive use of Unmanned Autonomous Vehicles (UAVs) may facilitate harvesting and pest monitoring of the livestock, while robots using vision positioning systems may identify and locate the fruit to harvest. This paradigm, typically referred to as “smart agriculture,” is being promoted by various international organizations, such as the agricultural European Innovation Partnership (EIP-AGRI).

In general, the agriculture environment exhibits favorable channel conditions (as the signal typically propagates in remote areas without buildings/obstacles), but relatively vast coverage areas are needed. Moreover, network operations rely on limited or even absent communication infrastructures and/or power grid, and may require renewable energy supplies, thus further motivating the use of low-power devices.

The role of NR-Light. NR-Light provides significant power enhancements with respect to the NR standard, and thus is well suited for agriculture scenarios in which devices are battery powered and the energy used by the radio module should be minimized. At the same time, NR-Light at mmWaves promotes better coordination among swarms of robots, and supports offloading of data with low latency. Finally, beamforming, as typically established at mmWaves, can provide a valid alternative to estimate the relative position of agriculture robots (e.g., in the crop field) when GPS sensors are not available, for example to reduce both costs and power consumption.

IV. KEY TECHNOLOGY ENABLERS FOR NR-LIGHT

Existing NR mmWave devices are deemed too complex, expensive and power-hungry for the use cases targeted by NR-Light. The following section demonstrates possible simplifications for NR-Light at FR2 that meets their requirements.

A. Simpler MIMO design

The main feature of mmWave systems is the realization of massive-MIMO (m-MIMO) to overcome the severe propagation loss experienced at high frequencies. However, a typical m-MIMO architecture requires several hardware components, thus consuming substantial energy. In turn, NR-Light use cases, like those in Sec. III, require low power consumption and reduced complexity, therefore a simplification of the radio front end might be desirable. For instance, unlike legacy mmWave terminals may incorporate even thousands of antennas, NR-Light devices may satisfy looser performance requirements at much smaller form factors, potentially including a relaxation of the number of MIMO layers.

At the same time, the research community should investigate which beamforming architecture would better support NR-Light use cases. Digital and hybrid architectures provide the best communication performance and flexibility, enabling the transceiver to direct beams in several directions simultaneously, despite involving more power-hungry blocks. While novel proposals suggest the usage of low-resolution Analog to Digital Converters (ADCs) in the RF chain [9], an analog architecture seems the most suitable choice for NR-Light devices to minimize power consumption.

B. Low-Cost Hardware Components

A critical property of mmWave systems is phase noise, which results in random oscillations in the phase of the signal, thus reducing the achievable spectral efficiency. This problem can be mitigated by using high-precision oscillators, which are expensive but able to produce a low-noise carrier signal. However, it may not be possible to apply this solution to NR-Light devices, since the cost may be too high. A more cost-effective solution is the configuration of 5G-NR-specific Phase Tracking Reference Signals (PTRSs) to track and compensate phase noise variations within the slot, and the adoption of a higher spacing between the subcarriers to avoid inter-carrier interference.

Another possible approach to decrease the cost of NR-Light devices consists of using lens-based antenna arrays. In analog architectures, one third of the total cost of the antenna array is due to phase shifters [10], and this term is proportional to the number of antenna elements in the array. Lens-based antennas represent a cheaper alternative to regular arrays, where beamforming is achieved through an electromagnetic lens, without the need for phase shifters.

Another promising research aspect to explore is how to reduce the cost of physical NR-Light hardware by cloud-based implementation of the Radio Access Network (RAN), thus realizing NR-Light functionalities via software.

C. Bandwidth Reduction

The high power consumption of the mmWave radio is due to its Radio Frequency (RF) components, whose power consumption grows linearly with the system bandwidth [11]. NR Release 15 devices support a bandwidth of up to 400 MHz per carrier in FR2, which can be further increased by means of Carrier Aggregation (CA). In turn, the loose network requirements of NR-Light use cases could make it theoretically possible to reduce the supported bandwidth, thus minimizing the power consumption. Moreover, bandwidth reduction enables the employment of cheaper ADCs, since the required sampling rate is reduced. For example, reducing the bandwidth from 200 to 50 MHz saves up to 23.5% of the cost of the radio module [3]. For these reasons, the 3GPP envisions a bandwidth ranging from 50 to 100 MHz for NR-Light devices operating in the mmWave bands.
D. Relaxation of the Maximum Modulation Order

The NR standard supports an efficient Adaptive Modulation and Coding (AMC) mechanism, which permits to adjust the modulation order and the coding rate used by the transmitter depending on the channel quality. The maximum modulation order supported by NR mmWave devices is 8 \[\text{[12 Sec. 5.1.3]}\]. For NR-Light, the 3GPP suggests to limit this value to 4, hence decreasing the cost of hardware components (e.g., relaxing the maximum modulation order from 6 to 4 saves up to 5.6% of the total cost) and reducing the processing time required to modulate/demodulate the signals \[\text{[3]}\].

E. Simplification of the Protocol Stack

5G NR’s main novelty is flexibility: it supports multiple numerologies for the Orthogonal Frequency Division Multiplexing (OFDM) waveform to accommodate diverse service requirements. For NR-Light, flexibility can be extended to the whole protocol stack by configuring a scalable structure compared to the mandatory features of Release 15 NR, e.g., a reduced maximum transport block size, a relaxed physical data channel, a reduced and simplified measurement and reporting mechanism. This improved flexibility is theoretically forward compatible with 5G’s slicing paradigm for adapting the protocol stack to the device requirements and data transmission profiles.

NR-Light can further promote energy efficiency by rethinking legacy NR protocol implementations. Beam management mechanisms, for example, are mandatory in NR to ensure that the end devices are properly aligned while communicating \[\text{[13]}\]. Existing beam searching techniques, however, require continuous exchange of control signals, thereby increasing the power consumption and computation requirements of the device. On the other hand, in many NR-Light use cases, nodes do not move, thus making it possible to decrease the periodicity at which beam management signals are broadcast (or, equivalently, reduce the beam sweep space).

F. Power Saving Functionalities

NR-Light communication may follow different transmission patterns compared to, e.g., NR cellular networks. For instance, for an IIoT scenario, we reasonably expect the traffic to be characterized by short and regular transmissions, e.g., for periodic reporting of sensor data, alternated by long idle periods. Therefore, the NR-Light system should preemptively specify the slots in which the device has to listen for control messages, and those in which the device can stay idle \[\text{[3]}\].

Moreover, NR-Light can inherit some of the network functionalities that were specifically designed for low-cost low-power IoT scenarios. In particular, NR-Light can implement a Discontinuous Reception (eDRX) mechanism, a Power Saving Mode (PSM) or wake-up-signals to optimize power consumption during idle modes and increase the battery lifetime. Additionally, given the directional/beamformed nature of mmWave communications, it could be possible to reduce the allowable transmission power budget for devices that are closer to the transmitter, thus promoting reduced interference while increasing the battery life.

V. PRELIMINARY EVALUATION OF AN INDOOR FACTORY SCENARIO USING NR-LIGHT AT MM WAVES

In this section we numerically evaluate whether NR-Light devices can successfully operate at mmWaves to satisfy industrial use cases requirements. To do so, we performed simulations using the ns-3 \[\text{mmwave module[1]}\], an open-source simulator for 5G mmWave networks. Based on current industry trends and research interests, we focus on a “factory of the future” use case (as described in Sec. III-A) and consider an indoor factory environment with an area of 20×20 m and 20 static NR-Light devices placed at random positions. A single base station operating at 28 GHz is deployed on the ceiling, at the center of the area. The channel model is based on the 3GPP Indoor Factory (InF) model, which features two propagation scenarios with different densities of obstacles, i.e., InF-SH (sparse) and InF-DH (dense).

The User Equipments (UEs) transmit data to a remote server. Specifically, 90% of the devices generate File Transfer Protocol (FTP) traffic modeled as a Poisson process of mean 500 kbps (“data-sensor” devices), while the remaining 10% (“video-stream” devices) generate a constant bit-rate video stream of 10 Mbps.

We compared different reduction/simplification strategies for NR-Light, based on those presented in Sec. IV, against a full-blown NR Release 15 device. Specifically, we investigated the impact of bandwidth reduction, relaxation of the maximum Modulation and Coding Scheme (MCS) order and transmission power, and MIMO antenna design at the device.

A. Impact of NR-Light Simplifications

First, we consider a baseline NR-Light device (referred to as “NR-L-Low”) featuring the most drastic reductions, as proposed by the 3GPP \[\text{[3]}\]: i.e., a bandwidth of 50 MHz, a maximum modulation order of 2, one antenna element, and a maximum transmission power of 13 dBm. Then, we evaluate the impact of progressively relaxing these reductions. The performance in terms of throughput and latency is shown in Fig. 2 while Tab. II reports numerical results also in terms of Packet Reception Ratio (PRR) and Signal-to-Interference-plus-Noise Ratio (SINR). For better comparison, we further estimate the average energy consumed by the NR-Light devices using the power consumption model in \[\text{[14]}\].

1) Bandwidth reduction: A progressive increase of the system bandwidth from 50 to 100 and 200 MHz brings a small performance degradation in terms of throughput. In fact, although a higher bandwidth introduces the possibility of encoding bigger Transport Blocks (TBs), it also causes a higher noise power. For low-capability devices in a challenging propagation environment, the latter is the dominant effect.

2) Maximum modulation order: We considered a pessimistic baseline with a maximum modulation order equal to 2. Then, we increased this value to 4 and 6, corresponding to MCS indices of 16 and 28, respectively \[\text{[12]}\]. We can see from Fig. 2 that the impact of this solution on the NR-Light performance is basically negligible (the throughput

\[\text{[1]}\] Available at https://github.com/nyuwireless-unipd/ns3-mmwave
Fig. 2: Joint average throughput (for video-stream) and latency (for data-sensor) NR-Light devices in an InF scenario. Configurations 1 and 2 feature relaxed reductions compared to NR-L-Low, consisting of a bandwidth of \{100, 200\} MHz, maximum MCS index of \{16, 28\}, \{4, 16\} antenna elements, and a maximum transmission power of \{18, 23\} dBm, respectively.

Table II: Numerical results for both InF-DH and InF-SH scenarios, considering both video-stream and data-sensor traffic. The latency is computed as the ratio between the number of packets received within the NR-Light requirement set for video-stream (50 ms) and data-sensor (20 ms) devices.

| InF scenario | NR-Light configuration | PRR video | PRR data | Latency video | Latency data | SINR [dB] | Power video [mW] | Power data [mW] |
|--------------|------------------------|-----------|----------|--------------|-------------|-----------|------------------|-----------------|
| InF-DH       | NR-L-Low (Baseline)    | 0.85      | 0.999    | 0.71         | 0.91        | 14.43     | 48.50            | 1.94            |
| BW: 100.0 MHz| 0.84 0.999 0.81 0.92   | 11.62     | 38.05    | 1.67         |
| BW: 200.0 MHz| 0.80 0.999 0.81 0.88   | 7.20      | 34.06    | 1.50         |
| Maximum MCS index: 16 | 0.83 1.00 0.79 0.94 | 12.65 | 40.55 | 1.68 |
| Maximum MCS index: 28 | 0.86 0.999 0.79 0.94 | 11.33 | 38.41 | 1.59 |
| Maximum TX power: 18.0 dBm | 0.95 1.00 0.81 0.95 | 19.34 | 148.47 | 4.84 |
| Maximum TX power: 23.0 dBm | 1.00 1.00 0.96 0.98 | 24.26 | 403.08 | 12.50 |
| UE antenna elements: 4  | 0.94 1.00 0.86 0.95 | 19.60 | 98.94 | 3.41 |
| UE antenna elements: 16 | 0.99 1.00 0.95 0.98 | 286.93 | 9.02 |
| InF-SH       | NR-L-Low (Baseline)    | 0.96      | 1.00     | 0.83         | 0.92        | 16.84     | 48.62            | 1.83            |
| BW: 100.0 MHz| 0.95 1.00 0.89 0.94   | 13.81     | 39.62    | 1.54         |
| BW: 200.0 MHz| 0.92 0.999 0.80 0.87   | 8.87      | 35.28    | 1.53         |
| Maximum MCS index: 16 | 0.95 0.999 0.85 0.95 | 15.04 | 37.38 | 1.58 |
| Maximum MCS index: 28 | 0.95 0.999 0.84 0.96 | 13.16 | 35.85 | 1.36 |
| Maximum TX power: 18.0 dBm | 1.00 1.00 0.93 0.97 | 23.04 | 132.10 | 4.65 |
| Maximum TX power: 23.0 dBm | 1.00 1.00 0.96 0.99 | 27.45 | 390.62 | 12.36 |
| UE antenna elements: 4  | 1.00 1.00 0.90 0.97 | 23.54 | 92.69 | 3.24 |
| UE antenna elements: 16 | 1.00 1.00 0.98 0.99 | 29.79 | 279.73 | 8.80 |

increases by only 2\%, meaning that the devices experiencing a good channel can satisfy their throughput requirements even with the minimum modulation order possible. Conversely, the remaining devices experience an SINR which is too low for the AMC mechanism to choose a higher MCS index.

3) Number of antenna elements at the device: Based on the discussion in Sec. IV-A, we consider analog beamforming for NR-Light devices. In this setting, the number of physical antennas at the UE has a significant impact on the system performance. Indeed, an increase from 1 to 4 and 16 antennas introduces a gradual improvement in both the throughput (up to +16\%) and latency (around −60\%), thanks to the higher gain achieved by beamforming: the average SINR improves by 12 dB when NR-Light devices operate with 16 antennas.

On the downside, Table III reports that the average power consumed by video-stream (data-sensor) devices increases from 48.5 (1.9) to 286.9 (9.0) mW when increasing the antenna array size from 1 to 16 in the InF-DH scenario. This is due to the higher number of electronic components (specifically phase shifters, converters and power amplifiers) in the RF chain, which makes the choice of the optimal MIMO configuration for NR-Light non-trivial.

4) Maximum transmission power: While decreasing the transmission power typically leads to performance degradation, in good SINR regimes this may promote energy savings, and mitigate interference. In this context, we studied the impact of decreasing the maximum transmission power of NR-Light devices from 23 dBm (i.e., the Release 15 NR benchmark [15]) to 13 dBm. From Fig. 2 we notice that this solution leads to an undesirable degradation of the throughput by 17\% and increase of the latency by 134\%, due to the resulting lower average SINR experienced by the devices. On the other hand, Table II illustrates that the energy consumption drops by up to approximately 8 (6) times for video-stream (data-sensor) devices, which is certainly in line with NR-Light’s requirements.

B. Guidelines for an Efficient NR-Light Configuration

The previous analysis highlights how devices featuring the most drastic restrictions proposed in [3] for the mmWave architecture are not able, in general, to meet NR-Light target performance requirements as reported in Table I. The bottle-
neck is represented by the UEs in the lowest SINR regimes. On one side, a system with a single antenna and a maximum transmission power of 13 dBm achieves an insufficient average SINR, regardless of the modulation order and bandwidth used, and should be avoided. At the same time, increasing the maximum MCS index would increase the cost and complexity of the devices (as discussed in Sec. 1V-D) beyond NR-Light expectations, with limited throughput/latency improvements. In turn, reducing the bandwidth has generally a positive impact on the devices experiencing bad channel quality.

Based on these considerations, we identified the following promising combination of parameters for NR-Light devices, referred to as “NR-L-Mid” devices, to achieve a good trade-off between network performance and energy consumption:

- 50 MHz of bandwidth;
- Maximum modulation order of 2 (corresponding to a maximum MCS index of 9);
- 4 antenna elements;
- Maximum transmission power of 18 dBm.

We now compare the performance of NR-L-Mid devices with two benchmarks: a typical Release 15 NR device (“NR”) and our pessimistic baseline featuring the most extreme NR-Light restrictions (“NR-L-Low”) as per the 3GPP [3].

From Fig. 3, we see that the proposed NR-L-Mid configuration significantly outperforms the pessimistic NR-L-Low baseline under several metrics, including energy efficiency. This is due to the fact that, although NR-L-Low devices exhibit the lowest power consumption, implementing the most aggressive restrictions, they transmit for the longest period of time, thus increasing the energy budget. Moreover, while the NR benchmark is certainly the preferred approach for high-end eMBB/URLLC use cases, NR-L-Mid devices obtain similar end-to-end throughput, latency and PRR performance, while consuming only 20% of the energy of a typical NR device. We claim that the proposed NR-L-Mid configuration strikes the right trade-off between power consumption and portion of time that is spent for data transmission.

VI. CONCLUSIONS

The standardization community agrees that a full-blown 5G NR architecture, while satisfying the needs of high-end eMBB and URLLC applications, may not support mid-market IoT use cases, ranging from video surveillance to industrial automation. To this aim, the 3GPP is working on a new (lighter) version of NR, referred to as NR-Light, to support balanced and mixed IoT-like requirements, ranging among good reliability, acceptable latency and throughput, and low energy/power consumption. However, while it is foreseen that NR-Light systems operate at mmWaves, numerical results validating this rationale are missing.

To fill this gap, in this paper we first illustrate the potential of mmWave communication for mid-market IoT use cases. Then, we highlight and motivate the design of an NR-Light candidate interface derived from NR by introducing a lower maximum MCS order, a restricted bandwidth support, and simpler antenna configurations. Finally, we demonstrate the feasibility of such a design on a typical IIoT use case via simulations. Our results show that down-selecting features from NR allows for significant gains in complexity and energy consumption, while still meeting application requirements.

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