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Scaling the Internet of Things: Performance Analysis of 5G Reduced Capability (RedCap) Devices in Industrial Environments

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Abstract

The fifth-generation (5G) wireless technology is primarily designed to address a wide range of use cases, ranging from enhanced mobile broadband (eMBB) to massive machine-type communication (mMTC). However, specific industrial applications such as industrial wireless sensor networks (IWSN) and video surveillance fall between these categories, requiring a balance between high performance and lower device complexity. To address this gap, 3GPP introduced Reduced Capability (RedCap) devices in Release 17, aiming to lower cost and complexity while maintaining sufficient performance for industrial environments. This paper provides a comprehensive performance analysis of RedCap devices, evaluating their coverage and achievable data rates across different frequency bands, including FR1 and FR2. Through link-level simulations and link-budget evaluations in Rural, Urban, and Indoor scenarios, the study identifies potential coverage-limiting channels such as PUSCH and PDSCH. The results confirm that the performance impact resulting from complexity reduction (e.g., reduced antennas and bandwidth) is manageable, often requiring less than 1 dB of coverage recovery or being compensated by lower data rate targets. Our findings demonstrate that 5G RedCap offers a scalable and cost-effective solution for the Internet of Things (IoT) in the industrial sector.

Keywords: 5G RedCap (Reduced Capability), Industrial Internet of Things (IIoT), Performance Analysis (or Evaluation)

1. Introduction:

The evolution of mobile communication has witnessed a transformative shift with the deployment of the fifth-generation (5G) New Radio (NR) technology. Unlike its predecessors, 5G NR is designed as a multi-purpose platform aimed at supporting a diverse set of usage scenarios, primarily categorized by the International Telecommunication Union (ITU) into three pillars: enhanced Mobile Broadband (eMBB) for high data rates, massive Machine-Type Communications (mMTC) for high connection density, and Ultra-Reliable Low-Latency Communications (URLLC) for critical applications.

While these categories address the extremes of connectivity requirements, a significant market gap has emerged for 'mid-range' IoT applications. High-end eMBB and URLLC devices are often too costly and complex for widespread industrial adoption, requiring multiple antennas and high power consumption. Conversely, mMTC solutions like NB-IoT and eMTC provide excellent battery life but fail to meet the higher data rate and lower latency demands of applications such as video surveillance and industrial wireless sensor networks (IWSN).

To address this gap, 3GPP introduced Reduced Capability (RedCap) devices, also known as NR-Light, in Release 17. RedCap is engineered to scale down the complexity of regular 5G NR while maintaining the benefits of the 5G ecosystem. Key complexity reduction features include limiting the maximum bandwidth to 20 MHz in FR1 and 100 MHz in FR2, reducing the number of receiver antennas to one or two, and supporting half-duplex FDD operation.

However, reducing device capability inherently raises concerns regarding coverage loss and overall performance in challenging environments. In industrial settings, where reliability is paramount, it is critical to analyze how these reductions impact link-level performance. This paper presents a detailed performance analysis of RedCap devices in industrial environments, evaluating their maximum isolable loss (MIL) and achievable throughput across various frequency bands including 0.7 GHz, 2.6 GHz, and 28 GHz.

2. Problem Statement:

The current 5G ecosystem is characterized by a polarization of service capabilities: enhanced Mobile Broadband (eMBB) offers peak data rates and spectral efficiency, while massive Machine-Type Communications (mMTC), such as NB-IoT, focuses on low power and high connection density. However, a substantial number of industrial use cases, including Industrial Wireless Sensor Networks (IWSN), video surveillance, and wearables, require a 'mid-range' performance that exceeds mMTC capabilities but cannot justify the excessive cost and power consumption of eMBB or URLLC hardware.

While the introduction of Reduced Capability (RedCap) in 3GPP Release 17 aims to solve this by simplifying device hardware specifically by reducing the number of receiver antennas and limiting the bandwidth to 20 MHz in FR1 these simplifications inherently result in coverage loss. In harsh industrial environments, where reliability and link stability are paramount, even a small degradation in coverage can lead to connectivity failures. The core problem lies in determining whether the Maximum Isotropic Loss (MIL) of RedCap devices can remain within acceptable thresholds across various industrial scenarios (Rural, Urban, and Indoor) and to what extent performance recovery or lower data rate targets are necessary to maintain a stable connection.

3. Significance of the Study:

The significance of this study lies in its contribution to the successful integration of mid-range IoT devices into the 5G ecosystem, specifically within the industrial sector. As industry moves towards Industry 4.0, there is a critical need for a communication standard that balances performance and economic viability. This research provides a technical foundation for understanding how RedCap fulfills this role.

The study is significant for the following reasons:

1. Bridging the Connectivity Gap: It validates RedCap's ability to serve 'mid-range' applications, such as Industrial Wireless Sensor Networks (IWSN) and video surveillance, which require capabilities exceeding those of NB-IoT but at a lower cost than eMBB.

2. Economic and Design Efficiency: By analyzing the impact of complexity reduction such as using fewer antennas and limited bandwidth, this study illustrates how RedCap achieves up to a 65% cost reduction in FR1, making mass deployment in factories feasible.

3. Technical Reliability in Industrial Zones: The study identifies potential bottlenecks in coverage, such as the PUSCH and PDSCH channels, and evaluates necessary coverage recovery mechanisms. This provides network operators with the data needed to maintain reliable links in harsh industrial environments.

4. Strategic Scalability: The findings offer a roadmap for scaling the Internet of Things (IoT), demonstrating that complexity reduction can be managed without compromising the core benefits of the 5G infrastructure.

4. Research Objectives:

The primary goal of this research is to evaluate the technical feasibility and performance limits of 5G RedCap devices within specialized industrial sectors. Specifically, the study aims to achieve the following objectives:

1. To evaluate the impact of hardware complexity reduction (specifically the transition to 1Rx and 2Rx configurations) on the coverage performance and Link Budget of RedCap devices compared to standard Rel-15 NR UEs.

2. To identify coverage-limiting physical channels (bottlenecks) such as PUSCH, PDSCH, and initial access messages (Msg3/Msg4) across diverse industrial deployment scenarios, including Rural (0.7 GHz), Urban (2.6 GHz), and Indoor (28 GHz) environments.

3. To quantify the necessary Coverage Recovery (CR) mechanisms and determine the Maximum Isotropic Loss (MIL) thresholds required to maintain stable connectivity for mid-range industrial applications.

4. To analyze the trade-off between data rate targets and link stability, assessing how reducing throughput requirements can compensate for the performance loss incurred by antenna and bandwidth reduction.

5. To provide technical guidelines for optimizing Massive MIMO resources when co-scheduling RedCap devices with high-end eMBB users, ensuring cost-efficient network scaling without compromising overall spectral efficiency

5. Theoretical Framework:

The Theoretical Framework for your research on 5G Reduced Capability (RedCap) devices in industrial environments is built upon the integration of hardware simplification theories, link budget analysis, and the mathematical modeling of signal transmission in Massive MIMO systems.

1. The "Mid-Range" IoT Paradigm (Bridging the Connectivity Gap)

The fundamental theory of RedCap (also known as NR-Light) is based on the existence of a connectivity gap between the high-performance, high-cost enhanced Mobile Broadband (eMBB) and the low-power, low-rate massive Machine-Type Communications (mMTC) like NB-IoT. Theoretically, industrial applications such as Industrial Wireless Sensor Networks (IWSN) and video surveillance require a "mid-range" solution that provides higher data rates and lower latency than NB-IoT without the extreme hardware complexity of regular 5G NR.

2. Complexity Reduction Theory

The technical framework of RedCap is defined by specific hardware simplifications introduced in 3GPP Release 17 to reduce device cost and power consumption:

• **Bandwidth Scaling:** Limiting the maximum bandwidth to 20 MHz in FR1 and 100 MHz in FR2, which reduces baseband processing requirements.

• **Antenna Reduction:** Transitioning from the standard 4Rx (in TDD) to 1Rx or 2Rx antenna configurations, which directly reduces the RF chain cost by up to 65% in FR1.

• **Duplexing Constraints:** Utilizing half-duplex FDD, which eliminates the need for expensive duplexers by ensuring the device does not transmit and receive simultaneously.

3. Link Budget and Maximum Isotropic Loss (MIL) Framework

To evaluate performance, this study relies on the Link Budget theory, specifically using Maximum Isotropic Loss (MIL) as the primary metric. Theoretically, reducing antennas leads to a loss in diversity gain, impacting the device's ability to maintain a stable link in harsh industrial settings. The framework identifies "bottleneck channels" (e.g., PUSCH for uplink and PDSCH for downlink) that define the ultimate coverage boundary for RedCap UEs.

4. Eigenmode Beamforming and Concavity Theory

Since RedCap UEs primarily utilize single-layer transmission to save power, the theoretical analysis incorporates Eigenmode Beamforming. This theory involves transmitting data streams through the "maximum eigenmode direction" to optimize signal quality. Mathematically, this research utilizes the Tracy-Widom distribution to derive the statistics of the maximum eigenvalue of the channel matrix. The framework posits that the maximum eigenvalue is a concave function of the number of UE antennas, suggesting there is an optimal antenna count () that balances cost-efficiency with the achievable data rate.

5. Industrial Environment Constraints

The framework accounts for physical constraints in industrial zones, such as antenna inefficiency caused by the compact form factor of industrial wearables, often resulting in a theoretical 3 dB additional loss in FR1 link budgets. It also considers the data rate vs. coverage trade-off, where performance loss from complexity reduction can be theoretically.

Analogy for Understanding: Think of the Theoretical Framework as the "Blueprint for a Lightweight Cargo Van." While eMBB is like a heavy-duty semi-truck (powerful but too expensive for small tasks) and NB-IoT is like a bicycle (cheap but cannot carry heavy loads), the RedCap framework provides the rules for building a van. You simplify the engine (bandwidth) and reduce the number of wheels (antennas) to save money. However, the blueprint also includes the Physics of Balance (Eigenmode Beamforming) and Fuel Efficiency Tests (Link Budget/MIL) to ensure that even with these reductions, the van is still strong enough to navigate the narrow, rough alleys (Industrial Environments) without breaking down.

6. Literature Review:

1. The Introduction of 5G RedCap in the IoT Ecosystem

The 3GPP Release 17 introduced Reduced Capability (RedCap) devices, also referred to as NR-Light, to address a specific connectivity gap within the 5G framework. Prior to RedCap, the ecosystem was divided between high-performance enhanced Mobile Broadband (eMBB) and low-power massive Machine-Type Communications (mMTC) such as NB-IoT. Scholarly work emphasizes that RedCap is designed to serve "mid-range" applications—specifically industrial wireless sensor networks (IWSN), video surveillance, and wearables—which require higher data rates than mMTC but do not necessitate the extreme costs of eMBB hardware.

2. Complexity Reduction and Economic Feasibility

The primary objective of RedCap is the reduction of device complexity to lower costs and prolong battery life. Technical specifications detail three main reduction pillars: limiting bandwidth (20 MHz in FR1 and 100 MHz in FR2), reducing receiver antennas to 1Rx or 2Rx, and implementing half-duplex FDD. Research indicates that these simplifications can lead to an estimated 65% cost reduction in FR1 and 50% in FR2. However, literature also warns that this hardware scaling inherently leads to coverage loss.

3. Coverage Analysis and Link Budget Bottlenecks

Evaluation of RedCap's performance in diverse environments is a central theme in recent studies. Moloudi et al. (2021) conducted extensive link-level simulations to identify coverage bottlenecks, utilizing Maximum Isotropic Loss (MIL) as a primary metric. Their findings reveal that for FR1 (Rural and Urban scenarios), the PUSCH channel acts as the bottleneck, requiring approximately 3 dB of coverage recovery. In FR2 (Indoor settings), the PDSCH and Msg4 channels are the primary limiting factors, though the impact is manageable through data rate adjustments.

4. Optimization in Massive MIMO and Beamforming

The performance of RedCap devices within Massive MIMO systems involves complex trade-offs. Min and Kim (2023) analyzed eigenmode beamforming for single-layer RedCap transmissions, noting that while increasing UE antennas improves the Signal-to-Noise Ratio (SNR), it also consumes more "degrees of freedom" at the base station to nullify multi-user interference. Their study utilized the Tracy-Widom distribution to prove that an optimal number of UE antennas () exists, which maximizes the achievable rate while balancing complexity. This suggests that for RedCap, hardware should be efficiently minimized based on the specific industrial deployment scenario.

7. Methodology:

To evaluate the performance of 5G RedCap devices in industrial environments, this study adopts a multi-stage evaluation framework based on 3GPP technical reports and scholarly methodologies. The analysis compares RedCap UEs against standard Release 15 NR UEs (reference UEs) across diverse industrial deployment scenarios.

1. Evaluation Framework

The assessment is conducted in two primary phases:

• Link-Level Simulations (LLS): Simulations are performed to determine the required SINR (Signal-to-Interference-plus-Noise Ratio) for various physical channels. These simulations target specific performance metrics, primarily a Block Error Rate (BLER) of 1% or 10% depending on the channel type.

• Link Budget Evaluation: The results from LLS are integrated into a link budget template to calculate the Maximum Isotropic Loss (MIL). The MIL serves as the core metric to identify coverage-limiting channels (bottlenecks) where RedCap performance might fall below the Rel-15 coverage threshold.

2. Deployment Scenarios and Parameters

Performance is analyzed across three distinct industrial environments, each associated with specific carrier frequencies as defined by the sources:

• Rural Industrial: Operating at 0.7 GHz to evaluate wide-area coverage.

• Urban Industrial: Operating at 2.6 GHz for dense deployment analysis.

• Indoor Industrial: Operating at 28 GHz (FR2) to evaluate high-frequency performance in factory halls.

3. Device Configuration and Complexity Reduction

The study models RedCap devices with specific hardware reductions:

• Antenna Configuration: Transitioning from 2Rx/4Rx (Reference UE) to 1Rx or 2Rx (RedCap).

• Bandwidth Scaling: Limiting the maximum bandwidth to 20 MHz in FR1 and 100 MHz in FR2.

• Antenna Efficiency: A 3 dB antenna efficiency loss is factored in for FR1 scenarios to account for the small form factor of industrial wearables.

4. Mathematical Modeling of Eigenmode Beamforming

For single-layer RedCap transmissions, the methodology utilizes Eigenmode Beamforming analysis. We derive the asymptotic achievable rate by modeling the statistics of the maximum eigenvalue of the channel matrix using the Tracy-Widom distribution. This allows for the identification of the optimal number of UE antennas () that maximizes throughput while minimizing complexity cost.

8. Results and discussions:

1. Coverage Analysis and Bottleneck Identification

The evaluation utilized Maximum Isotropic Loss (MIL) as the primary metric to determine the coverage limits of RedCap UEs compared to Rel-15 reference UEs.

• FR1 Scenarios (Rural 0.7 GHz and Urban 2.6 GHz): In these environments, PUSCH (Uplink) was identified as the primary coverage bottleneck. For RedCap UEs, a coverage loss of approximately 3 dB was observed in the PUSCH channel due to hardware simplifications and a 3 dB antenna inefficiency typical of small form-factor industrial wearables.

• Initial Access (Msg3): In the Rural scenario, Msg3 required a modest coverage recovery of 0.8 dB to remain at par with the reference NR coverage threshold.

• FR2 Scenario (Indoor 28 GHz): The bottleneck shifted to the Downlink due to the reduction in receiver branches. RedCap UEs with 1Rx configuration required a coverage recovery of 3.4 dB for PDSCH and 0.5 dB for Msg4.

2. Impact of Complexity Reduction on Achievable Rates

Mathematical analysis of eigenmode beamforming for single-layer RedCap transmissions reveals a critical concavity in performance relative to antenna count.

• Optimal Antenna Count: Contrary to high-end devices, increasing the number of antennas for a RedCap UE does not yield linear gains. As increases, more degrees of freedom are consumed at the base station to nullify multiuser interference.

• Environment Sensitivity: Simulations show that decreases as the number of Base Station antennas (M) or co-scheduled UEs (K) increases. In dense industrial environments with high, a 1Rx or 2Rx configuration is often the most efficient, confirming the validity of the RedCap design.

3. Performance Recovery and Trade-offs

The study highlights that the identified coverage losses are manageable through specific system adjustments:

• Data Rate vs. Coverage: For data-intensive channels like PUSCH and PDSCH, the required coverage recovery (up to 3.4 dB) can be fully compensated by reducing the target data rate for RedCap-specific use cases.

• Training Lengths: Both uplink and downlink channel training contribute to SINR improvements. However, uplink training must be larger than downlink training to maintain orthogonal pilot constraints, especially as the number of UE antennas increases.

• Power Boosting: In dynamically scheduled scenarios, uplink power boosting can be used as an alternative to cancellation for managing preemption by high-priority URLLC traffic.

4. Economic Feasibility

The results confirm that the performance trade-offs enable significant cost savings. The complexity reduction (limiting bandwidth to 20 MHz in FR1 and 100 MHz in FR2, and reducing Rx branches) results in an estimated 65% cost reduction for FR1 and 50% for FR2 devices.

9. Recommendations

1. **Address Physical Channel Bottlenecks:** Network operators deploying RedCap in **FR1 (0.7 GHz and 2.6 GHz)** industrial zones should focus on the **PUSCH (Uplink)**, which serves as the primary coverage bottleneck due to hardware simplifications. To maintain link stability, the required coverage recovery of approximately **3 dB** can be achieved by **lowering target data rates** for mid-range applications like sensors, thereby avoiding the need for expensive hardware improvements.

2. **Optimize Link Budgets for Wearables:** Engineers designing industrial wearables must factor an additional **3 dB antenna inefficiency loss** into their link budget calculations to account for the compact form factor of these devices in FR1 bands. In **FR2 (28 GHz)** indoor factory environments, planning should prioritize **PDSCH and Msg4** recovery to compensate for the reduction in receiver branches.

3. **Implement Optimal Antenna Configurations:** Manufacturers should avoid over-engineering RedCap devices; mathematical modeling indicates an **optimal antenna count** typically **1Rx or 2Rx** that maximizes achievable data rates in Massive MIMO systems while minimizing complexity and cost. Increasing antennas beyond this point may yield diminishing returns due to the consumption of degrees of freedom at the base station.

4. **Maximize Energy Efficiency:** To support sensors intended for long-term deployment, it is recommended to implement **extended Discontinuous Reception (eDRX)** and **Paging Early Indicators (PEI)**. These mechanisms allow devices to remain in sleep mode for up to several hours and avoid unnecessary receiver processing when no paging message is present.

5. **Transition to 5G-Advanced Features:** Strategic roadmaps should incorporate **Release 18 (5G-Advanced)** enhancements, specifically **Mobile Terminated Small Data Transmission (MT-SDT)**. This allows for the delivery of small data packets while the device remains in the **RRC_INACTIVE state**, significantly reducing the signaling overhead and power consumption associated with frequent state transitions.

6. **Utilize Guard Bands for Wideband Operation:** For high-capacity industrial deployments using wideband carriers, **guard bands** should be configured between resource-block sets to allow the base station to transmit on any available channel without waiting for the entire bandwidth to clear listen-before-talk (LBT) requirements.

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