

# Based on the Terminal Feedback PUR

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**ABSTRACT** This paper proposes a terminal-feedback-based pre-authorized uplink resource (PUR) scheduling scheme for NB-IoT systems to improve uplink radio resource utilization under massive machine-type communication scenarios. In the proposed approach, terminals provide lightweight feedback indicating the actual usage of allocated PUR resources, enabling the base station to promptly identify unused uplink grants and reclaim idle resources for subsequent scheduling. This mechanism reduces resource waste caused by empty packet transmissions and improves scheduling flexibility under dynamic traffic conditions. Furthermore, the proposed framework exploits the long-term channel stability of PUR terminals to support MU-MIMO transmission, thereby enhancing spectrum utilization and uplink capacity. Analytical modeling and simulation results demonstrate that the proposed method maintains high resource efficiency even under elevated empty-packet-rate conditions, where conventional PUR mechanisms suffer significant performance degradation. The scheme also enables more flexible resource reuse while introducing only limited signaling and power-consumption overhead. The results confirm that the proposed terminal-feedback strategy effectively improves uplink scheduling efficiency and spectrum utilization, providing a practical solution for large-scale NB-IoT deployments and industrial wireless communication systems.

**INDEX TERMS** NB-IoT, uplink scheduling, radio resource management, MU-MIMO

## I. INTRODUCTION

WITHIN the framework of Industry 4.0, high-performance industrial software processes real-time production data from numerous machines, maximizing overall productivity. Unlike traditional human-to-human communication, these environments rely on machine-to-machine (M2M) communication [1,2]. Conventional wireless solutions face limitations in capacity, reliability, and security [3]. In industrial production, equipment exhibits varying data importance and latency requirements; thus, it is essential to determine which Quality of Service (QoS) factors satisfy IoT service demands [4]. Furthermore, industrial control necessitates significant capacity [5-9], while poor wireless channels, signal attenuation, and conflicting requirements—such as large scale, high data intensity, ultra-low latency, ultra-high reliability, and energy efficiency—present ongoing challenges [5-9]. Narrowband IoT (NB-IoT) technology, derived from LTE [10], was redesigned to address the four major requirements of the Internet of Things (IoT), outperforming LoRaWAN and Sigfox in service quality and latency [11]. Uplink (UL) resource allocation can be as granular as a single subcarrier and employs repetition technologies. To optimize the protocol stack for massive machine-type communications (mMTC), NB-IoT simplifies the physical layer by omitting the Sounding Reference Signal (SRS) and the Physical Uplink Control Channel (PUCCH) used in LTE. Instead, control information (e.g., ACK/NACK) is integrated into specific NPUSCH formats,

such as NPUSCH Format 2, reducing unnecessary measurement and feedback overhead, supporting large-scale connectivity, refarming GSM bands, and fulfilling the four major IoT demands [12]. NB-IoT employs a 15 kHz subcarrier interval, with downlink multiple access, frame structure, and physical resource unit design consistent with LTE. The cell bandwidth occupies 180 kHz (1 RB), with 12 subcarriers at 15 kHz spacing. Each time slot is 0.5 ms, containing seven symbols. Uplink Resource Units (RUs) support two subcarrier spacings (SCS): 15 kHz: Up to 12 subcarriers per slot (0.5 ms), enabling multi-subcarrier scheduling. 3.75 kHz: Up to 48 subcarriers per slot (2 ms), supporting single carrier scheduling, primarily for extended coverage. NB-IoT uplink supports both single carrier and multi-subcarrier transmissions, as summarized in Table 1.

**TABLE 1.** NB-IoT's RU

| NPUSCH Format | $\Delta f$ | $N_{sc}^{RU}$ | $N_{slots}^{UL}$ | $N_{syms}^{UL}$ |
|---------------|------------|---------------|------------------|-----------------|
| 1             | 3.75 kHz   | 1             | 16               | 7               |
|               | 15 kHz     | 1             | 16               |                 |
|               |            | 3             | 8                |                 |
|               |            | 6             | 4                |                 |
|               |            | 12            | 2                |                 |
| 2             | 3.75 kHz   | 1             | 4                | 4               |
|               | 15 kHz     | 1             | 4                |                 |

## A. NPUSCH FORMAT

NPUSCH is divided into Format 1 for uplink shared channel data (UL-SCH) and Format 2 for Uplink Control Information (UCI). Format 2 consolidates control signaling, streamlining NB-IoT relative to LTE's PUCCH. Release 13 supported ACK/NACK feedback, with Release 16 expanding to include Scheduling Request (SR) signals. IoT communication predominantly occurs between devices, exhibiting distinct traffic characteristics from human communication. In sensor networks monitoring various environments [13], uplink transmissions often consist of numerous small packets, typically less than 100 bits, excluding application layer overhead, and sometimes only a few bits [3]. This leads to significant signaling overhead for small data transmissions [14,15]. Signaling constitutes a substantial portion of IoT transmissions. NB-IoT optimizes core network signaling, but random access and authorization signaling for empty ports remain. Most research focuses on unauthorized wireless communication mechanisms [16], aiming to reduce activity detection errors [17], improve NAMA for uplink, suppress user interference [18], and allocate subchannels based on timing requirements [19]. As terminal density increases, so does the probability of MTCDs [20], leading to resource conflicts and reduced system performance [21,22]. Unauthorized access research primarily improves random access to avoid conflicts [23-26], enhances terminal power utilization [27], coordinates inter-cell interference [28-30], reduces system noise, and improves wireless spectrum efficiency via link adaptation. Most IoT applications are uplink-dominated [31,32], and uplink transmission is more complex than downlink [33], resulting in greater uplink traffic. Release 15 introduced Early Data Transmission (EDT) technology [34, 35], reducing signaling for terminal data transmission. UL Semi-Persistent Scheduling (UL SPS) [36] periodically reports Buffer Status Reports (BSR), reserving reporting resources. SR technology [35] leverages HARQ-ACK feedback resources or non-competitive NPRACH resources to reduce BSR reporting overhead. These techniques aim to improve wireless resource utilization to meet the exponential growth in IoT device connectivity [37].

## II. RELATED WORK

### A. BACKGROUND WORK

UL SPS technology requires advance configuration of resources for BSR reporting, which are infrequently used. SR technology based on downlink HARQ feedback necessitates terminal transmission of downlink data—unsuitable for many IoT use cases. SR technology utilizing non-competitive NPRACH consumes valuable resources and is limited to terminals with special tasks. In sensor networks [38], reported data exhibits periodicity distinct from traditional SPS technology. Release 16 introduced a pre-authorization mechanism (PUR) [35] for uplink resources. After random terminal access, the base station configures PUR via dedicated RRC signaling. Prior to PUR transmission, the terminal measures the wireless channel to

determine if allocated uplink resources are usable. If no data is transmitted or channel quality is insufficient, the terminal refrains from using pre-authorized resources.

### B. PUR TECHNOLOGY

In PUR technology, after the base station configures the initial PUR resources and cycles, the terminal transmits uplink data according to the configured cycle and transmission count. The transmission count may be either finite or infinite. The  $H_{PUR}$  represents the counting unit above the  $H_{SFN}$ , and their relationship is defined as  $N_{H_{SFN}}^{H_{PUR}} = 1024$ . According to the 3GPP protocol,  $N_{SFN}^{H_{SFN}} = 1024$  and  $N_{subframe}^{SFN} = 10$ . The current  $H_{SFN,Ref}$  used for issuing PUR configuration signaling at the base station is defined in the formula, where offset, startSFN, and subframe are configuration parameters. The variables  $H_{SFN}$ ,  $SFN$ , and subframe represent the system time parameters. The configuration formula is given in Formula (1). The PUR progress mechanism is shown in Figure 1:

$$\begin{aligned} & [(H_{PUR}2^{20} + H_{SFN}2^{10} + SFN)10 + \text{subframe}] \\ & = [(H_{SFN,Ref}2^{10} + \text{offset}2^{10} \\ & \quad + \text{start}_{SFN})10 + \text{start}_{subframe}] \bmod T \end{aligned} \quad (1)$$

If the base station fails to detect data on the PUR resource multiple times, it implicitly releases the PUR resource. Compared with early data transfer (EDT), coverage gains range from 50% to 7% in depth [35]. NB-IoT achieves super-coverage through repetition [39], but wireless resources are wasted when terminals do not use PUR. Thus, wireless resource utilization in PUR can be improved. The parameters used in the efficiency model are defined as follows:  $N_{re}^{signaling}$ : number of resource elements (REs) required for a single transmission;  $N_{ru}$ : number of resource units (RUs) required for a single data packet;  $N_{re}^{ru}$ : number of REs contained in a single RU;  $N_{rep}$ : number of repetitions required for uplink transmission, with a repetition range of (1, 2, 4, 8, 16, 32, 64, 128). The variable  $x$  denotes the empty data upload rate of terminals. In conventional PUR resource allocation strategies,  $x$  is typically restricted to no more than 10%, since higher empty packet rates significantly increase signaling overhead and wireless resource waste, thereby diminishing advantages of PUR technology. To address this limitation, this paper proposes a feedback-based mechanism that mitigates resource inefficiencies by enabling the base station to reclaim unused PUR resources in a timely manner. This approach allows PUR to remain effective even under high empty packet rates scenarios (up to 40%), thereby expanding the operational applicability of NB-IoT sensor deployments in dynamic manufacturing environments. Accordingly, the transmission resource efficiency of PUR can be expressed as:

$$f(x) = \frac{N_{ru}N_{re}^{ru}N_{rep}(1-x)}{N_{re}^{signaling} + N_{ru}N_{re}^{ru}N_{rep}} \quad (2)$$

Since the method proposed in this paper is based on terminal feedback, the configuration signaling required by PUR still

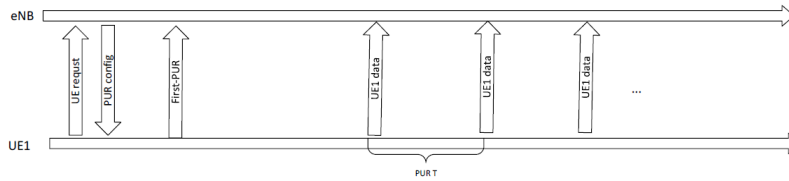


**FIGURE 1.** PUR schedule mechanism

exists. To accurately evaluate the impact of the proposed mechanism, the signaling overhead associated with resource release and potential reauthorization must be considered. In the standard PUR mechanism, if a terminal does not utilize the allocated resources, the base station must wait for either implicit release or manual signaling to reclaim them. Both processes introduce additional wireless resource overhead relative to the small data packets typically transmitted in NB-IoT systems. Therefore, Formula (2) serves as the baseline model for evaluating standard PUR efficiency, where  $x$  represents the empty data upload rate. The signaling term  $N_{re}^{signaling}$  remains a critical factor in the denominator, as it reflects the fixed cost of maintaining the pre-authorized link even when the effective data transmission ratio  $(1 - x)$  is low:

$$f(x) = \frac{N_{ru} N_{re}^{ru} N_{rep} (1-x)}{N_{re}^{sigaling} + N_{ru} N_{re}^{ru} N_{rep}} \quad (3)$$

### III. PROPOSED METHOD

### A. PUR SCHEDULING MECHANISM BASED ON TERMINAL FEEDBACK

PUR resource waste primarily occurs when the base station cannot promptly recover PUR authorizations from terminals that do not utilize them. If terminal data is not received repeatedly, implicit release is triggered, or the terminal initiates a signaling process to release PUR resources, increasing non-data transmission overhead and reducing wireless resource utilization. Channel variability in mobile terminals further limits PUR application. This paper proposes feedback on PUR resource usage to avoid waste and broaden PUR applicability. MU-MIMO technology enhances wireless resource utilization. In NB-IoT, small data packets and long business cycles, combined with downlink public signaling requirements, restrict terminal access to NDCI resources, limiting MU-MIMO usage. PUR configuration signaling does not require NDCI resources, allowing MU-MIMO implementation in NB-IoT via terminal feedback PUR scheduling.

### B. PUR BASED ON TERMINAL FEEDBACK

In the proposed terminal feedback-based PUR, the base station allocates indication resources to terminals before uplink transmission. Terminals provide feedback based on actual PUR resource usage. If the base station detects non-use on the indication resource, it counts consecutive non-use events to determine whether to trigger implicit release. Resources are then reauthorized to other terminals, avoiding waste and improving utilization. The indication signal

specifies whether the terminal will utilize PUR resources at subsequent time points

$$\begin{aligned} & \lfloor (H_{\text{PUR}}2^{20} + H_{\text{SFN}}2^{10} + \text{SFN})10 + \text{subframe} - \Delta_t \rfloor \\ &= \lfloor (H_{\text{SFNRef}}2^{10} + \text{offset}2^{10} \\ & \quad + \text{start}_{\text{SFN}})10 + \text{start}_{\text{subframe}} - \Delta_t \rfloor \bmod T \end{aligned} \quad (4)$$

Upon analyzing terminal non-use-the base station recycles and reauthorizes PUR resources. The empty data in the PUR scheduling mechanism is shown in Figure 2: Wireless resources can be reused by the base station only after the previously allocated resources have been successfully reclaimed. Therefore, the timing condition must allow the base station to determine whether a terminal actually utilizes the PUR resources while also satisfying the delay requirements for resource reauthorization. To ensure this requirement, the scheduling interval must include both the uplink data transmission duration and the scheduling processing delay. The variable  $N_{ruc}$  represents the transmission time occupied by the uplink data resources, while the scheduling delay is represented by  $(8 + k_0)$ . Thus, the recovered resource can be reassigned to other terminals only when the scheduling interval exceeds the uplink authorization delay. For the TDD mode the timing constraint can be expressed as  $\Delta_t > (8 + k_0) + N_{ruc}$ ,  $k_0 \in \{0, 8, 16, 32\}$ , where  $c$  denotes the number of subframes (or slots) contained in a single RU, as defined by the NPUSCH format in Table 1. For the FDD mode, the timing constraint becomes  $\Delta_t > k_0 + N_{ru}N_{rep}$ ,  $k_0 \in \{8, 16, 32, 64\}$ , where the repetition factor satisfies  $N_{rep} \in \{1, 2, 4, 8, 16, 32, 64, 128\}$ . A value of  $N_{rep} = 1$  is sufficient for the base station to reauthorize the recovered resources. Increasing  $N_{rep}$  improves the scheduling flexibility of the base station; however, when the values of  $k_0$  and  $N_{rep}$  exceed their practical limits, further increases provide no meaningful benefit. In general, smaller parameter values enable more accurate terminal judgment and better alignment with practical scheduling requirements. The PUR configuration cycle  $T$  is defined within the HSFN timing structure; therefore,  $\Delta_t$  cannot exceed the period  $T$ . When the PUR indicator resource is advanced by  $\Delta_t$ , the corresponding uplink authorization resource can be reassigned to other terminals by the base station. In this case, the PUR resource can be considered fully recovered, resulting in no additional wireless resource waste. Let  $N_{re}^{ind}$  denote the number of RE required to indicate whether the PUR resource is used. According to the NPRACH technical principle, the minimum value is  $N_{re}^{ind} = 1$ . Without considering MU-MIMO transmission,

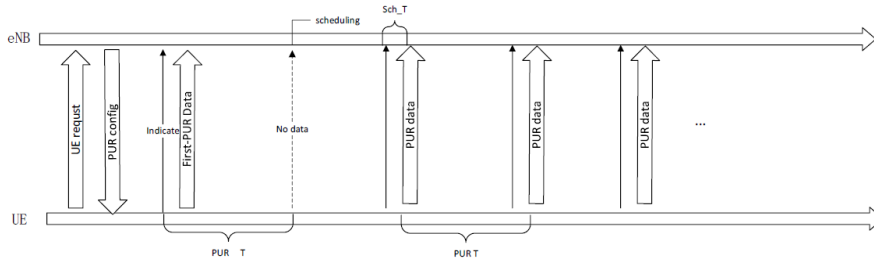


FIGURE 2. empty data in PUR schedule mechanism

the PUR utilization efficiency with terminal feedback can be expressed as

$$f(x) = \frac{N_{ru}N_{re}^{ru}N_{rep}(1-x)}{N_{re}^{ind} + N_{ru}N_{re}^{ru}N_{rep}(1-x)} \quad (5)$$

### C. TERMINAL FEEDBACK MECHANISM

PUR configuration includes periodic time-frequency resources, modulation coding scheme (MCS), transport block size (TBS), PUSCH repetitions, start position, wireless network temporary identifier (PUR-RNTI), timing advance (TA), allowed implicit release, effective configuration count, demodulation reference signal (DMRS) merging, power control parameters, PDCCH search space, coverage enhancement (CE) repetitions, and more. Prior to data upload, the terminal determines whether to use the obtained uplink resources based on wireless channel measurements. If no data is transmitted or channel quality is insufficient, the UE does not use pre-authorized resources. When the terminal's TA fails or coverage level changes, it refrains from uploading data, especially when moving between cells. After Release 16, the core network records terminal information for constant positions, enabling differentiated base station strategies. Mobile terminals transmit a signal on the indication resource only when data upload is required and channel conditions are met. If PUR resources are unused or unusable, no signal is sent. This ensures correct use of indication resources, prevents interference, and enables the base station to resolve PUR transmission information. Otherwise, PUR resources are recovered and implicit release statistics are updated, reducing empty port resource requirements. The feedback in the PUR scheduling mechanism is shown in Figure 3: Based on terminal feedback, PUR simplifies channel condition requirements for mobile terminals, allowing resource scheduling based solely on terminal service type. When unusable, PUR is released implicitly. Fixed terminals experience stable channels and valid TA when the base station position is unchanged. To conserve transmission power, terminals signal on indication resources only when not using authorized resources. The base station detects the indication signal, recovers PUR resources, and updates implicit release statistics. The digital transmission wireless resource utilization rate is shown in Figure 4.

### D. WIRELESS RESOURCE UTILIZATION COMPARISON

The improved PUR technology enhances wireless resource utilization and consequently increases the overall cell capacity. For simplicity, the analysis focuses on the utilization

of non-signaling wireless resource, which are primarily determined by the terminal's data transmission process. Under the proposed mechanism, the improved utilization ratio for PUR data transmission can be expressed as:

$$\begin{aligned} \Delta(x) &= \frac{\frac{N_{ru}N_{re}^{ru}N_{rep}(1-x)}{N_{re}^{ind} + N_{ru}N_{re}^{ru}N_{rep}(1-x)} - (1-x)}{1-x} \\ &= \frac{N_{ru}N_{re}^{ru}N_{rep}x - N_{re}^{ind}}{N_{re}^{ind} + N_{ru}N_{re}^{ru}N_{rep}(1-x)} \\ x &> \frac{N_{re}^{ind}}{N_{ru}N_{re}^{ru}N_{rep}} \end{aligned} \quad (6)$$

where  $N_{ru}$  denotes the number of resource units required for a single data packet,  $N_{re}^{ru}$  represents the number of resource elements contained in one RU,  $N_{rep}$  is the repetition factor for uplink transmission, and  $N_{re}^{ind}$  indicates the number of resource elements required for the PUR usage indicator. The PUR resource indicator reflects whether the pre-authorized resources are utilized. In theory, the indicator can be reduced to a minimum of one RE. When the empty packet rate  $x$  becomes sufficiently large, the proposed mechanism significantly improves wireless resource utilization. Otherwise, the resource consumption of the terminal must be evaluated to determine whether the feedback mechanism provides a net benefit. For the TDD mode, the PUR indicator resource can be placed within the available S-subframe resources (e.g., up-PTS). In this case, the additional signaling overhead can be considered negligible. Therefore, in the TDD configuration,  $N_{re}^{ind} = 0$ , which further increases the wireless resource utilization.

### E. MU-MIMO APPLICATION

MU-MIMO technology improves wireless resource utilization  $\frac{x}{1-x'}$ , with utilization positively correlated to the number of terminals. This paper demonstrates that MU-MIMO is effectively realized via terminal feedback PUR scheduling. Unlike dynamic scheduling, PUR-based MU-MIMO exploits stable channel conditions of fixed sensors. The base station utilizes historical Channel State Information (CSI) from prior PUR transmissions and the long-term statistical stability of industrial environments to perform spatial multiplexing without real-time CSI feedback. PUR configuration does not require NDCI resources, enabling MU-MIMO implementation in NB-IoT via terminal feedback PUR scheduling. To address pilot collision in ultra-low-cost devices, the base station assigns orthogonal DMRS to paired MU-MIMO terminals during initial RRC PUR

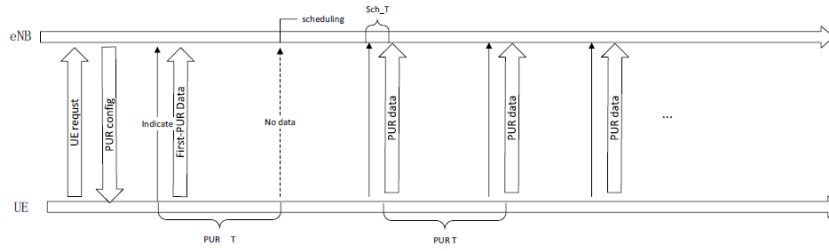


FIGURE 3. feedback in PUR schedule mechanism

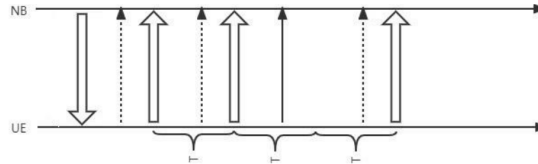


FIGURE 4. feedback in PUR schedule mechanism

configuration. Pre-allocated cyclic shifts of the base sequence ensure pilot orthogonality for small packets without extra signaling overhead. The base station employs a Successive Interference Cancellation (SIC) receiver to decouple overlapping uplink streams, ensuring reliable detection with low-complexity hardware. The scheduling principle authorizes resources in PUR as shown in Figure 5. At this stage, mobile terminals cannot accurately evaluate whether PUR resources should be utilized. However, from the perspective of PUR service terminals, the PUR-authorized wireless resources can also be reused to serve non-PUR terminals for uplink data transmission. Although authorizing non-PUR services terminals introduces additional constraints and computational complexity in uplink scheduling, it does not affect the allocation of the already authorized PUR resources to other terminals. Therefore, the system can further improve the utilization of digital transmission resources by allowing non-PUR services to reuse PUR-authorized resources. In this case, the utilization rate of PUR digital transmission resources can be expressed as:

$$f(x) = \frac{N_{ru}N_{re}^{ru}N_{rep} + (1-x)N_{ru}N_{re}^{ru}N_{rep}}{N_{ru}N_{re}^{ru}N_{rep}} = 2 - x \quad (7)$$

Since  $N_{re}^{ind} < N_{ru}N_{re}^{ru}N_{rep}$ , it follows that  $f(x) > 1$ . This indicates that the proposed mechanism can further increase the effective utilization of wireless transmission resources.

#### IV. EXPERIMENTAL VALIDATION

##### A. EXPERIMENTAL DESIGN

Experiments were conducted using MATLAB to verify algorithmic performance. Wireless resource scheduling is a core base station function and a key performance module. This experiment focuses on port resource scheduling, recovery, parsing, and terminal uplink authorization, including scenarios where terminals do not upload data or cannot process uplink transmissions. Sixty PUR service terminals were simulated, distributed across eleven cycles per protocol specifications. The simulation employed the Indoor Factory

(InF-SH) path loss model from 3GPP TR 38.901, with a shadow fading standard deviation of 6 dB, reflecting dense metallic machinery in workshops. Thermal noise power density was set at -174 dBm/Hz, and interference-to-noise ratio (INR) maintained at 3 dB, simulating electromagnetic interference from industrial motors. Terminals were distributed within a 100 m × 100 m factory, with a base station antenna height of 6 m. Terminal empty packet rates were set at 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% (cell level). All PURs were initialized within the minimum cycle and configuration resources to avoid conflicts. Wireless frame start positions between terminals were separated by up to  $4 \times 1024$  frames, satisfying 3.75 kHz subcarrier requirements for 128 repetitions. Minimum link adaptation requirements were calculated based on SINR. High-density machinery warranted a Multi-path Rayleigh Fading model with a maximum Doppler frequency of 5 Hz, representing low mobility for fixed and handheld sensors. Low empty packet rate requirements limit PUR technology adaptation and complicate cycle selection. Traditionally, efficiency was maintained by prohibiting PUR in high empty packet rate scenarios. This experiment explicitly tests rates up to 40% to demonstrate that the feedback-based recovery mechanism maintains high resource utilization, overcoming the prior 10% threshold. Scenarios were divided by empty packet rate, with high-rate scenarios compared directly. MU-MIMO improvement is well established; thus, its resource utilization enhancement is not further discussed.

##### B. EXPERIMENTAL RESULTS AND ANALYSIS

PUR wireless resource utilization is determined by terminal empty packet rate. Lower rates guarantee higher utilization. The relationship is depicted in Figure 6. Low empty packet rate requirements also restrict PUR adaptation and complicate cycle T selection. PUR technology conserves NDCI resources, but these are not newly utilized. To address these challenges, the feedback-based PUR scheduling mechanism allows terminals to report resource usage promptly, enabling

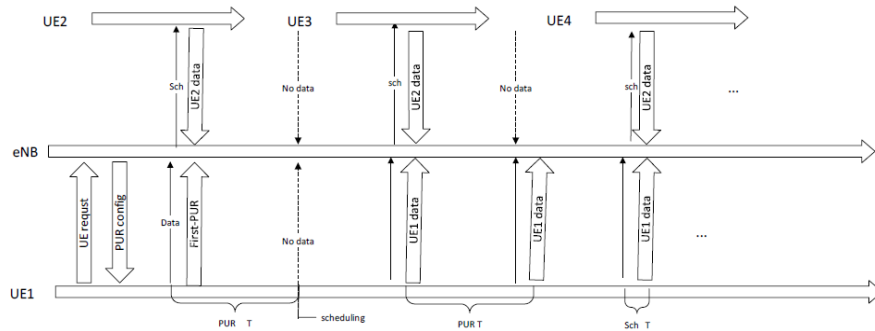


FIGURE 5. MU-MIMO in PUR schedule mechanism

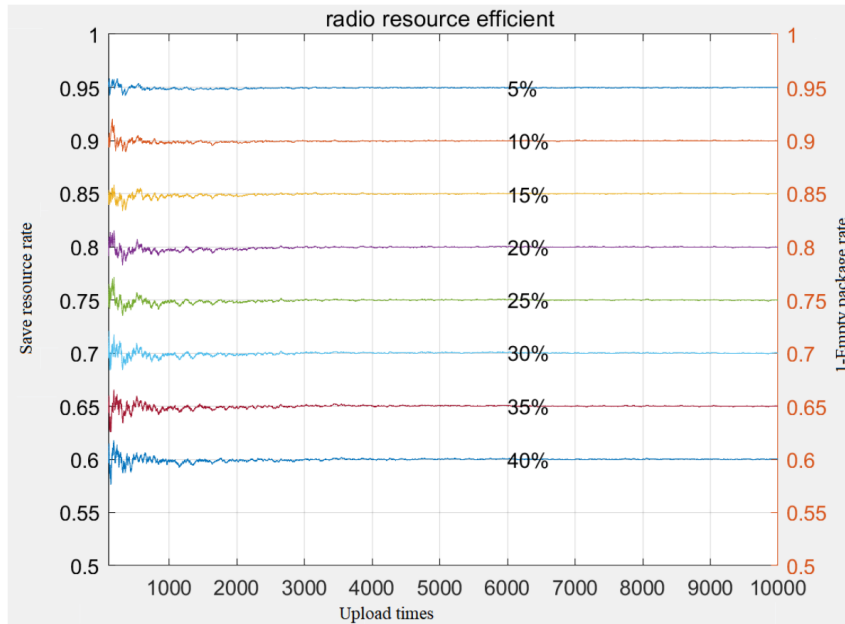


FIGURE 6. PUR radio resource efficient

timely recovery of unused PUR resources and improving wireless resource utilization. By leveraging PUR's NDCI-saving features, MU-MIMO is applied to NB-IoT, further enhancing resource efficiency. The uplink resource utilization of the NB-IoT wireless system is further improved. The resulting uplink resource utilization rate is illustrated in the following figure. In the calculation,  $N_{re}^{ind}$  represents the indicator resource overhead, which is implemented using NPUCCH resources. In practical deployments, this overhead can be further reduced through resource multiplexing. In the TDD mode, if the PUR indicator signaling is placed in the Up-PTS (uplink pilot time slot), the additional NPUSCH resource overhead can be considered negligible. Under this condition, the indicator resource consumption can be approximated as  $N_{re}^{ind} \approx 0$  and the theoretical wireless resource utilization can therefore approach 100%. Simulation results are consistent across scenarios. The feedback indicator for PUR resource usage is NPUSCH Format 2, with one RU per terminal. Among multiple PUR users, indicator resource usage can be reduced by multiplexing, theoretically to one RE. In this simulation, multiplexing

was not applied, so actual utilization may exceed simulation results.

### C. ANALYSIS

NB-IoT requirements include ultra-low cost, ultra-wide coverage, ultra-low power consumption, and massive capacity. The proposed method is limited to software changes, thus preserving cost and coverage advantages. The feedback mechanism requires terminals to send indication signals, incurring power consumption overhead. The base station adjusts its scheduling algorithm, with cell capacity positively correlated to wireless resource utilization. Power consumption impact arises from terminal transmission of indication signals prior to PUR resource usage, but display and release signaling are avoided, saving terminal power during release. For fixed terminals, increased indication signal power consumption is minimal due to stable channels and infrequent signaling. Analysis distinguishes between RF and non-RF power consumption; only emission power increase is considered. The increased transmitting power of

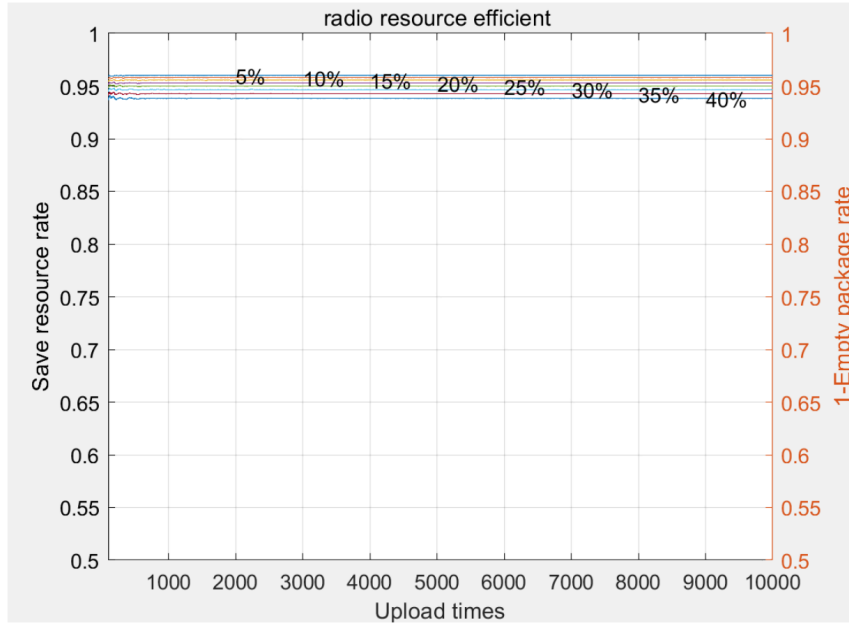


FIGURE 7. radio resource efficient in feedback

the mobile terminals is as follows:

$$p(x) = \frac{N_{re}^{ind}}{N_{ru}N_{re}^{ru}N_{rep}} \quad (8)$$

The transmission power of the fixed terminal increases as follows:

$$p(x) = \frac{xN_{re}^{ind}}{N_{ru}N_{re}^{ru}N_{rep}} \quad (9)$$

According to the current 3GPP protocol, it is known that  $N_{ru} \in \{2, 3, 4, 5, 6, 7\}$ , therefore, the transmission power increase range of the mobile terminal is,  $7.97 \times 10^{-5} < p(x) < 3.57 \times 10^{-2}$ , and the power increased by the fixed terminal is smaller ( $x < 1$  constant establishment). Since terminal feedback PUR eliminates release signaling, RF power consumption increase is limited.

## V. CONCLUSION

The widespread deployment of sensors in production lines generates fragmented data packets, often underutilizing NB-IoT wireless resources despite substantial capacity demands. PUR technology represents a significant advancement, streamlining access and authorization processes, improving digital transmission resource ratios, and reducing terminal power consumption. While traditional PUR is limited to stable, low-latency traffic with low empty packet rates, the proposed terminal feedback mechanism enables real-time recovery of unused authorizations, substantially improving resource utilization in high empty packet rate scenarios. This demonstrates that PUR can be effectively deployed even when empty data rates exceed the conventional 10% threshold, provided the indication resource cost  $\frac{N_{re}^{ind}}{N_{ru}N_{re}^{ru}N_{rep}}$  remains minimal. The mechanism also permits implicit release of PUR resources, eliminating wireless resource overhead from release signaling and conserving

resources and power. Terminal use of indicator resources and associated behavior slightly increases overhead and power consumption, but when empty packet rates are high, wireless resource utilization improves.

In TDD systems, the new overhead is negligible with efficiency gains more pronounced—only one RE is required. In non-up-pts resource allocation, multiple terminals must reuse indicator resources within a RU to minimize resource consumption. For MU-MIMO systems, independence of the empty port channel and proximity of terminal target power are essential to prevent low-power terminal signals from being overshadowed by high-power signals. Previously, PUR could not recycle unused resources, and strict configuration requirements were imposed. With the proposed recovery mechanism, PUR authorization becomes more flexible. Integrating PUR with spatial division multiplexing enables more efficient wireless spectrum utilization. By resolving CSI acquisition and pilot management challenges through pre-configuration and industrial environment stability, MU-MIMO is a viable solution for enhancing capacity in NB-IoT deployments. Continued analysis and study will further optimize wireless spectrum resource usage.

## AUTHOR CONTRIBUTIONS

Xiaoqing Chen designed, collected and analyzed the data, and drafted the manuscript. Xiaoqing Chen conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xiaoqing Chen participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

## CONFLICTS OF INTEREST

The author declares no conflict of interest.

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