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Analytical Modelling of NB-IoT Uplink Resource Split Between NPRACH and NPUSCH for Device Density Optimization

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ABSTRACT: Narrowband Internet of Things (NB-IoT) networks must support large numbers of sporadically active devices within a narrow uplink bandwidth. A key configuration choice is the split between random-access resources, Narrowband Physical Random Access Channel (NPRACH), and data-channel resources, Narrowband Physical Uplink Shared Channel (NPUSCH), which we capture with a single parameter, r_{UL}, defined as the fraction of uplink resources reserved for NPRACH. We develop a stylized analytical model that couples a multichannel slotted-ALOHA description of NPRACH with a simple NPUSCH capacity model and use it to characterize how the parameter r_{UL} affects random-access collisions, data-channel utilization, and end-to-end reliability. For representative single-cell parameters, the analysis indicates that very small values of r_{UL}, for example, below about 0.10, drive NPRACH into an overloaded regime with per-attempt collision probabilities exceeding 99 percent, while an intermediate range between 0.25 and 0.40 yields a stable operating region. Packet-level simulations for three traffic profiles, 30-byte, 150-byte, and 450-byte packets, confirm these trends and quantify their impact, relative to baseline configurations resembling typical deployments, tuning r_{UL} within the stable region increases the maximum supportable device density by approximately 61 to 238 percent, about 1.6 to 3.4 times, at a 99 percent packet-delivery target. These gains are achieved purely through software-level reconfiguration of the NPRACH/NPUSCH split, without changes to hardware or spectrum.

KEYWORDS: Narrowband IoT, resource allocation, device density optimization, collision analysis, NPRACH, NPUSCH, massive IoT.

I. INTRODUCTION

The Internet of Things (IoT) is expected to connect tens of billions of devices, many of which generate small, sporadic uplink messages that must be delivered reliably and at low cost. Narrowband IoT (NB-IoT) is the 3GPP cellular technology designed to meet this demand, offering wide-area coverage, extended battery life, and low device complexity by operating in only 180 kHz of spectrum [1]-[3]. Despite rapid standardization and commercial deployment, both analytical studies and measurement driven evaluations indicate that existing NB-IoT networks can operate well below their theoretical capacity when the uplink access procedure and resource allocation are not carefully tuned [3]-[6].

A central design challenge in NB-IoT is the allocation of uplink resources between random access and data transmission. In the uplink, the Narrowband Physical Random Access Channel (NPRACH) is used for contention-based access and initial synchronization, while the Narrowband Physical Uplink Shared Channel (NPUSCH) carries user data [1], [7]. We focus on a single dimensionless parameter, denoted by r_{UL}, that captures this allocation, where, r_{UL} is the fraction of uplink resources devoted to NPRACH, with the remaining fraction $1-r_{UL}$ available for NPUSCH. This abstraction is in line with recent work on uplink resource partitioning and NPRACH-aware allocation schemes [8], [9].

This single factor induces a fundamental trade-off. If r_{UL} is too small, NPRACH opportunities are too sparse to accommodate the offered traffic, leading to heavy random-access contention, frequent preamble collisions, and access failures. If r_{UL} is too large, excessive resources are reserved for NPRACH, starving NPUSCH and causing congestion, delays, or drops on the data channel. Detailed models of the NB-IoT random-access procedure including stochastic-geometry and Markov-chain analyses with coverage-enhancement groups [10], [11], packet-level evaluations of dense public and private deployments [4], [12], and survey work on congestion management [5], [13] all point to random access as a primary bottleneck in dense NB-IoT networks. At the same time, operators often configure NPRACH and NPUSCH parameters according to spectrum constraints and qualitative rules of thumb rather than explicit end-to-end optimization, leaving room for improvement in how r_{UL} is chosen in practice [3]-[6].

Recent work has explored data-driven and reinforcement-learning-based approaches to tune NB-IoT parameters adaptively, including random access configuration, access barring, scheduling policies, and uplink resource allocation [4]-[16]. These methods are promising for complex, timevarying environments, and surveys of Random Access (RA) congestion-control schemes increasingly emphasize learning-based adaptations [13]. However, such approaches offer limited analytical insight into the underlying capacity limits and failure mechanisms. In particular, there is comparatively little work that couples a tractable random-access model with an explicit representation of NPUSCH utilization, so as to expose simple operating regions and failure boundaries as functions of r_{UL} and the traffic load, and to provide closed-form design rules that can guide both static configuration and adaptive control.

In this paper, we develop a stylized but transparent analytical framework that links NB-IoT random access and data-channel utilization through a multichannel slotted-ALOHA model of NPRACH. We treat the random-access stage as a slotted-ALOHA system with multiple orthogonal preambles, derive the load and collision probability as functions of r_{UL} and the arrival rate, and couple the resulting successful-access rate to a simple model of NPUSCH capacity that captures the impact of packet size and coverage-enhancement level. The framework focuses on a single NB-IoT cell with homogeneous Poisson arrivals, a fixed coverage-enhancement mix, and a heuristic mapping from NPUSCH utilization to congestion probability. These assumptions enable closed-form expressions while intentionally abstracting away backoff dynamics, access class barring, and multi-cell effects. Within this setting, we study how to choose r_{UL} so as to maximize the supported device density under a target reliability constraint.

Our contributions are threefold. First, we formulate an analytical model that couples NPRACH contention and NPUSCH utilization through a single control parameter r_{UL}, making the main NB-IoT uplink bottlenecks explicit in terms of random-access load, collision probability, and data-channel occupancy. Second, we use this model to delineate qualitative operating regions, including collapse, congestion-limited, and stable regimes, in the (r_{UL}, λ) plane, where λ denotes the aggregate arrival rate of devices (devices/s), and to identify a practical range of r_{UL} values that keeps the system within the stable region under the assumed traffic model. Third, we validate the analytical predictions with packet-level simulations and quantify the achievable device-density improvements relative to typical baseline configurations, observing gains between approximately 61% and 238% (1.6–3.4 times more devices per km^2) across three representative traffic profiles. We translate these results into simple design guidelines that allow network operators to treat r_{UL} as an explicit tuning factor and to complement more detailed optimization and learning-based control schemes [14]-[16].

The rest of this paper is organized as follows. Section II presents the system model and mathematical analysis framework, deriving the impact of r_{UL} on random access and NPUSCH utilization. Section III validates the analysis with packet-level simulations and discusses the resulting device density gains. Section IV concludes the paper and outlines directions for future work, including extensions to multi-cell scenarios and adaptive tuning of r_{UL} and related NB-IoT configuration parameters.

II. SYSTEM MODEL AND ANALYTICAL FRAMEWORK

A. System Model, Assumptions, and Metrics

We consider a single NB-IoT cell in which devices generate uplink reports according to a homogeneous Poisson process with rate λ (devices/s). The uplink follows the tandem structure of NPRACH for initial access and NPUSC for data transmission. The resource-splitting parameter r_{UL} governs how much of the uplink resource budget is devoted to NPRACH versus NPUSCH.

We define:

$$r_{UL} = \frac{NPRACH\ resources}{(NPRACH\ resources\ +\ NPUSCH\ resources)}, (1)$$

so that r_{UL} is the fraction of uplink resources reserved for NPRACH, and the remaining fraction $1 - r_{\mathrm{UL}}$ is available for NPUSCH. Increasing r_{UL} makes random access more frequent but reduces the capacity of NPUSCH. Decreasing r_{UL} frees resources for NPUSCH but increases contention on NPRACH.

To keep the analysis tractable and aligned with our goal of obtaining closed-form expressions, we adopt a stylized model with the following simplifying assumptions, (i) a single cell with no inter-cell interference and homogeneous Poisson arrivals, (ii) a multichannel slotted-ALOHA description of NPRACH with $m = 48$ orthogonal preambles and independent preamble choices, without modelling detailed backoff dynamics or access-class barring, (iii) an NPUSCH service model based on a per-second Resource-Unit (RU) budget and an aggregate utilization metric, rather than a detailed scheduler, and (iv) a fixed distribution over Coverage-Enhancement (CE) levels and a heuristic mapping from NPUSCH utilization to congestion probability. These assumptions intentionally abstract away fine-grained protocol features in exchange for analytical transparency.

Within this framework, our primary performance metric is the maximum device density (devices/km^2) that can be supported while meeting a target end-to-end success probability $P_{\mathrm{succ}} \geq P_{\mathrm{tar}}$ (with $P_{\mathrm{tar}} = 0.99$ in our examples). At the analytical level, we track three quantities: (i) the random access collision probability P_{coll} on NPRACH, (ii) the congestion probability P_{cong} on NPUSCH, and (iii) the combined per-attempt failure probability P_{failure} resulting from both contention and congestion.

B. Random-Access Analysis via Multichannel Slotted ALOHA

In the NB-IoT configuration considered, each Random Access Opportunity (RAO) offers $m = 48$ orthogonal preambles. The nominal RAO period for the baseline configuration is δ_{RAO}. Allocating a fraction r_{UL} of the uplink resource budget to NPRACH effectively scales the RAO density, yielding

$$T_{\mathrm{RAO}} = \frac{\delta_{\mathrm{RAO}}}{r_{\mathrm{UL}}}. \quad (2)$$

Smaller values of r_{UL} correspond to sparser RAOs and thus higher contention. Let λ be the aggregate arrival rate of new reports (devices/s). Under the slotted-ALOHA model with independent choices of preamble and RAO, the expected load per preamble in each RAO is

$$G = \frac{\lambda \delta_{\mathrm{RAO}}}{r_{\mathrm{UL}}}, \quad (3)$$

which is dimensionless and can be interpreted as the average number of contending devices per preamble per RAO.

Under the standard independence assumption, the probability that a given preamble experiences no collision, i.e., exactly one device selects it, is Ge^{-G}, and the collision probability experienced by an individual device is

$$P_{\mathrm{coll}} = 1 - e^{-G}, \qquad S(G) = Ge^{-G}, \quad (4)$$

where $S(G)$ is the normalized slotted-ALOHA throughput. As G increases beyond 1, the throughput saturates and then decreases, while P_{coll} approaches 1, indicating an overloaded random-access channel.

For a representative configuration with λ= 50 devices/s, $m =$ 48 preambles, and $\delta_{\mathrm{RAO}} = 0.64$ s, low values of r_{UL} correspond to large G and near-certain collisions. For example, at $r_{\mathrm{UL}} = 0.05$ we obtain $G \approx 13.33$ and $P_{\mathrm{coll}} > 0.999$, effectively making random access unusable. At r_{UL}= 0.30, $G \approx 2.22$ and $P_{\mathrm{coll}} \approx 0.89$, which is still high at the per attempt level but lies near the high-efficiency region of the slotted-ALOHA curve.

TABLE I RANDOM-ACCESS OPERATING POINT VERSUS r_{UL} (REPRESENTATIVE PARAMETERS)

r_{UL}	Load G	P_{coll}	$S(G)$	Zone (Interpretive)
0.05	13.33	>99.9%	0.000	Collapse
0.10	6.67	99.9%	0.008	Collapse / Critical
0.15	4.44	98.8%	0.053	High-load
0.20	3.33	96.4%	0.119	Marginal
0.25	2.67	93.1%	0.184	Stable (Conservative)
0.30	2.22	89.1%	0.245	Stable
0.35	1.90	85.0%	0.286	Stable / Recommended
0.40	1.67	81.2%	0.313	Stable / Recommended
0.45	1.48	77.3%	0.329	Stable
0.50	1.33	73.6%	0.353	High-efficiency

Table I summarizes the random-access operating point for a range of r_{UL} values under this parameter set. The "Collapse" zone corresponds to very high collision probability and negligible throughput. The "Stable" zone combines high but manageable collision probabilities with the high-throughput region of the slotted-ALOHA curve. These qualitative zones will later be compared against simulation results in Section III. The table corresponds to the parameters $\lambda = 50$ devices/s, $\delta_{\mathrm{RAO}} = 0.64$ s, $m = 48$. $S(G) = Ge^{-G}$ is the normalized slotted-ALOHA throughput. Zone labels are qualitative and specific to this parameter set. They are used to interpret operating regions rather than to claim universal thresholds.

C. Data Transmission Phase and NPUSCH Utilization

Devices that successfully complete NPRACH proceed to NPUSCH for data transmission. Under the slotted-ALOHA model, the aggregate rate of successful random-access attempts is

$$\lambda_s = \frac{m\,Ge^{-G}}{T_{RAO}} = \frac{m\,S(G)}{T_{RAO}}\ [\text{devices/s}], \quad (5)$$

where G and T_{RAO} are given by (2)–(3). This is the arrival rate into the NPUSCH service system.

Each device carries a packet of size L bytes and belongs to a coverage-enhancement level CE $\in \{0,1,2\}$. In line with NB-IoT transport block sizing, we approximate the number of resource units (RUs) required for a packet as

$$N_{\mathrm{RU}} = \left\lceil \frac{L}{32} \right\rceil R_{\mathrm{CE}}\ [\text{RUs/packet}], \quad (6)$$

where $R_{\mathrm{CE}} \in \{1,8,64\}$ for CE $\in \{0,1,2\}$, respectively.

Let P(CE = i) denote the fraction of devices in each CE level. In our numerical examples we use a fixed distribution representative of urban deployments, leading to

$$E[N_{RU}] = \left\lceil \frac{L}{32} \right\rceil \sum_i \mathrm{P}(\mathrm{CE} = i) R_{\mathrm{CE}} = i. \quad (7)$$

The total NPUSCH RU budget per second is denoted by N_{total}. Allocating a fraction r_{UL} of the uplink to NPRACH leaves

$$C_{\mathrm{NPUSCH}} = N_{\mathrm{total}}(1 - r_{\mathrm{UL}}) \quad [\mathrm{RU_s/s}] \quad (8)$$

for data transmission. The resulting NPUSCH utilization is

$$\rho_{\mathrm{NPUSCH}} = \frac{\lambda_s E[N_{\mathrm{RU}}]}{C_{\mathrm{NPUSCH}}}. \quad (9)$$

This quantity captures how close NPUSCH is to saturation as a function of r_{UL}, the arrival rate, and the traffic mix.

D. End-to-End Failure Probability and Optimization

The end-to-end per-attempt failure probability combines contention failures on NPRACH and congestion failures on NPUSCH. We approximate it as

$$P_{\mathrm{failure}} = P_{\mathrm{coll}} + (1 - P_{\mathrm{coll}})P_{\mathrm{cong}}, \quad (10)$$

where P_{coll} is given by (4) and P_{cong} is the probability that a device that has gained access to NPUSCH fails to be served within the latency or buffer constraints of the application.

In principle, P_{cong} could be derived from a detailed queueing model of the NPUSCH scheduler. To keep the framework simple and analytically transparent, we instead adopt a heuristic mapping from utilization to congestion:

$$P_{\text{cong}} = \max\left\{0, \frac{\rho_{\text{NPUSCH}} - 0.8}{0.2}\right\}, \quad (11)$$

so that $P_{\text{cong}}= 0$ for $\rho_{\text{NPUSCH}} \leq 0.8$ and increases linearly to 1 as ρ_{NPUSCH} approaches 1. The threshold value 0.8 is chosen to reflect the utilization range where queueing delays begin to grow rapidly in M/D/1-type systems. The linear mapping itself is a modeling choice that is later calibrated against simulation in Section III.

Equations (4)–(11) together define P_{failure} as a function of r_{UL}, the arrival rate, and the traffic mix. In practice, NB-IoT devices are allowed multiple random-access attempts. Our simulator implements these attempts and their timers explicitly, while the analytical model uses P_{failure} as a first-order approximation of the per-attempt failure probability. The reliability constraint $P_{\text{succ}} = 1 - P_{\text{failure}} \geq P_{\text{tar}}$, combined with a traffic model and a deployment geometry, yields a maximum sustainable device density for each value of r_{UL}.

Rather than claiming universal boundaries, we interpret the results of this analytical model as a way to delineate qualitative operating regions in the (r_{UL}, λ) plane and to identify practical ranges of r_{UL} that keep the system out of collapse and congestion-dominated regimes for the scenarios of interest.

These regions are compared against packet-level simulation results in Section III, which both validate the analytical trends and quantify how they translate into concrete device-density gains.

III. VALIDATION AND RESULTS

A. Simulation Setup

We validate the analytical framework of Section II through a discrete-event NB-IoT uplink simulator that implements the NPRACH and NPUSCH procedures, the coverage enhancement levels, and the retransmission rules defined in the 3GPP specifications [1], [4], [7]. New reports are generated according to a homogeneous Poisson process with rate λ and immediately trigger a random-access attempt on NPRACH. Collisions are resolved exactly as in the analytical model. In each RAO, devices choose among the $m = 48$ orthogonal preambles uniformly at random; an NPRACH attempt succeeds if and only if it is the unique use of its preamble in that RAO. Upon successful random access, devices enter the NPUSCH scheduler, which allocates RUs according to the coverage-enhancement level and packet size. The simulator tracks both contention failures on NPRACH and congestion-induced failures on NPUSCH, so that the measured metrics are directly comparable with those defined in the mathematical analysis.

Unless stated otherwise, we consider a single-cell deployment with $\lambda = 50$ devices/s, $\delta_{\text{RAO}} = 0.64$ s, and an RU budget consistent with a single-carrier NB-IoT configuration. The coverage-enhancement distribution is fixed to the representative mix used in the analytical model, yielding the same mean RU requirement $E[N_{\text{RU}}]$. Each configuration is simulated for 400 s, and multiple independent runs are averaged so that 95% confidence intervals on P_{succ} are within a few percentage points and are omitted from the plots for clarity. A packet is declared successful if it is delivered within at most $A_{\max}$ random-access attempts and without exceeding an NPUSCH delay budget of 10 s, otherwise it is counted as a failure. The resulting overall success probability P_{succ} is compared against the reliability target P_{tar} (here, $P_{\text{tar}} = 0.99$) when computing the maximum sustainable device density.

B. Optimization Results

Table II summarizes the network capacity obtained from simulation for three packet sizes (30 B, 150 B, and 450 B) and several values of r_{UL}. For each packet size we select a baseline configuration that is representative of typical deployments (for example, $r_{\text{UL}}= 0.15$ for 30 B and 150 B traffic and $r_{\text{UL}} = 0.20$ for 450 B), and we report the corresponding device density (devices/km^2) at which the end-to-end success probability P_{succ} remains above 0.99. For all configurations, the table reports the device density and the per-attempt collision rate measured from simulation, together with the relative improvement with respect to the baseline configuration.

TABLE II: COMPREHENSIVEDEVICE-DENSITYOPTIMIZATIONRESULTS

Packet Size	r_{UL}	Device Density (devices/km2)	Improvement vs. baseline	Collision Rate
30 B	0.15	485	baseline	99%
	0.25	834	+72%	93%
	0.35	1,120	+131%	82%
	0.40	1,316	+171%	80%
150 B	0.15	331	baseline	99%
	0.20	634	+91%	96%
	0.30	960	+190%	89%
	0.35	1,120	+238%	82%
450 B	0.20	254	baseline	96%
	0.30	409	+61%	89%
	0.40	485	+91%	80%
	0.45	520	+105%	78%

The table reveals three consistent patterns. First, moving from the baseline configuration to the optimized r_{UL} often approximately doubles or more than doubles the sustainable device density. The improvements range from +61% (large packets) to +238% (mixed traffic) while still satisfying the same reliability target. Second, although the optimized points operate with very high random-access collision rates, between 78% and 93%, the overall success probability remains above 0.99 because devices are allowed multiple access attempts and NPUSCH remains uncongested. Third, the optimal r_{UL} shifts gradually with packet size, smaller packets favor larger values ofr_{UL}, whereas large packets benefit from leaving more resources for NPUSCH. These shifts are consistent with the analytical trade-off between collision probability and NPUSCH utilization derived in Section II.

C. Collision Zones and Capacity Optimization

To quantify how the analytical collision regions translate into practice, Figure 1 plots the per-attempt collision probability as a function of r_{UL} for the representative parameter set. The solid curve shows the multichannel slotted-ALOHA prediction from (4), and the markers overlay simulation results.

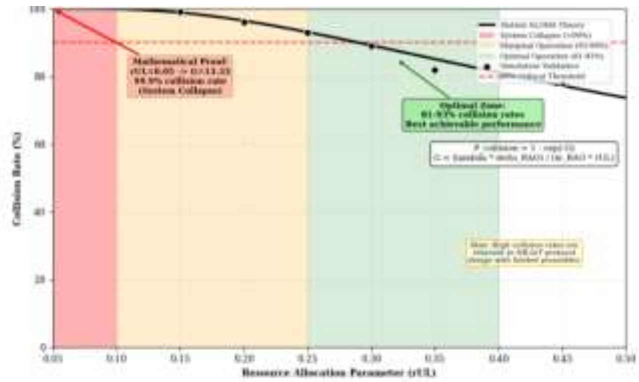

Figure 1. Random-access collision probability as a function of r_{UL} for the representative configuration ($\lambda =$ 50 devices/s, δ_{RAO} = 0.64 s, $m =$ 48). The curve shows the multichannel slotted-ALOHA prediction (4), and markers show simulation results. Shaded regions illustrate collapse (red), marginal (yellow), and stable (green) operating zones.

The background shading highlights three operating zones: a red "collapse" zone for $r_{\mathrm{UL}} < 0.10$, where $P_{\mathrm{coll}} > 99\%$ and throughput is negligible. A yellow marginal zone for $0.10 \leq r_{\mathrm{UL}} < 0.25$ where collisions remain above 93%, and a green stable zone for $0.25 \leq r_{\mathrm{UL}} \leq 0.40$ where collisions are still high but random access remains feasible. Simulation points track the analytical curve closely, typically within a few percentage points, supporting the collision component of the mathematical model.

Figure 2 complements the table by plotting the sustainable device density as a function of r_{UL} for each packet size. For each configuration, the device density corresponds to the maximum value at which the simulated end-to-end success probability satisfies $P_{\mathrm{succ}} \geq 0.99$. The shaded vertical band marks the practical optimization zone $0.25 \leq r_{\mathrm{UL}} \leq 0.40$, where all three traffic profiles achieve near-maximal capacity while remaining in the stable collision region. The annotations highlight, for example, the +171% gain for 30 B packets at r_{UL} = 0.40 and the +238% gain for 150 B packets at r_{UL} = 0.35, relative to their respective baselines in Table II.

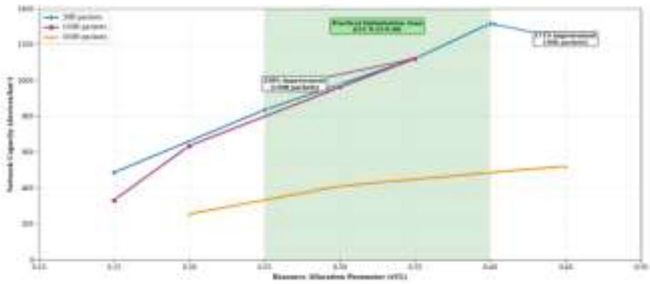

Figure 2. Network capacity (devices/km2) versus r_{UL} for three packet sizes. Each point gives the maximum sustainable device density for which $P_{\mathrm{succ}} \geq$ 0.99in simulation. The shaded region indicates the practical optimization zone where all traffic profiles achieve near-maximal capacity while remaining in the stable collision region.

Across the configurations in Table II and Figure 2, the practical range $0.25 \leq r_{\mathrm{UL}} \leq 0.40$ consistently delivers large gains while keeping the system within the stable collision region and below the NPUSCH congestion threshold. The exact optimum depends on the traffic mix and packet size, but the overall pattern is robust: values of r_{UL} around 0.30–0.35 strike a good compromise between collision probability and data-channel utilization. The simulations therefore corroborate the analytical trade-offs derived in Section II and indicate that many NB-IoT deployments can significantly increase device density through software-level reconfiguration of the NPRACH/NPUSCH resource split, without changing hardware or spectrum.

CONCLUSION

This paper presented an analytical framework and supporting simulation study for understanding how the NB-IoT uplink resource split between NPRACH and NPUSCH, captured by the parameter r_{UL}, affects random-access collisions, data-channel utilization, and end-to-end reliability. By modeling NPRACH as a multichannel slotted-ALOHA system and NPUSCH as a resource-unit budget driven by the successful random-access rate, we derived closed-form expressions for the collision probability, NPUSCH utilization, and a first-order approximation of the overall failure probability as functions of r_{UL} and the offered load.

Under a single-cell setting with homogeneous Poisson arrivals, a fixed coverage-enhancement mix, and a heuristic mapping from utilization to congestion probability, the analysis delineates qualitative operating regions in the (r_{UL}, λ) plane. Low values of r_{UL} lead to random-access overload, high values of r_{UL} limit NPUSCH, and an intermediate range around $0.25 \leq r_{UL} \leq 0.40$ yields a stable region where random access remains feasible and NPUSCH utilization stays below the congestion threshold for the traffic profiles we consider. Packet-level simulations confirm these trends and quantify their impact: relative to baseline configurations resembling typical deployments, tuning r_{UL} within this range supports approximately 61% to 238% more devices per km^2 (about 1.6–3.4 times) while maintaining $P_{succ} \geq 0.99$, despite high per attempt collision probabilities. The framework is intentionally simplified: it does not model dynamic access barring, detailed backoff behavior, or multi- cell interference, and it treats the mapping from utilization to congestion in a heuristic way. Within these limitations, the results indicate that revisiting the NPRACH/NPUSCH split can yield substantial gains using only software-level reconfiguration. Future work includes extending the model to multi-cell scenarios and more detailed schedulers, and combining the analytical insights with optimization or learning-based control schemes for closed-loop adjustment of r_{UL} and related NB-IoT parameters.

REFERENCES

1. Y . P. E. Wang, X. Lin, A. Adhikary, A. Gr ¨ovlen, Y . Sui, Y . Blankenship, J. Bergman, and H. S. Razaghi, "A primer on 3GPP narrowband Internet of Things (NB-IoT),"IEEE Communications Magazine, vol. 55, no. 3, pp. 117–123, Mar. 2017.
2. C. B. Mwakwata, H. Malik, M. Mahtab Alam, Y . Le Moullec, S. P ¨arand, and S. Mumtaz, "Narrowband Internet of Things (NB-IoT): From physical (PHY) and media access control (MAC) layers perspectives," Sensors, vol. 19, no. 11, art. 2613, Jun. 2019.
3. E. Rastogi, N. Saxena, A. Roy, and D. R. Shin, "Narrowband Internet of Things: A comprehensive study,"Computer Networks, vol. 173, art. 107209, May 2020.
4. S. Martiradonna, G. Piro, and G. Boggia, "On the evaluation of the NB-IoT random access procedure in monitoring infrastructures," Sensors, vol. 19, no. 14, art. 3237, Jul. 2019.
5. E. M. Migabo, K. Djouani, and A. M. Kurien, "The narrowband Internet of Things (NB-IoT) resources management performance: State of art, challenges, and opportunities," IEEE Access, vol. 8, pp. 97 658–97 675, 2020.
6. B. Martinez, F. Adelantado, A. Bartoli, and X. Vilajosana, "Exploring the performance boundaries of NB-IoT," IEEE Internet of Things Journal, vol. 6, no. 3, pp. 5702–5712, Jun. 2019.
7. 3GPP, "E-UTRA; medium access control (MAC) protocol specification," 3GPP TS 36.321, Rel. 13, v13.3.0, Jan. 2016. [Online]. Available: https://portal.3gpp.org
8. Y .-J. Yu and J.-K. Wang, "NPRACH-aware link adaptation and uplink resource allocation in NB-IoT cellular networks," IEEE Transactions on Vehicular Technology, vol. 70, no. 5, pp. 4894–4906, 2021.
9. Y .-J. Yu, Y .-H. Huang, and Y . Y . Shih, "Cross-cycled uplink resource allocation over NB-IoT," Sensors, vol. 21, no. 23, art. 7948, 2021.
10. Y . Liu, Y . Deng, N. Jiang, M. Elkashlan, and A. Nallanathan, "Analysis of random access in NB-IoT networks with three coverage enhancement groups: A stochastic geometry approach," IEEE Transactions on Wireless Communications, vol. 20, 2021.
11. C. Ramineniet al., "Performance evaluation of random access in narrow band Internet of Things systems,"Computer Networks, vol. 205, art. 109399, 2022.
12. P. J ¨orke, D. Ronschka, and C. Wietfeld, "Performance evaluation of random access for small data transmissions in highly dense public and private NB-IoT networks," inProc. IEEE 97th Vehicular Technology Conf. (VTC2023-Spring), 2023, pp. 1–7.
13. L. Iiyambo, G. Hancke, and A. M. Abu-Mahfouz, "A survey on NB-IoT random access: Approaches for uplink radio access network congestion management," IEEE Access, vol. 12, pp. 95 487–95 506, 2024.
14. N. Jiang, Y . Deng, A. Nallanathan, and J. A. Chambers, "Deep reinforcement learning for real-time optimization in NB-IoT networks,"arXiv preprintarXiv:1812.09026, Dec. 2018.
15. Y . Hadjadj-Aoul, M. Bagaa, T. Taleb, and M.-S. Alouini, "Access control in NB-IoT networks: A deep reinforcement learning approach," Information, vol. 11, no. 11, art. 541, Nov. 2020.
16. S. Anbazhagan and R. K. Mugelan, "Next-gen resource optimization in NB-IoT networks: Harnessing soft actor–critic reinforcement learning," Computer Networks, vol. 252, art. 110670, 2024.