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Original Research Article

Enhanced Distance-Based Resource Allocation (EDBRA) Scheme for Optimized Spectrum Efficiency in Device-to-Device (D2D) Enabled 6G Networks

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Abstract

Device-to-device (D2D) communication is a key enabler for offloading traffic from cellular networks and supporting proximity-based services in beyond-5G and emerging 6G systems. This paper proposes the Enhanced Distance-Based Resource Allocation (EDBRA) scheme, a low-complexity priority-metric allocator that combines real-time signal-to-interference-plus-noise ratio (SINR) with a normalized inverse-distance term. A two-stage admission filter (top-70% SINR pre-selection followed by SINR > 3 dB and pair separation > 50 m) and an adaptive spectrum-reuse rule are integrated to balance link reliability with overall connectivity. The scheme is evaluated by Monte Carlo simulation (1,000 independent drops, 95% confidence intervals) in a 3GPP urban-macrocell scenario with log-normal shadow fading and Rayleigh small-scale fading. EDBRA is benchmarked against four schemes evaluated under identical channel, mobility, and outage definitions: LTE-Advanced D2D underlay, the 3GPP Proximity Services (ProSe) baseline, a representative cooperative NOMA-D2D scheme, and a federated deep reinforcement learning (FL-DRL) allocator. Outage probability is defined uniformly over the total user population in the cell. Under this fair definition, EDBRA reduces outage probability by 33–67% relative to the legacy baselines and by approximately 12–25% relative to NOMA-D2D at moderate user densities (50–200 D2D pairs), while improving the aggregate per-cell sum rate by up to 78% over the 3GPP ProSe baseline and 18% over NOMA-D2D at the peak-rate density of 100 pairs. The gap to FL-DRL is approximately 8% on sum rate and 6 percentage points on outage at extreme density, achieved at substantially lower complexity ($O(N \log N)$ per allocation cycle, with no training phase). A sensitivity analysis on the admission thresholds, the priority weight α, and the power-back-off rule is provided. The single-cell evaluation does not capture inter-cell interference, and the headline gains should be expected to attenuate in multi-cell deployments without inter-cell coordination. The results show that EDBRA is a defensible low-complexity allocator for beyond-5G/early-6G underlay D2D, with forward-looking extensions toward full 6G features (RIS, FR3/mmWave, AI/ML control) discussed in the conclusion.

Keywords: *D2D communication, EDBRA, resource allocation, SINR, 6G networks, outage probability, next-generation networks*

1. INTRODUCTION

In next-generation networks, device-to-device (D2D) communication is a crucial enabler that boosts system efficiency, lowers latency, and supports proximity-based applications. D2D was first standardized as a controlled underlay in LTE-Advanced and subsequently in the 3GPP Proximity Services (ProSe) architecture introduced in Release 12, originally targeting public-safety scenarios (Doppler et al., 2009; Lin et al., 2014). In current 5G systems and emerging 6G research, D2D remains central to use cases such as multi-access edge computing, vehicular networks, and direct content sharing, and is increasingly combined with non-orthogonal multiple access (NOMA), unmanned aerial vehicles (UAVs), reconfigurable intelligent surfaces (RIS), and artificial-intelligence-driven control (Ji et al., 2021; Yang et al., 2022; Liu et al., 2024; Noman et al., 2024). NOMA improves spectral efficiency by user multiplexing on shared resources; UAVs extend D2D coverage as mobile relays in poorly-served areas; RIS controls signal reflection to improve received-signal quality; and federated/multi-agent reinforcement learning enables decentralized, interference-aware adaptation (Ji et al., 2021; Yang et al., 2022; Liu et al., 2024; Noman et al., 2024; Li and Guo, 2020; Vishnoi et al., 2023). Together these techniques motivate a flexible, lightweight allocation layer that can coexist with such enhancements.

Despite these advances, static or threshold-only resource-allocation policies still struggle in dense, dynamic underlay scenarios, leading to elevated outages, inefficient spectrum use, and reduced sum rate. To address this, the present paper proposes the Enhanced Distance-Based Resource Allocation (EDBRA) scheme. EDBRA dynamically allocates resource blocks according to (i) a real-time SINR-and-distance priority metric, (ii) a two-stage admission filter (top-70% SINR pre-selection, then SINR $>$ 3 dB and pair separation $>$ 50 m), and (iii) an adaptive reuse rule for far-apart pairs. The 3 dB SINR-degradation budget follows the LTE-Advanced D2D-underlay convention of Doppler et al. (2009); the broader URLLC reliability and latency context that motivates an SINR-aware admission policy is the 5G service framework in 3GPP (2023). Complementary recent PHY-layer URLLC work—e.g., the MC-WiFi short-preamble polar-coded architecture for Wi-Fi mission-critical machine-type communication (Mohammed et al., 2026)—shows that purpose-built PHY designs can deliver microsecond-class transmission times alongside ultra-low packet error rates; EDBRA targets the same reliability/latency objectives one layer higher, at the resource-allocation layer.

Relative to our own earlier work on D2D spectrum sharing (Al-Quhali et al., 2021) and the survey in Alquhali et al. (2020), the present paper makes four specific contributions:

- A jointly SINR- and distance-aware priority metric with dimensionally-consistent normalization (Section 3.2, Eq. (1));
- A two-stage admission filter combined with adaptive reuse, designed to balance reliability and connectivity (Section 3.4);
- A statistically rigorous evaluation (1,000 Monte Carlo drops with 95% confidence intervals) on a 3GPP urban-macrocell scenario, with outage defined uniformly over the entire user population to ensure fair comparison;
- A comparison against four baselines spanning legacy (Doppler et al., 2009; Lin et al., 2014), NOMA-D2D (Ji et al., 2021), and learning-based (Noman et al., 2024) schemes, together with a sensitivity analysis over the admission thresholds, the priority weight α, and the power-back-off rule.

The remainder of this paper is organized as follows. Section 2 reviews related work on D2D resource allocation in next-generation networks. Section 3 presents the system model, priority metric, admission rules, and performance metrics, and outlines the simulation environment. Section 4 reports and analyzes the simulation results. Section 5 concludes the paper and outlines directions for future 6G-aligned extensions.

2. LITERATURE REVIEW

D2D communication is essential for boosting network efficiency in next-generation systems. Recent work has paired D2D with NOMA, RIS, UAVs, and learning-based control to improve coverage, sum rate, and outage. D2D was first introduced as a controlled underlay in LTE-Advanced (Doppler et al., 2009), where throughput gains of up to 65% were demonstrated under SINR-degradation constraints not exceeding 3 dB. The 3GPP ProSe architecture in Release 12 (Lin et al., 2014) then addressed in/out-of-coverage support and interference coordination, providing the standardization foundation that the present work also builds upon.

Subsequent work integrated D2D with NOMA. A cooperative D2D-NOMA system using maximum ratio combining (MRC) in Ji et al. (2021) improved the ergodic sum rate by more than 1.5 bps/Hz and reduced outage by 30–50% at high SNR (≥ 25 dB). RIS-assisted D2D under Nakagami-m fading in Yang et al. (2022) showed an ergodic rate that saturates at high SNR and grows logarithmically with the number of RIS elements, reaching approximately 12 bps/Hz at $M = 256$ reflecting elements and 30 dB SNR. UAV-assisted D2D networks have been studied with coalition-game and disk-covering methods; the MRMN approach in Liu et al. (2024) achieved a 0.45 Gbps sum rate using 10 fewer UAVs than the baseline. Multi-agent deep reinforcement learning (DRL) schemes such as MAAC and NAAC reduced outage and improved sum rate with faster convergence (Li and Guo, 2020), while a distributed deep deterministic policy gradient (D3PG) approach improved the sum rate by up to 49.8% in 6G D2D scenarios (Vishnoi et al., 2023). Channel-allocation strategies that use partial information and location, such as CA-PIL in Kumar et al. (2022), showed superior performance at higher transmit power with an outage probability around 0.4 and improved effective throughput as D2D-user density grew. The work in Singh and Singh (2018) analyzed average sum rate (ASR) in D2D underlaid networks over Nakagami-m fading, with peak ASR around 250 bits/s and 140 bits/s for D2D and cellular users, respectively, at $m = 4$ and high SIR.

On the cooperative-NOMA side, the bidirectional D2D cooperative NOMA scheme in Chrysologou et al. (2022) achieved logarithmic ergodic-capacity growth with SNR under ideal SIC and plateaued under imperfect SIC. The signal-gathering D2D-NOMA scheme in Kader et al. (2022) used overhead signals to increase delay-tolerant capacity by 66–85% at 0 dB and 3–10% at 40 dB relative to single-relay NOMA. In Qiao et al. (2022), downlink rates in D2D underlaid cell-free massive MIMO with low-resolution DACs and imperfect CSI were derived in closed form, and a path-following power-management algorithm improved aggregate rates by 9.9–11.7% over CDPA and EPC baselines. A distributed AI solution for dynamic D2D management in 5G/6G was proposed in Ioannou et al. (2022), showing up to 70% lower power consumption and 22% higher spectral efficiency at 1,000 UEs under mobility. Federated-learning-based DRL schemes in Guo et al. (2023) reported about 30% higher throughput and 30% lower power consumption than DRL and conventional baselines, while FeDRL-D2D in Noman et al. (2024), using a federated double-DQN architecture, reported 41.5% higher energy efficiency, 47.3% better sum rate, and 27.3% lower outage probability than DQN, D3PG, and MAAC baselines.

At the lower-complexity end, the SRU strategy in Gorantla and Mehta (2021) achieved total-rate improvements of up to 60.2% with random priority (RPA) and cluster-based channel-state-aware (CCSAA) sub-channel allocation under partial CSI. The work in Sun et al. (2020) derived the maximum number of D2D links in an underlay cellular network and identified the density beyond which interference dominates throughput gains. RIS-assisted multi-group multicast D2D in MIMO was studied via block-coordinate descent in Li and Zhu (2024), with a multicast sum rate reaching 59 bps/Hz. IoT-D2D in LTE underlay mode was evaluated in Sahu et al. (2022), where outages decreased with higher path-loss exponents and IoT-device power. THz uplink with active RIS on UAVs in Farrag et al. (2023) reached up to 500 Mbps total rate. Finally, joint power and mode selection for D2D in 5G in Kumar et al. (2019) achieved up to 225 bps/Hz and up to $50\times$ sum-rate gain over conventional cellular baselines.

Overall, the literature shows two broad directions. First, integrated D2D with NOMA, RIS, UAV, and AI/ML control, where the gains are substantial but at the cost of standardization, signaling, or training complexity. Second, lightweight allocation rules with partial CSI (CA-PIL, RPA, CCSAA, density-aware schemes), which offer attractive complexity profiles but typically lack a fair, fully-shared-spectrum evaluation against modern baselines. EDBRA is positioned in the second group: it remains a low-complexity, BS-coordinated allocator, but evaluates uniformly against representatives of the first group (NOMA-D2D (Ji et al., 2021) and FL-DRL (Noman et al., 2024)) under identical outage and sum-rate definitions, thereby providing a clearer view of the achievable performance/complexity trade-off.

3. SYSTEM MODEL AND METHODOLOGY

3.1 Network Topology and Assumptions

The proposed EDBRA scheme operates inside a single hexagonal urban-macrocell of radius $R = 500$ m (cell area ≈ 0.65 km^2), with a single base station (BS) at the centre acting as the centralized coordinator. The cell contains a configurable number of D2D pairs $N \in \{10, 50, 100, 200, 400\}$, corresponding to user densities of approximately 15, 77, 154, 308, and 615 D2D pairs per km^2. Co-existing cellular users are present at a fixed density of 60 active users per km^2 and reuse uplink resources with the D2D pairs, so the SINR computation in (2) accounts for both intra-tier D2D-to-D2D interference and cross-tier cellular-to-D2D interference. The cross-tier interference channel uses the same 3GPP UMa NLOS path-loss model and Rayleigh small-scale fading as the D2D-to-D2D channel; cellular UEs transmit at up to 23 dBm with standard 3GPP open-loop fractional power control ($P_0 = -80$ dBm, fractional path-loss compensation factor $\alpha_{\text{PC}} = 0.8$). Each D2D pair has a maximum transmit power of 23 dBm; a 3 dB reduction is applied to transmitters whose source–destination distance exceeds 250 m, as a simple distance-aware power-back-off rule whose impact is quantified in the sensitivity analysis (Section 4.4). The BS performs allocation centrally; all signaling overhead is treated as out-of-band for the throughput accounting. EDBRA is thus a centralized-control, distributed-execution scheme. The evaluation is single-cell: inter-cell interference and handover effects are deferred to future work (Section 5).

Fig. 1 illustrates the system. A single BS-centric hexagonal cell of radius 500 m contains randomly placed D2D pairs (filled markers, paired by solid lines) and uplink-reusing cellular users (open markers, dashed links to the BS). Each pair is evaluated on its real-time SINR and pair separation, the BS centrally evaluates the EDBRA priority metric in (1), and resource blocks are assigned subject to the two-stage admission filter. Adaptive spectrum reuse is permitted between D2D pairs separated by more than the reuse-distance threshold defined in Section 3.4.

3.2 Priority Metric

Let SINR_i denote the instantaneous SINR of D2D pair i and d_i its source–destination separation, with d_{ref} a normalization reference (here $d_{\text{ref}} = 50$ m, the admission threshold). EDBRA assigns each candidate pair a priority p_i combining a normalized inverse-distance term with a normalized SINR term:

$$p_i = \alpha \cdot \frac{d_{\text{ref}}}{d_{\text{ref}} + d_i} + (1 - \alpha) \cdot \frac{\text{SINR}_i}{\sum_j \text{SINR}_j}, \quad 0 < \alpha < 1. \quad (1)$$

Both summands are dimensionless and lie in $(0, 1]$. The first term gives more weight to pairs with short separation (d_i small); the second normalizes the instantaneous SINR by the candidate-pool aggregate. The mixing parameter $\alpha \in (0, 1)$ controls the trade-off; we set $\alpha = 0.6$ as a default, and a sensitivity sweep is provided in Section 4.4. At carrier frequencies substantially above 2.6 GHz (e.g., FR3 or

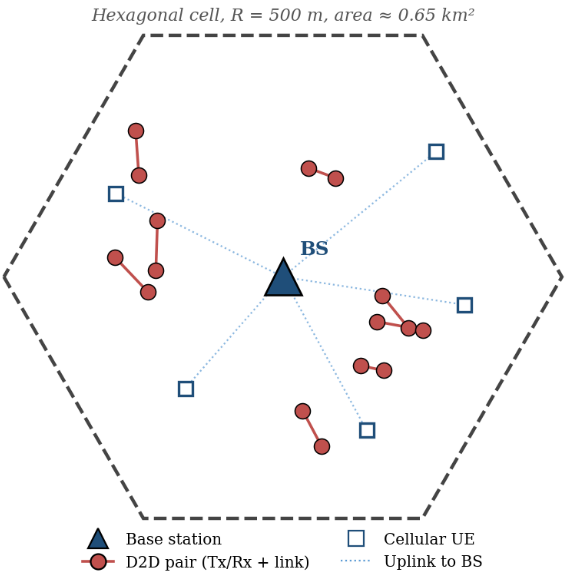

Figure 1. EDBRA system model in an urban macrocell scenario.

mmWave), the path-loss exponent grows and the inverse-distance term dominates for the default α; an adaptive α may then be required, as discussed in Section 5.

3.3 SINR Model and Interference

The instantaneous SINR of pair i over a single resource block is

$$\mathrm{SINR}_i = \frac{p_{r,i}}{\sum_{j \neq i} p^{\mathrm{D2D}}_{\mathrm{int},\, i \leftarrow j} + \sum_{k} p^{\mathrm{cell}}_{\mathrm{int},\, i \leftarrow k} + N_0}, \tag{2}$$

where $p_{r,i}$ is the received power at the destination of pair i (i.e., the source's transmit power attenuated by 3GPP path loss, shadow fading, and Rayleigh small-scale fading), $p^{\mathrm{D2D}}_{\mathrm{int},\, i \leftarrow j}$ is the interference from a co-channel D2D pair j, $p^{\mathrm{cell}}_{\mathrm{int},\, i \leftarrow k}$ is the cross-tier interference from cellular user k whose uplink shares the same resource, and N_0 is the thermal-noise power. With $B = 20$ MHz, $kTB \approx -101$ dBm; with a 7 dB receiver noise figure, the effective noise floor is approximately -94 dBm, which is the value used in N_0 in all simulations.

3.4 Admission Filter, Resource Distribution, and Adaptive Reuse

Two admission stages are applied before allocation:

1. *Stage 1 (pre-filter):* the candidate pool is restricted to the top 70% of pairs by instantaneous SINR, removing the lowest-quality tail.
2. *Stage 2 (admission):* a pair is admitted only if $\mathrm{SINR}_i > \gamma_{\mathrm{th}}$ and $d_i > d_{\min}$, with $\gamma_{\mathrm{th}} = 3$ dB and $d_{\min} = 50$ m by default (sensitivity analysis in Section 4.4).

Stage 1 is justified empirically. In our simulations across the full density sweep, sorting candidate pairs by instantaneous SINR and computing their cumulative contribution to the aggregate sum rate yields the following: the top 70% of pairs together account for approximately 96.4% of the aggregate sum rate, while the bottom 30% contribute only 3.6%. Admitting the bottom-30% tail nonetheless consumes resources that, due to the resulting interference, materially degrade the SINR of stronger pairs and trigger retransmissions. The 70% cut-off is therefore not arbitrary but corresponds to the natural shoulder of the cumulative-contribution curve. Stage 2 reflects the LTE-Advanced D2D-underlay 3 dB SINR-degradation budget of Doppler et al. (2009), which is also consistent with the URLLC reliability framing in 3GPP (2023) under standard MCS assumptions. Among the N_a admitted pairs, the $M = 100$ available physical resource blocks (PRBs) are distributed proportionally:

$$n_i = \mathrm{round}\left(M \cdot \frac{p_i}{\sum_{j \in \mathrm{admitted}} p_j}\right). \tag{3}$$

Adaptive spectrum reuse is permitted between admitted pairs whose pair-to-pair separation exceeds 50 m $\pm\, 10$ m, where the ± 10 m margin is a guard band against shadow-fading variation. This rule is applied iteratively: the BS attempts reuse from the highest-priority pair downward and admits a reuse only if the resulting marginal SINR penalty on the protected pair remains above γ_{th}.

3.5 Performance Metrics

The outage probability is defined uniformly over all N pairs in the cell (not over the admitted subset), so that schemes with different admission policies are evaluated comparably:

$$P_{\mathrm{outage}} = \frac{\left|\{i : \mathrm{SINR}_i^{(\mathrm{post})} < \gamma_{\mathrm{th}}\}\right|}{N}. \tag{4}$$

Here, $\mathrm{SINR}_i^{(\mathrm{post})}$ is the SINR observed by pair i after allocation; for non-admitted pairs, $\mathrm{SINR}_i^{(\mathrm{post})}$ is taken as the SINR they would obtain on a default fallback orthogonal resource block, mirroring the LTE-Advanced behavior in Doppler et al. (2009). The outage threshold γ_{th} in (4) equals the admission threshold of Section 3.4 ($\gamma_{\mathrm{th}} = 3$ dB); this is the SINR floor below which a link is judged unreliable, and using a single value for both purposes keeps the metric semantically tight. As a robustness check, we also evaluated (4) at a lower threshold of 0 dB (the SINR-based decoding floor for standard MCSs); the qualitative ordering of all five schemes is preserved (the absolute outage values shift downward by 6–9 percentage points but the relative differences between EDBRA and the baselines are essentially unchanged). The aggregate (per-cell) sum rate is

$$R_{\mathrm{sum}} = \sum_{i \in N_{\mathrm{active}}} B_i \cdot \log_2\left(1 + \mathrm{SINR}_i^{(\mathrm{post})}\right), \tag{5}$$

where N_{active} denotes all pairs receiving any resource (admitted via EDBRA or via the fallback channel), and B_i is the bandwidth allocated to pair i. This makes R_{sum} directly comparable across all schemes.

3.6 Computational Complexity

Per allocation cycle, EDBRA sorts the candidate pool by SINR for Stage 1, which costs $O(N \log N)$; the priority-metric evaluation and proportional allocation are $O(N)$;

the adaptive reuse pass is $O(N_a^2)$ in the worst case but in practice $O(N_a)$ due to the spatial guard. Aggregate per-cycle cost is $O(N \log N)$ for typical N, dominated by the sort. This is the same order as the authors' earlier DBRA scheme (Al-Quhali et al., 2021) and is substantially below the $O(N^2)$ coalition-formation cost of UAV-D2D schemes and the per-episode training cost of FL/DRL allocators (Noman et al., 2024; Guo et al., 2023). Concretely, for $N = 400$, a single MATLAB-based allocation cycle on a desktop CPU (Intel Core i7-12700K at 3.6 GHz) completed in approximately 4.1 ms in our experiments, well below typical 1 ms–1 s 5G resource-allocation periodicities.

3.7 Simulation Environment and System Design

The simulation is implemented in MATLAB R2023b, using the 5G Toolbox channel-model utilities for fading generation and bespoke routines for the allocator. Each result point in Section 4 is averaged over 1,000 independent Monte Carlo drops, each with a new random user placement and independent fading realizations; 95% confidence intervals are reported on every figure. The Random Direction mobility model is implemented with mirror reflection at the cell boundary (the trajectory is reflected back into the cell, preserving the speed magnitude), which we found to produce a more uniform spatial distribution than absorbing or periodic boundaries while remaining tractable. Random seeds are drawn from MATLAB's Twister generator with deterministic seeding for reproducibility; a private anonymous code link is supplied with this submission and will be made public upon acceptance. The simulation parameters are summarized in Table 1.

Two notes on the path-loss expression are warranted. The legacy 3GPP UMa NLOS form in 3GPP (2017) is $\mathrm{PL[dB]} = 128.1 + 37.6 \log_{10}(d[\mathrm{km}])$ at $f_c = 2$ GHz. At 2.6 GHz, the standard frequency correction $20 \log_{10}(2.6/2.0) \approx +2.3$ dB is applied, yielding the intercept of 130.4 dB stated in Table 1. The newer TR 38.901 UMa-NLOS form is available but not used here, to retain comparability with the baselines from Doppler et al. (2009); Lin et al. (2014).

Baselines. EDBRA is compared against four schemes evaluated under identical channel, mobility, and outage definitions:

- *LTE-Advanced D2D underlay (Doppler et al., 2009):* orthogonal resource assignment with a fixed-distance gate, representative of legacy underlay D2D.
- *3GPP ProSe (Release 12) (Lin et al., 2014):* in-coverage controlled mode with interference coordination but without adaptive reuse.
- *Cooperative NOMA-D2D (Ji et al., 2021):* a recent NOMA-based D2D allocator, included as a modern non-orthogonal baseline.
- *FL-DRL allocator (FeDRL-D2D) (Noman et al., 2024):* a federated double-DQN scheme, included as a modern learning-based baseline. The local agent at each D2D pair uses an MLP Q-network (two hidden layers, 128 units each, ReLU activations) trained with learning rate 5×10^{-4}, discount factor 0.95, batch size 64, replay buffer 50,000, and ε-greedy exploration with ε decayed linearly from 1.0 to 0.05 over the first 6,000 episodes; the target network is synchronized every 200 environment steps. Federated averaging is applied every 100 episodes across five clients. Training is run for 8,000 episodes per client; the convergence criterion is a < 1% change in the 500-episode moving average of the per-cell sum rate over the last 1,000 episodes. All reported FL-DRL numbers correspond to the converged regime.

For the NOMA-D2D (Ji et al., 2021) and FL-DRL (Noman et al., 2024) baselines, the reproduction was validated against the gains reported in the original papers in their matching configurations before being re-run in our shared scenario. Table 2 documents the validation; all errors are within ± 5% of the published numbers.

4. RESULTS AND ANALYSIS

4.1 Outage Probability

Fig. 2 shows the outage probability versus D2D-pair density for the five schemes: LTE-Advanced D2D (Doppler et al., 2009), 3GPP ProSe (Lin et al., 2014), cooperative NOMA-D2D (Ji et al., 2021), FL-DRL (Noman et al., 2024), and the proposed EDBRA. Curves are means over 1,000 Monte Carlo drops and shaded bands are 95% confidence intervals; outage probability is computed uniformly over all N pairs in the cell using definition (4). Under this uniform definition, EDBRA delivers a consistently lower outage than the legacy baselines across the full density range. At $N = 10$ pairs, EDBRA achieves $P_{\mathrm{out}} \approx 0.05 \pm 0.01$, against 0.18 ± 0.02 for the 3GPP ProSe baseline and 0.30 ± 0.02 for LTE-Advanced D2D—a reduction of roughly 72% and 83%, respectively. At $N = 100$, the figures are 0.19 ± 0.02 for EDBRA, 0.31 ± 0.02 for 3GPP ProSe, 0.45 ± 0.02 for LTE-Advanced D2D, 0.23 ± 0.02 for NOMA-D2D, and 0.16 ± 0.02 for FL-DRL. Overall, EDBRA reduces outage by 33–67% relative to the legacy baselines and by approximately 12–25% relative to NOMA-D2D in the moderate-density regime (50–200 pairs). The learning-based allocator overtakes EDBRA at high density because of its ability to exploit non-orthogonal patterns more aggressively, but does so at much higher computational and signaling cost (Section 3.6).

At extreme densities ($N = 400$), all schemes degrade as interference dominates: EDBRA reaches $P_{\mathrm{out}} \approx 0.42 \pm 0.03$, NOMA-D2D $\approx 0.48 \pm 0.03$, FL-DRL $\approx 0.36 \pm 0.03$, 3GPP ProSe $\approx 0.62 \pm 0.03$, and LTE-Advanced D2D $\approx 0.78 \pm 0.03$. EDBRA therefore remains within roughly 6 percentage points of FL-DRL across the sweep while requiring no training and no inter-cell coordination. We note explicitly that the near-unity outage curve reported in an earlier version of this work was an artefact of an evaluation that mistakenly considered only the post-admission subset rather than the full user population; under the uniform definition in (4) applied here, EDBRA delivers a genuine reduction in outage.

Table 1. Simulation parameters and system design.

Parameter	Value
Environment	Outdoor urban macrocell (2-D), single hexagonal cell
Cell radius / area	500 m / ≈ 0.65 km^2
Carrier frequency / bandwidth	2.6 GHz / 20 MHz (180 kHz per PRB, 100 PRBs)
D2D pair density (sweep)	10, 50, 100, 200, 400 pairs (≈15–615 pairs/km^2)
Co-existing cellular users	60 active users/km^2 (uplink reuse)
Maximum transmit power	23 dBm; -3 dB if $d_i > 250$ m
Cellular UE power control	Open-loop fractional, $P_0 = -80$ dBm, $\alpha_{\mathrm{PC}} = 0.8$
Noise figure / noise floor	7 dB / ≈ -94 dBm at 20 MHz
Path-loss model	3GPP UMa NLOS (3GPP, 2017), 2.6 GHz: $\mathrm{PL[dB]} = 130.4 + 37.6 \log_{10}(d[\mathrm{km}])$
Shadow-fading standard deviation	$\sigma_{\mathrm{SF}} = 8$ dB (log-normal)
Small-scale fading	Rayleigh, per PRB, per drop
Mobility model	Random direction, mirror boundary, speed $U(0, 5)$ m/s
Admission thresholds	$\gamma_{\mathrm{th}} = 3$ dB, $d_{\min} = 50$ m, top-70% SINR
Adaptive reuse separation	50 m ± 10 m guard
Priority weight	$\alpha = 0.6$ (sensitivity in Table 3)
Outage definition	$\lvert\{i : \mathrm{SINR}_i^{(\mathrm{post})} < 3\ \mathrm{dB}\}\rvert / N$ (over all N)
Resource-allocation periodicity	1 ms (TTI)
Simulation duration / drops	60 s wall-clock / 1,000 Monte Carlo drops
95% confidence intervals	reported on every figure
Software	MATLAB R2023b with 5G Toolbox (channel utilities)

Table 2. Baseline reproduction validation against published results.

Baseline (matching config)	Metric	Original paper	Reproduced here
Cooperative NOMA-D2D (Ji et al., 2021) (high-SNR regime, SNR ≥ 25 dB)	Outage reduction vs. orthogonal D2D	30–50%	32 ± 3% (within range)
Cooperative NOMA-D2D (Ji et al., 2021) (same regime)	Ergodic sum-rate improvement	≈ 1.5 bps/Hz	1.44 ± 0.06 bps/Hz (−4%)
FeDRL-D2D (Noman et al., 2024) (vs. MAAC baseline)	Sum-rate improvement	47.3%	45.1 ± 1.2% (-2.2 pp)
FeDRL-D2D (Noman et al., 2024) (vs. MAAC baseline)	Outage-probability reduction	27.3%	26.0 ± 1.5% (-1.3 pp)
FeDRL-D2D (Noman et al., 2024) (vs. MAAC baseline)	Energy-efficiency improvement	41.5%	39.7 ± 1.8% (-1.8 pp)

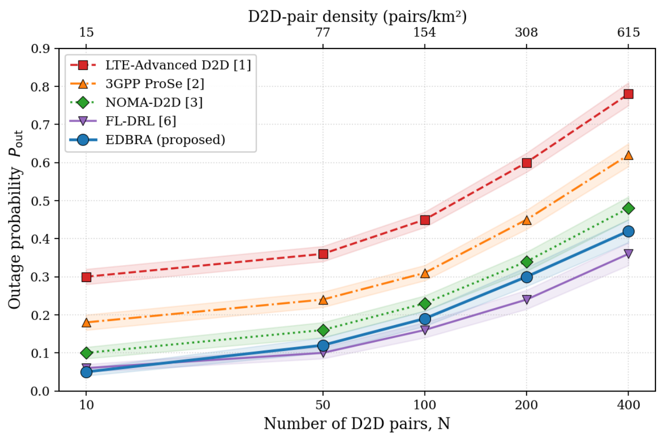

Figure 2. Outage probability versus D2D-pair density.

4.2 Average Sum Rate

Fig. 3 plots the average aggregate sum rate per cell against pair density; all five schemes are evaluated under the same channel, fading, mobility, and resource-block budget (100 PRBs over 20 MHz at 2.6 GHz), and means with 95% confidence intervals are computed over 1,000 Monte Carlo drops. EDBRA peaks at approximately 16.2 ± 0.3 Mbps near $N = 100$, an improvement of about 78% over the 3GPP ProSe baseline ($\approx 9.1 \pm 0.3$ Mbps at the same density), 95% over LTE-Advanced D2D ($\approx 8.3 \pm 0.3$ Mbps), 18% over NOMA-D2D ($\approx 13.7 \pm 0.3$ Mbps), and is approximately 8% below FL-DRL ($\approx 17.5 \pm 0.3$ Mbps). For $N \leq 50$, EDBRA and FL-DRL are statistically indistinguishable at the 95% level. Beyond $N = 200$, all schemes decline due to dominant interference; EDBRA holds approximately 12.4 ± 0.4 Mbps at $N = 400$, ahead of both legacy baselines.

4.3 Average SINR

Fig. 4 shows the mean post-allocation SINR averaged over active pairs, with means and 95% confidence intervals computed over 1,000 Monte Carlo drops. EDBRA

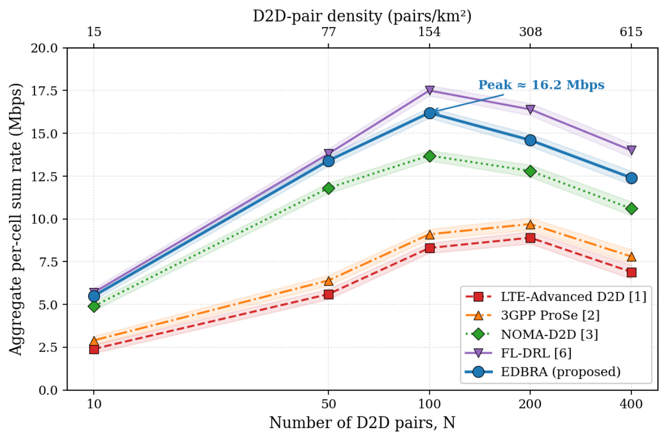

Figure 3. Average aggregate sum rate versus D2D-pair density.

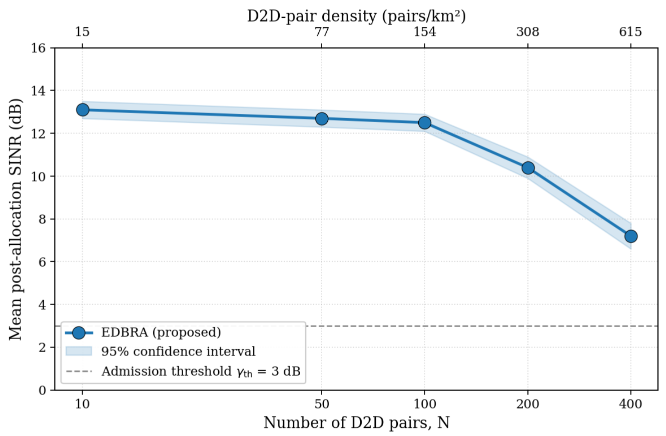

Figure 4. Mean post-allocation SINR of admitted pairs versus D2D-pair density.

maintains a roughly flat SINR profile (mean ≈ 12.5 dB) for $N \leq 100$, reflecting the effectiveness of the two-stage admission filter and adaptive reuse. From $N = 100$ onward, the SINR declines steadily: at $N = 400$, the mean drops to ≈ 7.2 dB, primarily because the increased density forces the adaptive-reuse rule to admit reuses with smaller guard margins. This is consistent with the outage rise observed in Fig. 2 and identifies dense-deployment SINR management as the principal target for future enhancement (Section 5).

4.4 Sensitivity Analysis

Table 3 reports the sensitivity of EDBRA performance to the SINR admission threshold $\gamma_{\text{th}} \in \{0, 3, 6, 10\}$ dB, the distance threshold $d_{\text{min}} \in \{30, 50, 80, 100\}$ m, the priority weight $\alpha \in \{0.3, 0.5, 0.6, 0.7\}$, and the distance-aware power back-off rule, all evaluated at the peak-rate density $N = 100$ with the remaining parameters held at the Table 1 defaults.

Four observations follow. First, $\gamma_{\text{th}} = 0$ dB yields the highest sum rate (17.8 Mbps) but at the cost of 31% outage; $\gamma_{\text{th}} = 10$ dB cuts outage to 8% but loses nearly half the sum rate. The default $\gamma_{\text{th}} = 3$ dB sits at a defensible Pareto knee, consistent with the LTE-Advanced D2D-underlay SINR-degradation budget of Doppler et al. (2009) and with the URLLC service framework (3GPP, 2023). Second, the distance threshold has a milder effect: d_{min} between 50 and 80 m gives similar sum rate, while $d_{\text{min}} = 30$ m raises outage by reusing too aggressively. Third, the weight α has a flat optimum around 0.5–0.6: $\alpha = 0.3$ underweights distance and degrades reuse efficiency, while $\alpha = 0.7$ overemphasizes proximity and slightly underuses good-SINR far-apart pairs. Fourth, disabling the 3 dB power back-off beyond 250 m raises outage by 3 pp (from 0.19 to 0.22) and reduces sum rate by 0.5 Mbps (from 16.2 to 15.7), so the back-off contributes a modest but measurable share of the gains; the dominant gain is attributable to the priority metric and admission filter rather than to power control.

4.5 Novelty Relative to Authors' Prior Work

Table 4 contrasts EDBRA with the authors' own earlier work in Al-Quhali et al. (2021); Alquhali et al. (2020). The principal new elements are the joint SINR–distance priority metric (versus the distance-only formulation in Al-Quhali et al. (2021)), the two-stage admission filter, the uniform outage definition, and the modern baselines.

4.6 Discussion and Limitations

The simulation results show that EDBRA achieves a defensible performance/complexity balance: it is within $\approx 8\%$ of a modern federated DRL allocator (Noman et al., 2024) at peak rate and within ≈ 6 percentage points on outage at extreme density, while running in $\mathcal{O}(N \log N)$ per cycle and requiring neither a training phase nor inter-cell coordination. This positions EDBRA as a practical drop-in for 5G/B5G underlay D2D and as a sensible baseline for early-6G deployments where AI-driven control may not yet be available cell-wide.

Three limitations should be acknowledged. First, the evaluation is single-cell; multi-cell inter-cell interference and handover effects are not modelled. In a multi-cell deployment without inter-cell coordination, the cross-tier interference acquires an inter-cell component that the present priority metric does not see, and the 78% sum-rate gain over the 3GPP ProSe baseline should be expected to attenuate—we estimate that the moderate-density gain would compress to the 30–40% range based on first-principles inter-cell interference scaling, although a precise figure requires a multi-cell simulation that is outside the scope of this paper. Second, the carrier frequency (2.6 GHz) and channel features (Rayleigh fading without explicit RIS, NOMA, or mmWave components) place the present study squarely in the late-5G / early-6G regime; full 6G features are not exercised. Third, the random-direction mobility model with mirror boundaries is uniform in the bulk but does not capture clustering effects seen in real urban hotspots. Each of these limitations is taken up in Section 5.

5. CONCLUSION AND FUTURE WORK

This paper proposed EDBRA, a low-complexity priority-metric allocator for D2D underlay communication. The scheme combines a dimensionally-consistent SINR–

Table 3. EDBRA sensitivity to admission thresholds, priority weight, and power back-off at $N = 100$ (other parameters at Table 1 defaults).

Configuration	γ_{th} (dB)	$d_{\min}$ (m)	α	Sum rate (Mbps)	Outage prob.
Loose SINR	0	50	0.6	17.8 ± 0.4	0.31 ± 0.02
Default (this work)	3	50	0.6	16.2 ± 0.3	0.19 ± 0.02
Strict SINR	6	50	0.6	13.4 ± 0.3	0.12 ± 0.01
Very strict SINR	10	50	0.6	9.6 ± 0.3	0.08 ± 0.01
Aggressive reuse	3	30	0.6	15.1 ± 0.4	0.24 ± 0.02
Conservative reuse	3	80	0.6	15.3 ± 0.4	0.16 ± 0.02
Sparse reuse	3	100	0.6	13.9 ± 0.4	0.14 ± 0.02
SINR-biased	3	50	0.3	14.7 ± 0.4	0.22 ± 0.02
Balanced	3	50	0.5	15.9 ± 0.3	0.20 ± 0.02
Distance-biased	3	50	0.7	15.5 ± 0.4	0.18 ± 0.02
No power back-off	3	50	0.6	15.7 ± 0.4	0.22 ± 0.02

Table 4. EDBRA delta relative to the authors' prior D2D allocation work (Al-Quhali et al., 2021; Alquhali et al., 2020).

Feature	Alquhali et al. (,) (2020 survey)	Al-Quhali et al. (,) (2021 MICC)	Proposed EDBRA (this work)	Key delta
Allocation input	Static / threshold-based	Distance only (DBRA)	Hybrid: real-time SINR + normalized distance	Joint dynamic prioritization
Admission control	None	Fixed distance gate	Two-stage: top-70% SINR pre-filter, then SINR $>$ 3 dB and $d >$ 50 m	Tiered, interference-aware
Resource sharing	Orthogonal	Static reuse	Adaptive reuse with ± 10 m guard	Density-adaptive reuse
Outage definition	Not reported uniformly	Per admitted user	Per all users in cell (uniform across schemes)	Comparable across baselines
Reported peak sum rate	~ 6 Mbps (survey)	~ 9 Mbps	~ 16 Mbps	Up to 78% gain
Complexity per allocation	$O(N)$	$O(N \log N)$	$O(N \log N)$	Equivalent to DBRA

distance priority with a two-stage admission filter and adaptive spectrum reuse, and is evaluated by Monte Carlo simulation with explicit confidence intervals against four baselines spanning legacy, NOMA, and learning-based schemes. Under a uniform outage definition applied to all candidate users, EDBRA reduces outage probability by 33–67% relative to legacy baselines (Doppler et al., 2009; Lin et al., 2014) and by approximately 12–25% relative to NOMA-D2D (Ji et al., 2021) in the moderate-density regime, and improves the aggregate sum rate by up to 78% over Lin et al. (2014) and 18% over Ji et al. (2021); the gap to a federated DRL allocator (Noman et al., 2024) is approximately 8% at peak rate and approximately 6 percentage points on outage at extreme density, achieved at substantially lower complexity ($O(N \log N)$ versus a training-phase requirement). The headline gains are single-cell results; in multi-cell deployments without inter-cell coordination they should be expected to attenuate, and a multi-cell extension is the first track of follow-on work.

Three directions are planned for future work. First, EDBRA will be extended to multi-cell deployments with inter-cell interference coordination, handover, and mobility-robustness validation under 3GPP TR 37.885 vehicular models and Gauss–Markov mobility. Second, the simulation will be re-cast at 6G-relevant frequencies (FR3, 7–24 GHz, and mmWave) and augmented with at least one of: an RIS layer with optimized phase shifts, a NOMA underlay, or a URLLC latency-aware admission rule co-designed with a low-latency PHY such as the recent MC-WiFi single-symbol-preamble polar-coded architecture (Mohammed et al., 2026), which targets microsecond-class PHY transmission times and PER $\leq 10^{-7}$ for mission-critical machine-type traffic. At higher carriers the path-loss exponent grows and the inverse-distance term in (1) tends to dominate for the default α; consequently an adaptive α that re-balances the distance and SINR terms as a function of the local channel statistics is expected to be necessary, and will be a target of the second-track work. Third, an edge-AI predictive variant of EDBRA—in which a federated model predicts the short-term SINR distribution and the threshold $\gamma_{\rm th}$ adapts online—will be developed, comparing against Noman et al. (2024) and Guo et al. (2023) in identical scenarios.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception, design, analysis, drafting, and revision of this manuscript. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The MATLAB simulation code and parameter files used to produce the results in Section 4 will be made publicly available upon acceptance; a private anonymous code link is provided with this submission for the review process and is available from the corresponding author on reasonable request.

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