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Impact of Channel Availability on Fairness, Access Rate, and Spectral Efficiency in D2D-Enabled NOMA Networks Using Utility-Based Resource Allocation

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ABSTRACT
Efficient channel utilization is a critical challenge in device-to-device (D2D) enabled non-orthogonal multiple access (NOMA) networks due to the increasing demand for spectrum resources and the need to support a large number of users. This paper investigates the impact of channel availability on network performance using a utility-based resource allocation framework. The developed scheme integrates utility-driven D2D user association with adaptive power allocation to improve spectrum utilization while satisfying signal-to-interference-plus-noise ratio (SINR) and interference constraints. The performance of the proposed algorithm is evaluated under varying numbers of available channels using three key metrics: Jain's fairness index, access rate, and spectral efficiency. Simulation results demonstrate that increasing the number of channels significantly enhances user admission capability and overall spectrum utilization. The developed utility-based approach achieves higher fairness among users, improves access rate by reducing channel contention, and provides superior spectral efficiency compared with the baseline D2D-NOMA resource allocation scheme. These findings confirm that channel availability plays a crucial role in the performance of D2D-enabled NOMA networks and that utility-based resource allocation offers an effective strategy for balancing fairness and spectrum efficiency in dense wireless environments.

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INTRODUCTION

The rapid proliferation of smart mobile devices and data-intensive multimedia applications, such as augmented reality (AR), virtual reality (VR), and ultra-high-definition (UHD) video, has led to an exponential surge in global wireless data traffic [1]. This explosion of demand has strained traditional cellular frameworks to their limits, necessitating the development of fifth-generation (5G) and beyond (5GB) networks capable of delivering multi-gigabit data rates and ultra-low latency [2]. To address these requirements, Device-to-Device (D2D) communication and Non-Orthogonal Multiple Access (NOMA) have emerged as two of the most critical enabling technologies [3]. Device-to-Device (D2D) Communication D2D communication enables proximate user equipment (UE) to establish direct communication links, bypassing the evolved NodeB (eNB) or cellular core network [4].

By offloading local traffic from the network infrastructure, D2D effectively reduces backhaul congestion, extends coverage for cell-edge users, and significantly improves system capacity [5]. The technology achieves performance improvements through proximity gain (high bit rates and low latency due to short distances), hop gain (using one transmission hop instead of two), and reuse gain (sharing radio

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resources with existing cellular users)[6]. D2D is primarily classified based on its spectrum usage into in-band (licensed cellular spectrum) and out-band (unlicensed ISM bands) [4]. In-band D2D is further divided into underlay mode, where resources are shared simultaneously with cellular users, and overlay mode, where dedicated resources are assigned [4]. While underlay D2D offers higher spectral efficiency, it introduces complex cross-tier and co-tier interference that requires robust management [7].

Non-Orthogonal Multiple Access (NOMA) While traditional Orthogonal Multiple Access (OMA) assigns unique time or frequency resources to each user, NOMA allows multiple users to share the same resource block by exploiting the power domain [8]. This approach significantly enhances spectral efficiency and supports the massive connectivity required for Internet of Things (IoT) ecosystems [9]. The fundamental mechanisms of NOMA include superposition coding at the transmitter to combine multiple signals and Successive Interference Cancellation (SIC) at the receiver to decode and remove interference based on varying power levels [9]. Combining these technologies into NOMA-enhanced D2D (or NOMA-D2D) provides a powerful paradigm for high-density networks [2]. In this scheme, the traditional "D2D pair" is expanded into a "D2D group," where a single D2D transmitter communicates with multiple D2D receivers simultaneously using NOMA protocols [8]. This integration further maximizes the number of accessed users and the overall network sum rate [2].

However, the implementation of NOMA-D2D introduces even more intricate layers of interference, including intra-group interference among receivers in the same group and inter-group interference among groups reusing the same subchannel[9]. Consequently, current research is increasingly focused on developing efficient channel allocation strategies that optimize the number of available channels to enhance fairness, access rate, and spectral efficiency, thereby improving the overall performance of next-generation D2D-enabled NOMA networks.

LITERATURE REVIEW

The integration of Device-to-Device (D2D) communication with Non-Orthogonal Multiple Access (NOMA) has attracted significant research interest as an effective approach for improving spectrum utilization, supporting massive connectivity, and satisfying the stringent throughput and latency requirements of fifth- and sixth-generation (5G/6G) wireless networks [8] By allowing multiple D2D users to reuse cellular spectrum through power-domain multiplexing, D2D-enabled NOMA enhances spectral efficiency while reducing transmission delay [10]. However, these gains are accompanied by increased co-channel interference, making efficient resource allocation a fundamental challenge [8].

Consequently, recent studies have focused on developing resource allocation strategies under different spectrum-reuse scenarios, including one-to-one, one-to-many, and many-to-many communication modes [1]. The growing demand for bandwidth-intensive applications such as augmented reality (AR), virtual reality (VR), intelligent transportation systems, and vehicle-to-vehicle (V2V) communications has further accelerated research in D2D-enabled NOMA networks (Zhao et al., 2017). These applications require high data rates, low latency, and reliable connectivity, making direct D2D transmission an attractive solution for reducing communication delay and improving spectrum utilization [1].

As network density increases, however, interference management and efficient channel utilization become increasingly critical for maintaining acceptable network performance (Interference Mitigation in Device-to-Device Communications, n.d.). Early studies primarily focused on demonstrating the feasibility and performance advantages of integrating D2D communication with NOMA [9]. [9]introduced the concept of D2D groups, where a single transmitter simultaneously serves multiple receivers using power-domain multiplexing. Their many-to-one matching framework significantly improved system sum rate compared with conventional D2D pairing schemes. Similarly, [8] proposed iterative resource allocation algorithms that prioritize the

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quality-of-service (QoS) requirements of cellular users while enabling D2D spectrum reuse, thereby demonstrating the practical feasibility of NOMA-underlaid D2D communications.

As network complexity increased, researchers began adopting optimization and game-theoretic approaches to address interference and resource allocation. [7]investigated uplink multi-carrier NOMA (MC-NOMA) using a Nash bargaining game to jointly improve throughput and fairness among users. [12]incorporated energy harvesting into D2D communications through a two-stage optimization framework consisting of non-cooperative power control and matching-based spectrum allocation to maximize energy efficiency. In the downlink scenario, [11] proposed joint subchannel allocation and power control algorithms that minimize transmit power while satisfying signal-to-interference-plus-noise ratio (SINR) constraints, highlighting the importance of coordinated optimization in interference-limited environments. [13] proposed a layered partial NOMA (P-NOMA) framework that allows partial signal overlap according to user QoS requirements while employing relay nodes to improve the performance of cell-edge users.

Similarly, [2] investigated millimeter-wave MIMO-NOMA-enabled D2D communications and employed particle swarm optimization (PSO) for power allocation, demonstrating the benefits of intelligent optimization techniques in high-frequency communication systems. Despite these advances, adaptive resource allocation in outdoor D2D environments remains challenging because user mobility and dynamic channel conditions continuously alter interference patterns, requiring more robust optimization strategies. Among recent contributions, [1] presented a hierarchical resource allocation framework for many-to-one spectrum reuse scenarios. Their approach combines discrete cellular user power selection with priority-based channel allocation in the outer optimization layer, while the inner layer models D2D users sharing the same channel as a non-cooperative game that converges to a Nash equilibrium for interference mitigation.

Simulation results demonstrated significant improvements in spectral efficiency and access rate compared with existing methods, particularly in ultra-dense D2D networks. The study illustrates the effectiveness of separating channel allocation and power optimization into hierarchical stages while maintaining efficient spectrum reuse under severe interference conditions. Overall, the existing literature demonstrates substantial progress in improving the performance of D2D-enabled NOMA networks through matching theory, game-theoretic optimization, hierarchical resource allocation, and intelligent optimization techniques.

Nevertheless, most studies primarily evaluate resource allocation algorithms under fixed channel configurations, with comparatively limited attention devoted to understanding how variations in the number of available channels influence key network performance indicators such as fairness, access rate, and spectral efficiency. A systematic investigation of this relationship, as explored in the [1] can provide valuable insights into channel provisioning strategies and network design for future D2D-enabled NOMA systems.

System Model and Problem Formulation

This study considers the uplink transmission of a single-cell Device-to-Device (D2D)-enabled Non-Orthogonal Multiple Access (NOMA) cellular network. The network topology consists of a set of primary cellular users (CUs), denoted by $\mathcal{N} = \{1,2,\dots,N\}$, coexisting with a set of secondary D2D user pairs, denoted by $\mathcal{M} = \{1,2,\dots,M\}$. A single Base Station (BS) positioned at the center of the cell coordinates uplink access while permitting D2D pairs to opportunistically share the licensed spectrum. The system operates under a full-load scenario where each cellular user occupies a dedicated uplink channel, whereas multiple D2D pairs are allowed to multiplex over the same spectrum channel subject to resource availability and co-channel interference constraints.

To enhance spectral utilization while curbing intra-cell and cross-layer interference, a two-stage hierarchical optimization framework is

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adopted. In the first stage, D2D pairs are grouped and assigned to cellular users using a utility-based clustering criterion that jointly accounts for target channel quality and cross-link interference footprints. In the second stage, transmit powers across all active links are jointly optimized to fulfill individual Quality-of-Service (QoS) requirements while maximizing total network performance. Subsequently, system performance is analyzed across varying channel counts to evaluate its impact on fairness, user access rates, and overall spectral efficiency.

Utility-Based Hierarchical Clustering

The operational fitness of pairing the j-th D2D pair with the i-th cellular user is governed by a utility function $U_{i,j}$, defined as:

$$U_{i,j} = \frac{g_{i,j}}{h_{i,j,\mathrm{B}} + \varepsilon}$$

where $g_{i,j}$ represents the communication channel gain between the i-th cellular user and the j-th D2D pair, $h_{i,j,\mathrm{B}}$ denotes the cross-layer interference channel gain from the j-th D2D transmitter to the BS when sharing channel i, and ε is a small positive regularization constant ($\varepsilon > 0$) included to prevent numerical instability during severe channel fading ($h_{i,j,\mathrm{B}} \to 0$). A higher utility value reflects a superior spectrum-sharing relationship, as it signifies strong local coupling alongside minimal cross-tier disruption to the central cell link.

The clustering mechanism maps each D2D pair to the specific cellular user that maximizes the candidate utility value while adhering to structural capacity constraints. This hierarchical arrangement defines the underlying spectrum-sharing topology prior to optimal power distribution.

SINR Characterization

Following cluster formation, the Signal-to-Interference-plus-Noise Ratio (SINR) for the i-th cellular user on its assigned uplink channel is given by:

$$\mathrm{SINR}_i = \frac{P_i g_{i,\mathrm{B}}}{\sum_{j\in\mathcal{D}_i} P_j\, h_{j,\mathrm{B}} + N_0}$$

where P_i denotes the transmit power of cellular user i, $g_{i,\mathrm{B}}$ is the direct channel gain between cellular user i and the BS, $\mathcal{D}_i$ represents the set of D2D pairs co-allocated to channel i, P_j is the transmit power of D2D transmitter j, $h_{j,\mathrm{B}}$ is the cross-layer interference gain from D2D transmitter j to the BS, and N_0 represents the variance of the additive white Gaussian noise (AWGN).
Correspondingly, the received SINR at the j-th D2D receiver sharing channel i is formulated as:

$$\mathrm{SINR}_j = \frac{P_j g_j}{P_i h_{i,j} + \sum_{k\in\mathcal{D}_i, k\neq j} P_k\, h_{k,j} + N_0}$$

where g_j is the direct communication channel gain of D2D pair j, $h_{i,j}$ denotes the co-channel interference channel gain originating from cellular user i to D2D receiver j, and $h_{k,j}$ denotes the mutual D2D-to-D2D interference gain from transmitter k ($k \in \mathcal{D}_i, k \neq j$) to receiver j.

Joint Power Optimization Formulation

Upon establishing the hierarchical clusters, transmit powers are jointly optimized to maximize system-wide capacity under strict QoS and power budget bounds. The joint power optimization problem is formulated as:

$$\max_{\{P_i,P_j\}} \sum_{i=1}^{N} \log_2(1+\mathrm{SINR}_i) + \sum_{j=1}^{M} \log_2\left(1+\mathrm{SINR}_j\right) \text{ s.t. } \begin{cases} \mathrm{SINR}_i \geq \Upsilon_i, & \forall i \in \mathcal{N} \\ \mathrm{SINR}_j \geq \gamma_j, & \forall j \in \mathcal{M} \\ 0 \leq P_i \leq P_{i,\max}, & \forall i \in \mathcal{N} \\ 0 \leq P_j \leq P_{j,\max}, & \forall j \in \mathcal{M} \end{cases}$$

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RESULTS AND DISCUSSION

This section evaluates the proposed PUMM algorithm against Algorithms 1, 2, and 3 of [1]. The performance is assessed in terms of spectral efficiency, fairness, and access rate under varying network conditions. The results demonstrate the effectiveness of PUMM in improving channel utilization and resource allocation compared with the benchmark algorithms. Detailed results and discussions are presented in the following subsections.

Effect of Number of Channels on Fairness

Figure 1 shows the fairness performance under different numbers of available channels. At 10 channels, the fairness values are approximately 0.33, 0.28, and 0.36 for Algorithm 1, Algorithm 2, and PUMM, respectively. These increase to 0.43, 0.37, and 0.49 at 30 channels and 0.48, 0.45, and 0.58 at 50 channels. PUMM consistently achieves the highest fairness, indicating a more balanced allocation of available channel resources among D2D users. This result is consistent with [1], which associated improved channel access with enhanced allocation fairness

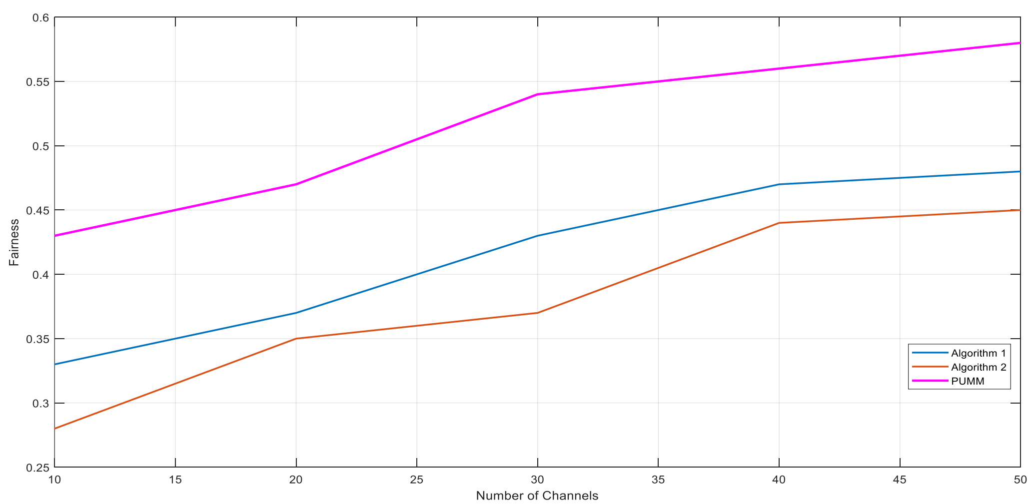

Fig 1: Effect of Number of Channels on Fairness

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Effect of Number of Channels on Access Rate

Figure 2 presents the access rate as the number of available channels increases. At 10 channels, the access rates are approximately 63%, 42%, and 74% for Algorithm 1, Algorithm 2, and PUMM, respectively. At 30 channels, the rates increase to 70%, 58%, and 80%, while at 50 channels they reach 81%, 62%, and 89%, respectively. PUMM therefore maintains the highest access rate across all evaluated channel conditions. The observed increase in access rate with channel availability is consistent with the findings of [1].

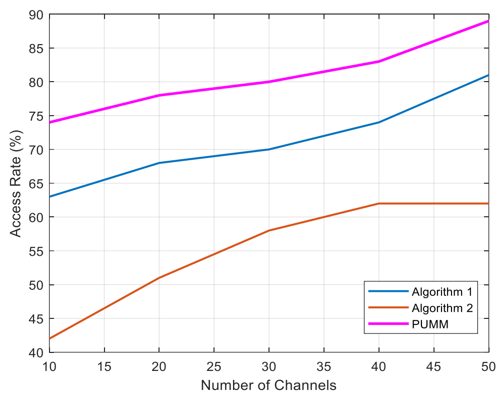

Fig 2: Effect of Number of Channels on Access Rate

Effect of Number of Channels on Spectral Efficiency

Figure 3 presents the effect of the number of available channels on spectral efficiency (SE). At 10 channels, the SE values are approximately 520-, 560-, and 650-bit/s/Hz for Algorithm 1, Algorithm 2, and PUMM, respectively. At 30 channels, these values increase to 870-, 930-, and 1030-bit/s/Hz, while at 50 channels they reach 1010-, 1110-, and 1210-bit/s/Hz, respectively. The results show that SE increases with channel availability for all schemes, with PUMM consistently achieving the highest SE. This trend agrees with the findings of the base paper, [1], which reported improved SE with increasing channel availability due to greater opportunities for D2D users to access network resources.

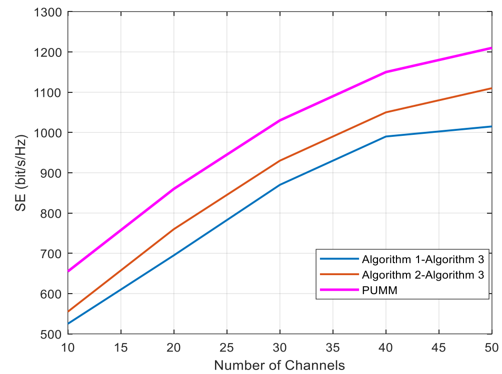

Fig 3: Effect of Number of Channels on Spectral Efficiency

Overall Observation

Overall, the results indicate that increasing the number of available channels improves spectral efficiency, fairness, and access rate across the evaluated schemes, with PUMM consistently achieving the best performance. This suggests that the proposed approach makes more effective use of available channel resources while supporting broader and more balanced D2D access.

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