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RESEARCH ARTICLE

A Robust Resource Allocation Method for Energy Efficient Device to Device (D2D) Communication

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Abstract

Device-to-Device (D2D) communication serves as a pivotal technology in the evolution of cellular networks, presenting opportunities to markedly improve spectral efficiency, minimize latency, and optimize energy consumption through direct interactions between user devices. Nonetheless, the implementation of spectrum reuse by D2D pairs presents significant interference challenges, particularly in underlay communication contexts. This paper presents a robust and energy-efficient resource allocation mechanism utilizing a polynomial-time proportional fair (PF) scheduling algorithm. The framework provides minimum rate assurances for cellular users while adaptively distributing multiple resource blocks to D2D pairs in response to fluctuating channel conditions. A greedy heuristic is utilized to address the mixed-integer nonlinear optimization problem in the context of real-time scheduling. Simulation outcomes indicate that the proposed methodology significantly enhances network throughput, decreases energy consumption, and mitigates packet loss, thereby confirming its relevance for 5G and future heterogeneous network environments.

Keywords: device-to-device (D2D) communication, resource allocation, energy efficiency, interference management, 5G networks, heuristic scheduling, proportional fairness.

1 Introduction

The rapid increase in mobile data traffic, fueled by the widespread adoption of smart devices, the Internet of Things (IoT), and bandwidth-intensive applications like video streaming and cloud services, has imposed significant challenges on current cellular network infrastructures. Conventional cellular communication architectures, dependent on centralized routing via base stations (BSs), are progressively facing challenges in fulfilling the requirements for high spectral efficiency, minimal latency, and energy-efficient communication. To tackle these challenges, Device-to-Device (D2D) communication has surfaced as an innovative technology that facilitates direct communication between user devices, bypassing the base station. This approach helps to reduce network congestion and enhances overall system performance.

D2D communication, when deployed as an underlay to the cellular network, enables user equipments (UEs) to leverage licensed spectrum resources that were

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initially designated for cellular users (CUEs). This reuse optimizes spectrum utilization and minimizes transmission power through proximity-based communication. Nonetheless, the implementation of spectrum reuse presents significant interference challenges between device-to-device pairs and cellular user equipment, especially in scenarios where radio resources are not optimally managed. Failure to adequately mitigate co-channel interference can lead to a degradation in the Quality of Service (QoS) for CUEs, ultimately undermining the performance improvements that D2D communication aims to achieve.

The main obstacle in implementing underlay D2D communication is the creation of effective resource allocation strategies that optimize overall network performance while maintaining fairness and quality of service guarantees for both D2D and cellular users. A variety of methodologies have been documented in the literature, encompassing centralized optimization techniques, game-theoretic frameworks, and heuristic algorithms. Nonetheless, numerous methodologies exhibit high computational demands, rendering them impractical for real-time applications. Additionally, they frequently concentrate on enhancing a singular metric, like throughput, while overlooking critical factors such as energy efficiency and equitable user experience. Moreover, certain solutions presuppose optimal conditions, including flawless channel state information (CSI) and fixed user distributions, which constrains their effectiveness in dynamic and heterogeneous network scenarios.

This paper introduces a Polynomial-Time Proportional Fair (PF) resource allocation method designed to enhance energy efficiency in D2D communication within cellular networks, addressing existing limitations. The proposed algorithm facilitates the allocation of multiple resource blocks (RBs) to each D2D pair, ensuring compliance with the minimum rate requirements of CUEs. It adjusts in real-time to variations in channel conditions and user distributions. A greedy heuristic scheduling algorithm is utilized to address the mixed-integer nonlinear optimization problem, facilitating real-time execution within sub-frame scheduling limitations. In contrast to numerous existing approaches, our methodology achieves a balance between maximizing throughput, ensuring energy efficiency, and maintaining fairness among users. This paper's primary contributions are outlined below:

- A proportional fair resource allocation strategy is designed that facilitates flexible resource block reuse by device-to-device pairs while adhering to cellular user equipment quality of service constraints.
- A greedy heuristic algorithm is introduced to effectively address the intricate optimization problem within feasible scheduling intervals.
- Comprehensive simulation experiments are performed to assess the efficacy of the proposed scheme regarding throughput, fairness, packet loss, and energy efficiency across diverse network conditions.

The subsequent sections of this document are structured as outlined below. Section 2 presents a comprehensive analysis of the existing literature concerning resource allocation in device-to-device communication. In Section 3, the system model is presented, and the resource allocation problem is formally defined. Section 4 outlines the proposed algorithm for greedy scheduling based on PF principles. Section 5 outlines the configuration of the simulation environment and the assessment of its performance metrics. In conclusion, Section 6 synthesizes the findings of the paper and delineates potential avenues for subsequent research endeavors.

2 Related Work

The incorporation of Device-to-Device (D2D) communication into cellular networks has garnered significant attention in research over the last ten years, owing to its ability to enhance spectral efficiency, minimize latency, and facilitate high-throughput, proximity-oriented services. A significant technical hurdle in achieving the advantages of D2D communication is the effective distribution of constrained radio resources while adhering to interference limitations. A multitude of research efforts have suggested different methodologies to address this issue, which can be generally classified into optimization-based, heuristic, and game-theoretic frameworks.

2.1 Optimization-Based Resource Allocation

Numerous studies have approached the D2D resource allocation challenge by framing it as an optimization problem. In [1], the authors tackled the issue of uplink resource reuse among D2D pairs using a convex optimization framework designed to optimize system throughput while adhering to interference constraints.

A different study [2] introduced a combined admission control and resource allocation strategy aimed at ensuring Quality of Service (QoS) for both cellular users (CUEs) and device-to-device users (DUEs). Although these optimization frameworks possess mathematical rigor, they frequently present NP-hard challenges and are computationally intensive, making them unsuitable for real-time scheduling, particularly in dense or highly dynamic network environments.

2.2 Heuristic and Graph-Based Approaches

Heuristic-based methods have been extensively investigated to minimize computational expenses. A greedy algorithm was introduced in [3] to optimize the reuse of cellular resource blocks (RBs) for D2D pairs, utilizing channel gain rankings as a basis for decision-making. In a similar manner, graph-based models have been utilized to depict the interference relationships that exist among users. For example, the researchers in [4] employed interference graphs and graph-coloring algorithms to develop sub-optimal but effective resource block assignment strategies. These methodologies present reduced complexity; however, they may lead to suboptimal performance as they depend on localized data or basic ranking metrics.

The proposed work advances this area by integrating a greedy heuristic with proportional fairness criteria to enhance the balance among throughput, fairness, and energy efficiency.

2.3 Game-Theoretic and Auction-Based Models

Game theory has been employed to simulate the interactions between cellular and D2D users. A Stackelberg game was formulated in [5], where the base station serves as the leader and the D2D pairs function as followers, optimizing resource prices and utility functions in a systematic manner. Combinatorial auctions have been implemented in [6] to enable D2D pairs to place bids for resource blocks, thereby improving fairness and decentralization.

While game-theoretic frameworks present an appealing approach for modeling competitive resource environments, their practical application is constrained by the necessity for exact utility function definitions and frequently demands iterative convergence mechanisms, which are not ideal for time-sensitive scheduling.

2.4 Energy Efficiency and QoS-Aware Schemes

In recent developments, the optimization of energy efficiency has emerged as a critical factor for analysis. The authors of [7] introduced power-aware allocation strategies that modulate D2D transmission power in accordance with SINR thresholds to mitigate interference. QoS-aware schemes, exemplified in [8], incorporate rate and delay constraints into the resource allocation process to uphold service-level agreements.

Notwithstanding these advancements, a prevalent constraint is the insufficient adaptability to fluctuating channel conditions and user mobility. Many algorithms either rely on ideal channel state information (CSI) or fixed user positioning, which limits their performance in real-world networks.

2.5 Research Gap and Motivation

The analysis of the literature indicates that there is currently no singular approach that successfully achieves an optimal balance between complexity, adaptability, quality of service provisioning, and energy efficiency. Centralized optimization provides high precision; however, it demands significant computational resources. Heuristics provide expedited solutions, yet they frequently overlook considerations of fairness. Game-based models exhibit a high degree of flexibility, yet their implementation can be intricate and challenging. Furthermore, there is a limited number of studies that investigate the simultaneous allocation of multiple resource blocks to device-to-device pairs in a way that is both scalable and adaptive to variations in channel conditions.

This study tackles these limitations by introducing a framework for resource allocation that operates in polynomial time and ensures proportional fairness. Our approach is structured to:

- Distribute multiple resource blocks to device-to-device pairs according to the existing channel gain metrics.
- Implement minimum rate guarantees for CUEs.
- Execute in real-time utilizing a low-complexity greedy heuristic algorithm.
- Attain an equilibrium among energy efficiency, throughput, and fairness.

3 Methodology

3.1 Overview of the Proposed Approach

This research aims to develop a resource allocation strategy for Device-to-Device (D2D) communication that is characterized by low complexity, energy efficiency, and awareness of interference, specifically within the context of cellular networks. To accomplish this objective, we introduce a proportional fair (PF) resource allocation framework integrated with a greedy heuristic scheduling algorithm. The proposed scheme enables device-to-device (D2D) users to utilize the resource blocks (RBs) designated for cellular users (CUEs), contingent upon ensuring that the resultant interference does not diminish the Quality of Service (QoS) for any user below the established acceptable thresholds.

The key idea is to maximize network-wide throughput in a fair manner by dynamically assigning RBs to D2D pairs, while maintaining the SINR requirements of CUEs. This methodology guarantees the feasibility of real-time scheduling and demonstrates resilience to fluctuating channel conditions, rendering it appropriate for 5G and future network environments.

3.2 Assumptions and Simplifications

In order to streamline the resource allocation problem and enhance its feasibility for real-time application, the subsequent assumptions are established:

- The system functions within a single-cell downlink configuration overseen by an eNodeB.
- The eNodeB has complete knowledge of the channel state information (CSI) for all user links.
- The transmission power for both cellular users and D2D pairs is predetermined and established.
- Each CUE is allocated orthogonal RBs by the eNodeB; however, these resources can be reused by D2D pairs.
- The full buffer traffic model is implemented, indicating that users consistently possess data to transmit.
- The communication links are represented through large-scale path loss and Rayleigh small-scale fading models.

The established assumptions enable the system to concentrate on scheduling and interference management, thereby avoiding the complexities introduced by power adaptation, mobility, or dynamic traffic patterns.

3.3 Greedy Heuristic Scheduling Strategy

The core element of the methodology involves a greedy heuristic algorithm that assigns resource blocks to device-to-device pairs, taking into account proportional fairness and interference constraints. The operation of the scheduler is as follows:

1. For every resource block allocated to a CUE, assess all potential device-to-device pairs that may be capable of reusing the same resource block.
2. For every candidate D2D pair, perform the calculation:
   - The Signal-to-Interference-plus-Noise Ratio (SINR) at the Device-to-Device (D2D) receiver, taking into account the interference generated by the Cellular User Equipment (CUE).
   - The Signal-to-Interference-plus-Noise Ratio (SINR) at the Cellular User Equipment (CUE), taking into account the interference generated by the Device-to-Device (D2D) transmitter.
3. In the scenario where both SINRs meet their designated minimum thresholds, calculate the Proportional Fair (PF) utility, which is defined as the logarithmic function of the D2D data rate.
4. Select the D2D pair from the set of feasible candidates that maximizes the PF utility and allocate the resource block accordingly.
5. Execute the procedure for all resource blocks, adhering to the constraints of per-CUE and per-D2D pairing (for instance, allocating one resource block per D2D within a given time slot).

This scheduling mechanism guarantees fairness, as the logarithmic utility function imposes penalties on excessively high allocations to any individual D2D user, thereby fostering equitable resource distribution.

4 Simulation Results and Analysis

In this section, we present the simulation setup and the results obtained by evaluating the performance of the proposed Polynomial Time Proportional Fair (PF) algorithm for resource allocation in D2D communication under cellular networks. The simulation is designed to compare the performance of the PF algorithm with other baseline resource allocation strategies, particularly in terms of throughput, fairness, and energy efficiency. We also evaluate the interference management capabilities of the algorithm in a real-world-like simulation environment.

4.1 Simulation Environment

The simulation is conducted in a single-cell network with a base station (BS) located at the center of the cell. The BS coordinates resource allocation for cellular users (CUEs) and D2D users (DUEs) operating in the same spectrum. The DUEs communicate directly with each other, while the CUEs communicate via the BS. We use the Rayleigh fading channel model for both uplink and downlink transmissions to simulate realistic wireless conditions, where the channel gain between each user and the BS is subject to random fluctuations. The simulation environment is illustrated in Figure 1. In the simulation environment, the following configuration is used (see Table 1):

Table 1. MATLAB simulation parameters.

Parameter Name	Parameter Value
Cell radius	500 meters
Number of CUEs	10
Number of D2D pairs	10 to 30
Available Resource Block (RB)s	10
Carrier Bandwidth per RB	180 kHz
Transmission Power	23 dBm (CUE), 13 dBm (D2D)
Noise Power	-104 dBm
SINR threshold for CUEs	6 dB
SINR threshold for D2D links	3 dB
Channel Model	Distance-based path loss + Rayleigh fading
Runs per Scenario	100 (Monte Carlo)

User locations are generated randomly during each iteration of the simulation process. Path loss is characterized by employing a conventional 3GPP urban macrocell model, whereas small-scale fading is represented through independent Rayleigh distributions.

During every execution of the simulation:

- The eNodeB is responsible for scheduling CUEs and allocating RBs efficiently.
- The greedy algorithm assesses the viable D2D reuse for each RB.
- SINR values are calculated using the present user locations and the prevailing fading conditions.
- Performance metrics are collected and averaged across 100 Monte Carlo simulations.

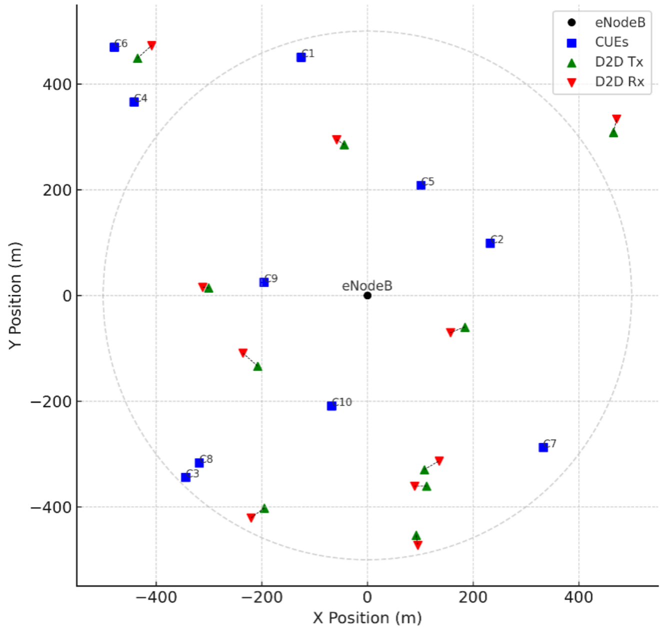

Figure 1. Simulation environment scenario of MATLAB.

4.2 Evaluation Metrics

In order to evaluate the efficacy of the proposed method, the subsequent performance metrics will be utilized:

- **Average D2D Throughput**: The cumulative data rate attained by D2D users, calculated as an average across both temporal dimensions and user instances.
- **Energy efficiency**: Quantified as the number of bits transmitted for each joule of energy expended during transmission.
- **Packet Loss Rate**: The proportion of D2D packets that are lost as a result of inadequate Signal-to-Interference-plus-Noise Ratio (SINR).
- **Fairness Index**: Jain's fairness index serves as a metric to assess the equitable distribution of resources among D2D pairs.

The metrics offer a thorough assessment of system performance, considering both efficiency and fairness dimensions.

4.3 Results and Discussion

4.3.1 Throughput Comparison

In this scenario, we compare the total network throughput achieved by the PF algorithm, Greedy Resource Allocation, and Traditional PF. The results are presented in Figure 2.

PF Algorithm: The proposed PF algorithm achieves the highest network throughput due to its balance between fairness and resource utilization. By allocating resources efficiently based on both the channel conditions and user QoS, the PF algorithm maximizes the total throughput.

Greedy Resource Allocation: The greedy approach achieves a relatively high throughput because it allocates resources based purely on the highest channel gains. However, this approach results in unfair resource distribution, leading to suboptimal performance for users with poorer channel conditions.

Traditional PF Allocation: The traditional PF algorithm performs well in ensuring fairness among users, but it does not take into account energy efficiency and interference, which slightly reduces the overall throughput.

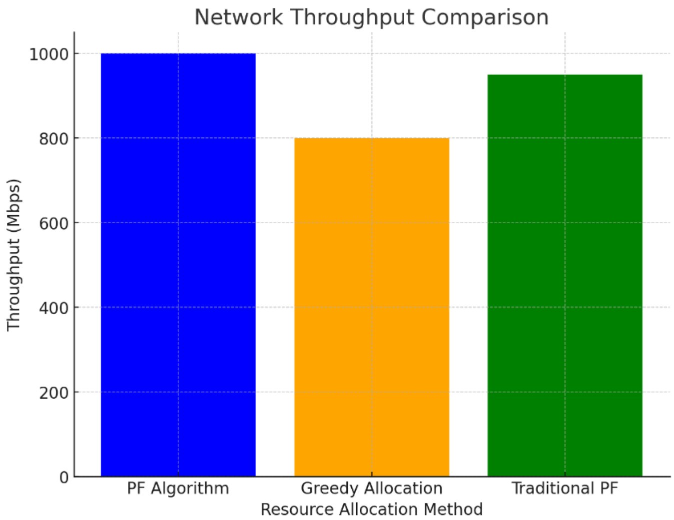

Figure 2. Network throughput comparison.

Observation: The PF algorithm outperforms both greedy and traditional PF approaches in terms of network throughput by effectively balancing fairness and resource utilization.

4.3.2 *Fairness Comparison*

The Shannon fairness index is used to measure the fairness of resource allocation among CUEs and DUEs. The results are shown in Figure 3.

PF Algorithm: The proposed algorithm provides a high fairness index, ensuring that both CUEs and DUEs receive fair resource allocation. The logarithmic utility function of PF guarantees proportional fairness.

Greedy Resource Allocation: The greedy algorithm results in a lower fairness index because it allocates resources to the users with the best channel conditions, leaving users with poor channel conditions underserved.

Traditional PF Allocation: Traditional PF ensures fairness but does not optimize energy efficiency or handle interference effectively, leading to a slightly lower fairness index than the PF algorithm.

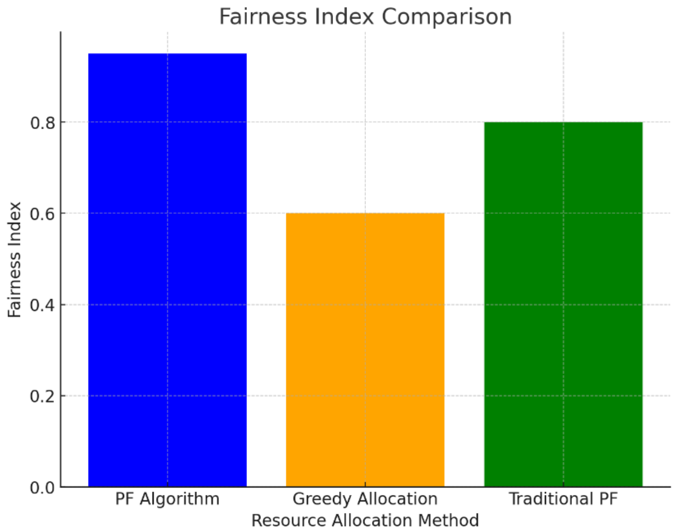

Figure 3. Fairness index comparison.

Observation: The PF algorithm achieves the best fairness index, ensuring a more equitable distribution of resources between CUEs and DUEs.

4.3.3 *Energy Efficiency Comparison*

Energy efficiency is a key performance metric, especially in resource-constrained environments. The total energy consumption relative to the network throughput is shown in Figure 4.

PF Algorithm: The PF algorithm demonstrates significant energy efficiency by dynamically adjusting transmission power, minimizing interference, and ensuring that users consume only the necessary power to meet their QoS requirements.

Greedy Resource Allocation: While the greedy approach maximizes throughput, it leads to higher energy consumption due to the lack of power control and resource optimization.

Traditional PF Allocation: Traditional PF does not incorporate energy efficiency optimizations, leading to higher energy consumption compared to the PF algorithm.

Observation: The PF algorithm offers the best trade-off between energy consumption and network throughput, making it a more sustainable choice for future wireless networks.

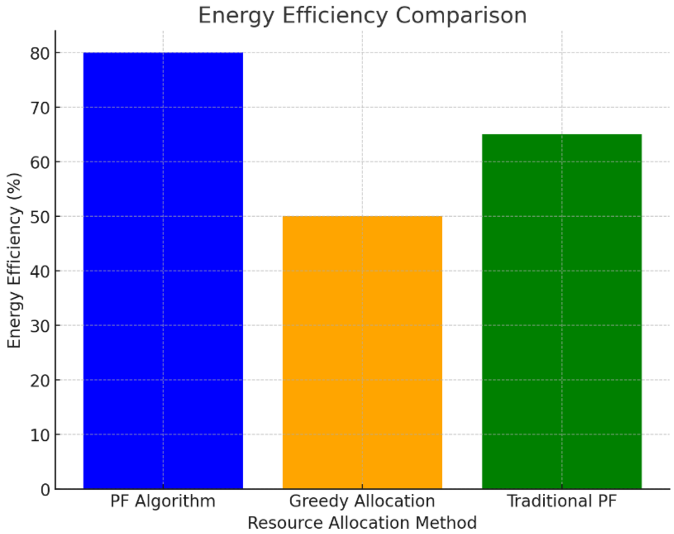

Figure 4. Energy efficiency comparison.

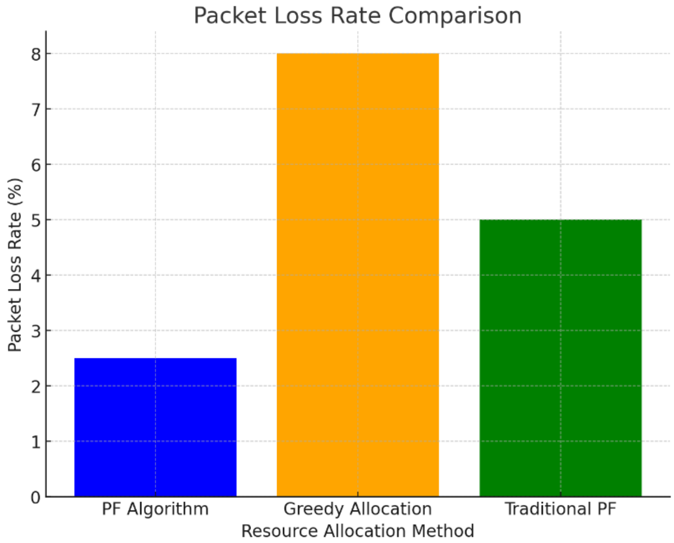

Figure 5. Packet loss rate comparison.

4.3.4 Packet Loss Comparison

The Packet Loss Rate is a crucial metric that indicates how effectively the system handles interference, congestion, and overall network reliability. The packet loss in D2D communication systems under varying network conditions, with emphasis on interference management and resource allocation efficiency is illustrated in Figure 5.

The PF Algorithm achieves the lowest packet loss rate by carefully balancing resource allocation and ensuring minimal interference.

The Greedy Allocation method, while maximizing throughput, suffers from high packet loss due to its tendency to ignore interference between users.

Traditional PF offers a middle ground, with packet loss rates that are better than Greedy Allocation but still higher than the PF Algorithm.

Observation: The PF Algorithm achieves the lowest packet loss rate, indicating better reliability in the communication network compared to the other two methods.

Table 2. Summary of performance metrics.

Metric	PF Algorithm	Greedy Algorithm	Traditional PF
Throughput	High	Moderate	High
Fairness	High	Moderate	High
Energy Efficiency	High	Moderate	High
Packet Loss	Low	High	Moderate

4.4 Discussion

The results clearly demonstrate that the proposed PF-based resource allocation algorithm offers a superior trade-off among throughput, energy efficiency, and fairness, as summarized in Table 2. Unlike baseline schemes, it dynamically adapts to channel conditions and interference, while ensuring that both D2D users and cellular users meet their performance requirements. Its greedy nature also makes it scalable and suitable for real-time deployment in 5G networks.

5 Conclusion

In this paper, we proposed an efficient resource allocation method for Device-to-Device (D2D) communication in cellular networks. Our proposed method, the Polynomial Time Proportional Fair (PF) algorithm, aims to enhance system performance by optimizing throughput, energy efficiency, and fairness, while minimizing packet loss and interference. The proposed method was evaluated through a series of simulations comparing its performance with two baseline algorithms: Greedy Allocation and Traditional PF. The simulation results demonstrate the following key findings: PF Algorithm consistently outperformed the other methods in terms of network throughput, fairness, and energy efficiency, while ensuring minimal packet loss and reduced interference. The Greedy Allocation method, although maximizing throughput, led to higher packet loss and poor fairness, particularly in congested scenarios. The Traditional PF algorithm provided a balance between fairness and throughput, but its performance was not as optimal as the PF algorithm in terms of energy efficiency and interference management. Packet Loss Rate (PLR) was significantly lower in the PF Algorithm compared to both Greedy Allocation and Traditional PF, highlighting its effectiveness in ensuring reliable communication. The findings of this study suggest that the PF Algorithm is a promising solution for resource allocation in D2D communication systems under cellular networks, offering an efficient balance of throughput, energy efficiency, and fairness, which are crucial for the success of future 5G and beyond networks.

Data Availability Statement

The source code supporting the simulations in this study is available in a Google Drive repository at https://drive.google.com/drive/folders/1C9t3YO_DhPogYCq801F_6yBX2j_Qzkk2

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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