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Optimal Power Allocation and Delay Minimization Based on Conflict Graph Algorithm for Device-to-Device Communications

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Abstract: Device-to-device (D2D) technology is a promising technique in terms of being capable of providing efficiency, decreased latency, improved data rate, and increased capacity to cellular networks. Allocating power to users in order to reduce energy consumption and maintain quality of service (QoS) remains a major challenge in D2D communications. In this paper, we aim to maximize the throughput of D2D users and cellular users subject to QoS requirements and signal-to-interference-plus-noise ratio (SINR). To this end, we propose a resource and power allocation approach called optimal power allocation and delay minimization based on the conflict graph (OP-DMCG) algorithm that considers optimal power allocation for D2D multi-users in the cellular uplink channels and minimization of the total network delay using conflict graphs. Based on the simulations presented in this paper, we show that the proposed OP-DMCG algorithm outperforms the greedy throughput maximization plus (GTM+), delay minimization conflict graph (DMCG), and power and delay optimization based uplink resource allocation (PDO-URA) algorithms in terms of both total network throughput and total D2D throughput.

Keywords: D2D communication; power allocation; resource allocation; 5G

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1. Introduction

The number of devices connected is increasing exponentially [1], creating a bottleneck in cellular networks that is becoming unsustainable [2]. In this sense, 5G can provide support to overcome these problems. The 5G technology [3,4] provides connections with higher rates and less latency when compared with 4G [5]. The world with 5G and beyond 5G technology will allow advances in several areas such as virtual reality, autonomous cars [6], remote medical services, internet of things (IoT) [7] as many others. However, the 5G uses millimeter waves with high frequency that have difficulty getting through obstacles being absorbed by trees and rain [8].

To enhance the efficiency and coverage of cellular networks, device-to-device (D2D) technology can be utilized. This approach enables users with higher power signals to assist nearby users with lower power signals. By establishing a direct communication link between devices, D2D communication can offload traffic from the base station and provide more reliable and efficient connections between users. This technique can also improve network coverage and reduce power consumption, leading to enhanced overall network performance.

D2D technology is a promising technique [9] in terms of yielding efficiency, decreasing latency, improving data rate, and increasing capacity to cellular networks. This feature allows direct communication between users inside the mobile network coverage area with users outside this area without using an eNodeB as a bridge.

There are some advantages of D2D communication, such as:

- Better cell coverage extension;
- Decreased device energy consumption;

- Better use of resources;
- Increased signal capillarity.

Allocating power and resources in order to provide quality of service still represent a challenge in D2D communications [10]. Power and resource allocation in D2D communication pose several challenges, particularly in interference control and gains. The farther apart users are, the greater the interference and the lower the gain. Another significant challenge is energy conservation, exacerbated by the substantial volume of transmitted and shared data, which can rapidly deplete the battery life of mobile devices [11]. In this work, intending to maximize the total throughput of D2D users and cellular users, an algorithm is proposed that considers an optimal power allocation for multi-user D2D communication in cellular uplink channels seeking to minimize the total delay using conflict graphs.

The proposed resource allocation method uses the estimated delay as a utility function seeking to allocate the idle resources of the cellular users (CUEs) to the device-to-device users (DUEs). The method starts by randomly allocating idle resource blocks to each D2D pair. After this process, it is decided on the reuse of resource blocks from the CUEs using conflict graphs.

We argue that a power allocation algorithm in multi-user cellular networks with uplink channel reuse can be used to optimize the total throughput of D2D users and cellular users subject to quality-of-service (QoS) requirements in relation to signal-to-interference-plus-noise ratio. To this end, in this work, we consider the distances of all devices involved to calculate the channel gains and interference. Using a Z-matrix [12,13], the vector containing the values of power of each user equipment is calculated.

Through simulations, it is shown that the proposed optimal power allocation and delay minimization based on conflict graph (OP-DMCG) algorithm provides a higher throughput for D2D transmissions and to the overall network transmissions of a cellular network system than the other considered algorithms from the literature that also consider device-to-device communications.

This paper is organized as follows: In Section 2, we discuss some related works. Section 3 presents the system model, the scenario under consideration and the algorithms that are used to compare the results obtained by the proposed algorithm. The proposed algorithm, namely, the optimal power allocation delay minimization conflict graph algorithm for D2D communications, is presented in Section 4. Section 5 details the simulation setup and presents the simulation results and the comparison with those of the algorithms considered in this work. Finally, in Section 6, we present the concluding remarks and the future scope of this work.

2. Related Works

Several studies have demonstrated that device-to-device communications can improve data rate [14], transfer rate, and spectral efficiency [15] of cellular networks. However, a major challenge is the potential increase in interference, which could have detrimental effects on network performance. To address this issue, numerous research efforts have been focused on developing effective resource allocation schemes. In their recent work, Gupta et al. [16] compiled various resource allocation methods from the literature aimed at minimizing interference by efficiently allocating resources. In [17], a compilation of regression techniques contributing to the computational model was presented.

In [18], the authors propose a resource allocation scheme based on deep reinforcement learning to maximize the effective communication throughput of D2D peers in a cellular communication system. The proposed scheme involves designing the state, action, and reward functions for the learning process. Using these functions, each D2D pair selects the appropriate channel resource and transmits power iteratively through observations, resulting in an optimized resource allocation strategy.

In [19], a theory-based selection method of graphs and a resource allocation algorithm for D2D devices in cellular communication systems are proposed. These methods aim to improve network performance by reducing the frequency range or increasing total flow.

The algorithm selects D2D pairs based on the centrality concept of graph theory, and a modified resource allocation algorithm for full-duplex environments is used to reduce the frequency band range.

There are also studies in the literature that have explored algorithms inspired by animal behaviors to optimize resource allocation in D2D communication systems. One such study is presented in the article by Zhang et al. [20], where a pigeon swarm-based resource allocation algorithm is proposed with a "one to one" correspondence. By fitting the problem to this optimization algorithm and adjusting the parameters, the convergence speed is accelerated, interference is reduced, and system performance is optimized.

3. D2D-Based Resource Allocation Algorithms

In this section, firstly, we briefly present the considered communication system model. Next, we introduce the algorithms that we consider in this work to compare their results against those of the proposed algorithm.

The scenario considered in this paper has a single cell with M cellular users (CUEs), K D2D pairs, and BS base stations, as we can see in Figure 1. The index sets of CUEs is $m \in \{1, 2, ..., M\}$, and the index sets of D2D pairs is $k \in \{1, 2, ..., K\}$.

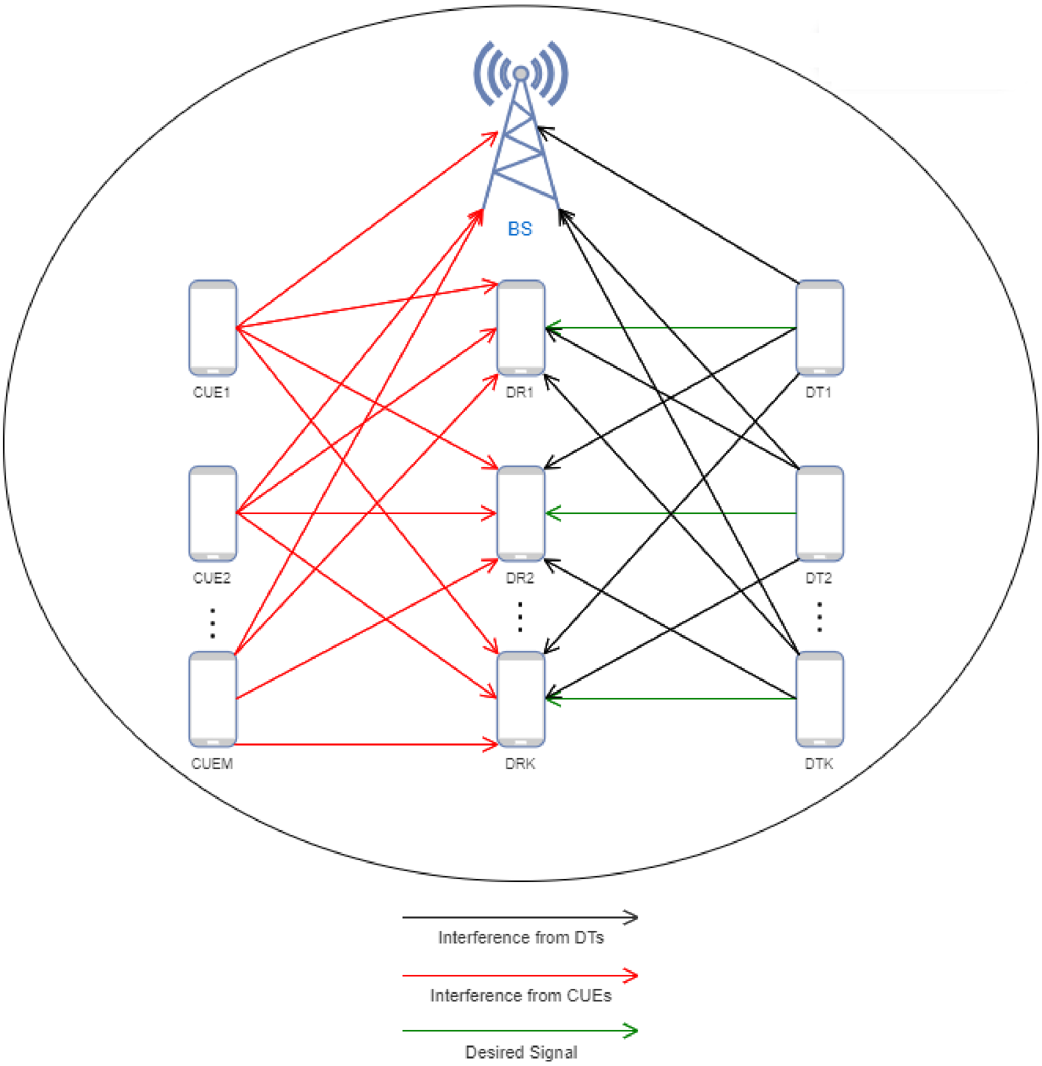

Figure 1. System model.

Channel coefficients are calculated according to the distances between the cellular users, the base station, and the D2D pairs.

In this work, we consider three resource allocation algorithms. More specifically, in Section 3.1, we describe the greedy throughput maximization plus (GTM+) algorithm, in Section 3.2 the delay minimization conflict graph (DMCG) algorithm, and in Section 3.3 the power and delay optimization based uplink resource allocation (PDO-URA) algorithm.

3.1. Greedy Throughput Maximization Plus

The greedy throughput maximization plus (GTM+) algorithm [21] aims to efficiently maximize the total throughput of a D2D system subject to transmission interference constraints in the uplink. It is designed to provide a fast solution to this maximization problem.

The algorithm starts by randomly pre-allocating idle resource blocks. In cases where no idle resource block is available, a D2D pair is randomly selected for each resource block and treated as if it were a mobile user. The number of interactions is then selected to determine how to reuse all resource blocks from CUEs.

All unallocated D2D pairs are grouped together to maximize their own utility before performing the iterations. The largest group is chosen, and the D2D pairs within it that best maximize the total utility are selected as candidates for reusing resource blocks from CUEs. To ensure that the SINR restrictions are met, one candidate is removed at a time until the requirement is satisfied. Once the group is marked as complete, the iteration is finished. This routine is repeated until all groups are marked as complete.

The utility function $u_n(m)$ in Equation (1) represents the flow of the system:

$$u_n(m) = W_m \log_2(1 + \frac{P_m G_{mB}}{\sigma_n^2 + P_n G_{nB}}) + W_m \log_2(1 + \frac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn}}), \quad (1)$$

where the D_n group reuses C_m blocks with the assumption that there are no other CUEs or D2D pairs inside the cell, and W_m denotes the allocated bandwidth, with P_m and P_n representing the respective transmit powers of the CUE and DUE. The noise power is denoted as σ_n^2, and G_{nn} stands for the channel gain existing between the two endpoints of the DUE pair n. Additionally, G_{mn} signifies the channel gain extending from CUE m to DUE pair n, whereas G_{mB} characterizes the channel gain between CUE m and the serving base station. Lastly, G_{nB} pertains to the channel gain between the sender of DUE pair n and the associated base station.

A conflict graph $G_{(m')}$ is formed for a group m, with each vertex corresponding to a D2D pair and weights defined by the utility function of each pair. If the mutual interference between two pairs exceeds the defined threshold, an edge is added to the graph, indicating that the two pairs cannot reuse the same resource block at the same time.

The conflict graph $G_{(m')}$ is then used to determine the candidates, with each vertex representing a D2D pair. The pairs that maximize the throughput of the system are kept, and those that cannot coexist are removed. This guarantees that at least one D2D pair will reuse idle resource blocks, leading to an efficient resource allocation.

3.2. Delay Minimization Conflict Graph

This algorithm aims to optimize resource allocation by considering the channel transmission quality, the maximum delay criterion, and the delay estimate, with the goal of reducing the average delay of the system. To estimate the delay, the algorithm uses concepts from deterministic network calculation, service curve, and envelope process multi-fractal bounded arrival process (MFBAP) [22,23].

Deterministic network calculation is used to estimate resources and provide a good quality of service for networks. The envelope process for packet arrival traffic is an upper bound for the actual accumulated packet traffic process. In the case of the deterministic envelope process, the limiting function $\hat{A}(t)$ that corresponds to the maximum value of a flow $A(t)$ In the time interval $[s, s+t]$, can be expressed as shown in Equation (2).

$$\hat{A}(t) = \sup_{s \geq 0} A[s, s+t] \tag{2}$$

Employing MFBAP as a deterministic alternative [24], Equation (3) is derived, where $H(t)$ represents the Hölder exponent, t denotes the time instant, $\bar{a}$ and σ stand for the mean and standard deviation of the incoming traffic, k is the constant associated with the probability of violation (for $\varepsilon = 10^{-6}$) of the envelope process, and B indicates the buffer size.

$$\hat{A}_{MFBAP}(t) = \bar{a}t + k\sigma t^{H(t)} + B \tag{3}$$

Therefore, the estimated upper delay limit $\hat{d}$ is calculated according to Equation (4), where A^* is the MFBAP envelope process, and S is the system's service curve.

$$\hat{d} = \inf\{d \geq 0 | \forall t \geq 0 : A^*(t-d) \leq S(t)\} \tag{4}$$

The service curve $S_n(t)$ [25] can be written as in Equation (5), where c is the mean service rate in the system's server, and N is the number of time intervals T per complete cycle P, where $P = \frac{t}{NT}$.

$$S_n(t) = cTP + cT\min\left\{\frac{\max[t - PNT - (n-1)T; 0]}{T}; 1\right\} \tag{5}$$

To optimize the resource allocation and minimize delay in wireless networks, this study utilizes the scheduling algorithm presented in [26].

The algorithm consists of three phases. In the first phase, it estimates the required number of scheduling blocks (SB) for each user and prioritizes them based on the average channel gain. Next, it allocates SBs to the users, following the prioritization and ensuring compliance with the estimated delay limit and maximum delay criterion. Finally, any remaining SBs are allocated to users according to their estimated delay priority.

The resource allocation follows a priority scheme, with users ranked in increasing order based on their average channel gain. The average channel gain G_k for user k is calculated using Equation (6), where $g_{k,n}$ is the average channel gain for the user in the nth SB, and N is the total number of available SBs.

$$G_k = \frac{1}{N}\sum_{n=1}^{N} g_{k,n} \tag{6}$$

The amount N_k of SBs required for each user k is calculated according to Equation (7).

$$N_k = round\left(\left(\frac{G_k}{G_1 + G_2 + \cdots + G_k}\right) * N\right) \tag{7}$$

The algorithm presented in [26] allocates the scheduling blocks (SBs) based on the channel quality and delay requirements of each user. The allocation priority is determined by estimating the number of SBs required for each user, based on the average channel gain, as shown in Equation (7). The SBs with the highest signal quality indicator are then allocated to the users based on their estimated number of required SBs.

In addition to the quality-of-service requirements, the method also considers the delay limit for each user. The algorithm estimates and checks the delay limit for each allocation, ensuring that it satisfies the stopping criterion. The allocation process continues until the stopping criterion is met, guaranteeing the fair allocation of resources based on the channel quality and delay requirements of each user. This approach ensures an efficient allocation of resources while maintaining fairness among all users.

The delay minimization conflict graph (DMCG) algorithm [27] is a resource allocation method that leverages D2D communication in wireless networks. The algorithm optimizes the estimated delay as a utility function to allocate idle resources of the CUEs to the DUEs while respecting mutual interference constraints.

The DMCG algorithm, illustrated in Algorithm 1, aims to minimize the estimated delay limit for each user while considering mutual interference constraints. The method starts by randomly allocating idle resource blocks to each D2D pair. The algorithm then decides whether to reuse the resource blocks of the CUEs. Unmarked peer groups are created and follow the same process as in GTM+ (described in Section 3.1), removing pairs of DUEs that cannot coexist due to high mutual interference and keeping D2D pairs that minimize system delay.

The approach entails the selection of candidates through the identification of the maximum independent weight set within the conflict graph $G_{m'}$. This method effectively eliminates D2D pairs that cannot coexist due to substantial mutual interference, retaining those pairs that contribute to minimizing system delay. A notable divergence between the DMCG and GTM+ algorithms lies in the fact that the former employs the estimated delay function as a utility function rather than network throughput.

Algorithm 1: DMCG

```
M CUEs, N DUEs, K Idle Resource Blocks;
/* U is the set of unmarked groups */ U ← {1,2,...,M};
/* Γ is the set of DUEs that join the group m */ Γ_1, Γ_2, ..., Γ_M ← 0;
*/ for n ∈ {1,2,...,N} − {δ_1, δ_2, ..., δ_K} do
    /* Run Algorithm 2*/
    m* ← OptimizeDelay(n, U);
    /* D_n join the group m* */
    Γ_{m*} ← Γ_{m*} ∪ {n};
end
while U ≠ 0 do
    Forms the conflict graph G_{m*} for the largest group Γ_{m'} in U
    Δ_{m'} ← set maximum weight independent of G_{m'}
    for n' ∈ Δ_{m'} do
        /* Checks if the DUE pair n' meets the SINR requirement */
        if P_{m'} G_{m'n'} + Σ_{n∈Δ_{m'}−{n'}} P_n G_{nn'} ⩾ I_{n'} then
            Removes n' from Δ_{m'}
        end
    end
    /*In descending order, sort the DUEs in Δ_{m'} by their interference in C_{m'}*/
    /* Removes one DUE from Δ_{m'} until the maximum tolerable interference
     constraint I_{m'} is met */
    while Σ_{n∈Δ_{m'}} P_n G_{nB} ⩾ I_{m'} do
        Removes the first element from Δ_{m'}
    end
    for n ∈ Γ_{m'} − Δ_{m'} do
        /* Run Algorithm 2 */
        m* ← OptimizeDelay(n, U − {m'});
        /* D_n join the group m* */
        Γ_{m*} ← Γ_{m*} ∪ {n};
    end
    /* Group m' is marked */
    U ← U − {m'};
end
```

3.3. Power and Delay Optimization Based Uplink Resource Allocation Algorithm

In this subsection, we briefly describe the approach presented in [28] for resource allocation in multi-sharing uplink scenarios of mmWave cyclic prefix-orthogonal frequency division multiplexing (CP-OFDM) wireless networks [29], incorporating device-to-device communications. The power and delay optimization based uplink resource allocation algorithm comprises two distinct steps [28]. Initially, network resources are allocated to cellular user equipment in terms of both power and transmission rate. This allocation is carried out through a method designed to maximize throughput. Subsequently, unused resources are allocated with a focus on minimizing delay. To achieve this objective, Algorithm 1, called the delay minimization conflict graph, is used. This algorithm facilitates the allocation of idle resources to D2D user equipment within the network by taking into account conflict graphs and estimated delay information. The estimation of delay is conducted using network calculus concepts such as envelope process and service curve, as it can be verified in Algorithm 2, ensuring efficient resource allocation in the system.

Algorithm 2: Optimize Delay

```
/* DUE n and set C */
/* Initialize */
Delay* ← 1000;
m* ← 0;
/* Calculates m* */
for m ∈ C do
    /* Check the constraint */
    if P_n G_nB ≤ I_m then
        /* Estimates the delay limit */
        d̂ = inf{d ≥ 0|∀t ≥ 0 : A*(t − d) ≤ S(t)};
        /* Optimize delay */
        if d̂(m) ≤ Delay* then
            Delay* ← d̂(m);
            m* ← m;
        end
    end
end
/* Find the optimal group: m* */
```

To encapsulate the PDO-URA algorithm, which addresses communications between cellular user equipments and device-to-device user equipments within a cyclic prefix-orthogonal frequency division multiplexing (CP-OFDM) network [29], a pseudo-code is presented in Algorithm 3. This algorithm delineates solutions aimed at maximizing throughput and minimizing user delay by breaking down the problem into distinct optimization challenges. Initially, power allocation is performed to minimize bit error rate (BER) in transmission links. Subsequently, the allocation of resource blocks (transmission rate) for CUEs is determined, taking delay minimization into account. Finally, the unallocated resource blocks designated for CUEs are optimally distributed to DUEs, also considering delay minimization, utilizing the conflict graph algorithm.

Algorithm 3: PDO-URA

M CUEs, N DUE pairs, K idle RBs and $M - K$ real CUEs;
/*Initialize */
For computing the rate to CUE users in order to minimize delay and optimize power efficiency:
/* Run Algorithm 1 */
For allocating idle resources to DUE users considering delay minimization:
/* Run Algorithm 2 */

The part of power allocation of the PDO-URA is related to the approach presented in [26]. The algorithm proposed in [26] aims to optimize power allocation for users in a wireless network. With the knowledge of the channel at the eNodeB, a power allocation vector is computed to minimize the bit error rate in a cyclic prefix-orthogonal frequency division multiplexing (CP-OFDM) transmission link. The algorithm adaptively selects the coding rate, the best modulation format, and the power allocation vector for multiple CUEs to maximize the goodput function [30] represented by Equation (8). The algorithm uses selection optimization to find the best average delay of the CUEs in a CP-OFDM wireless network. The parameters used in the algorithm are defined to achieve the best results, where N_{FFT} is the Inverse fast Fourier transform size, L is the filter size, L_{CH} is the channel impulse response size, N_p is the number of information bits, N_u is the total number of bits transmitted, and r is the convolutional coding rate.

$$\zeta(\phi, w) \triangleq \frac{N_{FFT}}{N_{FFT} + L + L_{CH} - 2} \frac{N_p}{N_u} r m_{mod}[1 - \Phi(\gamma_{eff})] \tag{8}$$

The goodput power allocation algorithm, as presented in Algorithm 4, aims to minimize network delay by taking into consideration the queue buffer of cellular users and implementing an optimal throughput optimization policy. The algorithm ensures efficient allocation of resources by maximizing the network throughput while minimizing delay. The power allocation is calculated based on the current state of the system and the estimated channel quality. This allows for adaptability to changing network conditions and ensures efficient utilization of available resources.

Hence, the simulations presented in Section 5 integrate the goodput power allocation (Algorithm 4) and the resource allocation method (Algorithms 1 and 2) composing the PDO-URA approach (Algorithm 3).

Algorithm 4: Goodput Algorithm

Calculates the previous average arrival rate $\bar{a}$
Define $\mu_m^{\{0\}} = \frac{1}{\bar{a}_m}$
Calculate $r^{(0)} = argmax_{r \in C} \mu^{(0)T} \cdot r$
Initialize the non-idle state size $\eta_m^{(0)} = min_{m \in M} \frac{q_m^1}{r_m^{(0)}}$
Initialize the constellation size $m_{mod} = 0$ and $\varsigma_{max} = 0$
Define the order so that $\frac{q^1_{\pi(1)}}{r^{(0)}_{\pi(1)}} \geq \frac{q^1_{\pi(2)}}{r^{(0)}_{\pi(2)}} \geq \cdots \geq \frac{q^1_{\pi(M)}}{r^{(0)}_{\pi(M)}}$
Define $u = 0$

Algorithm 4: *Cont.*

```
repeat
    Define η^(u+1) = η^(u)
    for m = 1 until M do
        η* = η^(u+1);
        repeat
            Increases η*_π(m)
            repeat
                m_mod = m_mod + 2;
                for b = 0 : B − 1 do
                    Calculates w̄_b(m_mod)
                end
                Collect w̄(m_mod) = [w̄_0(m_mod), ··· , w̄_(B−1)(m_mod)]^T
                Select r' = argmax_(r∈C) ς(r, m_mod, w̄(m_mod))
                if ς(r, m_mod, w̄(m_mod)) ≥ ς_max then
                    Define m* = m_mod
                    r* = r';
                    w* = w̄(m_mod);
                    ς_max = ς(r, m_mod, w̄(m_mod));
                end
            until m_mod = m_mod_max;
            Return φ* = {m*_mod, r*} and w*
            Solves the maximization problem and calculates the evolution of the
             queue state
            if q_π(m)^(η*_π(m)) ≥ 0 then
                η_π(m)^(u+1) = η*_π(m);
            end
        until q_π(m)^(η*_π(m)) < 0;
    end
    u = u + 1;
until η_m^(u) − η_m^(u−1) < ε, ∀m ∈ M;
η* = η^(u);
Calculates the current weight vector μ^t
Calculates the current allocation rate: r* = argmax_(r∈C) (μ^t)^T · r
```

4. Optimal Power Allocation and Delay Minimization Conflict Graph Algorithm for D2D Communications

In this section, we introduce the proposed algorithm for maximizing the total thorughput of D2D and cellular users while meeting their respective QoS requirements.

The proposed algorithm, named optimal power allocation and delay minimization conflict graph (OP-DMCG), combines the resource allocation method described in Section 3.2 with a power allocation method described in Section 4.2. The OP-DMCG algorithm aims to minimize the estimated delay for each user, respect mutual interference constraints, and optimize power allocation to maximize the total throughput and total D2D throughput.

4.1. Resource Allocation

A key part of maximizing the efficiency of a wireless network system is the resource allocation [31]. Resource allocation methods are responsible for allocating the appropriate spectrum of resources from cellular and D2D users. Furthermore, through an optimized resource allocation, interference problems can be minimized.

The proposed resource allocation uses the PDO-URA method described in Section 3.3.

4.2. Power Allocation

Power control involves managing interference while protecting the quality of service. In this section, we present a method to calculate the vector of power allocation that optimizes the total throughput of D2D users and cellular users subject to quality-of-service requirements in relation to SINR.

As it can be seen in [32], it is necessary to consider the distance between all involved devices. The Rayleigh channel [33] coefficients are found from these distances and the gains are calculated using these coefficients.

The instantaneous SINR in BS (γ_{b_k}) and DR_i (γ_i), i = 1, 2, . . ., N, can be written, respectively, as:

$$\gamma_{b_k} = \frac{p_c g_{b,c_k}}{\sum_{i=1}^{K} p_i g_{b,i} + \sum_{j=1,j\neq i}^{K} p_{c_j} g_{b,c_j} + N_0} \tag{9}$$

$$\gamma_i = \frac{p_i g_{i,i}}{\sum_{j=1,j\neq i}^{N} p_j g_{i,j} + \sum_{i=1}^{N} P_{c_k} g_{i,c_k} + N_0}, \tag{10}$$

where p is the transmitted powers, g represents the gains and N_0 is the variance of the independent circularly symmetric complex Gaussian noise with zero mean.

A quality-of-service-driven power allocation scheme is subsequently devised for all users, incorporating constraints to ensure the desired signal-to-interference-plus-noise ratio and adhering to prescribed limitations on transmit power within the network.

The task of power allocation can be succinctly expressed in scalar form through the introduction of the following vectors:

$$G \triangleq \begin{bmatrix} g_{1,1} & -\bar{\gamma}_1 g_{1,2} & \cdots & -\bar{\gamma}_1 g_{1,N} & -\bar{\gamma}_1 g_{1,c_1} & -\bar{\gamma}_1 g_{1,c_2} & \cdots & -\bar{\gamma}_1 g_{1,c_K} \\ -\bar{\gamma}_2 g_{2,1} & g_{2,2} & \cdots & -\bar{\gamma}_2 g_{2,N} & -\bar{\gamma}_2 g_{2,c_1} & -\bar{\gamma}_2 g_{2,c_2} & \cdots & -\bar{\gamma}_2 g_{2,c_K} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ -\bar{\gamma}_N g_{N,1} & -\bar{\gamma}_N g_{N,2} & \cdots & g_{N,N} & -\bar{\gamma}_N g_{N,c_1} & -\bar{\gamma}_N g_{N,c_2} & \cdots & -\bar{\gamma}_N g_{N,c_K} \\ -\bar{\gamma}_{b_1} g_{b,1} & -\bar{\gamma}_{b_1} g_{b,2} & \cdots & -\bar{\gamma}_{b_1} g_{b,N} & g_{b,c_1} & -\bar{\gamma}_{b_1} g_{1,c_2} & \cdots & -\bar{\gamma}_{b_1} g_{1,c_K} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ -\bar{\gamma}_{b_K} g_{b,1} & -\bar{\gamma}_{b_K} g_{b,2} & \cdots & -\bar{\gamma}_{b_K} g_{b,N} & -\bar{\gamma}_{b_K} g_{1,c_2} & g_{b,c_K} & \cdots & -\bar{\gamma}_{b_K} g_{b,c_K} \end{bmatrix} \tag{11}$$

$$\bar{p} \triangleq \begin{bmatrix} p_1 & p_2 & \cdots & p_N & p_{c_1} & p_{c_2} & \cdots & p_{c_K} \end{bmatrix}^T \tag{12}$$

$$\bar{n} \triangleq \begin{bmatrix} N_0\bar{\gamma}_1 & N_0\bar{\gamma}_2 & \cdots & N_0\bar{\gamma}_N & N_0\bar{\gamma}_{b_1} & N_0\bar{\gamma}_{b_2} & \cdots & N_0\bar{\gamma}_{b_K} \end{bmatrix}^T \tag{13}$$

$$\bar{p}_{max} \triangleq \begin{bmatrix} p_1^{max} & p_2^{max} & \cdots & p_N^{max} & p_{c_1}^{max} & p_{c_2}^{max} & \cdots & p_{c_K}^{max} \end{bmatrix}^T, \tag{14}$$

where G is called a Z-matrix [12,13] because all of its off-diagonal elements are non-positive, p is the vector of powers, n is the vector that relates the instantaneous SINR with the variance, and p_{max} is the maximum power. According to Lemma 1 in [32], if matrix G defined in Equation (11) satisfies Equation (15), then a unique lower bound for the power allocation is given by Equation (16), satisfying the condition $p_{min} \preceq p_{max}$. Thus, p_{min} represents the optimal solution to the power allocation optimization problem.

$$g_{i,i} > \bar{\gamma}_i \sum_{j=1,j\neq i}^{N+K} g_{i,j}, \forall i = 1, 2, \cdots, N+K \tag{15}$$

$$p_{min} = G^{-1} n \tag{16}$$

The proposed optimal power allocation and delay minimization based on the conflict graph algorithm for device-to-device communications approach is detailed in Algorithm 5.

Algorithm 5: OP-DMCG

```
M CUEs, N DUEs, K Idle Resource Blocks, Z Initial amount of CUEs;
for j = 1 until Z + 1 do
    Randomly Generates Locations of CUEs and DUEs;
    Calculate the Gains g_{N,N}, g_{b,c_k}, g_{b,N} and g_{N,c_k};
    Calculate the Z-matrix using Equation (11);
    Calculate the Power using Equation (16);
end
/* Find the optimal power: Pm /*;
/* U is the set of unmarked groups */ U ← {1,2,...,M};
/* Γ is the set of DUEs that join the group m */ Γ_1, Γ_2, ..., Γ_M ← 0;
for n ∈ {1,2,...,N} − {δ_1, δ_2, ..., δ_K} do
    /* Run Algorithm 2*/ m* ← OptimizeDelay(n, U);
    /* D_n join the group m* */
    Γ_{m*} ← Γ_{m*} ∪ {n};
end
while U ≠ 0 do
    Forms the conflict graph G_{m*} for the largest group Γ_{m'} in U
    Δ_{m'} ← set maximum weight independent of G_{m'}
    for n' ∈ Δ_{m'} do
        /* Checks if the DUE pair n' meets the SINR requirement */
        if P_{m'} G_{m'n'} + Σ_{n∈Δ_{m'}−{n'}} P_n G_{nn'} ⩾ I_{n'} then
            Removes n' from Δ_{m'}
        end
    end
    /*In descending order, sort the DUEs in Δ_{m'} by their interference in C_{m'}*/
    /* Removes one DUE from Δ_{m'} until the maximum tolerable interference
      constraint I_{m'} is met */
    while Σ_{n∈Δ_{m'}} P_n G_{nB} ⩾ I_{m'} do
        Removes the first element from Δ_{m'}
    end
    for n ∈ Γ_{m'} − Δ_{m'} do
        /* Run Algorithm 2 */ m* ← OptimizeDelay(n, U − {m'});
        /* D_n join the group m* */
        Γ_{m*} ← Γ_{m*} ∪ {n};
    end
    /* Group m' is marked */
    U ← U − {m'};
end
```

5. Simulation and Results

In this section, we present simulations and numerical results of the implemented scenario to evaluate the performance of the proposed optimal power allocation and delay minimization based on the conflict graph algorithm for device-to-device communications algorithm in maximizing the total throughput of both D2D and cellular users, while adhering to QoS requirements. In our research, we conduct a performance comparison of our algorithm against established methods from the existing literature, including the greedy throughput maximization plus, delay minimization conflict graph, and power and delay optimization based uplink resource allocation resource allocation techniques.

We emphasize the significance of parameter tuning to ensure a fair and meaningful comparison across algorithms. The selected parameters align with the characteristics of 5G wireless networks and adhere to established practices in D2D multi-sharing communication [21,34]. This tuning process enhances the relevance and validity of our comparative analysis, reflecting real-world scenarios in the context of evolving wireless communication technologies.

The values for the parameters used in the simulations of this work are given in Table 1.

Table 1. Parameter values.

Parameters	Values
BS	1
Ratio	500 m
Initial CUEs	50
Final CUEs	100
DUEs	160
Model	Rayleigh

The computational complexity of algorithms has a direct impact on processing time. The proposed OP-DMCG algorithm has a complexity of $O(n^3)$ since it involves matrix inversion in its calculation. In contrast, the DMCG and GTM+ algorithms exhibit $O(n^4)$ complexity in the worst case. Finally, the PDO-URA algorithm demonstrates a linear complexity of $O(n)$. Table 2 illustrates the computational complexity of each algorithm employed in this study.

Table 2. Computational complexity.

Algorithms	Complexity
OP-DMCG	$O(n^3)$
GTM+	$O(n^4)$
PDO-URA	$O(n)$
DMCG	$O(n^4)$

One of the greatest problems in cellular networks today is the number of users that is growing more and more and the dynamics of changing the number of people using a cell. In this sense, in this work, the number of cellular users varied from 50 CUEs to 100 CUEs. The performance of each algorithm was tested with these numbers of CUEs.

In order to have more reliable results, the algorithms were executed 100 times for each number of CUEs, and the average of the final value was used at each point of the graphs of total throughput and total D2D throughput.

Another point that has to be considered in the algorithms and in the simulations is the way D2D links are initially created. To this end, in this work, after determining the locations of each device, a search is performed among all devices in the cell to decide which CUEs and DUEs will be chosen to define the D2D links. The same process is performed between the receivers and transmitters of the system. Notice that in the case of the DMCG algorithm, after defining the positions of D2D links, this approach also removes D2D pairs that cannot coexist due to high mutual interference and keeps D2D pairs that minimize system delay.

Three methods of search were simulated. The random search is shown in Section 5.1, the closest search in Section 5.2, and the radius search in Section 5.3.

5.1. Random Search

In the first method, the cellular users, the D2D receivers (DRs), and the D2D transmitters (DTs) positions are randomly generated, and the links between them are also randomly determined.

Figure 2 shows the total throughput in Mbits/s, as we can see the optimal power allocation and delay minimization based on the conflict graph algorithm for device-to-device communications provided higher total throughput than the other algorithms.

A similar result is seen in Figure 3 when we analyze the total D2D throughput in Mbits/s. The OP-DMCG provided better results regarding total D2D throughput when compared to the other algorithms.

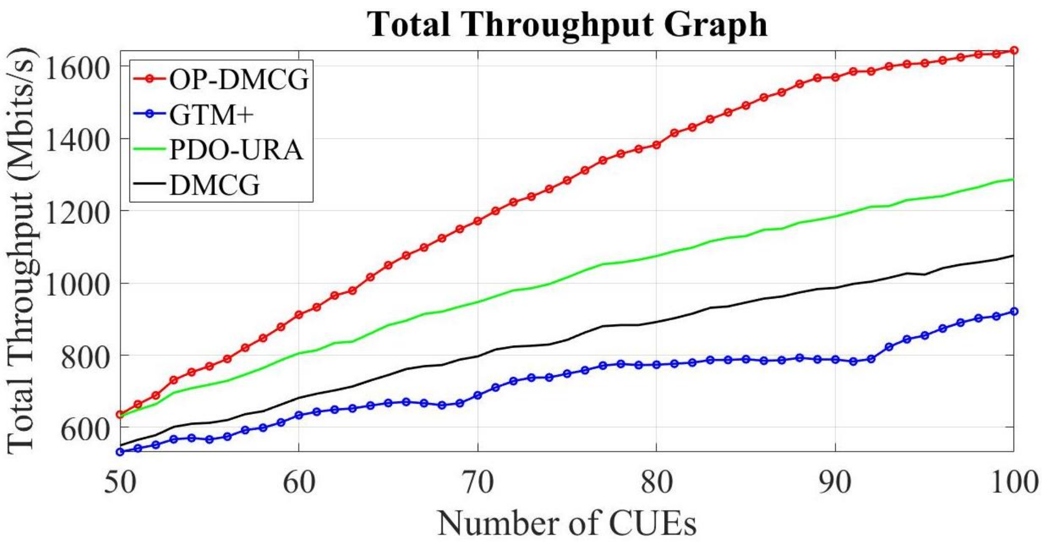

Figure 2. Total throughput—random search.

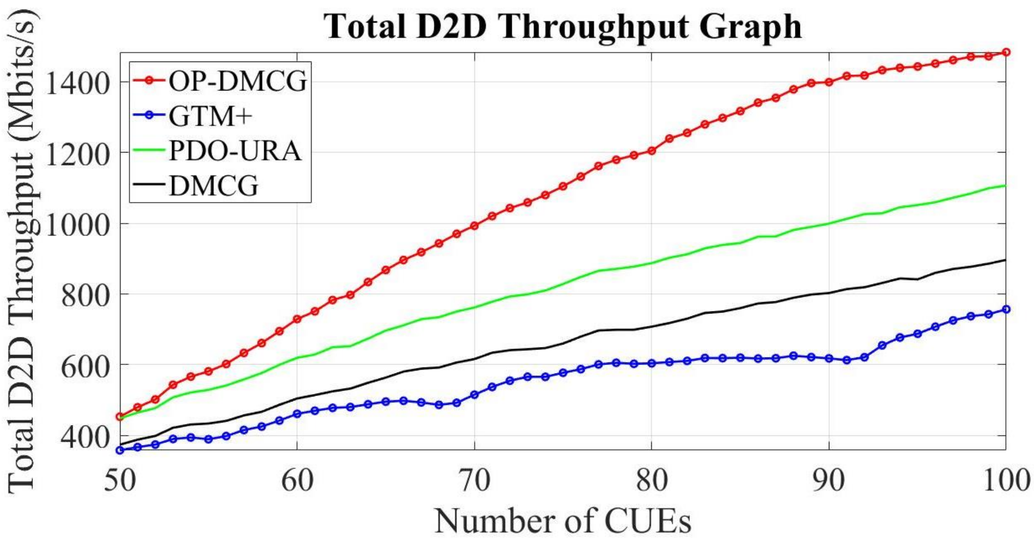

Figure 3. Total D2D throughput—random search.

Figure 4 illustrates the fairness index, revealing that the OP-DMCG fairness index increases until it reaches around 89 CUEs and subsequently decreases consistently during varying numbers of CUEs, as observed at different time intervals. The fairness index [35] is a measure used to determine if users are receiving a fair distribution of system resources. The closer the value of this parameter is to 1, the fairer the allocation of resources in the network is considered. The fairness index is calculated according to Equation (17).

$$Fairness = \frac{[\sum_{k=1}^{K} r_k]^2}{K \sum_{k=1}^{K} r_k^2}, \tag{17}$$

where K represents the total number of cellular users, and r_k denotes the throughput of user k.

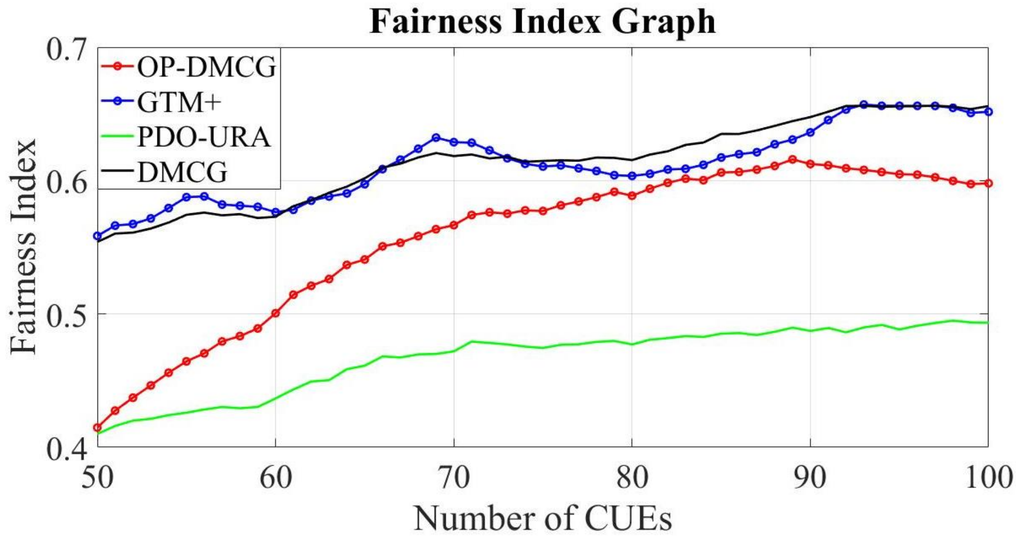

Figure 4. Fairness index—random search.

Lastly, as illustrated in Figure 5, it is evident that the OP-DMCG algorithm exhibits lower delay compared to DMCG, GTM+ and PDO-URA algorithms, mainly for a number of CUEs higher than 70.

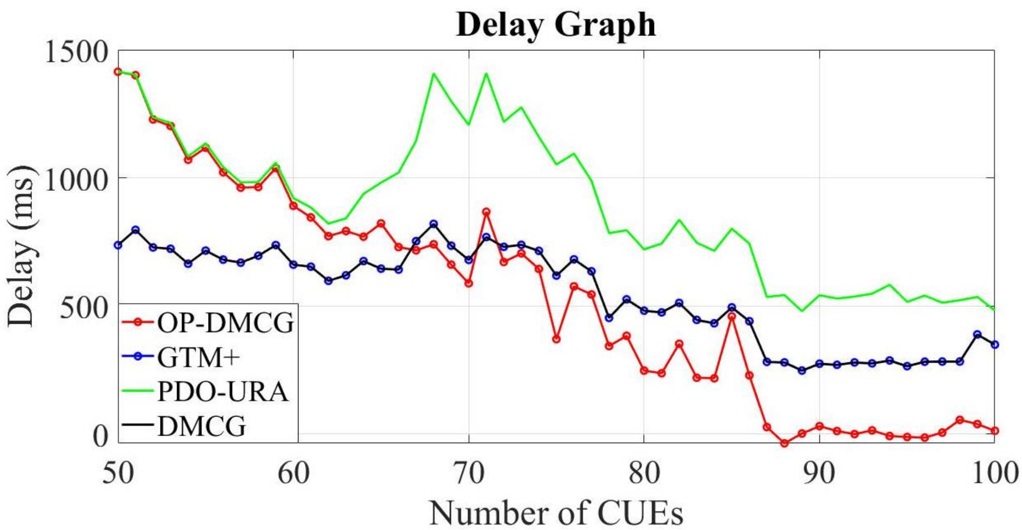

Figure 5. Delay—random search.

5.2. Closest Search

The second method, namely the closest search method, randomly generates the positions of CUEs, DRs and DTs. Next, the method checks which DR is closest to each CUE and creates the link. In the same way, the links between DRs and DTs are defined; that is, there is a verification of which DT is closer to each DR, and the link between them is created.

Figures 6 and 7 display the simulation results regarding total network throughput and total D2D throughput obtained using this D2D creation link method. Consequently, the simulation results confirm that the OP-DMCG exhibits superior performance in terms of throughput and D2D throughput when compared to other algorithms even when varying the search method.

Figure 8 illustrates the fairness index, indicating that the OP-DMCG algorithm demonstrates a lower value compared to the GTM+ and DMCG algorithms, and higher values when compared to the PDO-URA algorithm.

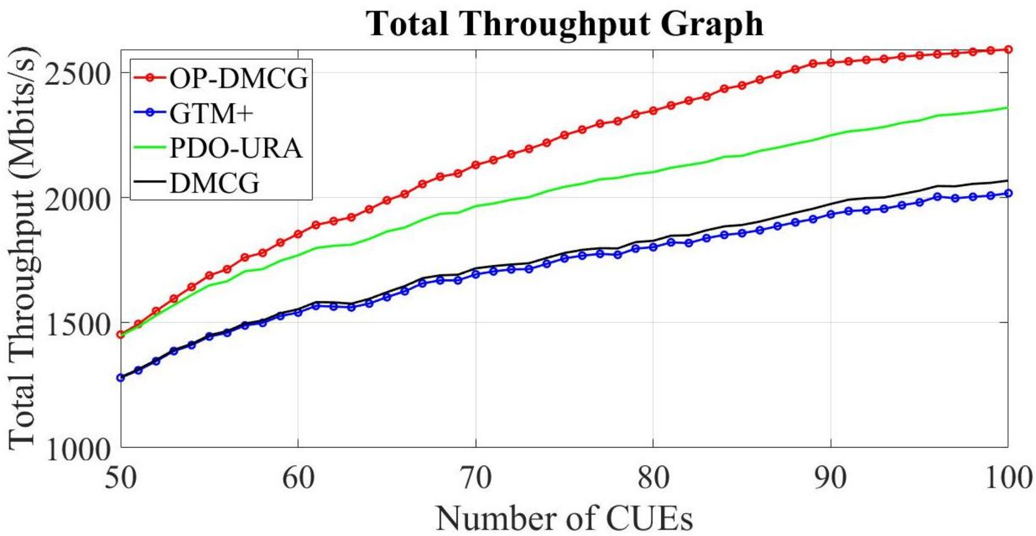

Figure 6. Total throughput—closest search.

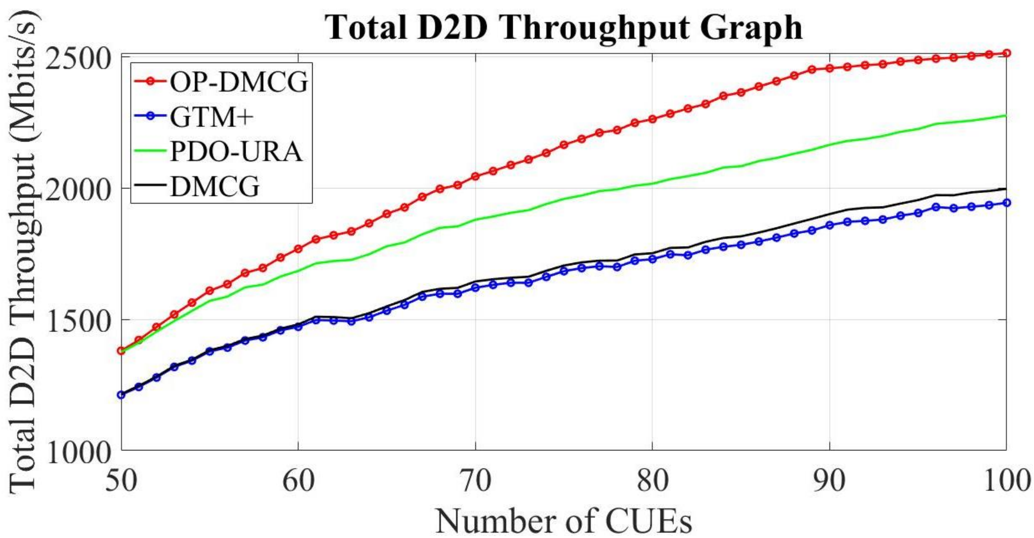

Figure 7. Total D2D throughput—closest search.

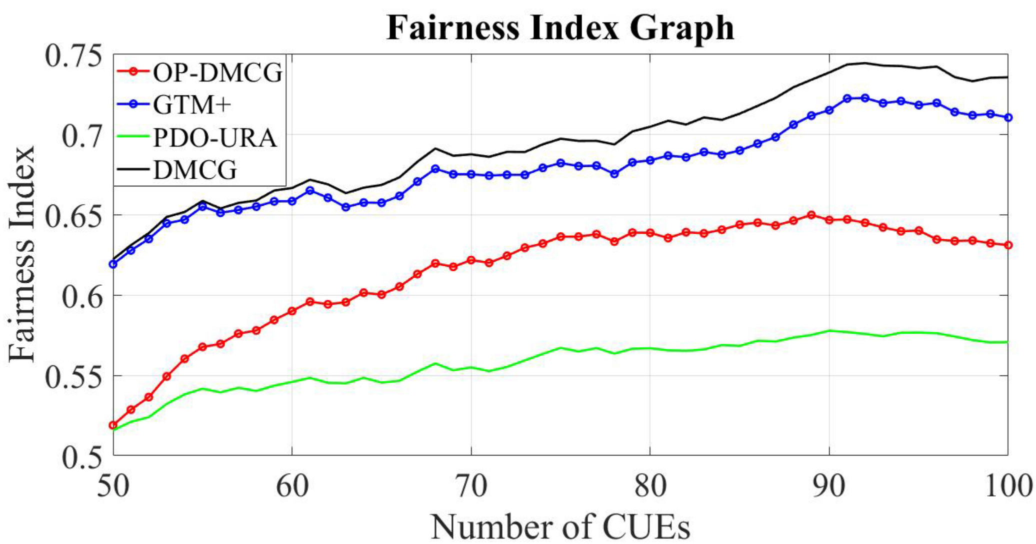

Figure 8. Fairness index—closest search.

Furthermore, Figure 9 shows that when the number of CUEs exceeds 60, the delay of OP-DMCG is lower compared to the other algorithms.

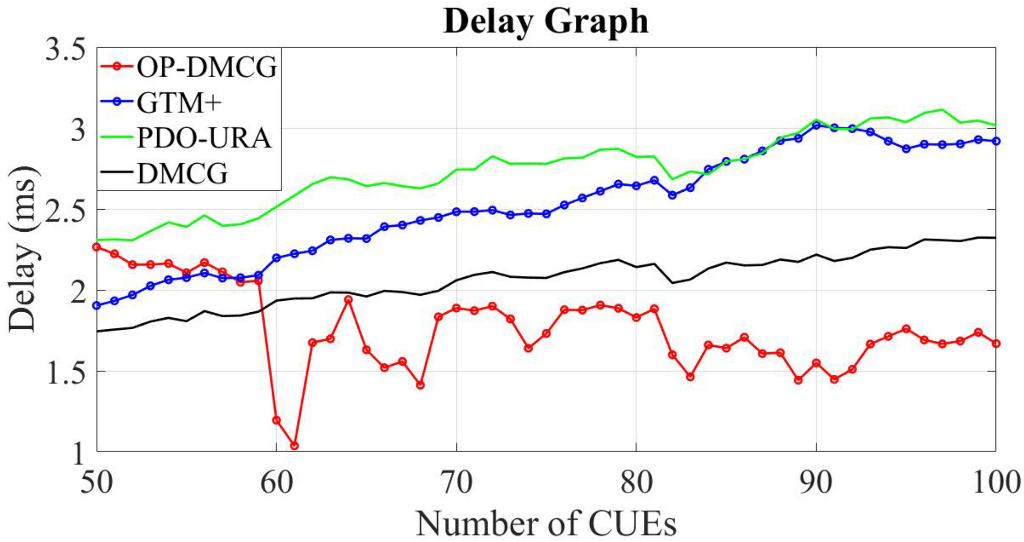

Figure 9. Delay—closest search.

5.3. Radius Search

The last method, namely radius search, generates the positions of CUEs, DRs, and DTs randomly. Subsequently, the method verifies which DRs are located within a 15 m radius of each CUE; a distance value chosen through a comprehensive simulation-based search aimed at optimizing various performance metrics, including throughput, delay, and fairness index. From this group of DRs, one is selected randomly, and a link is established between the chosen DR and the corresponding CUE. Similarly, the links between DRs and DTs are established by checking which DTs are within the 15 m radius of each DR. One of the DTs from this group is randomly selected, and the D2D link is created between the chosen DR and the respective DT.

Figures 10 and 11 showcase the simulation results obtained through the utilization of the D2D creation link method. Notably, the search method significantly enhances the outcomes in terms of throughput and device-to-device throughput, surpassing the performance of the preceding methods, namely random search and closest search. Again, the OP-DMCG algorithm demonstrates superior performance in terms of throughput in comparison to the DMCG, GTM+, and PDO-URA algorithms.

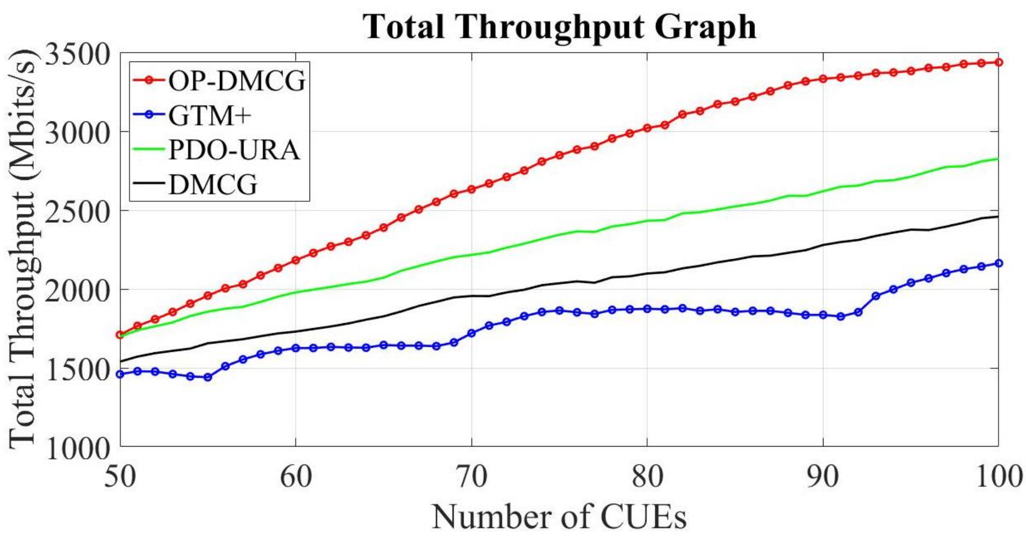

Figure 10. Total throughput—radius search.

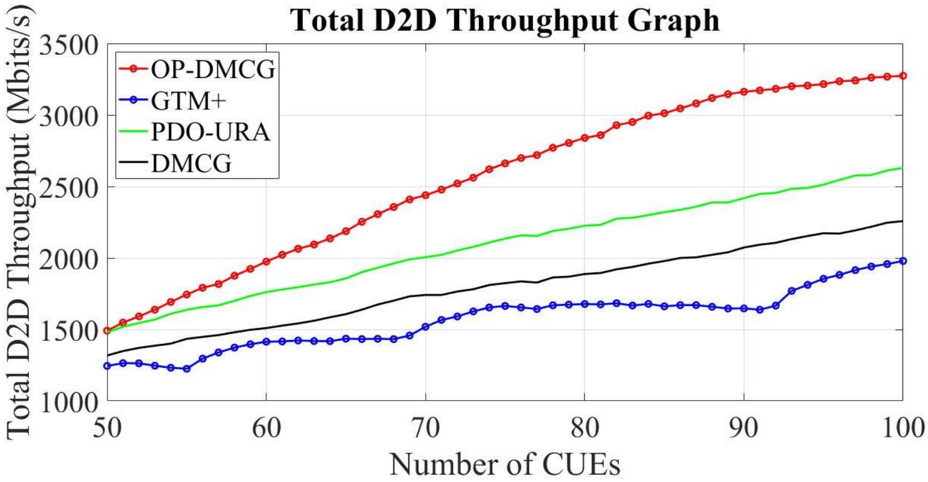

Figure 11. Total D2D throughput—radius search.

Figure 12 depicts the fairness index, highlighting that the DMCG and GTM+ algorithms demonstrate the highest values in comparison to other algorithms. Nevertheless, the PDO-URA algorithm exhibits lower fairness index values than OP-DMCG.

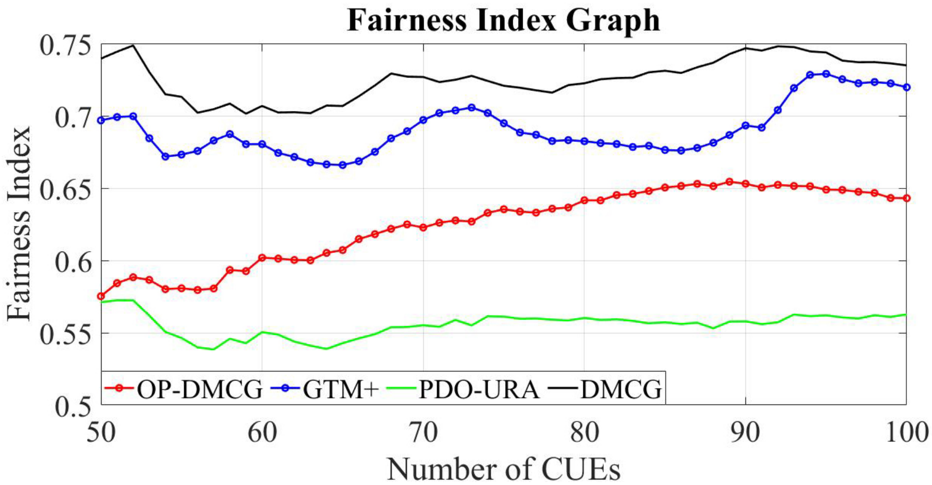

Figure 12. Fairness index—radius search.

Furthermore, as illustrated in Figure 13, it can be observed that when the number of CUEs exceeds 70, the delay of OP-DMCG is lower compared to the other algorithms.

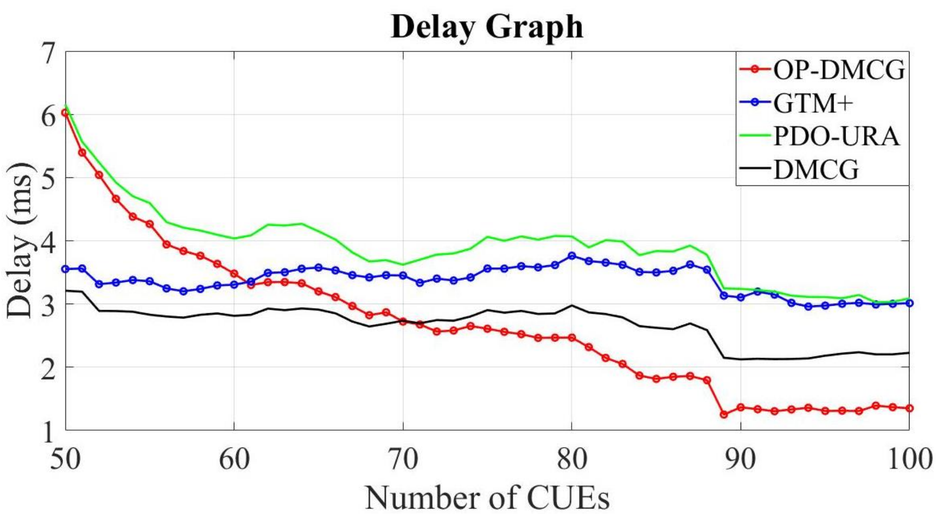

Figure 13. Delay—radius search.

6. Conclusions

In this work, we analyze, considering some particular algorithms, how the use of resource allocation and power allocation methods can influence the total throughput and the total D2D throughput of a cellular network system using device-to-device communication. In this sense, based on some results and approaches, we also propose a resource and power allocation algorithm whose performance was compared against others from the literature.

The simulations conducted highlight the substantial influence of resource and power allocation methods on the overall performance of the system. It is evident from the numerical results that modifying these allocation strategies significantly affects both total system throughput and device-to-device throughput.

Our proposed solution, the optimal power allocation and delay minimization based on conflict graph algorithm for device-to-device communications, consistently demonstrates superior performance compared to the greedy throughput maximization plus, delay minimization conflict graph, and power and delay optimization based uplink resource allocation algorithms, as observed through comprehensive analysis of both total system throughput and total device-to-device throughput metrics.

The fairness index graphs reveal that the OP-DMCG algorithm penalizes this parameter to provide higher throughput and lower total delay compared to other algorithms. In other words, it tends to be less equitable when compared to alternative algorithms, allocating more resources to users with better channel conditions.

In addition to the results discussed earlier, another conclusion derived from this study is that the initial creation process of device-to-device links influences the final result. Our meticulous observations unveiled that the utilization of a radius search mechanism exhibited superior efficacy when gauged against both the closest search and the random search methodologies. The advantages of the radius search became evident through its demonstrated effectiveness in enhancing not only the overall throughput but also the specific D2D throughput performance. This suggests that the radius search strategy at the onset of D2D link creation can significantly contribute to optimizing the overall network performance, showcasing its potential as a preferred approach in the context of enhancing communication efficiency when compared to the closest search and random search.

In summary, our findings highlight the OP-DMCG algorithm, specifically when utilizing the radius search technique, as the optimal choice in terms of achieving superior results in both total throughput and total device-to-device throughput, surpassing alternative approaches considered in our study. The efficacy of the OP-DMCG algorithm is notably enhanced by the strategic deployment of the radius search, a method that consistently demonstrated its ability to create efficient D2D links.

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