Sum Rate And Fairness Maximization In Device-To-Device Communication Underlaying Cellular Networks

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Abstract: Device-to-Device (D2D) communication is one of the revolutionary technologies in the 5G mobile communication systems, it can provide high connection speed and massive device connectivity. However, the inclusion of D2D Users (DUs) into the cellular network interferes with (Cellular Users) CUs, thus hindering CU’s communication. Therefore, efficient resource allocation techniques for D2D communication need to be formulated to enhance system capacity while limiting interference experienced by CUs. In this article, resource allocation scheme for D2D communications underlay network is proposed. First, a resource allocation optimization problem is formulated to maximize the system sum rate, which is modelled into a maximum weight bipartite problem and solved using the Hungarian method. Then, a fair resource allocation optimization problem is formulated into a max min utility problem, which is solved using the bisection method together with the Hungarian method. The max sum algorithm leads to a higher sum rate compared to max min algorithm. However, the max min algorithm enhances fairness among DUs compared to max sum algorithm, by maximizing the minimum achievable rate of the DUs and ensuring uniformity in data rates among the D2D users.

Index Terms: 5G, bisection method, D2D, Hungarian method, max min, max sum, resource allocation

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1 INTRODUCTION

1.1 Background

The growing number of connected devices coupled with the continuous evolution of technology have contributed to the increase of demand for high data rates for efficient and effective communication. Device-to-Device (D2D) communication has been proposed as one of the key enablers of the 5G systems. D2D communication permits direct communication between devices in close range under the control of the evolved node B (eNB) [1]. This technology is expected to greatly improve spectrum utilization and user throughput of the 5G systems [2]. The performance gain is expected because of the possibility of reusing the spectrum resources assigned to the Cellular users (CUs) with D2D underlay network. However, inclusion of D2D users (DUs) into the cellular network causes interference to the CUs, thus hindering CU’s communication [3]. Therefore, the main challenge facing D2D communication is restraining interference on the CUs so as to guarantee their Quality of Service (QoS). Hence, efficient resource allocation techniques for D2D communication need to be formulated to enhance system capacity while limiting interference experienced by CUs and maintaining fairness among the users.

1.2 Related Works

In [4], a resource allocation scheme was designed to enhance system sum rate and alleviate interference in dense networks of D2D pairs that re-use Resource Blocks (RBs) of CUs. They formulated the optimization and proposed a heuristic RB allocation algorithm. In [5], the authors proposed a resource sharing algorithm using the Stackelberg game to enhance system sum rate in D2D communications. Authors in [6], addressed the problem of allocating resources to the D2D communication network using the Graph matching algorithm to achieve proportional fairness among the DUs, while guaranteeing minimum rates of CUs. Authors in [7], investigated power allocation for D2D communications operating in the cellular networks with max min fairness. Their aim was to maximize the minimum individual energy efficiency of D2D pairs. The authors in [8], proposed a Gain-Aware Uplink-Downlink resource allocation scheme for maximizing the D2D sum rate. Lagrangian dual algorithm was used to perform power allocation. In addition, a fair channel allocation was designed for the D2D pairs. D2D communication in millimeter wave cellular network was studied in [9] by considering fair resource distribution in the network while optimizing the spectral efficiency.

1.3 Contributions

In this paper, a downlink and uplink resource allocation scheme for D2D communication is proposed. The scheme accomplishes two main goals: max sum optimization and max min optimization of the user data rates. Max sum optimization is geared towards ensuring a high sum rate from the perspective of network operator while max min optimization is undertaken to enhance fairness among the D2D pairs.

1.4 Paper Organization

The rest of the article is organized as follows. In Section II the system model is described. Section III addresses resource allocation problem to maximize the system sum rate, whereas Section IV considers the maximization of the minimum rate. Section V presents simulation results and discussion. The paper finally draws conclusions in Section VI.

2 SYSTEM MODEL

A single outdoor micro-cell having an eNB at the center with K CUs and L DUs are considered in this work. The DUs reuse both downlink and uplink RBs of CUs for communication. The system model is illustrated in Fig 1. The eNB coordinates all communication incidences in the cell. It is responsible for device discovery, setting up the session and managing radio resources. Further, it is assumed that the eNB and DUs are aware of channel state information (CSI) and all the interference thresholds. The frequently used notations in this paper are described in Table 1.

TABLE 1

SUMMARY OF NOTATIONS

Notation	*Description*
P_l, P_k, P_b	*Tansmit power for D2D pair, CU and eNB*
$g_{l,l}$	*D2D transmitter (DTx) – D2D receiver (DRx) channel gain*
$g_{b,l}$	*eNB – D2D pair l channel gain*
$g_{k,l}$	*CU k – D2D pair l channel gain*
$g_{l,k}$	*D2D pair l – CU k channel gain*
$g_{k,b}$	*CU k – eNB channel gain*
$g_{b,k}$	*eNB – CU k channel gain*
$\gamma_k^{c,dl}, \gamma_k^{c,ul}$	*SINR for CU k in downlink and uplink phases*
γ_l^d	*SINR for l^{th} D2D pair*
$\gamma_k^{tgt,ul}, \gamma_k^{tgt,dl}$	*Target SINR for CU k in uplink and downlink phase*
γ_l^{tgt}	*Target SINR for l^{th} D2D pair*
R_k^{ul}, R_k^{dl}	*Channel rates for CU k in uplink and downlink phase*
R_l	*Channel rate for l^{th} D2D pair*
N_0	*Noise spectral density*

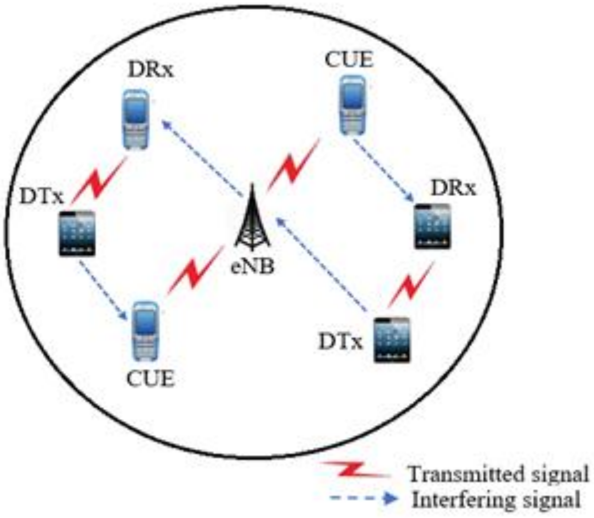

Fig 1: *System Model*

The SINR at the k^{th}CU and the eNB is given by (1) and (2) respectively.

$$\gamma_k^{c,ul} = \frac{P_k g_{k,b}}{\sum_{l=1}^{L} x_{kl}^{ul} P_l g_{l,b} + N_0} \quad (1)$$

$$\gamma_k^{c,dl} = \frac{P_b g_{b,k}}{\sum_{l=1}^{L} x_{kl}^{dl} P_l g_{l,k} + N_0} \quad (2)$$

The SINR at the D2D receiver (DRx) during uplink and downlink resource sharing is given by (3)

$$\gamma_l^d = \frac{P_l g_{l,l}}{\sum_{k=1}^{K} x_{kl}^{dl} P_k g_{b,l} + \sum_{k=1}^{K} x_{kl}^{ul} P_k g_{k,l} + N_0} \quad (3)$$

where x_{kl}^{ul} and x_{kl}^{dl} are binary indicators of optimization for the uplink and downlink phases respectively. They take a value of 1 when the RB of the CU is reused by a DU and zero otherwise. The achievable channel rates are then given by the Shannon Capacity Theorem as [12].

$$\begin{aligned} R_k^{ul} &= W \log_2(1 + \gamma_k^{ul}) \\ R_k^{dl} &= W \log_2(1 + \gamma_k^{dl}) \\ R_l &= W \log_2(1 + \gamma_l^d) \end{aligned} \quad (4)$$

where W is the bandwidth, R_l is the channel rate of DU l, R_k^{ul} and R_k^{dl} are uplink and downlink channel rates for CU k respectively. The system sum rate is given by:

$$R_{tot} = \sum_{l=1}^{L} R_l + \sum_{k=1}^{K} R_k^{ul} + \sum_{k=1}^{K} R_k^{dl} \quad (5)$$

In the mmWave frequency range, the 28GHz, 38 GHz and 70-80 GHz bands are expected to a play great role in the next generation of cellular wireless networks since they possess favourable propagation characteristics [1]. In this paper, the 28 GHz frequency band is considered for outdoor propagation conditions. The spectrum at 28 GHz has a lower path loss compared to the other potential frequency bands in the mmWave frequency range [1]. In an environment which is characterized by obstacles and dense users, the signal received by the users is composed of both non line of sight (NLOS) and line of sight (LOS) components, which are consistent with their log-normal shadow fading. In [13], the statistical data both for the path loss for LOS (PLOS) and path loss for NLOS (PNLOS) for 28 GHz channel model are provided.

3 RESOURCE ALLOCATION FOR SUM RATE MAXIMIZATION

In this section, a resource allocation algorithm is proposed to maximize system sum rate while taking into account the minimum SINR requirements of users. The resource allocation problem is formulated in (6);

$$\max_{x,p}(R_{tot}) \quad (6)$$

subject to constraints (7) – (14).

$$\gamma_k^{c,ul} \geq \gamma_k^{tgt,ul} \quad (7)$$

$$\gamma_k^{c,dl} \geq \gamma_k^{tgt,dl} \quad (8)$$

$$\gamma_l^d \geq \gamma_l^{tgt} \quad (9)$$

$$P_k \leq P_k^{max} \quad (10)$$

$$P_l \leq P_l^{max} \quad (11)$$

$$P_{b,k} \leq P_{b,k}^{max} \quad (12)$$

$$\left(\sum_{l=1}^{L} x_{kl}^{ul}\right)\left(\sum_{l=1}^{L} x_{kl}^{dl}\right) = 0, \forall l \in L, \quad (13)$$

$$x_{kl}^{ul}, x_{kl}^{dl} \in \{0,1\}, \forall k \in K, \forall l \in L \quad (14)$$

The constraints in (7) and (8) ensures that the SINR requirements for CUs in uplink and downlink phases are met. Constraint (9) provides target SINR for the DU. Constraints (10), (11) and (12) limit the maximum transmission power of the CUE, DUE and eNB respectively. Constraint (13) ensures that the DU reuses either the uplink or downlink resources at a time. Constraint (14) is the RB reuse indicator for the D2D pairs, it takes either 0 or 1. The optimization problem is broken down into two sub-problems that are solved separately to tackle the complexity issue. First, power allocation for a single DUE–CUE pair is performed to maximize data rate. Then, RB assignment for multiple DUs is performed using the maximum weight bipartite graph and solved using the Hungarian method [12].

3.1 Power Allocation

To allocate transmission power to k^{th} CU and l^{th} DU, (6) is reduced to (15), by considering a single CU-DU pair. The uplink reuse of the RBs is considered first for this case.

$$\max_{P_k,P_l}(R_k^{ul}+R_l) \qquad (15)$$

subject to constraints (16) – (19).

$$\gamma_k^{c,ul} \geq \gamma_k^{tgt,ul} \qquad (16)$$

$$\gamma_l^{d} \geq \gamma_l^{tgt} \qquad (17)$$

$$P_k \leq P_k^{max} \qquad (18)$$

$$P_l \leq P_l^{max} \qquad (19)$$

The feasible region for power allocation is enclosed by constraints (16)-(19), which are the power and SINR constraints. The power allocation problem is solved using geometric programming method. The following lemmas are used to obtain the optimal transmit power allocation (P_k^*, P_l^*) for problem (15).

Lemma 1. The optimal solution (P_n^*, P_m^*) has either cellular user or the D2D pair transmitting at its maximum power (either $P_k^* = P_k^{max}$ or $P_l^* = P_l^{max}$)

Proof 1: The proof of Lemma 1 is similar to the one done in [13].

Lemma 2. The optimal solution (P_n^*, P_m^*) is located at the corner and extreme points of the feasible region

Proof 2: The proof of Lemma 2 is similar to the proof presented in [14].

The power allocation for downlink phase is done using the same approach as that for the uplink phase. The uplink and downlink phases need to be overlapped so as to make the reuse of both uplink and downlink RBs possible.

3.2 Resource Block Assignment

In this section, the D2D pairs are assigned RBs depending on throughput gain they are introducing in the network. The throughput gain represents the increase in throughput in the network as a result of allowing D2D communication to operate as underlay in the cellular network. The D2D pair is only permitted to access the network if it results in a positive throughput gain. The gain as a result of the resource sharing between the CU and DU pair in the uplink phase is given in (20).

$$T_{k,l}^{G,ul} = W\log_2\left(1+\frac{P_l g_{l,l}}{P_k g_{k,l}+N_0}\right)+W\log_2\left(1+\frac{P_k g_{k,b}}{P_l g_{l,k}+N_0}\right)- W\log_2\left(1+\frac{P_k g_{k,b}}{N_0}\right) \qquad (20)$$

When the DUE l reuses the downlink RB to CUE k, the gain is given by (21).

$$T_{k,l}^{G,dl} = W\log_2\left(1+\frac{P_l g_{l,l}}{P_b g_{b,l}+N_0}\right)+W\log_2\left(1 + \frac{P_b g_{b,k}}{P_l g_{l,k}+N_0}\right)-W\log_2\left(1+\frac{P_b g_{b,k}}{N_0}\right) \qquad (21)$$

In (20) and (21), the first term represents the throughput of l^{th} DU pair, while the second term represents the throughput of the k^{th} CU when sharing its RB with the l^{th} DU pair, while the third term is throughput of the k^{th} CU when it is not sharing its RB with l^{th} DU pair. Therefore the optimal reuse partner for the l^{th} DU pair is the one with which it can attain maximum throughput gain. The problem of optimal resource allocation for multiple D2D pairs is modelled as a maximum weight bipartite matching problem by (22).

$$\max_{x_{kl}^{ul},x_{kl}^{dl}} \sum_{l=1}^{L}\sum_{k=1}^{K}\left(x_{kl}^{ul}T_{k,l}^{G,ul}+x_{kl}^{dl}T_{k,l}^{G,\mathrm{dl}}\right) \qquad (22)$$

Subject to the constraints (13) and (14)

In the bipartite graph matching, when DU l reuses the uplink resource block of CU k, it establishes a connection (edge) in the bipartite graph and takes, $T_{k,l}^{G,ul}$ as its weight and in the downlink it establishes a connection (edge) with $T_{k,l}^{G,dl}$ as weight, else there is no connection between DU l and CU k. From the weighted bipartite graph, a throughput gain matrix denoted as $\boldsymbol{T^G}$ is realized. The maximum weight bipartite matching problem represented in (22) is then solved using the Hungarian method based on the throughput gain matrix to obtain optimal RBs reuse pattern between D2D pairs and CUs.

4 RESOURCE ALLOCATION FOR MINIMUM RATE MAXIMIZATION

In this work, fairness in the D2D communication is understood as the maximization of the minimum achievable rate of the DUs. The resource assignment algorithm for maximizing the minimum D2D achievable channel rate is proposed to increase the fairness among DUs in the network. The optimization problem is given in (23);

$$\max_{x,P}\min_{l\in L}(R_l) \qquad (23)$$

subject to the constraints (7) and (14)

4.1 Resource Block Assignment to Multiple D2D Pairs

The resource allocation problem given in (23) is solved by applying the results obtained for optimal power allocation and the throughput gain matrix T^G obtained by (22). The D2D pairs with low achievable channel rates contribute a lower throughput gain in the network compared to the ones with higher achievable channel rates, when they share CUs' resources. The original optimization problem (23) is simplified into a form given in (24) by considering the throughput gain as a result of sharing the RBs of the CUs.

$$\max_{x_{kl}^{ul},x_{kl}^{dl}}\min_{l\in L}\sum_{k=1}^{K}\left(x_{kl}^{ul}T_{k,l}^{G,ul}+x_{kl}^{dl}T_{k,l}^{G,\mathrm{dl}}\right) \qquad (24)$$

subject to the constraints (13) and (14)

For maximizing the minimum achievable channel rate of D2D pairs, a low-complex RB assignment algorithm is proposed to solve problem (24) by exploiting the Hungarian method. The proposed algorithm solves the optimization problem in two essential parts. In the first part, the throughput gain matrix (T^G) is initialized and its elements arranged in an ascending order and stored in vector u. This is followed by an initialization of matrix W, which is a zero matrix of size $2K \times L$. Then a and b are initialized, where a is the index of the minimum value of vector u whereas b is the index of the maximum value of vector u. In the second part, the bisection search method presented in [15],[16] is used to determine the position of the optimal minimum throughput gain in the throughput gain matrix. To achieve this, the elements of vector u are scanned through and if the mid value of the vector is greater than $T_{k,l}^{G}$ the corresponding entry in W is set to 1, otherwise the entry is left as 0. Then, Hungarian method is applied on W to determine the assignment, labelled as X and the minimum total cost, which is the sum of the elements which are assigned. If the minimum total cost equals 0, then the mid value is equal or less than the anticipated optimal minimum throughput gain. Similarly, if the minimum total cost is greater than zero, the mid value is greater than the anticipated optimal minimum throughput gain. Lastly, when the bisection search has been completed, the Hungarian method returns the spectrum sharing assignment.

5 SIMULATION RESULTS AND DISCUSSION

In this section the performance of proposed scheme is evaluated through selected simulation results. Further, the max sum and max min algorithms are compared to evaluate the merits and shortcomings of each of the two algorithms. The simulations are done in the MATLAB software. In the MATLAB simulations, there are L D2D pairs and K CUs which are distributed randomly in the coverage of the eNB. In the simulations, the CUEs, DUEs and eNB are set to a maximum transmit power of 23 dBm, 23 dBm, and 46 dBm, respectively [8]. The simulation parameters used in this work are listed in Table II [1], [11], [13]. The proposed scheme i.e., max sum and max min algorithms are compared to a benchmark scheme i.e., Maximize Throughput Gain (MTG) resource allocation algorithm in developed in [17], where the DUs in the network are allowed only to reuse the uplink RBs of CUs.

TABLE 2

SIMULATION SYSTEM PARAMETERS

Parameter	*Value*
Cell radius	*500 m*
Carrier frequency	*28 GHz*
Radius of D2D pairs	*10 m*
PLOS [dB] (d)	$65 + 21\,log_{10}[d]\ dB$
PNLOS [dB] (d)	$71.1 + 34\,log_{10}[d]\ dB$
Target SINR for CUs $(\gamma_k^{tgt,ul}\ and\ \gamma_k^{tgt,dl})$	*0 dB*
Target SINR for DUs (γ_l^{tgt})	*0 dB*
Noise Spectral density (N0)	*-174 dBm/Hz*

5.1 Varying Number of D2D Pairs

Fig. 2 shows how the system sum rate varies with increase in number of D2D pairs from 5 to 40, while maintaining $K = 20$ and other parameters as per Table 2. The system sum rate increases with the increase in number of the D2D pairs in the network. The max sum algorithm performs better compared max min one, since it tries to maximize the users that contribute an higher data rate in the network while max min algorithm maximizes the worst D2D users in the network therefore yielding a lower system sum rate.

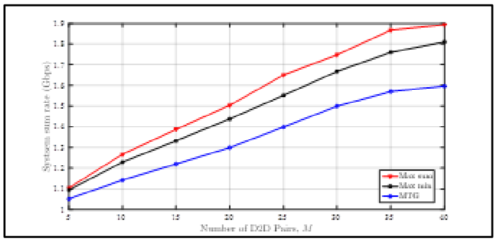

Fig. 2*. Variation of system sum rate with increase in D2D pairs*

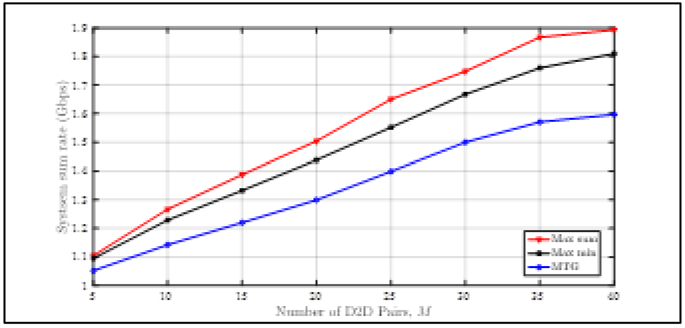

Fig. 3 *presents a comparison of the proposed algorithms and MTG algorithm as the number of D2D pairs in the network increases.*

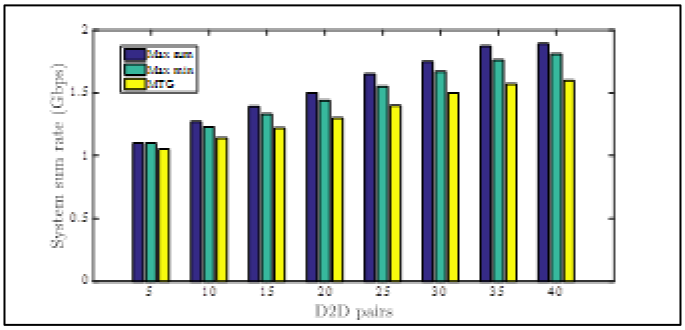

Fig. 3*. System sum rate for proposed and benchmark algorithms*

From Fig. 3, it is observed that the system sum rate achieved by the max sum and max min algorithms is better compared to that of the benchmark resource allocation scheme. Fig. 4 shows the variation of minimum D2D rate with increase in D2D pairs, with $K = 20$ and other parameters set as per Table 2. The minimum D2D rate is higher for the max min algorithm compared to the max sum one. For instance, when $L = 30$, the worst D2D pair contributes 11.5 Mbps and 9.3 Mbps, for max min and max sum algorithm, respectively. Further, the minimum D2D rate decreases as D2D pairs increase, because of the increased interference as D2D pairs in the system increase. Consequently, lowering chances of getting a CU reuse partner.

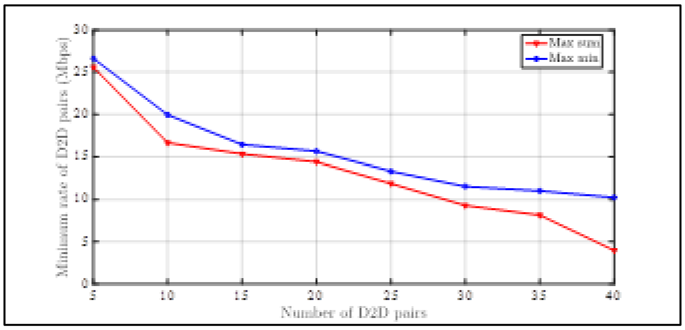

Fig. 4*. Variation of minimum D2D rate with increase in D2D pairs*

Table 3 and Fig. 5 provide a comparison of the max sum algorithm and max min algorithm when $L = 10$, $K = 5$ and other parameters set as shown in Table 2.

TABLE 3

SUM RATE AND INDIVIDUAL CHANNEL RATES FOR D2D PAIRS

	Max sum [Mbps]	*Max min [Mbps]*
R_1	*47.60*	*23.77*
R_2	*79.46*	*27.02*
R_3	*0*	*19.19*
R_4	*30.49*	*23.79*
R_5	*28.79*	*28.79*
R_6	*26.54*	*26.54*
R_7	*0*	*15.50*
R_8	*13.50*	*23.81*
R_9	*27.42*	*27.42*
R_{10}	*59.14*	*27.23*
$\sum_{l=1}^{10} R_l$	*312.94*	*243.05*

It is observed that max sum algorithm achieves a higher sum rate (22.3% better) compared to the max min algorithm. However, this increased sum rate comes at the cost of fairness. As seen in Fig. 5, the max min algorithm helps in avoiding lower D2D rates achieved by some D2D pairs when using the max sum algorithm such as rates by D2D pair 3, 7 and 8: $R_3 = 0$, $R_7 = 0$ and $R_8 = 13.50$ Mbps, respectively. However, the compensation of this benefit is low D2D sum rate, 243.05 Mbps as compared to 312.94 Mbps achieved by the max sum algorithm. With max sum algorithm, the network prefers allocating resources to D2D pairs experiencing good channel conditions to achieve higher channel rates. For example, with the max sum algorithm it achieves $R_1 = 47.60$, $R_2 = 79.46$ and $R_{10} = 59.14$ Mbps instead of $R_1 = 23.77$, $R_2 = 27.02$ and $R_{10} = 27.23$ Mbps with max min algorithm.

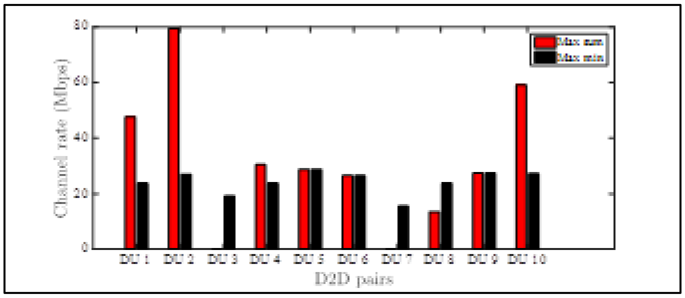

***Fig.5**. Individual channel rates for D2D pairs*

5.2 Varying D2D Cluster Radius

In Fig. 6, the variation in performance for max sum and max min algorithms was considered for different D2D cluster radii while maintaining $K = 20$ and $L = 40$. The sum rate, minimum D2D rate and success rate for both max sum and max min algorithms decrease with an increase in the D2D cluster radius. This is as result of the decreased D2D link channel gain as the cluster increases. The system sum rate is higher at all values of the cluster radius for the max sum algorithm. Since max sum algorithm aims at optimizing the sum rate as opposed to ensuring uniformity (fairness) in all the network users. In the range of D2D cluster radius from 10m to 60m, the proposed algorithms have superior performance compared to the MTG scheme. At a D2D cluster radius equal to 30m, the system sum rate achieved by the max sum and max min algorithms is about 28% and 11% higher than the MTG scheme.

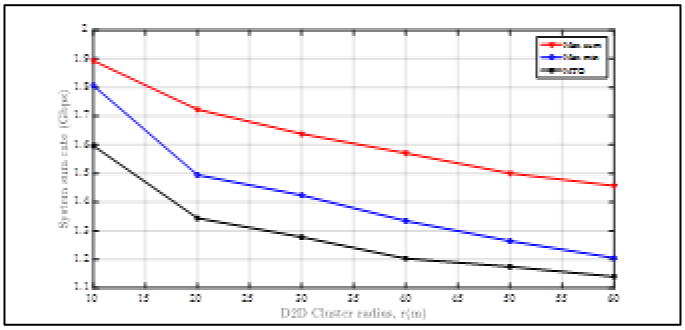

***Fig. 6**. Variation of system sum rate with increase D2D Cluster radius*

Fig. 7 shows variation in the minimum D2D rate as D2D cluster radius increases. The minimum D2D rate is higher for max min algorithm compared to max sum algorithm. The max min algorithm achieves fairness compared to the max sum algorithm. For instance when the cluster radius equals 30m, the D2D pair experiencing worst channel conditions achieves 0 Mbps as it is not prioritized when max sum is the design objective, which is a case of unfairness.

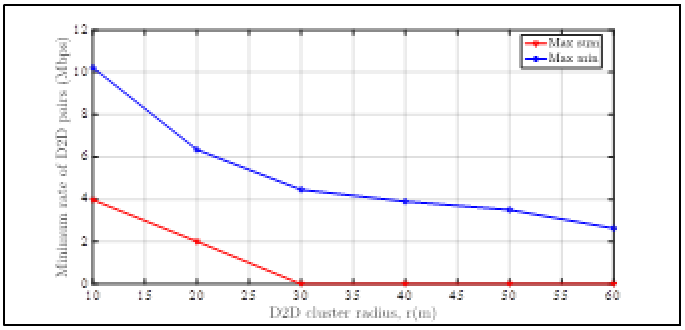

***Fig.7**. Variation of minimum D2D rate with increase in D2D Cluster radius*

6 CONCLUSION

In this paper, the problem of maximizing the system sum rate and minimum achievable rate of the D2D users has been investigated through resource allocation for D2D communications underlaying the cellular network. A resource allocation optimization problem has been formulated to maximize the system sum rate. Then, a fair resource allocation optimization problem has been formulated into a max min utility problem. The optimization problems have been solved using the Hungarian method. The results showed that the max sum algorithm produces a higher sum rate compared to max min algorithm. However, this increased sum rate comes at a cost of the fairness. The max min approach helps in avoiding low D2D rates achieved by some D2D pairs when using the max sum approach. However, the max min algorithm achieves a low sum rate compared to that of the max sum approach. The system sum rate achieved by the max sum and max min algorithms is better compared to that of the benchmark resource allocation scheme.

7 ACKNOWLEDGMENT

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