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Throughput Performance in D2D Communication Networks: Effects of Power, Density and User Distance

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Abstract

Device-to-Device (D2D) communication plays a vital role in enhancing spectral efficiency and data rates in next-generation wireless networks, but interference management and optimal power control remain key challenges. This study aims to address these gaps by developing a modified Power Control Scheme for D2D communication (mPCS-D2D) using a Hierarchical Clustering Algorithm (HCA) to improve throughput while minimizing interference. The scheme combines proximity-based clustering for general D2D users and social relationship-based clustering for mmWave D2D communication. Simulations were conducted to evaluate the throughput performance of mPCS-D2D under varying D2D transmit power levels, user densities, and inter-user distances. Results showed that the proposed scheme significantly outperformed the baseline PCS-D2D model across multiple scenarios. At 10 m and 15 m distances with a pathloss exponent of 4.5, mPCS-D2D improved throughput by 5.15% and 4.42%, respectively. Under varying user densities and pathloss exponents (3.5 and 4.5), throughput gains ranged from 4.33% to 4.77%, while across 10 m, 15 m, and 20 m distances, it achieved improvements of 4.13% to 5.53%. These findings demonstrate that the proposed mPCS-D2D scheme effectively enhances data transmission rates under diverse network conditions. The study concludes that integrating hierarchical clustering into power control mechanisms can significantly improve D2D communication efficiency. The proposed method offers practical implications for designing scalable, interference-aware D2D systems in future wireless networks.

Keywords: Throughput; Hierarchical Clustering; Device-to-Device networks; mmWave

INTRODUCTION

The rapid evolution of wireless communication has catalyzed significant technological advancements, particularly with the integration of millimeter-wave (mmWave) frequencies in 5G and upcoming 6G networks. These high-frequency bands offer considerable potential for boosting data rates and network throughput. However, their deployment introduces new challenges, especially in Device-to-Device (D2D) communication, a technique that facilitates direct data exchange between nearby user devices without routing through a base station. A primary concern in this context is interference, which significantly affects network performance. In D2D-enabled mmWave systems, interference arises not only among D2D users (DUEs) but also between DUEs and cellular users (CUEs), further exacerbated by the inherent propagation characteristics of mmWave signals (Charar & Guennoun, 2021; Reddy et al., 2024). This leads to degraded network performance indicators such as reduced throughput, lower energy efficiency, increased outage probability, and compromised fairness among users. Researchers worldwide have recognized these issues and responded with various strategies to mitigate interference and optimize power control. Sarma et al. (2021) proposed a power control scheme for D2D communication over the uplink channel in a 5G mmWave network, aiming to reduce interference and enhance system throughput. To tackle the formulated interference minimization problem, they transformed it into a semi-convex optimization problem using asn exponential expression in the Laplace domain. The study introduced transmission power bounds to reduce complexity and ensure power remained within optimal limits, promoting improved throughput. Based on Charar and Guennoun (2021), an energy-efficient power allocation scheme was proposed using fractional programming and game theory to enhance the energy performance of D2D communication in 5G networks. Saif et al. (2023) also presented a non-cooperative game-theoretic model to minimize interference and energy consumption while maintaining reliable communication links. Furthermore, Reddy et al. (2024) proposed a multi-hop D2D approach that reduces energy consumption while satisfying Quality of Service (QoS) requirements. These studies provide compelling solutions tailored to specific performance metrics, signifying substantial progress in D2D communication research. Additionally, the increased network density and dynamic nature of mmWave communication environments require scalable and adaptive power control mechanisms that can accommodate varying interference patterns and user mobility. As noted by Zhang et al. (2022), the growing complexity of next-generation networks necessitates more integrated optimization strategies that holistically address multiple performance parameters to enhance network resilience and user satisfaction. Therefore, the focus of this research is to develop and evaluate an optimized power control mechanism using hierarchical clustering for D2D communication in mmWave-enabled networks. The study aims to simultaneously maximize throughput thereby contributing a comprehensive and modifiable solution to the growing demands of next-generation wireless systems.

METHODS

The methodology employed in the development of an improved power control scheme for Device-to-Device (D2D) communication using a hierarchical clustering algorithm used for maximizing throughput in D2D communication networks was done in three phases. The simulated network environment included cellular users (CUEs) and D2D users (DUEs), distributed randomly within a defined cell area as seen in the network conceptual framework as shown in figure 1.

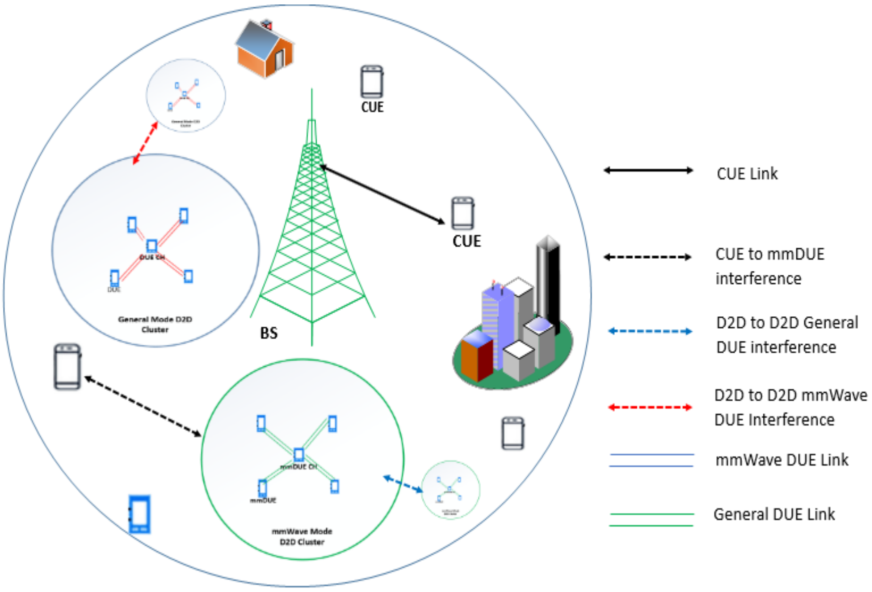

Figure1. Network Conceptual Framework for D2D Communication Network.

Two clusters are formed for CUEs and DUEs to enable them communication in general and mmWave mode respectively. The distance range for which D2D general mode communication can take place is represented mathematically as

$$d_{\min} < d_{comm} > d_{\max} \,. \tag{1}$$

Where, $d_{\min}$ is the minimum acceptable distance for establishing D2D communication, d_{comm} represents the allowable range for D2D communication, and $d_{\max}$ stands for the maximum allowable distance for D2D communication. The distance value for establishing D2D communication is given as:

$$d_{\min} \le d_{comm} \le d_{\max} = 10m \le d_{comm} \le 20m \tag{2}$$

Now, in order to form cluster for D2D general mode communication, the proximity model equation is given as:

$$d_{G-Cluster} = \frac{d_{\min} + d_{\max}}{2} \tag{3}$$

where, $d_{G-Cluster}$ is the acceptable distance between any DUE for potential cluster formation. This implies that a DUE must satisfy the condition ($10m \le d_{G-Cluster} \le 15m$) for it to join a cluster.

1. D2D General Mode Communication using proximity model

In the first stage, clustering was conducted based on geographic proximity to form initial communication hierarchies. The network was initialized and DUEs and CUEs randomly placing a predefined number of CUEs and DUEs within the simulation area. Each user was assigned a specific Resource Block (RB) to enable signal transmission and reception. The proposed formula for estimating the Resource Capability (RC) of a node for cluster head selection is given as:

$$RC = w_1 v_c + w_2 M + w_3 S \qquad \forall w_1 > w_2 > w_3 \tag{4}$$

where: w are the weight coefficients that represent the relative importance of each factor v_c denote the computational capability of the node, M stands for the memory size of the DUE, S represents the storage capacity of the DUE. After cluster formation, all cluster member node share their resource capability, the node with the highest resource capability is selected as the Cluster Head (CH).

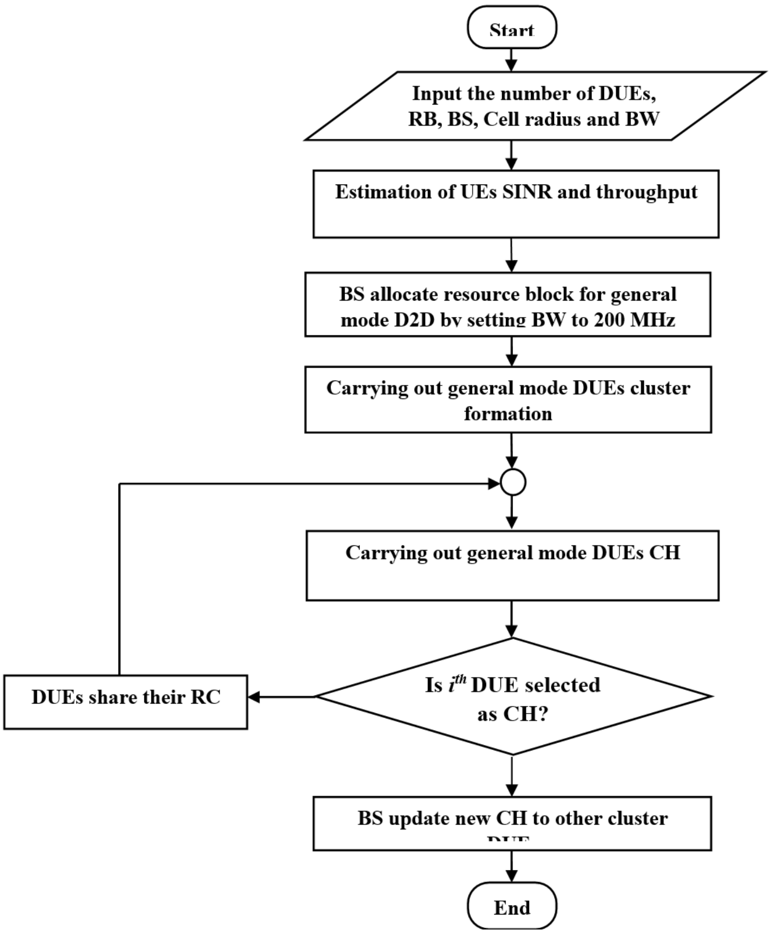

Figure 2. Flowchart for general Mode Cluster Formation

2. D2D mmWave Communication based on social interactions between DUEs.

In the second stage, the social interactions between DUEs was used to form a cluster for mmWave communication. The degree of closeness centrality (shortest distance between a reference node and other devices) can be used to estimate the closeness of D2D users which is now used to assign weights to users. The proposed closeness of centrality for DUEs is given as:

$$C_c\left(U_{DUE_a}\right)=\frac{\left[\sum_{b=1}^{N_{DUE}} d\left(U_{DUE_a},U_{DUE_b}\right)\right]^{-1}}{N_{DUE}-1} \tag{5}$$

where: N_{DUE} is the total number of DUE nodes

d(.) stands for the shortest distance between reference DUE node and all other node,

U_{DUE_a} denotes for the reference DUE node, U_{DUE_b} represents any other DUE node

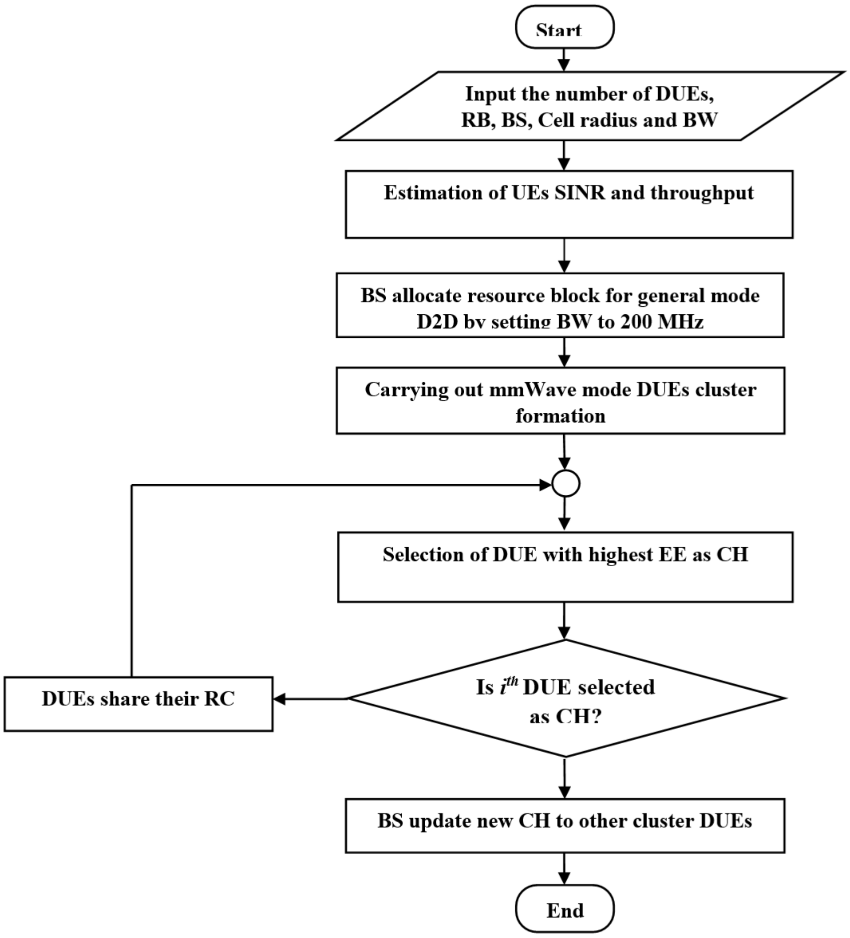

Figure 3. Flowchart for mmWave Mode Cluster Formation

3. Modified Power Control SchemeD2D Communication (mPCS-D2D)

The final stage of the methodology involved the implementation of an improved power control scheme, integrating both levels of clustering to form a modified Power Control Scheme (mPCS-D2D). Network parameters such as the cell radius, user density, bandwidth requirements, and thermal noise density were initialized based on standardized 5G simulation models. Hierarchical clustering results were used to guide power allocation. At the cluster level, CHs coordinated power control to reduce interference across clusters. At the DUE level, individual users adjusted their transmission power according to SINR feedback and interference constraints to achieve energy-efficient communication. Using Shannon's formula, the total throughput associated with the D2D users in cluster general communication mode with total bandwidth, B^n is expressed as:

$$R_{CDUE}^{n} = B^{n} \log_2(1+\gamma_{CDUE}^{n}) \tag{6}$$

The total throughput associated with the cluster D2D users in mm-Wave communication mode is expressed as:

$$R_{mmCDUE}^{n} = B^{n} \log_2(1+\gamma_{mmCDUE}^{n}) \tag{7}$$

This further implies that the total throughput associated with the D2D users in mm-Wave communication mode is expressed as Sarma *et al.,* (2021):

$$R_{mmDUE}^{n} = B^{n} \log_2(1+\gamma_{mmDUE}^{n}) \tag{8}$$

The effectiveness of the proposed enhanced power control scheme was evaluated using throughput as key performance metric:

4. Simulation Parameters

Table 1 presents the simulation parameters used to evaluate the performance of the developed improved power control scheme for device to device communication networks which is used to maximize throughput.

Table 1. Simulation Parameter

Parameters	Values
Cell radius	500m
Bandwidth	200MHz
Operating frequency (mm-Wave mode)	28GHz
Thermal Noise density	-174dBm/Hz
Υ_c^{th}	0 dB
Υ_d^{th}	0 dB
Maximum D2D transmit power	15mW
Rician channel K factor	8
Minimum Distance	10m
Maximum Distance	20m
Maximum Power	15mW
Pathloss Exponent	3.5 - 4.5
Number of D2D Users	100

RESULTS

The higher D2D power and shorter distances generally improve throughput, increasing user density leads to a decrease in throughput due to higher interference. However, hierarchical clustering techniques like mPCS-D2D can still provide significant throughput gains compared to existing methods like PCS-D2D.

1. **Throughput values versus D2D Power**

Throughput increases with higher D2D power, as greater power enhances signal strength, leading to improved throughput. The mPCS-D2D approach outperforms PCS-D2D in throughput by about 5.15% at a distance of 10 meters, and 4.42% at 15 meters, highlighting the advantage of hierarchical clustering in D2D communication. Figure 4. Illustrates that throughput increases with higher D2D transmit power due to improved signal strength.

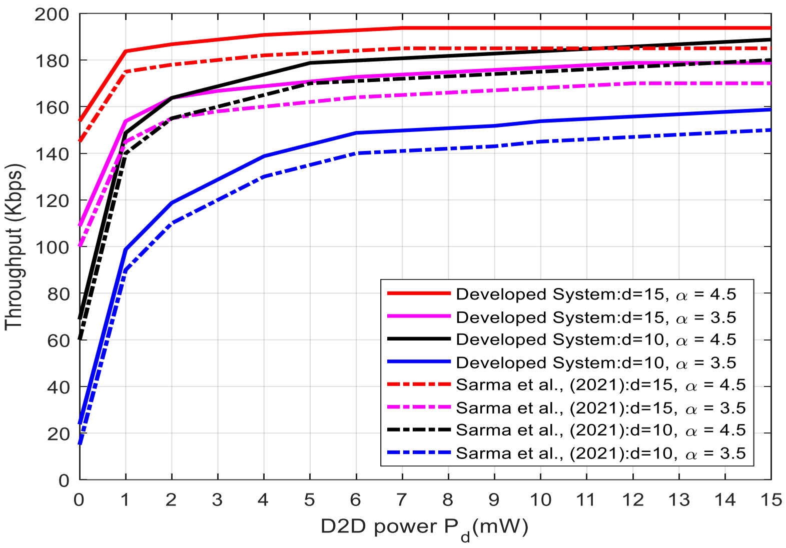

Figure 4. Throughput versus D2D power.

Table 2. Table of values of throughput values against D2D power

D2D Power (mW)	**Throughput (Kbps)**				**Throughput (Kbps)**			
	Sarma et al. (2021) d=10 m α=4.5	**Developed System d=10m α=4.5**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**	**Sarma et al. (2021) d=15 m α=4.5**	**Developed System d=15m α=4.5**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**
0	60.0000	67.8074	13.01%	5.15%	145.0000	152.8074	5.38%	4.42%
1	140.0000	147.8074	5.58%		175.0000	182.8074	4.46%	
2	155.0000	162.8074	5.04%		178.0000	185.8074	4.39%	
3	160.0000	167.8074	4.88%		180.0000	187.8074	4.34%	
4	165.0000	172.8074	4.73%		182.0000	189.8074	4.29%	
5	170.0000	177.8074	4.59%		183.0000	190.8074	4.27%	
6	171.0000	178.8074	4.57%		184.0000	191.8074	4.24%	
7	172.0000	179.8074	4.54%		185.0000	192.8074	4.22%	
8	173.0000	180.8074	4.51%		185.0000	192.8074	4.22%	
9	174.0000	181.8074	4.49%		185.0000	192.8074	4.22%	
10	175.0000	182.8074	4.46%		185.0000	192.8074	4.22%	
11	176.00	183.8074	4.44%		185.00	192.8074	4.22%	

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12	177.0000	184.8074	4.41%		185.0000	192.8074	4.22%	
13	178.0000	185.8074	4.39%		185.0000	192.8074	4.22%	
14	179.0000	186.8074	4.36%		185.0000	192.8074	4.22%	
15	180.0000	187.8074	4.34%		185.0000	192.8074	4.22%	

	Throughput (Kbps)				**Throughput (Kbps)**			
D2D Power (mW)	**Sarma et al. (2021) d=10m α=3.5**	**Developed System d=10m α=3.5**	**Percentage Improvement**	**Average Percentage Improvement**	**Sarma et al. (2021) d=15m α=3.5**	**Developed System d=15m α=3.5**	**Percentage Improvement**	**Average Percentage Improvement**
0	15.0000	22.8074	52.05%	11.41%	100.0000	107.8074	7.81%	5.23%
1	90.0000	97.8074	8.67%		145.0000	152.8074	5.38%	
2	110.0000	117.8074	7.10%		155.0000	162.8074	5.04%	
3	120.0000	127.8074	6.51%		158.0000	165.8074	4.94%	
4	130.0000	137.8074	6.01%		160.0000	167.8074	4.88%	
5	135.0000	142.8074	5.78%		162.0000	169.8074	4.82%	
6	140.0000	147.8074	5.58%		164.0000	171.8074	4.76%	
7	141.0000	148.8074	5.54%		165.0000	172.8074	4.73%	
8	142.0000	149.8074	5.50%		166.0000	173.8074	4.70%	
9	143.0000	150.8074	5.46%		167.0000	174.8074	4.68%	
10	145.0000	152.8074	5.38%		168.0000	175.8074	4.65%	
11	146.0000	153.8074	5.35%		169.0000	176.8074	4.62%	
12	147.0000	154.8074	5.31%		170.0000	177.8074	4.59%	
13	148.0000	155.8074	5.28%		170.0000	177.8074	4.59%	
14	149.0000	156.8074	5.24%		170.0000	177.8074	4.59%	
15	150.0000	157.8074	5.20%		170.0000	177.8074	4.59%	

2. Throughput values against D2D users at varying distance

Figure 5. compares the throughput performance of mPCS-D2D and PCS-D2D across different D2D user densities and distances.

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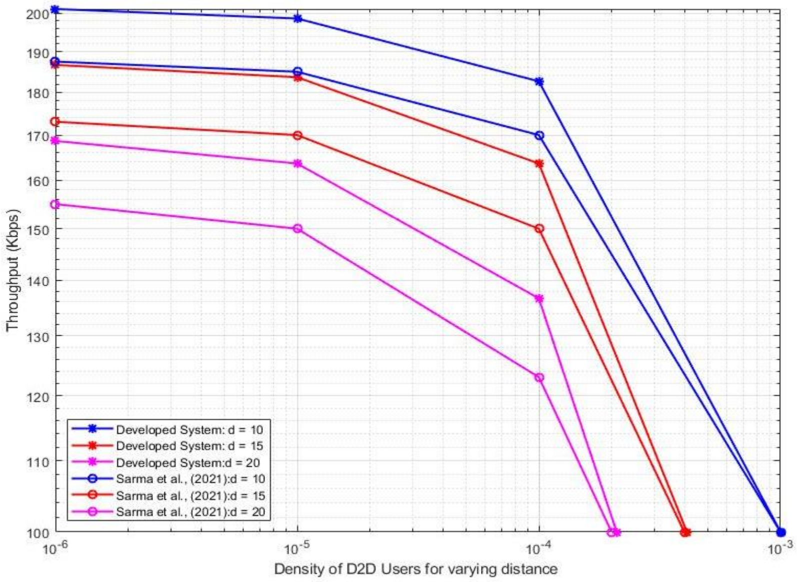

Figure 5. Throughput against density of D2D users at varying distance.

Table 3. Throughput values against Density of D2D users for varying distance

Density of D2D Users for varying distance	Throughput (Kbps)				Throughput (Kbps)			
	Sarma et al. (2021) d=20 m	**Developed System d=20m**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**	**Sarma et al. (2021) d=15 m**	**Developed System d=15m**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**
1.00E-06	155.000	162.8074	5.04%	5.53%	173.0472	180.8546	4.51%	4.77%
1.00E-05	150.000	157.8074	5.20%		170.000	177.8074	4.59%	
0.0001	123.000	130.8074	6.35%		150.000	157.8074	5.20%	

	Throughput (Kbps)			
Density of D2D Users for varying distance	**Sarma et al. (2021) d=10 m**	**Developed System d=10m**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**
1.00E-06	187.538	195.3456	4.16%	4.13%
1.00E-05	185.000	192.8074	4.22%	
0.0001	170.0000	176.8074	4.00%	

3. Throughput values against density of D2D users

Figure 6. Illustrates the impact of D2D user density and path-loss parameters (3.5 and 4.5) on throughput. As the density of D2D users increases, throughput decreases due to congestion and interference.

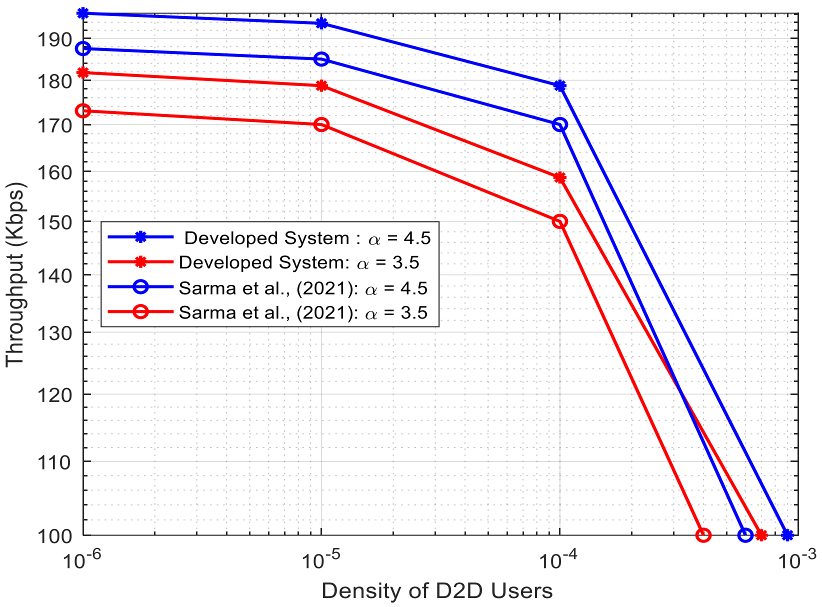

Figure 6. Throughput plot against density of D2D users

Table 7. Throughput values against density D2D users

	Throughput (Kbps)				Throughput (Kbps)			
Density of D2D Users	**Sarma et al. (2021) α=3.5**	**Developed System α=3.5**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**	**Sama et al. (2021) α=4.5**	**Developed System α=4.5**	**Percentage Improvement using equation (3.14)**	**Average Percentage Improvement using equation (3.18)**
1.00E-06	173.0472	180.8546	4.51%	4.77%	187.5382	195.3456	4.16%	4.33%
1.00E-05	170.000	177.8074	4.59%		185.000	192.8074	4.22%	
0.0001	150.000	157.8074	5.20%		170.000	177.8074	4.59%	

DISCUSSION

This study set out to enhance throughput in Device-to-Device (D2D) communication within 5G millimeter-wave (mmWave) networks by introducing a modified Power Control Scheme (mPCS-D2D) that leverages hierarchical clustering. The results obtained affirm the initial objective, demonstrating that mPCS-D2D consistently outperforms the baseline PCS-D2D scheme. The hierarchical clustering framework is instrumental in mitigating interference and maximizing throughput thus supporting more efficient communication even under challenging conditions such as increased user density and higher pathloss. The results demonstrate that the developed mPCS-D2D scheme significantly improves data transmission rates compared to the baseline PCS-D2D model. At both 10 m and 15 m distances with a pathloss exponent of 4.5, mPCS-D2D achieved throughput improvements of 5.15% and 4.42%, respectively. When evaluated against varying user densities and pathloss values (3.5 and 4.5), mPCS-D2D maintained higher throughput, with gains ranging from 4.33% to 4.77% over PCS-D2D. Furthermore, across distances of 10 m, 15 m, and 20 m, mPCS-D2D consistently outperformed PCS-D2D with improvements between 4.13% and 5.53%. These outcomes confirm the effectiveness of hierarchical clustering in mPCS-D2D for enhancing throughput and scalability, directly aligning with the study's goal of developing an efficient power control scheme to manage interference and maximize throughput in D2D communication network.

CONCLUSION

This study addresses the challenge of improving throughput in Device-to-Device (D2D) communication by developing a modified power control scheme based on hierarchical clustering, known as mPCS-D2D. The core objective was to enhance data transmission rates by organizing Device User Equipments (DUEs) into clusters formed through geographic proximity and social relationship patterns. This clustering strategy allowed for better interference management and more efficient resource utilization giving room for maximizing throughput. The simulation results using MATLAB 2021a demonstrated that throughput in D2D communication networks improves with increased transmission power, as stronger signals enhance data rates, and the proposed mPCS-D2D scheme consistently outperforms the existing baseline PCS-D2D scheme, showing throughput gains of 5.15% at 10 m and 4.42% at 15 m. However, as the density of D2D users increases, throughput tends to decline due to congestion and interference. Despite this, mPCS-D2D maintains superior performance with improvements ranging from 4.13% to 5.53% across user densities at distances of 10 m, 15 m, and 20 m. Additionally, throughput is higher at shorter distances, such as 10 m, where mPCS-D2D reaches 188.32 kbps compared to 150.47 kbps at 20 m, indicating that reduced separation between devices helps alleviate interference effects. Overall, the results highlight the robustness and scalability of mPCS-D2D, especially in dense and power-variable D2D environments. The implications of this research are significant for next-generation wireless systems, where higher data rates and spectral efficiency are critical.

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