Adaptive Interference-Avoidance and Mode Selection Scheme for D2D-Enabled Small Cells in 5G-IIoT Networks

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***Abstract*— Small cell and device-to-device (D2D) communications can fulfill high-speed wireless communication in indoor industrial internet of things (IIoT) services and cell-edge devices. However, controlling interference is crucial for optimizing resource sharing (RS). To address this, we present an adaptive interference avoidance (IA) and mode selection (MS) framework that incorporates MS, channel gain factor (CGF), and power-allocation (PA) techniques to reduce reuse interference and increase the data rate of IIoT applications for 5G D2D-enabled small cell (SC) networks. Our proposed approach employs a two-phase RS algorithm that minimizes the system's computational complexity while maximizing the network sum rate. First, we adaptively determine the D2D user mode for each cell based on the D2D pair channel gain ratios (CGR) of the cellular and reuse mode (RM). We compute the CGF for each cell with a D2D pair in RM to select the reuse partner. Then we determine the optimal distributed power for the D2D users and IoT-user equipment (IUEs) using the Lagrangian dual decomposition method to maximize the network sum rate while limiting the interference power. The simulation results indicate that our proposed approach can maximize system throughput and signal-to-interference plus noise ratio (SINR), reducing signaling overhead compared to other algorithms.**

***Index Terms*—Adaptive, Channel gain factor, D2D pairs, Interference-avoidance, IIoT, Mode Selection, Small-cell.**

I. Introduction

The future of large-scale communication in the IIoT will lean towards heterogeneous networks (HetNets) for ubiquitous wireless connection and coverage. The combination of cell size shrinking (i.e., Base station densification) and D2D communication can satisfy the area throughput, thus improving the quality of service (QoS) of cell-edge IUEs and indoor IIoT devices (i.e., sensors, networks devices, and machinery connected to the internet) in cellular networks. IIoT environments are typically vast and multi-tasking, making wireless connectivity difficult. However, the use of SCs and D2D communications can address the need for high-speed wireless communication, optimal responsiveness, scalability, availability, and reliability of mission-critical applications within the IIoT environment [1]. When an IIoT application is deployed in industrial manufacturing and production companies, it establishes a networked ecosystem where humans and machines interact. IIoT data structurally organized and comprehensively visualized, for instance, is used in the automotive manufacturing industry to generate an actionable solution with little or no human intervention. Industrial robots (mechanical devices used to perform repetitive tasks) use a variety of sensors (such as vision, position, acoustic, force-torque, collision detection, pressure, accelerator sensors, and so on) to achieve excellent operations and controls and provide real-time feedback on system performance. There are six (6) main production application lines for industrial robots in the automotive manufacturing industry, namely as; assembly, painting, welding, machine tending, material removal and polishing, and quality inspection line [2], [3]. A network is only one cell, and one network supports each application. Hence a dedicated cell (i.e., SC network), such as a femtocell, could be deployed for each of these application lines, and D2D communication on sensors in harsh environments or out of coverage.

In automotive quality inspection, for example, robots are used to grease camshafts, fill engines with oil, tighten car seat screws, perform electrical inspections [3], and so on. Due to the hidden position, tight spaces and location, and angle of inclination, the network may be poor. The sensor data acquired from the greasing of camshafts by a robot can be transmitted using D2D direct link to another end user (sensor) already connected to IIoT networks for further processing. D2D communication can improve indoor IIoT-UEs' system throughput, spectrum utilization, and power consumption. However, to avoid costly interference to macro-users (general IIoT network), the SCs are deployed orthogonally to the macro-cell. As D2D users operate within SC networks, the IIoT environment becomes more complex due to interference constraints caused by generated electromagnetic radiation in the IIoT environment and blockages. If not addressed, the

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interference may degrade system performance [4]. As a result, improving IIoT SC capacity requires a suitable mechanism that optimizes resource reuse, transmission mode for the potential D2D users, and guaranteed QoS for the cellular IUEs within the SCs. Several studies on interference control on D2D and cellular users include power control (PC) [5], MS [6], and resource-allocation (RA) algorithms [7].

Most significant studies on the MS for interference management in D2D-enabled cellular HetNets (CHetNets) either focused on the derived fixed transmit power for users, as in the case of [9], [10] and [11], which defined a region called an interference-limited area (ILA) to manage the UE interference with D2D pair for a predetermined threshold lower than the D2D pair signal-to-interference ratio (SIR) [10] or considered UE's distance [12] within a fixed interference region to select a communication mode. The implementation process limits the efficient use of spectrum resources. Most D2D-enabled CHetNets schemes and algorithms also ignored channel state information (CSI), a critical input in D2D's PC and RA. It is difficult to argue that D2D-related schemes do not vary in dependence on CSI. For PC, a CSI with downplayed interference estimates leads to a lower transmit power than the required transmitter. If the RA algorithm input contains CSI errors, the D2D transmitter may reuse the inappropriate resource block (RB), causing significant interference to the cellular user. Thus, CSI acquisition is a critical component of D2D communication, and it has demonstrated that CSI feedback within links outperforms the case without feedback [13]. In addition, different channel allocations, MS, and PC for users led to various system performances. As a result, increasing SC capacity necessitates CSI, MS, and PC to minimize interference among D2D-enabled SCs. It is worth mentioning that there is a difference between the IIoT networks and HetNets, even though both networks employ wireless. The distinction depends on network architecture, coverage and capacity requirements, and applications and data requirements. The HetNets are designed as a hybrid of various cell types to provide seamless coverage, improve network capacity, and support voice and data services for cellular users. But the IIoT networks are enterprise networks that extend IoT services to manufacturing and industrial processes, and may use different network designs and various wireless technologies to facilitate real-time data collection and analysis, industrial applications, and may necessitate a high volume of data transmissions.

Motivated by the work in [5] and [7], in this paper, an adaptive IA and MS scheme for D2D-enabled SCs in 5G-IIoT networks is proposed, which (i) adaptively accounts for the simultaneous mitigation of multiple co-tiered interferences (CTI) among SCs and co-channel interference (CCI) between D2D pairs and cellular IUEs (CIUEs) that may arise due to network dynamism, (ii) employs CGF to compute channel reuse partner selection and MS, and (iii) allocate distributed power among the SCs and D2D users to improve SC uplink capacity as users share the same spectrum resources. As a result, potential D2D users can communicate with the SC base station (SCBS) or via D2D mode. The scheme is deployed hierarchically with a partially centralized architecture, allowing SCBSs to communicate with the MeNB to manage interference power and allocate resources. Each SCBS delivers a pilot signal to estimate the CSI of neighboring SCBSs, the requested channels, and the interfering channels through feedback from its associated users. The MeNB uses the information from all SCBSs to accomplish adaptive IA and RA among the SCBSs. The MeNB then notifies each SCBS of its assigned resource blocks. Finally, each SCBS uses its allotted resource to accomplish MS, resources, and PA for each associated user to achieve user fairness. The proposed approach computes the potential sum rate for each SCBS. The sum rate reveals the impact of different environmental parameters, promoting an effective way for RA for the network system. Besides, the proposed IA is adaptive because it seeks the best combination of orthogonal frequency allocation and reuse frequency among SCBSs. The adopted approach differs from either the centralized or distributive method. A single base station is responsible for coordinating and executing all instructions in a centralized approach, necessitating high degree communication between nodes and the base station. As a result, there is high overhead and latency. Contrast to the distributive method, processing and decision-making across multiple network nodes are distributed. As a result, the network is scalable, fault-tolerant, and free of communication bottlenecks. The optimization problem is NP-hard and combinatorial. As a result, it is tasking to solve in polynomial time.

To that end, the main contribution is as follows:

1. Unlike the [10], [6], and [5] that do not consider MS, we design a hierarchically with a partially centralized architecture for 5G-IIoT D2D-enabled SCBSs to communicate with the MeNB for allocation of resources and interference management.
2. We propose a framework for adaptive IA and MS for 5G-IIoT D2D-enabled SCBSs network problem to maximize the network sum rate by identifying and analyzing the maximum CTI among small cells and CCI between D2D pairs and CIUEs that may arise due to network dynamism.
3. Due to RS, we formulated the problem as NP-hard and sectioned the optimization problem into two phases to lower the system's complexity. During the first phase, we compute the D2D pair mode decision for the orthogonal SCBSs by comparing the ratio of the D2D pair channel gain of cellular and reuse mode, and vice versa, to decide the D2D pairs mode of operation. Subsequently, for D2D users in the reuse mode, we use the CGF to select a potential reuse channel with enhanced QoS control, unlike the previous studies (such as [5], [13], and [14]) that employs branch and bound, channel power gain, distances, and admission control among all users. The power allocation is solved iteratively with the Lagrangian dual decomposition method for optimal distributed power in the second phase.
4. We conducted simulations to evaluate the proposed scheme which outperforms existing algorithms in uplink sum rate, interference thresholds, and SINR for SCBSs.

The paper is structured as follows. Section II discusses the system model and problem formulation. Section III describes the adaptive IA and MS procedures. Section IV presents the simulation results, and section V concludes the paper.

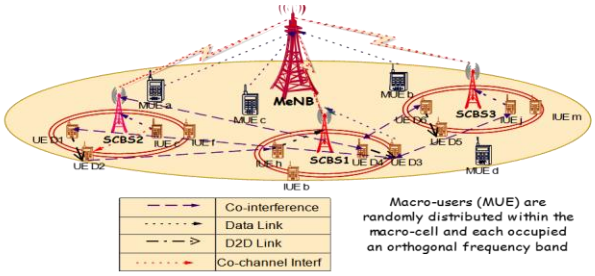


Fig. 1. System Model [7]

II. System Model and Problem Formulation

A. System Model

Consider an uplink transmission of D2D-enabled SCs in 5G-IIoT networks, where $\mathcal{M}$ SCBSs are underlaid with the macro-eNodeB (MeNB) in HetNet as shown in Fig. 1. All SCBSs shares frequency bandwidth of $\mathcal{W}_{\mathfrak{f}}$ that is orthogonal to the frequency bandwidth $\mathcal{W}_{\mathfrak{B}}$ assigned to the MeNB. For control information sharing, each SCBS is linked to the centralized MeNB via the $\mathcal{X}2$ interface. Assuming that no co-channel interference exists between the MeNB and all the SCBSs, two types of interference are considered: CTI among neighboring SCBSs and the CCI between the CIUEs and D2D users reusing the same resources. Interference affects the channel reuse condition of the D2D users which can be mitigated adaptively to achieve fairness among all users. Let $\mathcal{M} = \{1,2,\ldots.,m\}$ be the SCBSs' corresponding set. Each SCBS $i \in \mathcal{M}$ has a subchannel set $\mathcal{K}_i$ containing $|\mathcal{K}_i| = \mathcal{L}$ orthogonal frequency from total subchannels set, $\mathcal{K}$ ($\mathcal{K}_i \subseteq \mathcal{K}$), in a frequency division duplexing (FDD) access mode. Assume that each SCBS $i \in \mathcal{M}$ serves $\mathcal{C}_i$ orthogonal CIUEs and only one D2D pair[1], r, where $\mathcal{C} = \{\mathcal{C}_i | i = 1,2,\ldots.,c_i\}$ and $r_i = 4\mathcal{C}_i$. Conventionally, each SCBS $i \in \mathcal{M}$ subchannel ($\tau \in \mathcal{K}_i$) serves its $\mathcal{C}_i$ IUEs. The CIUEs can only communicate in cellular mode (CM). Let $\mathfrak{R}_c$ and $\mathfrak{R}_d$ be the corresponding set of all the CIUEs and D2D pairs respectively, where $\mathfrak{R}_d = \mathcal{M}$. Note that $\mathfrak{R}_d = \{r_j | j = 1,2,\ldots,r\}$. The potential D2D user support two operation modes; D2D direct mode or CM depending on the mode decision variable Φ_j. In CM, D2D transmitters are given additional orthogonal spectrum resources to communicate with their receivers via the base station. Thus, interference with traditional CIUEs is avoided. The D2D transmitters communicate with the receivers directly in the reuse mode (RM) by sharing CIUEs spectrum resources, improving spectral efficiency but causing interference to the reuse partners. As a result, we introduce a CGF Ω to obtain the best D2D pair's reuse partner to minimize interference and optimize resource sharing.

Let Φ_j be the MS variable. Denote $\Phi_j = 1$ as the RM and $\Phi_j = 0$ as the CM. Let $\mathcal{R}_d^j$ and $\mathcal{R}_c^i$, be the D2D sets in the RM and CM, respectively.

Furthermore, we introduce $\rho_{i,j}$ to indicate whether D2D pair j, reuses the resource of CIUE i or not, where $\rho_{i,j} = 1$ indicates reuse and $\rho_{i,j} = 0$ indicate non-reuse. Assume that all links undergoes independent block fading, and that the channel gain between IUE i and the SCBS can be modeled as:

$$H_{i,\beta} = K\, g_{i,\beta} B_{i,\beta} D_{i,\beta}^{-a} \qquad (1)$$

where K, $g_{i,\ell}$, $\mathfrak{B}_{i,\ell}$, a, $\mathcal{D}_{i,\ell}$ is a path-loss constant, the exponential distributed fast-fading gain, log-normal distributed slow fading gain, pathloss exponent, and the distance between the IUE i and the SCBS i, respectively. Similarly, the channel links $\mathcal{H}_{i,j}$, $\mathcal{H}_{j,\beta}$, and $\mathcal{H}_j$ are denoted as the channel between the IUE i and the D2D pair j, the D2D pair j to the SCBS i, and between the D2D's transmitter and its receiver respectively. Based on each SCBS $i \in \mathcal{M}$, the SINR for IUE on subchannel ($\tau \in \mathcal{K}_i$) can be express as follows[15];

$$\xi_i^c = \frac{P_i^c H_{i,\beta}^c}{N_o + \sum_{j \in R_d^j} \rho_{i,j} P_j^d H_{j,\beta}^d} \quad \forall i \in C \qquad (2)$$

and accordingly, assuming that D2D user reuses the D2D pair's resources in the CM, the D2D pair's SINR in the CM and RM are expressed as;

$$\xi_{j,0}^d = \frac{P_{j,0}^d H_{j,\beta}^c}{N_o + \sum_{i \in R_d^j, i \neq j} \rho_{i,j} P_i^d H_{i,\beta}^d}, \ \forall j \in R_c^i \qquad (3)$$

$$\xi_{j,1}^d = \frac{P_{j,1}^d H_{j,1}^d}{N_o + \sum_{i \in R_c} \rho_{i,j} P_i^c H_{i,j}^c + \sum_{i \in R_c^i} \rho_{i,j} P_i^d H_{i,j}^c}, \ \forall j \in R_d^j \ (4)$$

and thus, the D2D pair's SINR can be rewritten as follows;

$$\xi_{j,\phi_{j\in(0,1)}}^d = \phi_j \xi_{j,\phi_j}^d + (1 - \phi_j) \xi_{j,\phi_j}^d, \forall j \in R_d^j \cup R_c^i \ (5)$$

where P_i^c and P_j^d are transmit powers of IUE i and D2D user j, respectively, and N_o is the additive white noise power. To minimize complex reuse interference, the distance from the D2D pair transmitter to its receiver is assume to be less than r_{max} and that the SCBS is fully aware of all network link CSI, including D2D CSI, which is approximated by the D2D receiver and fed directly back to the SCBS via the control channel, and the SCBS controls resource allocation.

B. Problem formulation

To reduce any harmful co-tier and co-channel interference in the SCBS networks, we formulate the system sum-rate optimization problem by maximizing the system uplink throughput while satisfying the QoS constraints for both IUEs and D2D pairs through joint optimization of channel reuse partner selection, MS, and PC. As a result, we express the optimization problem as;

$$\max_{\phi_j, \rho_{i,j}, P_{j,0}^d, P_{j,1}^d, P_i^c} [\Upsilon] = \sum_{i \in M} \sum_{t \in K_i} \sum_{r_j \in R_c^i \cup R_d^j} \log\left(1 + \xi_{j\phi_j}^d\right) + \sum_{i \in M} \sum_{C_i \in R_c} \log\left(1 + \xi_i^c\right) \ (6)$$

$$s.t. \begin{cases} B1: \xi_i^c \geq \xi_{imin}^c, \ \forall i \in C_i, \\ B2: \xi_{j,1}^d \geq \xi_{jmin}^d, \ \forall j \in R_d^j, \\ B3: \xi_{j,0}^d \geq \xi_{imin}^c, \ \forall j \in R_c^i, \\ B4: \sum_{i \in M} \sum_{j \in R_d^j} \rho_{i,j} \leq 1, \ \forall i \in \{R_c \cup R_c^i\}, \end{cases}$$

[1]The D2D pair consists of transmitter and receiver. NB: sum-rate, system throughput and capacity are used interchangeably.

$$\begin{cases} B5: \sum_{i\in M} \sum_{i\in\left(R_c\cup R_c^i\right)} \rho_{i,j} \le 1,\ \forall j\in R_d^j, \\ B6: P_{j,1}^d H_{j,\beta}^d \le \sum_{i\in C_i} I_o,\ \ \forall \tau \in K_i, \\ B7: \sum_{i\in M}\sum_{j\in R_d^j} P_{j,1}^d H_{j,\beta}^d \le \sum_{i\in M}\sum_{i\in R_c\cup R_c^i} I_1,\ \forall i\in M, \\ B8: \sum_{k_i\in K} P_i^c \le P_{\max}^c,\quad \forall i \in C_i, \\ B9: \sum_{k_i\in K} P_{j,1}^d \le P_{\max}^d,\quad \forall j\in R_d^j, \\ 10: \sum_{k_i\in K} P_{j,0}^d \le P_{\max}^c,\quad \forall j\in R_c^i, \\ B11: \sum_{j\in R_d} \Phi_j \le Z, \\ B12: \rho_{i,j} \in \{0,1\},\ \ \forall i\in R_c, \forall j\in R_d^j \end{cases} \quad (7)$$

where $$I_o = \frac{P_i^c H_{i,\beta}^c}{\xi_{imin}^c} - N_o \text{ and } I_1 = \frac{\sum_{i\in R_c\cup R_c^i}\left(P_i^c + P_i^d\right) H_{i,\beta}^c}{\xi_{imin}^c} - N_o \quad (8)$$

For received SINR at each SCBS and the overall SCBS networks, the D2D pair and each pair link must meet the minimum SINR requirement for frequency reuse. The D2D users' interference to CIUEs must be less than the interference thresholds I_o (co-channel interference) and I_1 (co-tier interference), respectively. The computation in (8) is adaptive as the network conditions change for all users to create fairness, flexibility, and low complexity towards indiscriminate RA for the D2D pairs since the IUEs are assumed to operate at the same transmit power. Constraints (B1) - (B3) described the QoS condition for each IUE and D2D pair. Constraint (B4), (B5), and (B12) ensure that the IUE channel resource can only be reuse by one D2D user and that each D2D pair can only share one channel. Hence lowers the interference complexity possibilities. Constraint (B6) and (B7) restrict both the aggregated interference within and between the SCBS networks to the computed tolerable interference thresholds in (8). Constraints (B8) - (B10) are the power transmission constraint for the IUE and D2D user. Constraint (B11) ensures that the additional resource for the D2D pair in cellular mode should not be larger than $\mathcal{Z}$. The optimization problem in (6) is NP-hard, combinatorial and non-convex problem [13].

III. Adaptive Interference Avoidance (IA) and Mode Selection (MS) Algorithm

The optimization problem is decomposed into two phases to lower the computational complexity.

A. Phase 1: Channel Reuse Partner Selection (CRPS) and Mode Selection (MS).

This phase computes the channel reuse for each D2D pair, $\mathcal{j}\in \mathcal{R}_d^{\mathcal{j}}$ in RM. The reuse partner that leads to the highest CGF among the IUEs within each SCBS is prioritized to be used as a reuse partner. As a result, as the number of reusable channels decreases, and the algorithm's complexity decreases. The channel gain factor Ω is defined as (9a):

$$\Omega_i = \frac{H_{i,\beta}^c}{H_{j,\beta}^d},\ \Omega_j = \frac{H_{j,1}^d}{H_{i,j}^c}\ (9a) \text{ and } \varphi_i^c = \frac{H_{j,\beta}^d}{H_{j,1}^d},\ \varphi_j^d = \frac{H_{j,1}^d}{H_{j,\beta}^d}\ (9b)$$

The $c_i{}^{th}$ with the Ω_i lowest value is chosen and can maximize the throughput as compared to most other IUEs for any given transmission power constraint between the IUEs and D2D users [7]. Consequently, the $r_{\mathcal{j}}{}^{th}$ with the $\Omega_{\mathcal{j}}$ highest value can also be chosen for higher throughput. However, prior to CRPS, for MS computed in 9(b), $\mathcal{Z}$ is satisfied optimally with equality when $\mathcal{Z} = \varphi_i^c >> \varphi_{\mathcal{j}}^d$ for constraint (B11) to choose the D2D pairs that operates in CM for each SCBS $i \in \mathcal{M}$, and the rest $\mathcal{R}_d - \mathcal{Z}$ D2D pairs operates in RM and vice-versa[2]. The larger $\mathcal{Z}$ is, the more chances the D2D pairs operate in the CM. With this condition, we defined the mode selection criteria as;

$$\begin{cases} \Phi_j^d = 1,\ if\ \ \varphi_j^d > \varphi_i^c\ \ \forall j\in R_d \\ \Phi_j^d = 0,\ if\ \ \varphi_j^d < \varphi_i^c\ \ \forall j\in R_d \end{cases} \quad (10)$$

In ascending order, the D2D pair with higher $\varphi_{\mathcal{j}}^d$ operates in RM, else CM. Therefore, for each D2D pair in the SCBS $i \in \mathcal{M}$, we compute $\mathcal{Z}$ and thus separate each D2D pair in each SCBS $i \in \mathcal{M}$ into RM and CM accordingly. The D2D user sets in the RM and CMs are expressed as; $\mathcal{R}_d^{\mathcal{j}} = \{\mathcal{j} \mid \Phi_{\mathcal{j}} = 1,\ \mathcal{j}\epsilon\Re_d\}$ and $\mathcal{R}_c^i = \{\mathcal{j} \mid \Phi_{\mathcal{j}} = 0,\ \mathcal{j}\epsilon\Re_d\}$, respectively.

B. Phase 2: Power Optimization

Based on the tight relationship between the users' minimum SINR requirement within the SCBS networks and interference from co-channel D2D users, a distributed optimal transmit power that achieve maximum network sum rate is derived using the formulated constraints in (7) if B6 and B7 are controlled with an appropriate resource algorithm. The variable $\rho_{i,\mathcal{j}}$, of B4 and B5 is relaxed to a continuous real variable with a range of [0,1]. Thus, the optimization problem is simplified as a convex problem with a concave objective function and convex constraints. As a result, the Lagrangian function based on (6) is expressed as follows:

$$\begin{aligned} L\left(P_{j,0}^d, P_{j,1}^d, P_i^c\right) &= \sum_{i\in M}\log_2\left(1+P_{j,0}^d\eta_{j,0}^d\right) + \sum_{i\in M}\log_2\left(1+P_{j,1}^d\eta_{j,1}^d\right) + \sum_{i\in M}\log_2\left(1+P_i^c\eta_i^c\right) \\ &-\alpha_1\left(\xi_{i\min}^c - P_{j,0}^d\eta_{j,0}^d\right) - \alpha_2\left(\xi_{j\min}^d - P_{j,1}^d\eta_{j,1}^d\right) - \alpha_3\left(\xi_{i\min}^c - P_i^c\eta_i^c\right) + \lambda_1\left(P_{\max}^c - \sum_{k_i\in K} P_i^c\right) \\ &+\lambda_2\left(P_{\max}^c - \sum_{k_i\in K} P_{j,0}^d\right) + \lambda_3\left(P_{\max}^d - \sum_{k_i\in K} P_{j,1}^d\right) \end{aligned} \quad (11)$$

where $$\eta_{j,0}^d = \sum_{\tau\in k_i}\frac{H_{j,\beta}^c}{N_o + \sum_{i\in R_d^j, i\neq j} P_i^d H_{i,\beta}},\ \eta_{j,1}^d = \sum_{\tau\in k_i}\frac{H_{j,1}^d}{N_o + \sum_{i\in C_i} P_i^c H_{i,j} + \sum_{i\in R_c^i} P_i^d H_{i,j}} \quad (12)$$

$\eta_i^c, \eta_{\mathcal{j},0}^d$ and $\eta_{\mathcal{j},1}^d$ are the channel-to-interference plus noise ratio (CINR) obtained from (2), (3) and (4), respectively. $\alpha_1 - \alpha_3$ and $\lambda_1 - \lambda_3$ are the non-negative Lagrangian multipliers for the constraints. To obtain the solution to (11), the dual function is defined as [15]:

$$f\left(\alpha_1,\alpha_2,\alpha_3,\lambda_1,\lambda_2,\lambda_3\right) = max\ \left\{L\left(P_{j,0}^d, P_{j,1}^d, P_i^c\right)\right\} \quad (13)$$

Thus, the dual problem is express as;

$$min\left\{f\left(\alpha_1,\alpha_2,\alpha_3,\lambda_1,\lambda_2,\lambda_3\right)\right\} \quad (14)$$

We therefore, rewrite the equation (14) as;

$$f\left(\alpha_1,\alpha_2,\alpha_3,\lambda_1,\lambda_2,\lambda_3\right)=\sum_{i\in M} f_n\left(\alpha_1,\alpha_2,\alpha_3,\lambda_1,\lambda_2,\lambda_3\right)+$$
$$\lambda_1\sum_{k_i\in K} P_{\max}^c+\lambda_2\sum_{k_i\in K} P_{\max}^d+\lambda_3\sum_{k_i\in K} P_{\max}^c-\alpha_1\xi_{i\min}^c-\alpha_2\xi_{j\min}^d-\alpha_3\xi_{i\min}^c$$

and

$$f_n\left(\alpha_1,\alpha_2,\alpha_3,\lambda_1,\lambda_2,\lambda_3\right)=$$
$$max\left\{\begin{array}{l}\log_2\left(1+P_{j,0}^d\eta_{j,0}^d\right)+\log_2\left(1+P_{j,1}^d\eta_{j,1}^d\right)+\log_2\left(1+P_i^c\eta_i^c\right)\\ -\left(\lambda_2-\alpha_1\eta_{j,0}^d\right)P_{j,0}^d-\left(\lambda_1-\alpha_3\eta_i^c\right)P_i^c-\left(\lambda_3-\alpha_2\eta_{j,1}^d\right)P_{j,1}^d\end{array}\right\} \quad (15)$$

The optimal solution of (15) can be found using the Karush-Kuhn-Trucker (KKT) conditions [16]. Thus, the optimal transmit powers of the D2D users for both CM and RM as well as the CIUEs in each SCBS $i \in \mathcal{M}$ are given as;

$$P_{j,0}^d=\left(\frac{1}{\ln 2\left(\lambda_2-\alpha_1\eta_{j,0}^d\right)}-\frac{1}{\eta_{j,0}^d}\right)^+,\ P_{j,1}^d=\left(\frac{1}{\ln 2\left(\lambda_3-\alpha_2\eta_{j,1}^d\right)}-\frac{1}{\eta_{j,1}^d}\right)^+,$$
$$P_i^c=\left(\frac{1}{\ln 2\left(\lambda_1-\alpha_3\eta_i^c\right)}-\frac{1}{\eta_i^c}\right)^+ \quad (16)$$

Considering constraints (B1-B3), the maximum transmit power for the IUEs as well as D2D pairs in CM and RM can be obtained as;

$$\xi_i^c=P_i^c\eta_i^c\geq\xi_{i\min}^c\Rightarrow P_i^c\geq\frac{\xi_{i\min}^c}{\eta_i^c},\ \xi_{j,0}^d=P_{j,0}^d\eta_{j,0}^d\geq\xi_{i\min}^c\Rightarrow P_{j,0}^d\geq\frac{\xi_{i\min}^c}{\eta_{j,0}^d},$$
$$\xi_{j,1}^d=P_{j,1}^d\eta_{j,1}^d\geq\xi_{j\min}^d\Rightarrow P_{j,1}^d\geq\frac{\xi_{j\min}^d}{\eta_{j,1}^d} \quad (17)$$

Therefore, the optimal transmit powers of the IUEs and the D2D users for reuse and cellular mode can be express as;

$$P_i^{c*}=\left\{min\left(\left(\frac{1}{\ln 2\left(\lambda_1-\alpha_3\eta_i^c\right)}-\frac{1}{\eta_i^c}\right)^+,\frac{\xi_{i\min}^c}{\eta_i^c}\right)\right\}\geq P_{\max}^c$$
$$P_{j,0}^{d*}=\left\{\min\left(\left(\frac{1}{\ln 2\left(\lambda_2-\alpha_1\eta_{j,0}^d\right)}-\frac{1}{\eta_{j,0}^d}\right)^+,\frac{\xi_{i\min}^c}{\eta_{j,0}^d}\right)\right\}\geq P_{\max}^c$$
$$P_{j,1}^{d*}=\left\{\min\left(\left(\frac{1}{\ln 2\left(\lambda_3-\alpha_2\eta_{j,1}^d\right)}-\frac{1}{\eta_{j,1}^d}\right)^+,\frac{\xi_{j\min}^d}{\eta_{j,1}^d}\right)\right\}\geq P_{\max}^d \quad (18)$$

where $(x)^+ = max\,(x, 0)$. To obtain the dual variables optimum value in (18), we employ an algorithm-based bisection scheme as in [17]. Therefore, the optimization problem in (6) reduces to;

$$\max_{P_{j,0}^d,P_{j,1}^d,P_i^c}\Upsilon=\sum_{i\in M}\sum_{t\in K_i}\sum_{r_j\in R_c^i\cup R_d^j}\log\left(1+\xi_{\phi_j}^d\right)+\sum_{i\in M}\sum_{C_i\in R_c}\log\left(1+\xi_i^c\right)$$
$$s.t.\ \ B6: P_{j,1}^{d*}H_{j,\beta}\leq\sum_{i\in C_i}I_o,\ \ \forall\tau\in K_i \quad (19a)$$
$$B7:\sum_{i\in M}\sum_{j\in R_d^j}P_{j,1}^{d*}H_{j,\beta}\leq\sum_{i\in M}\sum_{i\in C_i\cup R_c^i}I_1,\ \forall i\in M \quad (19b)$$

The constraints (B6) and (B7) are used to adjust the D2D pairs transmit power based on the interference thresholds I_o and I_1 for the SCBS networks. From (B6), the initial D2D transmit power in RM can also be obtained as: $P_{jm}^d = \frac{I_0}{H_{j,\beta}}$. Table 1 summarizes the optimal solution for the adaptive IA and MS for D2D-enabled SCs in 5G-IIoT networks.

Algorithm 1: Proposed Adaptive Interference-Avoidance and Mode Selection Algorithm for D2D-enabled SCs

Initialize: $\alpha_0 = 0, \alpha_f = \delta\vartheta\ \lambda_0 = 0,\ \lambda_f = \delta\vartheta$
Compute $\eta_i^c, \eta_{j,0}^d, \eta_{j,1}^d, P_i^c, P_{j,0}^d$ *, and* P_{jm}^d*,*
For each SCSB $i \in \mathcal{M}$
Compute equation (9b) and determine $\mathcal{R}_d^j$ *and* $\mathcal{R}_c^i$ *using equation (10)*
Allocate additional channel to $\mathcal{R}_c^i$
Compute equation (9a) for the D2D pair in reuse mode and select the ${c_i}^{th}$ *with the* $\mathcal{T}$ *lowest value.*
For n = 1: no of small cells operating D2D mode
  For j = 1: $\mathcal{R}_d^j$ *in reuse mode*
  Compute $P_{j,1}^{d*}$ *in equation (17), If* $\frac{\xi_{min}}{\eta_{j,1}} < P_{max}$
   else
   While $\left|\frac{\xi_{min}}{\eta_{j,1}} - P_{max}\right| \geq \varepsilon$
    Compute $\lambda_i = \frac{\lambda_0 + \lambda_f}{2},\ \alpha_i = \frac{\alpha_0 + \alpha_f}{2}$
    Compute the transmit power from eqtn 16.
    $P_{j,1}^{dd} = \left(\left(\frac{1}{Ln2(\lambda_i - \alpha_i * \eta_{j,1})}\right) - \frac{1}{\eta_{j,1}}\right)$
    If $P_{j,1}^{dd} > 0,\ \forall j \epsilon \mathcal{R}_d^j, P_{j,1}^{dd} = P_{j,1}^{dd}, \lambda_* = \lambda_i$ *and* $\alpha_* = \alpha_i$
     break
    Else
     $P_{j,1}^{dd} = min(P_{j,1}^{dd})$
    End
   End
Compute $P_{j,1}^{d*} = min\left(P_{j,1}^{dd}, P_{jm}^d\right)$.
End
Do the same for $P_i^{c*}, P_{j,0}^{d*}$
Compute the system throughput in (19) subject to eqtn (19a) and (19b) using equation (8).
End

The variable ε, is an insignificant positive number that defines the power selection process's tolerance. It is critical to note that the initial starting point, the iteration order, and the accuracy required to allocate power process for each user's optimal power [15] determines the local optimum. As a result, to determine the precise required iteration times for the optimum solution is a difficult task. Fortunately, when the power constraint is met, the iteration process converges. Furthermore, the interference constraint adjusts each D2D user's transmit power based on the incoming interference thresholds (Co-tier and Co-channel interference threshold) to maximize the network throughput. As a result, with less interference, co-tier and co-channel users achieve suitable throughput, which leads to improved system throughput.

C. IA and MS Operational Procedure

The IA and MS operational procedure of the system is assumed as follows:

1. The $\mathcal{C}_i$ IUEs and r_i D2D user are assigned to each SCBS $i \in \mathcal{M}$ with the best coverage (i.e., largest time-averaged received signal power at the IUE) based on the pilot signal called reference signal received power (RSRP) averaged over a moving average window. By this pilot signal, each SCBS $i \in \mathcal{M}$ acquired the CSI of neighboring SCBSs through its assigned $\mathcal{C}_i$ IUEs and exchanged information to execute dynamically in real-time [20].
2. Each SCBS $i \in \mathcal{M}$ assumes co-tier interference among the neighboring SCBSs based on measurement reports. However, the MeNB uses these reports to constructs an interference table, allowing SCBS $i \in \mathcal{M}$ to monitor neighbor SCBS control channels and reference signal transmissions. The interference table helps each SCBS $i \in \mathcal{M}$ to determine neighboring SCSBs' cell identification and path loss between them. Additionally, each $\mathcal{C}_i$ IUEs set, and $\mathcal{R}_d$ D2D users can send measurement reports of received signal strength indicators (RSSI) from neighboring SCBSs to the MeNB.
3. Each SCBS $i \in \mathcal{M}$ selects subchannel ($\tau \in \mathcal{K}_i$) from the total subchannels, $\mathcal{K}$ ($\mathcal{K}_i \subseteq \mathcal{K}$), to serve $\mathcal{C}_i$ IUEs and r_i D2D user based on the QoS class indicator (QCI) and traffic loads. As a result, allowing the $\mathcal{C}_i$ IUEs set to estimates local CSI and the interfering channels.
4. Each SCBS $i \in \mathcal{M}$ has knowledge of the average channel power of its assigned $\mathcal{C}_i$ IUEs, obtained from wide-band channel quality indicator (CQI) reports. As a result, allocate a uniform power to all channels of $\mathcal{C}_i$ IUEs, potentially varying the power levels among different $\mathcal{C}_i$ IUEs. The SCBS $i \in \mathcal{M}$ measures the uplink (UL) CSI of a r_i D2D user in D2D mode through the signaling feedback channel since each SCBS $i \in \mathcal{M}$ has no direct knowledge of the D2D link.
5. The signaling information includes the CSI of the desired D2D link and the interfering signal powers involving the D2D user. As a result, each SCBS $i \in \mathcal{M}$ uses the mode criteria in equation (10) for adaptive MS operation. In ascending order, it determines the D2D pair, $\mathcal{R}_d^j$ with higher φ_j^d to operate in RM, else CM, $\mathcal{R}_c^i$. As a result, for each D2D user in the SCBS $i \in \mathcal{M}$, $\mathcal{Z}$ is satisfied optimally with equality when $\mathcal{Z} = \varphi_i^c >> \varphi_j^d$ for constraint (B11), which allows the D2D user to operate in CM and the rest $\mathcal{R}_d - \mathcal{Z}$ D2D pairs [15] in RM and vice-versa. A larger $\mathcal{Z}$ increases the likelihood of the D2D pairs operating in the cellular mode.
6. Next, each SCBS $i \in \mathcal{M}$ with a reuse D2D user conducts a reuse operation for its D2D user using the CGF in (9a) to find the best D2D pair's reuse partner that minimizes reuse interference and optimizes RS. As a result, the system algorithm complexity is reduced when compared with the exhaustive search (of exponential power $\mathcal{K}_i^{\mathcal{M}-m}$) of allocated subchannels for each D2D pair.
7. Each SCBS $i \in \mathcal{M}$ then employs the proposed adaptive IA scheme to perform semi-static RA and per subchannel PA for its assigned $\mathcal{C}_i$ IUEs, $\mathcal{R}_d^j$ and $\mathcal{R}_c^i$ D2D users based on their different QoS. An adaptive IA and MS scheme of the SCBSs ensures that the interference and MS conditions for the $\mathcal{C}_i$ IUEs, $\mathcal{R}_d^j$ and $\mathcal{R}_c^i$ D2D users do not exceed a predetermined threshold, thereby improving spectrum reuse within each SCBS and increasing overall system throughput.
8. The interference table created by the MeNB is updated for interference management and RA for each SCBS using the proposed IA scheme. When the gain difference of channels from an SCBS and the interfering SCBS exceeds a predetermined threshold, the interference conditions between the SCBSs are declared and constrained by constraint (B7).
9. The MeNB IA scheme output (i.e., resource management) determines the subchannel set for each SCBS $i \in \mathcal{M}$, achieving a tradeoff between interference control and spectrum reuse among SCBSs to improve overall system throughput.

D. *Complexity Analysis and Overhead*

Given the number of SCs is $\boldsymbol{\mathcal{M}}$ and the average number of IUEs is $\Re_c$, the complexity is O$|\boldsymbol{\mathcal{M}}\Re_c|$. In both CM and RM, the number of D2D pairs is O$|\mathcal{R}_c^i|$ and O$|\mathcal{R}_d^j|$, respectively. For the sub-channel allocation per reuse cell m, each $\mathcal{R}_d^j$ choses the best sub-channel using the CGF as O$|\mathcal{R}_d^j * \tau|$. Finally, for the PA, at each round, the maximum O$|\mathcal{R}_d^j * \mathcal{K}|$ iterations are done to obtain optimal power. The number of rounds is equal to the network's sub-channels. The proposed scheme's complexity is expressed as O$|(\boldsymbol{\mathcal{M}}\Re_c+\mathcal{R}_c^i+\mathcal{R}_d^j * \tau+\mathcal{R}_d^j * \mathcal{K})|$. The scheme's complexity grows linearly as the number of D2D pair increases.

The proposed algorithm's implementation for IA and MS schemes is a hierarchically centralized network system. Each SCBS $i \in \mathcal{M}$ has a different RA and interference management (IM) to the MeNB. Assuming the IM (RA) is performed at each transmission period interval, $\mathbb{T}_{\mathcal{PS}}$, (as in LTE-A 1ms), The SCBS $i \in \mathcal{M}$ can have a fractional allocation of subchannels to its users over a long transmission period (e.g., 10ms or 100ms). If each SCBS $i \in \mathcal{M}$ performs RA at each $\mathbb{T}_{\mathcal{S}}$, a $\mathcal{C}_i$ IUEs set and a r_j D2D user can use a subchannel $\mathcal{K}_i$ for $\mathcal{C}_i\mathcal{K}_i\mathbb{T}_{\mathcal{S}}$ and $r_j\mathcal{K}_i\mathbb{T}_{\mathcal{S}}$ to the nearest transmission period, $\mathbb{T}_{\mathcal{PS}}$. The IA and MS scheme is determined by parameters set that maximizes the objective function. Based on the proposed algorithm, the parameters set include η_i^c, $\eta_{j,0}^d$ and $\eta_{j,1}^d$. Each SCBS $i \in \mathcal{M}$ manages the joint IA and MS procedures. However, each SCBS $i \in \mathcal{M}$ has no direct knowledge of the D2D link and only received CSI feedback from the D2D pair. The CSI feedback is necessary for supporting the MS procedure. As a result, the D2D user in each SCBS requires extra signaling content. The MS variable Φ_j^d is computed for each SCBS $i \in \mathcal{M}$ only when $\mathcal{Z} = \varphi_i^c >> \varphi_j^d, \forall j \in \mathcal{R}_d$ for the D2D pair to operate in CM, and the rest $\mathcal{R}_d - \mathcal{Z}$ D2D pair per SCBS $i \in \mathcal{M}$ operates in a RM. For the SCBS $i \in \mathcal{M}$ with the D2D user (DUE) in cellular, a τ_i^c subchannel is allocated per DUE, which increases the signaling overhead as m ($\mathcal{C}_i\mathcal{K}_i + \mathcal{R}_c^i\tau_i^c$). For each SCBS $i \in \mathcal{M}$ with reuse DUE $\mathcal{R}_d^j$, a CGF computation (as in 9(a)) is executed to select a reuse partner with the highest CGF among the $\mathcal{C}_i$ IUEs per SCBS $i \in \mathcal{M}$. This process reduces system complexity in searching for the reuse channel per SCBS $i \in \mathcal{M}$ (which could be $\mathcal{K}_i^{\mathcal{M}-m}$ for exhaustive search) with a signaling overhead ($\mathcal{M} - m$) $\mathcal{R}_d^j\tau$. The joint IA and MS perform IM to achieve a configuration that optimizes system performance as each SCBS $i \in \mathcal{M}$ decides the D2D pair MS request based on the MS procedure and allocate per subchannel power based on their QoS with signaling overhead of $\mathcal{R}_d^j \mathcal{K}_i$ per SCBS with reuse DUE, $\mathcal{R}_d^j$. The MeNB compares the average interference power among the interfering SCBS $i \in \mathcal{M}$ using constraint (B7) and computes the overall system throughput. The SCBS $i \in \mathcal{M}$ is responsible for actual interference power and the channel gain to its users ($\mathcal{C}_i$ IUEs set and a r_j D2D user), since the MeNB does not know each user's location within the SCBS $i \in \mathcal{M}$. In summary, the resource management at the MeNB is performed through the adaptive IA on coarse time-scale, $\mathbb{T}_{\mathcal{PS}}$, while each SCBS performs semi-static RA using the IA and MS algorithm to its users at each $\mathbb{T}_{\mathcal{S}}$. Therefore, no stringent latency (delay) constraint on the proposed algorithm.

IV. Simulation Results

To verify the proposed scheme's effectiveness, we present the simulation results and benchmark their performance. The experimental setup consists of six (6) orthogonal SCs distributed randomly within a 500m macro-cell coverage area. The homogeneous poison point process (PPP) with density θ_s models the spatial position of the SCBSs, while IUEs and D2D users are modeled separately and randomly distributed within each SC of radius 25m. The sub-channel allocation in each cell is used to determine the CGF and mode decision for D2D users since each cell operates independently. I_o and I_1 are for controlling the co-tier and co-channel cumulative interference, respectively. The SCs allocate up to 52 subchannels for data transmission per user and for every subchannel, independent block fading is assumed. As a result, the fading behavior of the desired links determines the MS. Each plotted figure for cumulative distribution function (CDF) shows the results obtained by averaging a minimum of 1,000 channel realizations. Table 1 describes the simulation parameters.

Table 1: Simulation Parameters

Parameters	Values
Macro cell radius, R	250m
Small cell radius (r)	25m
Uplink bandwidth	12MHz
Number of Small cells	6
Carrier Frequency	2GHz
Pathloss model for IUEs	128.1+37.6*log10(dis [Km])
Pathloss model for D2D pair	140.7+37.6*log10(dis [Km])
SINR Threshold	10dB
Noise Power	-122dBm
Maximum Power for IUEs	20dBm
Maximum Power for D2D pair	15dBm

To validate the proposed framework, we use two metrics: CDF and the system throughput to compare with the following schemes:

- SINR-Aware Scheme [19] measure and determine a D2D user mode of operation for both CM and RM based on SINR values. The highest SINR value uses CM.
- Adaptive resource sharing algorithm (ARSA) Scheme [20] uses the combined channel gain ratio (CGR) of the D2D pair to its interference in CM and D2D user to its interference in RM to determine the D2D pair with the highest throughput for RS.
- Random Selection Scheme (RSS) [21] selects a random reuse partner for D2D users in RM but uses the same mode decision principle as the proposed approach for resource sharing.
- QoS-Aware Scheme [14] determines the best mode for a D2D user using the maximum throughput value for the D2D pair in CM to the D2D pair in RM to decide the D2D user mode.
- Joint MS and PC (JMAPC) scheme [6] considered the D2D user distance within a fixed interference region to select the communication mode. We compare all the above scheme's performances to our proposed approach.

Fig. 2 depicts the system SINR's CDF of the proposed scheme compared to the five approaches mentioned above. The proposed approach outperforms the SINR-aware, ARSA, QoS-aware, RSS and JMAPC scheme by 15.46%, 16.62%, 21.37%, 25.24%, and 32.46%, respectively in Fig. 2. The RSS and JMAPC scheme perform poorly due to the incorrect CSI with downplayed interference estimates, resulting in lower transmit power. The proposed approach has demonstrated that the D2D pairs in reuse mode are absolutely dependent on CSI.

In Fig. 3, the CDF of the proposed scheme's system throughput compared to the five approaches was plotted. The proposed approach outperforms the SINR-aware, ARSA, QoS-aware, RSS, and JMAPC scheme by 6.41%, 11.52%, 13.87%, 19.76%, and 25.39%, respectively. As discussed in Fig. 2, the RSS and JMAPC scheme performs poorly due to the CSI errors, which results in the reuse of inappropriate resource blocks, potentially affecting the cellular users' performance with significant interference within the network. The system SINR vs. the interference power of the proposed scheme compared to the five approaches was plotted in Fig. 4. The proposed scheme's system SINR surpasses the five approaches mentioned above, although there is a decrease in the scheme's system SINR as the interference power rises.

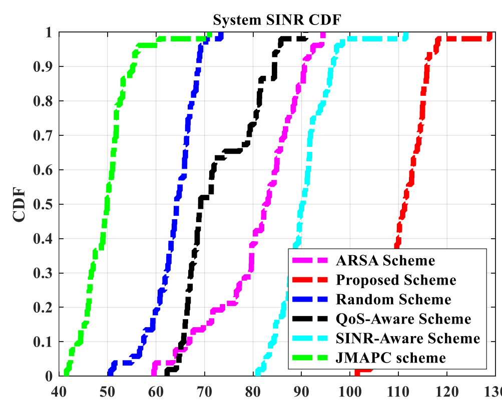


Fig. 2 The system's SINR CDF for proposed scheme compared with five other schemes.

The most affected approaches are the QoS-aware and ARSA, while the proposed scheme, the SINR-aware, and the RSS scheme show a slight decrease in value and then stabilizes as the interference power rises. The JMAPC scheme submerged

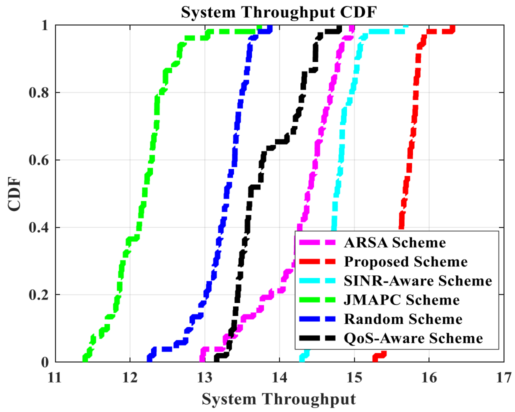
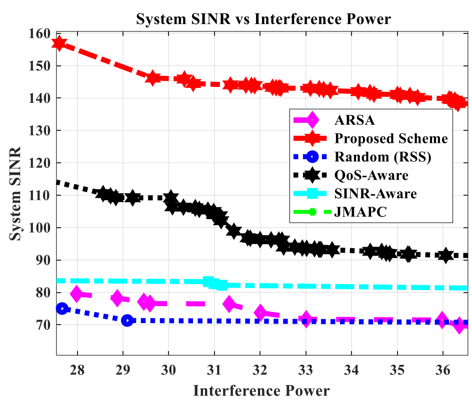


Fig.3: The system's Throughput CDF for proposed scheme compared with five other schemes.

with the rise in interference power. The drop in the system SINR for the QoS-aware, JMAPC, and ARSA is due to the inaccurate CSI estimation and in-perfection of the mode selection scheme used for D2D pair's mode of operation, resulting in lower transmit power.

Fig. 5 presents the comparison of the proposed scheme's system throughput versus interference power against five other approaches. The findings indicate that as interference power increases, there is a slight decrease in system throughput. The QoS-aware and RSS respond to the increased interference power by transmitting with a higher power to enhance their performance. This is due to the absence of a better QoS reuse partner for D2D users in the reuse mode, resulting in significant interference, as illustrated in Fig. 7. Despite this, the proposed scheme outperforms all five approaches. Again, as interference power rises, the SINR-aware, JMAPC, and ARSA approach decline slightly in throughput due to inappropriate CSI estimation and failure of the MS scheme to select appropriate D2D users in both CM and RM as shown in Fig. 6 and Fig. 7.



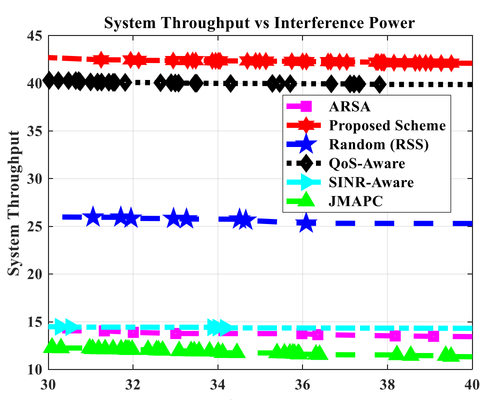
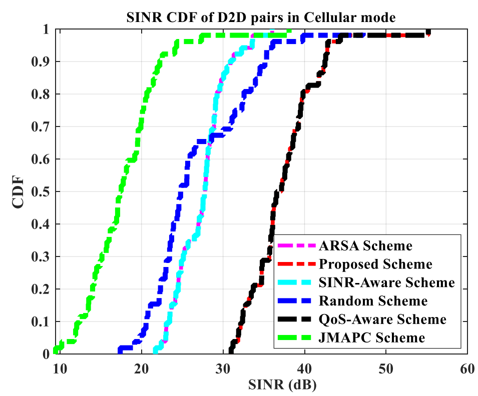


Fig. 4 and Fig 5: The system SINR and throughput vs. interference power for proposed scheme compared with five other schemes.

Fig. 6 depicts the SINR CDF of D2D pairs in CM for the proposed scheme alongside the five other approaches. The Proposed and QoS-aware scheme achieves nearly identical performance, and thus the same as the SINR-aware and ARSA in Fig. 6. The proposed approach and QoS-aware outperform all the other schemes. The Proposed and QoS-aware mode selection scheme outperforms the RSS by 11.69%, SINR-aware and ARSA by 22.29%, and JMAPC by 26.62%, respectively.

Fig. 7 depicts the proposed scheme's SINR CDF for the D2D pairs in RM with the five other approaches. The proposed approach outperforms ARSA, QoS-aware, RSS, SINR-aware, and JMAPC by 13.26%, 46.16%, 53.55%, 59.15%, and more than 100%, respectively. The performance of the proposed scheme is attributed to the use of the MS scheme and CGF to explore the CSI between the cellular IUEs and D2D users, which is critical for D2D PC and RA. The performance of ARSA is linked to the role of CSI input, except that the MS scheme performs poorly compared to the proposed approach. Summarily, the ability of these schemes to explore CSI between the cellular IUEs and the underlay D2D pairs significantly



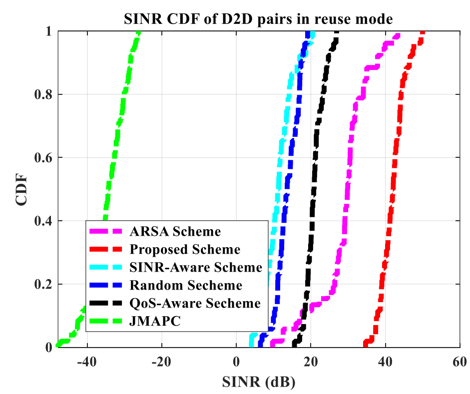


Fig. 6 and Fig 7: The CDF of SINR for D2D pairs in CM and RM for proposed scheme compared with five other schemes.

influences the scheme performance. Thus, the MS performance alone cannot improve the system throughput, as evidenced by the RSS, QoS-aware, SINR-aware, and JMAPC approaches. Fig. 8 displays the co-tier and co-channel interference thresholds vs. interference power for our proposed scheme and four other approaches (ARSA, RSS, SINR-Aware, and QoS-

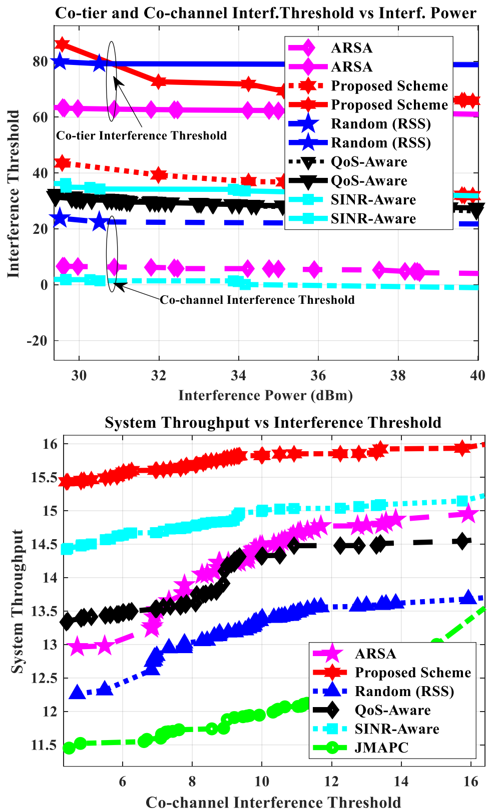


Fig. 8 and Fig 9: The Interference Threshold vs. Interference Power and throughput vs. the Co-channel interference threshold for proposed scheme compared with five other schemes.

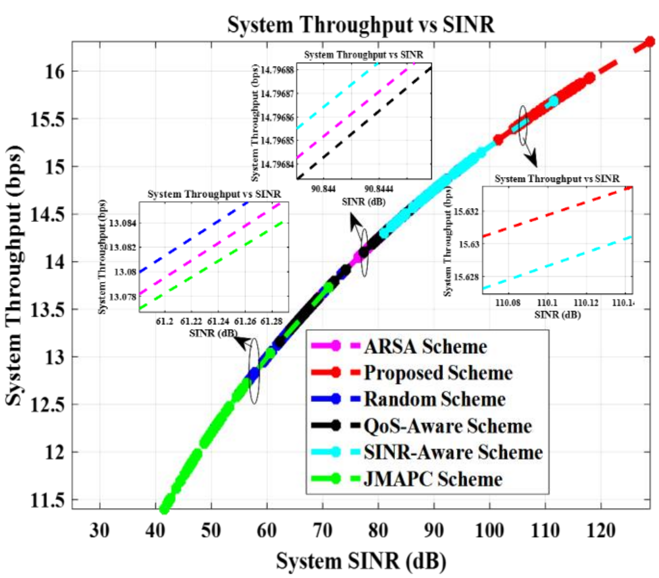


Fig. 10. The system throughput against the SINR for the proposed scheme with five other schemes.

Aware). As the interference power rises, all the methods adjust their thresholds to mitigate interference, with the proposed approach exhibiting the most aggressive response. As a result, it highlights the effectiveness of distributed power control in interference management. The RSS scheme demonstrates higher power transmission, indicating inefficient resource block usage due to incorrect CSI and downplayed interference estimation. The QoS-Aware and SINR-Aware schemes have lower co-tier interference thresholds in contrast to RSS, ARSA, and the proposed approach due to better control over interfering links, reducing the impact of interference from D2D pairs through cellular mode absorption. Considering the co-channel interference threshold, the SINR-Aware and ARSA have lower interference thresholds than the proposed scheme, QoS-Aware, and RSS. The reason is the poor CSI estimation between cellular IUEs and underlay D2D pairs within the same small cells, resulting in lower transmit power than the required transmitter, as interference from neighboring small cells further complicates the network. In addition, during mode operation, underlay D2D pairs with strong interfering links are absorbed into the CM. In summary, co-tier interference tends to be stronger than co-channel interference due to the random distribution of small cells. Fig. 9 depicts the proposed scheme system throughput vs. co-channel interference threshold alongside the five other approaches. As the co-channel interference threshold for all the approaches rises, so does the system throughput. The proposed method surpasses the others in terms of higher system throughput value. SINR-aware, ARSA, and QoS-aware gain a higher throughput value compared to the RSS and JMAPC scheme. The RSS, and JMAPC scheme's poor performance is due to a lack of proper CSI estimation and high interference power, resulting in packet loss and a significant impact on the RA within the networks. The effectiveness of strict interference power control measures has aided the proposed scheme's performance.

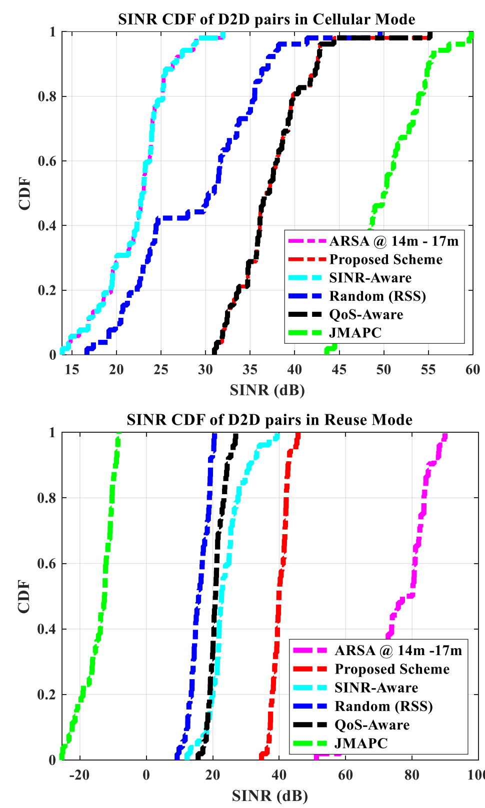


Fig. 11. The SINR CDF for D2D users in (a) cellular mode and (b) reuse mode for the proposed scheme with five other schemes when distance between D2D pairs is increased from 14m to 17m.

Fig. 10 depicts the proposed scheme system throughput vs. the system SINR alongside the five other approaches. The proposed method outperforms the other five. The bottom stage of the plot demonstrates the best SINR value for the RSS scheme, the middle stage demonstrates the best SINR value for the SINR-

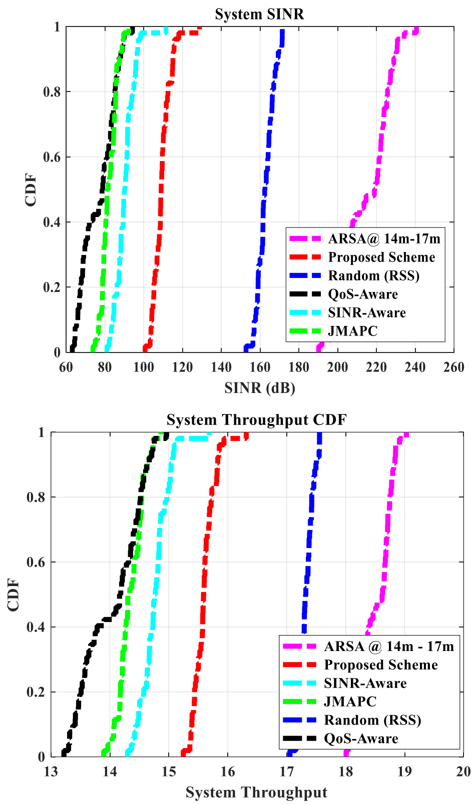


Fig. 12. The (a) CDF of the system SINR and (b) system throughput for the proposed scheme with five other schemes when distance between D2D pair is increased from 14m to 17m.

-aware approach, and the top shows the best SINR value for the proposed method. These stages reference the performance indices of each scheme achievement in the small cell networks. As a result, the larger the SINR, the higher the user requirement and the more spectrum resources occupied by these users to meet their minimum SINR requirement. The proposed scheme mode selection and CGF significantly contributed to the SINR performance observed in all results.

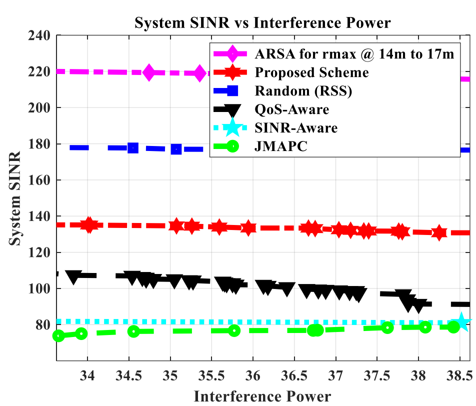


Fig. 13. System SINR vs. interference power for the proposed scheme compared with five schemes when distance between D2D pairs is increased from 14m to 17m.

Fig. 11 displays the SINR CDF for D2D users in (a) cellular mode and (b) reuse mode, comparing the proposed scheme with

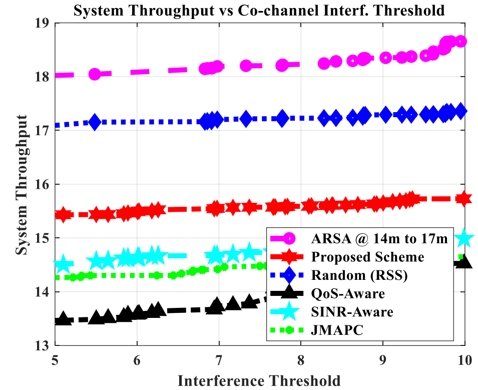


Fig. 14. System throughput vs. co-tier interference threshold for the proposed scheme compared with five schemes when distance between D2D pairs is increased from 14m to 17m.

five others when the distance between D2D pairs increases from 14m to 17m. Both Fig. 11(a) and (b) show performance degradation compared to Fig. 6 and Fig. 7. In Fig. 11(a), the proposed scheme and QoS-Aware exhibit an 8.06% degradation, while ARSA and SINR-Aware experience a 33.46% degradation. Interestingly, RSS and JMAPC demonstrate improvements of 11.45% and 40.09%, respectively. The poor performance of the proposed scheme, QoS-Aware, SINR-Aware, and ARSA is due to the MS scheme's inability to accurately measure CSI between D2D pairs and interfering links with SCBSs. In Fig. 11(b), the proposed scheme, ARSA, and SINR-Aware find reuse partners with improved QoS, leading to enhanced performance. However, there is a notable improvement for ARSA and SINR-Aware compared to Fig. 7 due to their tracking of interfering

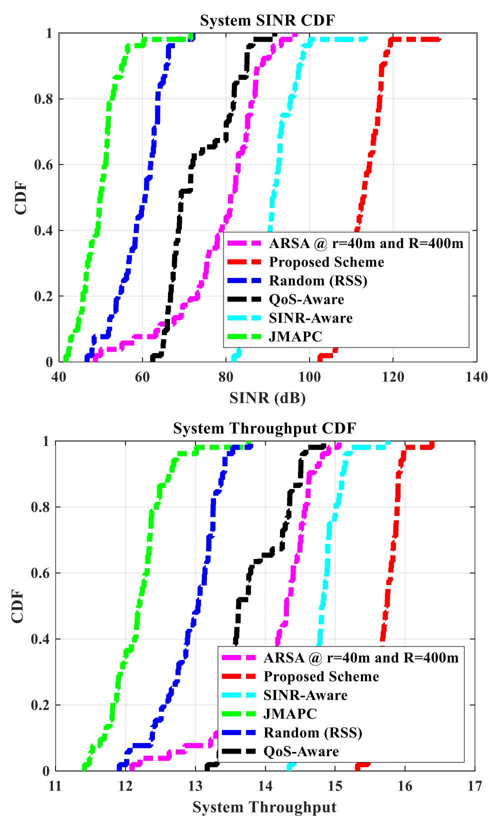


Fig. 15 and Fig. 16: The system SINR and throughput CDF when the radius is increased from r = 25m to 40m and R = 250m to 400m for the proposed scheme compared with five schemes.

links. Unfortunately, the proposed scheme suffers slightly from the increased distance between D2D pairs. The impact of these distance changes on system SINR and system throughput are shown in Fig. 12. In Fig. 12(a), the proposed scheme, SINR-Aware, and QoS-Aware experience a degradation of 22.81%, 20.37%, and 19%, respectively, while ARSA, RSS, and JMAPC show improvements of 93.04%, 38.49%, and 33.2% compared to Fig. 2. In Fig. 12(b), the proposed scheme, SINR-Aware, and QoS-Aware also exhibit decreases of 30.86%, 25.22%, and 27.94%, while ARSA, RSS, and JMAPC gain 3.73%, 41.17%, and 50.23%, respectively compared to Fig.3. The performance of JMAPC and RSS stems from their likelihood of encountering reuse partners with improved QoS, which enables them to boost their transmit power in response to increased interference. The performance of ARSA is due to its ability to explore CSI between CIUEs and underlay D2D pairs.

Fig. 13 depicts the performance of the system SINR vs. interference power for the proposed scheme with five other approaches as the D2D pair distance increased from 14m - 17m. There is a general decrease in all the schemes system SINR as the interference power rises. However, ARSA, RSS, and JMAPC maintain a relative transmission power to satisfy their QoS requirement even after the interference thresholds are applied as shown in Fig. 14, while the proposed scheme, QoS-Aware, and SINR-Aware scheme lose most of their signals after the applied interference thresholds. Fig. 15 and Fig. 16 are the results of the system SINR CDF and system throughput CDF when the radius of the SCBSs and the MeNB increase from $r = 25m\ to\ 40m$ and $R = 250m\ to\ 400m$, respectively. The increment leads to a corresponding performance for the system SINR and the system throughput. For instance, the proposed scheme, SINR-Aware, ARSA, QoS-Aware, RSS, and JMAPC shows an improved system SINR of 4.32%, 3.05%, 37.95%, 2.24%, 11.45%, and 1.43%, respectively, compared to Fig. 2 while there is also a corresponding increase in the system throughput of the proposed scheme, SINR-Aware, ARSA, QoS-Aware, RSS, and JM APC by 3.88%, 2.16%, 48.45%, 1.85%, 16.15%, and 2.15% respectively compared to Fig. 3.

V. Conclusion

This paper proposed a framework for IA and MS schemes in 5G-IIoT networks, addressing interference issues in D2D-enabled SC communication. To lower the complexity, the proposed approach utilizes two phases. Firstly, a mode selection scheme adaptively chooses between cellular and reuse modes based on channel gain ratios of D2D pairs. Secondly, the CGF is computed for D2D users in RM to select the best reuse partner, minimizing reuse interference while maintaining QoS requirements. An optimal distributed power strategy, employing the Lagrangian dual decomposition method, is implemented to maximize system throughput. Numerical results demonstrate that the proposed method outperforms the five compared approaches in system throughput, interference thresholds, and average SINR value without additional complexity or signaling overhead. The effectiveness of the proposed scheme highlights the positive impact of MS and CGF on effective interference control in wireless fading channels.

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