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Abstract—Device-to-Device (D2D) communication could improve the efficiency of resource utilization in cellular networks by allowing nearby devices to communicate directly with each other. Nevertheless, one main challenge in D2D communication is resource allocation. We observed that the transmission quality in D2D communications can be significantly improved through a proper resource exchange. Based on this observation, we propose a novel D2D resource allocation framework for an LTE-Advanced system. We theoretically prove that any arbitrary algorithm, either distributed or centralized, will converge in the proposed framework whenever all performed exchanges are beneficial. Based on the concept of beneficial exchange, we propose a Trader-assisted Resource Exchange (T-REX) mechanism, an exchange-based mechanism that converges in polynomial time and achieves Pareto optimal, as an efficient and flexible solution to the D2D resource allocation problem. The eNodeB regulates the D2D resource allocation through designing the trader preference functions in the T-REX mechanism. By applying game-theoretic analysis to the D2D communication system, we prove that all rational D2D pairs will truthfully report their information when the trader preference functions are properly designed. Finally, our simulation results show that the proposed T-REX mechanism significantly mitigates the interference experienced by D2D devices in LTE-Advanced systems.

I. INTRODUCTION

Improving the coverage and efficiency of resource utilization is one of the key challenges in the next-generation cellular systems. Device-to-Device (D2D) communication could improve the coverage and resource utilization by allowing nearby devices to communicate directly [2]. Traditionally, two cellular devices communicate with each other through multi-hop transmission, with a base station (BS) as their intermediate infrastructure. Such a transmission scenario is inefficient in terms of both resource utilization and transmission delay when these two devices are in close proximity to each other. 3GPP has begun to examine the service requirement for Proximity-based Services (ProSe), which is the D2D communications for LTE-Advanced, and then has started ProSe radio access network standardization recently [2]. It allows two nearby devices to communicate with each other directly using existing WLAN or WPAN techniques in an unlicensed spectrum or an LTE-Advanced transmission technique in licensed spectrum. This approach improves the transmission quality from the proximity [2], reduces the transmission delay by utilizing one-hop direct connection instead of two-hop cellular connection, and provides an extra dimension for resource reuse in the cell system.

Resource allocation is one of the key challenges in D2D communications in a cellular system [2]. As specified by [2], D2D communications can be executed in unlicensed or licensed spectra. Since the former choice is relatively unreliable due to its openness to other out-of-system devices, in this paper we study the latter choice, in which the resources utilized by D2D communications are dedicated resources (spectrum, resource blocks, etc.) licensed to the cellular system or a specific purpose (public safety, for instance) [2]. When D2D communications are utilizing a licensed spectrum, the BSs should regulate the resource allocation of D2D communications in order to 1) prevent undesired interference to existing cellular users, 2) enhance resource utilization efficiency according to (possibly frequency and spatially diverse) channel conditions, and 3) reuse resources if possible. Additionally, the BSs should be able to respond quickly to requests from the D2D devices and rapid changes in inter/intra-cell interference. Therefore, it is necessary to develop a low-complexity yet efficient algorithm for resource allocation.

Specifically, the resource allocation schemes of LTE D2D broadcast communications are classified into Mode 1 and Mode 2. The scenario for Mode 1 is D2D communications within the coverage of the eNodeB, while Mode 2 represents out-of-LTE-coverage scenarios. The eNodeB may involve in the D2D resource allocation in Mode 1. According to the agreement in 3GPP RAN1#76 standard meeting in February 2014, the eNodeB can schedule the exact resources used by a UE to transmit direct data and direct control information.
[?]. In such a case, D2D resource allocation mechanisms are schedule-based. To be more specific, the agreement in 3GPP RAN1#76bis standard meeting in March 2014 states that the eNodeB uses PDCCH or ePDCCH to allocate resources to a D2D transmitter for Scheduling Assignment (SA) and Data transmission [?]. Also, D2D Grant is sent by the eNodeB in Mode 1 resource allocation to schedule SA and data transmission. The detailed design of D2D Grant on (e)PDCCH was still under discussion in the latest 3GPP RAN1#78 standard meeting in August 2014 [?]. In such a case, the eNodeB is responsible for the resource allocation according to the requests from the D2D devices. We focus on the Mode 1 in this work as it involves more new challenges.

The ad-hoc characteristic of D2D communication poses a new challenge to the D2D resource allocation problem in LTE D2D communication Mode 1: the truth-telling issue. Specifically, the BS requires the channel measurements from D2D devices in order to allocate resources efficiently. Nevertheless, the BS cannot validate these reports, since the transmissions occur only between the corresponding D2D devices. Notice that while the reporting protocols and formats are standardized and will be certified in advance in licensed cellular communication systems, the measurements reported in a report could be any value since the exact value, such as signal reception strength, cannot be validated by others except the device itself. This gives the D2D devices the potential to cheat by reporting the measurements untruthfully when the untruthful reports would be advantageous to the D2D devices in terms of the resource allocation. When D2D devices or corresponding users are rational, they will behave selfishly and therefore make use of this advantage.

To illustrate, let us assume that the BS tends to allocate the resource to the devices claiming to have the highest transmission qualities (Best CQI Scheduling in LTE-Advanced, for instance). In such a case, D2D devices tend to report a forged measurement value higher than the real value of their most desired resources in their reports. This forged report will increase the probability that the desired resources will be allocated to them. The BS therefore cannot provide an efficient allocation, since the information she has received does not reflect the true system state. To tackle this issue, it is necessary to employ a game-theoretic analysis [?]. Game theory is a mathematical tool to theoretically analyze the selfish behaviors of agents in an interactive system. We will apply game theory to provide a solid foundation for the proposed solution. Specifically, a strategy-proof solution [?], which guarantees truthful reporting, will be applied to prevent untruthful reports from users.

The transmission quality in D2D communications can be significantly improved when a proper resource exchange is executed. Let us consider an OFDMA-based cellular system with four D2D pairs using licensed OFDMA resource blocks. The system allocated resource blocks in units of resource block groups (RBGs). The example is illustrated in Fig. 1. At upper subfigure, the two D2D pairs in the middle are using RBG 1 and 2, respectively. The main interference sources of these two pairs are other two boundary D2D pairs using the same RBGs as them. These two boundary pairs cause significant interference to the middle D2D pairs due to proximity, and vice versa. Nevertheless, the interference can be significantly reduced if those two pairs in the middle exchange the resource blocks they have with each other, as illustrated in the lower subfigure of Fig. 1. With this new allocation, all pairs experience improved transmission quality, since the interference is alleviated by the higher propagation loss from longer distances. This potentially beneficial exchange can be identified by the eNodeB or D2D pairs themselves. In addition to its simplicity, the resource exchange approach provides other benefits to D2D resource allocation: 1) the resource exchange process can be locally implemented by a simple three-way handshake signaling flow, and 2) it can be launched locally for timely response to rapid environmental changes, or globally triggered by cellular BSs for system-wide optimization. Based on these observations, we apply the resource exchange approach in our proposed D2D resource allocation framework.

In this paper, we aim to provide a comprehensive D2D resource allocation framework for an LTE-Advanced system. The framework is based on the resource exchange approach, in which a series of dedicated RBGs are predefined and reserved for D2D communications. Each D2D pair possesses an RBG in a frame after a resource request is accepted by the Evolved Node B (eNodeB). 1 The eNodeB or D2D pairs may trigger a resource exchange among D2D pairs or between the eNodeB and a D2D pair if proper exchange pairs are identified. This framework matches Mode 1 of LTE D2D resource allocation schemes, where D2D transmissions are within the coverage of eNodeB and schedule-based. Additionally, we prove that every resource exchange reduces the total system interference when it is beneficial. This provides a sufficient condition to guarantee the convergence of any arbitrary algorithm in our framework.

To improve the efficiency of resource utilization, the system-wide optimization can be performed by the eNodeB, in which the truth-telling issue may occur as we mentioned previously. In such a case, we provide a game-theoretic analysis for investigating the truth-telling issue in the proposed framework. We propose using the Trader-assisted Resource EXchange (T-REX) mechanism to handle the resource exchange operations. The eNodeB participates in the operations through identifying optimal exchange sequences and applying trader preference functions. We prove that the truth-telling issue can be resolved through the proposed mechanism when a proper trader preference function is chosen. Finally, we evaluate the performance of the proposed solutions through simulations using the models and parameters suggested in the latest 3GPP technical contribution [?]. In summary, we make the following contributions:

1) We propose a novel LTE-Advanced D2D resource allocation framework based on the resource exchange approach. We reuse most existing LTE-Advanced components and followed the same signaling flow logic in order to minimize the protocol impacts.
2) We theoretically prove that the resource exchange approach is equivalent to the traditional resource alloca-

\[1^\text{eNodeB and BS are interchangeable in this paper.}\]
tion approach in the solution feasibility. Additionally, we prove that any arbitrary algorithm, either distributed or centralized, will converge in the proposed framework whenever all exchanges are beneficial.

3) Based on the idea of beneficial exchange, we propose the Trader-assisted Resource Exchange (T-REX) mechanism as an efficient and flexible solution to the D2D resource allocation problem in the proposed framework. The T-REX mechanism is a centralized algorithm operating in the eNodeB. It identifies the beneficial exchanges through analyzing the corresponding exchange graph. The algorithm’s complexity is polynomial, which makes it a practical solution to large-scale D2D networks. In addition, the derived allocation is Pareto optimal; therefore, the efficiency is guaranteed. In addition, we prove that the T-REX mechanism is strategy-proof when the trader preference functions are properly designed; that is, all D2D pairs truthfully report their information even if they are rational and selfish. We are one of the first groups to apply game-theoretic analysis to the D2D resource allocation problem.

II. RELATED WORK

Regarding resource allocation in D2D communications within a cellular system, Yu [?] proposed resource sharing modes and the corresponding closed form solutions to determine the optimized resource allocation for D2D communication underlying cellular networks. Fodor [?] demonstrated the major difficulties in D2D transmission design, in view of peer discovery and resource allocation. When D2D devices co-exist with traditional cellular ones, the resources for D2D devices should be carefully allocated to minimize interference. In such an approach, Wang [?] presented a resource sharing scheme allowing D2D UEs to reuse resources from multiple cellular users. Zulhasnine [?] proposed an algorithm to assign D2D devices to shared resource blocks with acceptable interference. Zhu [?] presented an algorithm to maintain tolerable interference among D2D UEs sharing different RBGs. Chen [?] investigated the coexistence of D2D and cellular users given partial frequency reuse. The interference limited area is proposed to limit mutual interference. Le [?] proposed to formulate the resource allocation as a two-phase integer programming problem to determine the spectrum allocation of UEs first and allocation of D2D users later. Wang [?] proposed to separate the spectrum into dedicated area and contention area to reduce the interference and achieve proportional fairness criteria. Lee [?] proposed a two-stage formulation on the resource block allocation and scheduling on conventional UEs and D2D pairs. Both conservative and aggressive allocation policies are considered and simulated. They concluded that D2D pairs will have higher data rates when the resource allocation is conservative, that is, resources are allowed to be reused among D2D links only.

In addition, the D2D transmission may be virtual, relayed by the eNodeB, or direct. The mode selection further complicates the problem. Janis [?] proposed a method to allocate resources and assign transmission modes to D2D devices with limited interference to cellular ones. Belleschi [?] proposed a single-cell formulation for D2D communication, in which a D2D device may adopt the D2D or cellular modes to minimize the overall power. A load-control algorithm was introduced to approximate the optimal solution for the NP-hard formulation. Nevertheless, most of the existing literature does not address the issues caused by the rationality of D2D devices and users, such as truth-telling. As we have illustrated in Section I, rational D2D devices and users may untruthfully report their information and behave maliciously in order to achieve better performance for themselves. When rationality is a concern, the mechanisms proposed above may receive forged information from the D2D devices and therefore be unable to make correct decisions.

There exist several works on addressing the selfish behaviors of UEs and D2D pairs using game theory. Wang [?] formulated the UE-D2D resource allocation problem as a Stackelberg game. In their design, the UE is the leader who determines the price of the interference, where D2D pairs are the followers to determine the transmission power accordingly. The set of D2D pairs who can join the game is determined according to their priority. The fairness among D2D pairs is achieved through adjusting the priority of D2D pairs according to their long-term satisfactions. A similar design can be found in [?], were a differentiated price scheme is proposed to further increase the revenue of the BS. Wen [?] formulated the power control on D2D communication as a potential game, where an interference price is imposed to guarantee the convergence of best-response dynamic algorithm. Uykan [?] also proposed a potential game approach to the channel allocation problem in D2D communications. In their formulation, the utility of a D2D pair includes the interference it caused to other transmissions, which can be considered as a cost or payment it requires to pay for the interference. Li [?] proposed a coalition game formulation to regulate the resource sharing between multiple D2D pairs. A set of D2D pairs will form a coalition when they choose the same spectrum. They proposed a coalition formulation algorithm to find the optimal coalition combination. Their design relies on an assumption that the individual profits from the coalition are transferable. There exists other works tackling the truth-telling problem in D2D communications. Xu [?] formulated a sequential second-price auction for the D2D resource allocation. Users’ payoff is maximized and the system sum rate is improved using the proposed resource allocation algorithm. Additionally, Xu [?] proposed a reverse iterative combinatorial auction design to treat multiple D2D pairs as packages. This design allows multiple D2D pairs coexist in the same spectrum in order to further enhance the performance. Nevertheless, most existing game-theoretic works relies on pricing, external cost, or transferable utilities. These designs require monetary transfer processes, which significantly increases the complexity of implementation in the cellular network. It may be preferable to have a direct mechanism involving no payment process.

The concept of resource exchange is proposed by Chen[?] for the channel allocation problem in macrocell-femtocell overlay system. It can be considered as a variety of the house allocation problem [?]. In this game, each player owns a single
house and has his unique preference on every other player's house. The house allocation problem can be solved by a strategy-proof mechanism called Top Trading Cycle Algorithm (TCCA) [2]. Nevertheless, their approach is limited to one cell only. They did not address the convergences in multi-cell system.

III. D2D RESOURCE ALLOCATION FRAMEWORK

We design our D2D resource allocation framework according to the following principles: 1) Reuse the existing components of the LTE-Advanced standard as much as possible in order to minimize the protocol impact, and 2) maintain high flexibility in configuration and deployment for different service requirements.

In our framework, we define a set of RBGs dedicated for D2D communication only. Each RBG contains a fixed number of resource blocks, as illustrated in Fig. 2(a). The dedicated resource design has been proposed in several widely known standards, such as Terrestrial Trunked Radio (TETRA) [7], a European Telecommunications Standards Institute (ETSI) standard for public safety networks used by government agencies or emergency services. This design is especially useful for public safety service using a dedicated public safety spectrum for proximity services [2] or commercial service providers holding multiple contiguous or non-contiguous narrowband spectrum licenses.

An eNodeB governs a cell, which consists of several service areas [2]. All RBGs are reused in every service area. D2D pairs in the same service area are allocated with different RBGs, so D2D devices suffer only inter-service area interference [3]. This inter-area interference, which is the main interference to D2D pairs in the system, will be spatially diverse and changing due to device mobility or resource re-allocation. The proposed resource allocation framework should properly address the diverse interference experienced by each D2D pair in different RBGs in a timely manner.

A. Resource Granting

The requesting and granting of D2D resources are realized through the following signaling flow (Fig. 2(b)), which is similar to the uplink resource granting signaling in LTE-Advanced system. When a potential D2D pair is identified and notified through peer discovery, one of the D2D devices triggers the resource granting procedure by sending a D2D scheduling request (D2D SR) on her dedicated SR resource in the physical uplink control channel (PUCCH) to the serving eNodeB. This device is also considered as the D2D pair head of this pair. Next, the eNodeB will send a resource grant for channel quality indicator (CQI) and buffer status report (BSR) transmission to both D2D devices if she accepts the request. The grant also indicates the corresponding resource in the physical uplink shared channel (PUSCH) for the D2D device to upload the information. Here we reuse the same CQI and BSR format in the LTE-Advanced standard. Then, the D2D pair head will report the CQI and BSR to the eNodeB using the granted PUSCH resource. Finally, the eNodeB will grant RBG to the D2D pair for them to perform D2D communication. The granted RBG depends on the CQI and BSR reported by the D2D devices and the availability of the RBGs in the service area.

The CQI should contain the channel measurement on all the subcarriers related to the dedicated RBGs. Therefore, the CQI reporting type should be an eNodeB-configured sub-band feedback on all the subcarriers dedicated for D2D RBGs. The CQI can be derived through the traditional measurement method [?] or establishing new function blocks for this purpose [?]. A possible implementation will be triggering one or some of the D2D pair in the service area to transmit reference signals in a predefined period with all D2D communications halted, so it can measure the quality in different RBGs accurately [?]. Nevertheless, it may introduce too much overhead to the system [?]. Another possible implementation is by defining a silent period so all D2D pairs may measure the background interference from other service areas at the same time. The interval of silent period may follow the CQI updating period, which is determined by the eNodeB in advance. This is similar to the downlink CQI measurement where the eNodeB may periodically send a reference signal for UEs to measure the quality, except that here we do not need any reference signal. An energy level detection process for interference measurement is sufficient.

The channel quality availability we assumed in the proposed framework is also supported by the latest advances in 3GPP LTE-Advances standardization. Currently, 3GPP working group is in the progress of standardizing the new reference signal between D2D devices (e.g. D2DSS). With the reference signals between D2D pairs, channel measurement could be conducted. The channel measurement on PC5 link or sidelink is also in the standardization process. Specifically, RAN1 has granted the request from RAN2 to support RSRP measurement on PC5 link in release 13 [?]. Other measurements, such as RSRQ, are also not precluded in future releases [?]. The channel status information could be reported through the D2D links or to the coordinating base station [?]. This part is motivated by utilizing ProSe service for UE-to-Network Relay so UE or eNodeB can decide whether the PC5 link is suitable for relay before the actual transmission. The design surely can be extended to the unicast D2D or UE-to-UE relay scenarios. There is also an agreement that a specific sidelink discovery gap can be requested by UEs and granted by eNodeB in a pattern. It is also suggested that UE should utilize the granted gaps to perform channel measurements [?].

The BSR contains the QoS requirement of the D2D pair, which helps the eNodeB to determine the amount of RBGs reserved for this D2D pair. For instance, the eNodeB may
reserve one specific RBG in several subsequent frames for the D2D pair. Finally, the resource grant for RBG is sent to both D2D devices, which indicates the RBG that this pair is granted and the corresponding leasing time. The resource granting procedure is terminated here. Notice that similar to standard LTE signaling design for carrier quality measurements, the eNodeB prefers to maintain up-to-date information on each D2D pair’s transmission quality, which is indicated by CQI. We may follow the standard LTE signaling protocol, where CQI updates can be actively requested by the eNodeB in a predefined while adjustable period or passively triggered by some D2D pairs when necessary using the same flow except the resource granting part. The reporting period can be dynamically adjusted according to the current loading and QoS requirements to avoid unnecessary overhead. In current LTE standard, the period can be adjusted from 2ms to 160ms.

### B. Resource Exchange

A resource exchange can be triggered by the eNodeB when 1) a new D2D pair joins and requests an RBG, 2) a D2D pair’s RBG grant is terminated, and 3) one or more D2D pairs update their CQIs. Whenever the above situations occur, the eNodeB may identify the beneficial exchange sequence in the updated D2D pair set or CQIs. If an exchange sequence is found, the eNodeB may trigger the resource exchange among all pairs in the sequence by sending new RBG grant to the pair heads. The notified D2D pairs will acknowledge and then use the newly granted RBG in the subsequent transmission. The exchange process is terminated here. The signaling flow of UE-triggered resource exchange mode is illustrated in the left subfigure of Fig. 2(c). Note that when the exchange process is terminated, both D2D pairs will use newly exchanged RBGs for their own D2D transmission.

An exchange may also occur between a D2D pair and the eNodeB. The eNodeB may allocate an unallocated RBG to a D2D pair in exchange for the RBG this D2D pair owns. In such a case, only one D2D pair is notified using the resource granting signaling.

When eNodeB is not available or the traffic are delay-sensitive, a resource exchange can also be distributively triggered by the D2D pair in delay-sensitive applications. This optionally deployed D2D-triggered mode requires a shared RBG containing at least three subframes as a communication channel between D2D pairs. This shared RBG is preserved for all D2D pairs to communicate with each other. D2D pairs that wish to communicate with others should listen to the shared RBG to receive the requests. All D2D pairs may access the shared RBG using a slotted-ALOHA mechanism in every $3n+1$ subframe. The signaling flow of D2D-triggered resource exchange mode is illustrated in the right subfigure of Fig. 2(c). A D2D pair head may broadcast its possessed and desired RBGs to other nearby D2D pairs in the same service area through the shared RBG. If the other D2D pair head that holds the requested RBG also favors the exchange, she may respond to the request in the following subframe of the shared RBG. Finally, the original D2D pair head sends an acknowledgement in the third subframe, and both pairs switch to the exchanged RBGs immediately and may utilize the newly exchanged RBGs for D2D transmissions. After the exchange, both pairs should notify the eNodeB about the exchange so that the eNodeB can maintain an up-to-date RBG allocation status.

The above mode reduces the eNodeB’s loading by offloading some responsibilities of the eNodeB to the D2D pairs themselves. It also reduces the CQI reporting signaling and eNodeB-triggered delay to perform exchanges through the eNodeB. Nevertheless, the exchange requests in the first step may be lost when multiple D2D pairs broadcast their requests simultaneously. It is also desirable when the channel/environment is relatively stable. In the scenario where channels are relatively stable, devices in low mobility, or network in heavy loading, the eNodeB can even further reduce the overhead by forcing all D2D resource exchange to operate in D2D-triggered mode.

### C. Compatibility

Given that the D2D communication standard in LTE-Advanced is not finalized yet, we consider the proposed framework as a candidate for the future LTE D2D communication design. The compatibility issues should have been minimized since we reuse most standard function blocks in current LTE-Advanced standard such as CQI reporting and resource grant process. We believe that other incompatibilities, if exist, would be minor and can be fixed soon when the LTE D2D standard is finalized. Additionally, the proposed framework does not necessarily restricted to LTE but can be applied to other scheduling-based resource allocation/grant problems such as channel allocation in multi-channel Wi-Fi networks, spectrum allocation in cognitive radio networks, and resource allocation in heterogeneous networks. The framework is especially useful for the system that requires resources to be granted explicitly and seldom reused by other nearby entities.

### IV. System Model

The proposed framework provides necessary functions for an LTE-Advanced system to support resource allocation for D2D communications. Nevertheless, further study is required
on how the service provider configures and regulates the D2D communications by the support of these functions.

Let us consider a cellular system with one BS $s$ and a set of $N$ D2D pairs. These D2D pairs are within the BS's service coverage. The coverage is divided into $M$ D2D service area, while the set of D2D pairs within service area $m$ is $D_m = \{d_{m1}^m, d_{m2}^m, \ldots \}$. There is a set of RBGs $B = \{1, 2, \ldots, L\}$ preconfigured in the system. These RBGs are reused in every service area. Each D2D pair requires an RBG to perform D2D transmissions, and all D2D pairs in the same service area use different RBGs. Let $b_{m}^{d_{i}^{m}} \in B$ be the RBG allocated to D2D pair $d_{i}^{m}$ in service area $m$. Then the RBG allocation in service area $m$ is $b_m = (b_{m}^{d_{1}^{m}}, b_{m}^{d_{2}^{m}}, \ldots, b_{m}^{d_{|D_m|}^{m}})$. Accordingly, a portion of RBGs $B_{m}(b_m) = \{j|j \in b_m\} \in B$ is allocated to the D2D pairs in service area $m$, and other RBGs $B_{m}^{-1}(b_m) = B \setminus B_{m}$ are held by the BS in this area. Finally, the overall RBG allocation in all service areas is denoted by $b = (b_m)$.

The interference experienced by a D2D pair in our framework comes from other D2D pairs using the same RBG in other service areas. Specifically, let the interference experienced by D2D pair $d_{i}^{m}$ be $I_{i}^m(b_m, b_{-m})$, which is

$$I_{i}^m(b_m, b_{-m}) = \sum_{i' \in D_m, m' \neq m} 1(b_{i'}^{m'} = b_{i}^{m}) P g_{i',i}^{m',m}$$

where $b_{-m}$ is the RBG allocation in all service areas except area $m$, $P$ is the transmission power of D2D devices, and $g_{i',i}^{m',m}$ is the channel gain from D2D pair $j$ in service area $m'$ to pair $i$ in service area $m$. Since D2D pairs in the same area use different RBGs, there is no intra-area interference, and we have $g_{i',i}^{m,m} = 0$, $\forall i, i' \in D_m$.

A. Resource Exchange Problem

Given an initial RBG allocation $b^0$, our goal is to reach the optimal RBG allocation $b^*$ with the lowest overall system interference through exchange operations. The objective function can be denoted as

$$\min_{m,i \in D_m} I_{i}^m(b)$$

We would like to mention that the objective can be expanded to other performance metrics such as throughput or latency. We choose to use the interference as the objective in this work as it is more fundamental and can be directly linked to CQI information defined in LTE, while other metrics may involve the traffic patterns and significantly increase the complexity of the model. In most cases, lower interference leads to higher throughput and lower latency when other traffic pattern remains. Given that interference is such a representative metric, we choose to use this as the main objective of the mechanism.

In our framework, two D2D pairs may apply an exchange operation by switching their possessed RBGs. Additionally, a D2D pair may also exchange her RBG with the BS for an RBG still unallocated to other D2D pairs. After an exchange operation is executed, a new allocation $b^*$ is derived.

An exchange sequence defines a series of exchanges in a service area from an initial allocation $b_m^0$. For a newly arrived D2D pair, she may virtually receive a randomly-assigned RBG in the initial allocation. Notice that all exchanges are limited to devices in the same service area. For convenience, we denote $s_m^j$ as the "holder" of RBG $j \in B_{m}^{-1}(b_m^0)$ in the BS. In addition, an exchange pair $(x, y)$, where $x, y \in D_m \cup \{s_m^j|j \in B_{m}^{-1}(b_m^0)\}$, denotes an exchange between $x$ and $y$. Then, we define an exchange sequence $S_m$ for service area $m$ as

$$S_m = [(x_1, y_1), (x_2, y_2), \ldots]$$

The new RBG allocation $b_m$ is completely determined by the initial allocation $b_m^0$ and the exchange sequence $S_m$. We denote this process as $EX(b_m^0, S_m) = b_m$. Thus, our objective is to find the exchange sequence $S$ that minimizes the total interference in the resource exchange problem. We first show the feasibility of arbitrary RBG allocation in the resource exchange problem.

Theorem 1. [Feasibility of Exchange Approach] Given arbitrary $b_m^0$ and $b_m$, there exists an exchange sequence $S_m$ that $EX(b_m^0, S_m) = b_m$. In addition, the $S_m$ can be found in linear time.

Proof: We prove this by constructing an exchange sequence that achieve $b_m$. We first expand the RBG allocation vector $b_m^0$ and $b_m$ to $v_m^0$ and $v_m$ by including the holders $\{s_j^{(m)}\}$ and $\{s_j^{(m)}\}$ into the allocation. Then, we construct a resource exchange graph using all D2D pairs and holders in the BS as vertices. Then, each vertex $x$ constructs a directed edge from herself to the vertex $y$ with $v_x^{0,m} = v_y^{m}$.

Since both $v_m^0$ and $v_m$ are one-to-one mapping from $B$ to $D_m \cup \{s_j^{(m)}|j \in B_{m}^{-1}(b_m^0)\}$, each vertex in the graph has exactly one directed edge to and from another vertex. In other words, any vertex belongs to a cycle or has one directed edge pointing to herself. For the latter case, the vertex is removed from the graph. For the rest of the vertices, let $C = \{v_1, v_2, \ldots, v_k\}$ be a series of vertices belonging to a cycle in the graph. Then, we construct a sequence $S_C = \{(v_1, v_2), (v_2, v_3), \ldots, (v_{k-1}, v_k)\}$. Finally, an exchange sequence $S_m = [S_C]$ is built by merging all constructed sequences together.

It can be verified that for every exchange $(x, y)$ indicated in the $S_m$, the vertex $x$ possesses the desired RBG indicated in $b_m$. For any vertex $x$ that does not involve in $S_m$, she has a directed edge to herself, which means $v_x^{0,m} = v_x^{m}$; so no exchange is required. In sum, the new allocation $b_m$ is achieved through the exchange sequences $S_m$ from the initial allocation $b_m^0$.

Theorem 1 indicates that the resource exchange approach does not put any additional constraints on the feasible allocation. Any RBG allocation can be achieved through the exchange operations from any initial RBG allocation. The proposed resource exchange approach therefore can be applied to any resource allocation problem regardless of the corresponding objective. Nevertheless, this also suggests that the proposed approach may have the same hardness as the original resource allocation problem. For instance, the allocation problem with the objective function in (2) is NP-hard [2]. Therefore, an
optimal solution may be unachievable when a short response time is a concern. An efficient approximate method is required.

B. Beneficial Exchange

A beneficial exchange is an exchange sequence wherein all D2D pairs in the service area experience equal or less interference after the exchanges. It can be a good starting point for the approximate algorithm. We first state its formal definition:

Definition 1. [Beneficial Exchange] A beneficial exchange is an exchange sequence \( S_m \) for an initial RBG allocation \( b^0_m \) where

\[
I^m_i(b^0_m, b^0_{-m}) \leq I^m_i(EX(b^0_m, S_m), b^0_{-m}), \forall i \in D_m
\]  

(4)

A beneficial exchange can be considered as a local greedy solution to the interference minimization problem. Nevertheless, we prove that when the above conditions are met, the interference after the exchanges. It can be a good starting point for the approximate algorithm. We first state its formal definition:

\[
\sum_{m} \sum_{i \in D_m} I^m_i(b^*_m, b^-_{-m}) = \sum_{m} \sum_{i \in D_m} I^m_i(b^0_m, b^-_{-m}) = \Delta I^m
\]

(7)

Therefore, the total system interference is reduced when a beneficial exchange occurs.

Theorem 2 is important, as it guarantees the convergences of any algorithm using beneficial exchanges in the proposed D2D resource allocation framework. Note that the convergence also holds for distributed algorithms whenever every exchange between two D2D pairs is a beneficial exchange. In conclusion, any arbitrary beneficial-exchange-based greedy algorithm, either centralized or distributed, converges under either the eNodeB-assisted mode or D2D-triggered mode in the proposed framework.

V. ENodeB-ASSISTED D2D RESOURCE ALLOCATION

A D2D-triggered resource allocation approach is suitable for small networks with few D2D pairs. In contrast, it is more desirable to have an eNodeB-assisted resource allocation approach when the D2D pairs are numerous or resource utilization efficiency is a serious concern. In this approach, the CQIs from the D2D pairs become necessary information for the eNodeB to determine the efficient allocation. Nevertheless, as we have illustrated in Section I, rational D2D pairs have the incentive to report CQIs untruthfully if the allocation mechanism is not properly designed. These forgery CQI reports not only give unfair advantages to these D2D pairs but also reduce the resource utilization efficiency since the eNodeB does not receive correct information. Therefore, it is necessary to address the truth-telling issue in an eNodeB-assisted resource allocation approach.

A. Game Model Formulation

We construct a Nash game model for the proposed framework in order to analyse the truth-telling issue. In a Nash game, there are three components: players, actions, and utility functions. We define all D2D pairs as the players. The action of a D2D pair \( d^m \) is the CQI \( \psi^m_i \) she reports to the BS. Her utility is defined as the experienced Carrier to Interference Ratio (CIR), which is given as follows

\[
u^m_i(b_m, b_{-m}) = \frac{P^m_{g^m_i}}{N_0 + I^m_i(b_m, b_{-m})},
\]

(8)

where \( g^m_i \) is the channel gain between the two devices in D2D pair \( d^m \), and \( N_0 \) is the Gaussian white background noise. A D2D pair’s utility is higher when she possesses an RBG with lower interference \( I^m_i(b_m, b_{-m}) \).

The RBG a D2D pair \( d^m \) possesses is determined by an exchange-based mechanism, which is affected by not only her reported CQI \( \psi^m_i \) but also other D2D pairs’ reported CQIs, which are denoted by \( \psi^m_{j,i} \). Given the CQIs \( \psi^m_{j,i} \) reported
by other D2D pairs, a rational D2D pair will choose the CQI that maximizes her utility. Specifically, let the RBG allocation mechanism be $M(\psi^m_i, \psi^m_{-i}, b^0_m)$, which outputs a new allocation $b_m$, the D2D pair $d^m_i$’s best response is

$$BE^m_i(\psi^m_{-i}, b^0_m) = \max_{\psi} u_i (M(\psi, \psi^m_{-i}, b^m_0), b^0_m).$$  

(9)

Note here that the utility function is not limited to CIR but can be other performance metrics such as throughput or latency. The choice of utility function depends on the objective define in the system model. Regardless of the exact form of the function, the best response of the D2D pair is to maximize her utility function.

B. Nash Equilibrium

The Nash equilibrium (NE) is a solution concept for predicting the outcome of a game with rational players. Nash equilibrium is an action profile wherein each player is assigned an action, which is her best response to the other players’ actions in the profile. Therefore, if all players follow this action profile, no player has incentive to deviate from the action described in the profile. A formal definition of the Nash Equilibrium in the resource exchange game is as follows:

**Definition 2** (Nash Equilibrium). In the resource exchange game in service area $m$, with a mechanism $M(\psi^m_i, \psi^m_{-i}, b^0_m)$, an action profile $\Psi^m_m = \{\psi^m_1, \psi^m_2, ..., \}$ is a Nash Equilibrium if and only if $\forall \psi^m_i \in D_m$,

$$BE^m_i(\psi^m_{-i}, b^0_m) = \psi^m_i.$$  

(10)

Note that the corresponding equilibrium action $\psi^m_i$ of a D2D pair $d^m_i$ is not necessarily equal to its true experienced CQI $\psi^m_i$, i.e., it is possible that a mechanism eventually has an equilibrium where some D2D pairs choose to report their CQIs untruthfully. In such a case, since the mechanism receives forged reports, it cannot provide efficient allocation.

To prevent the undesirable untruthful reporting behaviours, the proposed mechanism should be **strategy-proof** [2]. A strategy-proof mechanism promises that the truthful action profile, i.e., that all players report their private information truthfully, is a Nash equilibrium. The formal definition of a strategy-proof mechanism in the proposed game is as follows:

**Definition 3** (Strategy-proof Mechanism). A mechanism $M$ with an allocation function $m(\Psi^m_m, b^0_m)$ is strategy-proof if and only if the action profile $\{\psi^m_i\}$ is a Nash equilibrium for all $b^0_m$.

If the mechanism is strategy-proof, there exists Nash equilibrium where all players truthfully report their private information, that is, the experienced CQI in the proposed game. Therefore, the correctness of information collected by the mechanism is guaranteed, and the truth-telling issue is resolved.

VI. T-REX: A TRADING-BASED RESOURCE EXCHANGE MECHANISM

We propose the **Trading-based Resource Exchange (T-REX)** mechanism for resolving the resource exchange problem in the proposed D2D resource allocation framework. T-REX is a centralized resource exchange mechanism operating on the eNodeB. It determines the resource exchange sequences of all D2D pairs in the D2D service area according to the collected CQIs. Firstly, the T-REX mechanism collects the CQIs from all D2D pairs in a service area. The **preference** of each D2D pair on RBGs is then constructed according to the reported CQIs. Then the T-REX mechanism constructs an exchange graph according to the preferences of D2D pairs. The mechanism in turn identifies the exchange sequence by searching for cycles in the exchange graph. After the exchange sequence is derived, all involved D2D pairs and traders are then requested to perform resource exchanges accordingly.

A. Preference on RBG

We define the preference of a D2D pair on the RBGs based on her expected utility in (8). A D2D pair experiences different level of interference in different RBGs. The less interference an RBG has, the higher utility the D2D pair has if she possesses the RBG, and thus the more preferred she is. The preference of D2D pair $d^m_i$ can be represented as a relation $\succ^m_i$. We define $\succ^m_i j \sim I^m_i(b_m|b^m_{-i}=j, b_{-m}) < I^m_i(b_m|b^m_{-i}=k, b_{-m})$.

Finally, we denote the preference profile of all D2D pairs in $D^m$ as $\succ^m = (\succ^m_1, \succ^m_2, ..., \succ^m_{|D^m|})$. Notice that the preference of a D2D pair does not affected by the preferences of other pairs in the same service area since there is no intra-area interference in the proposed framework.

The preference of the eNodeB on the RBGs, on the other hand, cannot be constructed in the same way since these RBGs are specifically for D2D communications only. Thus, it is pointless to define the eNodeB’s preference according to her experienced interference in these RBGs. Instead, we propose the trader approach here. For each service area $m$, there is a set of (virtual) traders $T^m_i \in T^m, i = 1 \sim |B^m_{-i}|(b_m)$. The eNodeB internally assigns each unallocated RBG $j \in [B^m_{-i}(b_m)]$ to a trader. A trader’s preference $\succ^t_i m$ for the RBGs is given by a trader preference function $I^t_i m (\cdot)$. It should be noted that these traders are not the actual players in the resource exchange game since their preferences are directly controlled by the eNodeB. The traders are tools offered by the T-REX mechanism for the eNodeB to regulate the resource exchange game.

Notice that the resource exchange game with only D2D pairs is not considered a variant of the house allocation problem [2], in which a strategy-proof solution called the Top-Trading Cycle Algorithm (TTCA) is illustrated. Nevertheless, when there are unallocated RBGs, TTCA only provides a locally optimal performance, as we will illustrate in Section VII.

B. Mechanism Design

The T-REX mechanism works as follows: a resource exchange graph is initialized with all D2D pairs and traders
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in a service area as vertices. For each vertex, the preference is determined by either the corresponding reported CQI $\psi_i^m$ (D2D pair) or the trader preference function $F_i^m(\cdot)$ (trader). In addition, each vertex is also marked with an RBG according to the initial allocation $b_i^0$. After the initial graph is defined, each vertex constructs a directed edge to the vertex owning her most preferred RBG in the current graph.

The T-REX mechanism then searches cycles in the graph, which always exists because each vertex has exactly one directed edge. When a cycle is found, the vertices in the cycle exchange their RBGs with each other according to their edges, and we eliminate them from the graph. It should be noted that it is possible for a vertex to have a directed edge pointing to itself, which means that the owner already possesses the most preferred RBG. In such a case, the vertex is simply removed from the graph. Then, the remaining edges in the graph are reconstructed according to the preference of each vertex on the RBGs held by remaining vertices, and the T-REX mechanism again identifies cycles. The exchange procedure is executed repeatedly until all vertices are removed from the graph. The pseudo-code of the T-REX mechanism is shown in Algorithm 1, while the flow chart is illustrated in Fig. 4.

We illustrate an example of the T-REX mechanism. We consider a D2D service area with 3 D2D pairs and 5 RBGs. The preferences of D2D pairs and traders are listed in Fig. 3. The T-REX mechanism constructs the resource exchange graph as shown in Fig. 3. We can see that a cycle is formulated among D2D pairs 1, 2, and 3, and Trader 1. An exchange sequence $\{(s_1, s_2), (s_2, d_1)\}$ is then identified. Then, D2D pairs 1, 2, and Trader 1 are removed from the graph, and the edges are reconstructed. In the reconstructed graph, D2D pair 3's directed edge points to itself since her most preferred RBG in the current graph is RBG 3. Since she already possessed the desired RBG, she is directly removed from the graph. The T-REX mechanism ends at the third round since all D2D pairs are removed from the graph.

The T-REX mechanism operates in one service area. When multiple service areas exist, the T-REX mechanism can function independently in these areas. Although it is possible that the resulting RBG allocation in one area affects the preferences of D2D pairs in other service areas, the overall RBG allocation $b$ will converge to a stable one when the T-REX mechanism is applied sequentially in all areas in arbitrary orders.

**Theorem 3.** The T-REX mechanism converges in a D2D system with multiple service areas.

**Proof:** We prove the convergence of the T-REX mechanism by showing that all exchange sequences are beneficial exchanges. Let $b_i^0$ be the initial RBG allocation. Then, let $C$ be a cycle found in the resource exchange graph and $S_c$ be the corresponding exchange sequence. The resulting RBG allocation is $b_m = EX(b_i^0, S_c)$.

Case 1: $d_i^m \not\in C$. In this case, the RBG allocated to D2D pair $d_i^m$ is unaffected by the exchanges. Therefore, her experienced interference remains unchanged.

Case 2: $d_i^m \in C$. In this case, the RBG allocated to D2D pair $d_i^m$ is changed. Let $k$ and $j$ be the RBG allocated to D2D pair $d_i^m$ before and after the exchanges. Since $d_i^m \in C$, we have $j \succ_i^m k$, which means $I_i^m(b_k|b_j = k, b_{-m}) < I_i^m(b_k|b_j = k, b_{-m})$. Therefore, the interference experienced by D2D pair $d_i^m$ is lower under the new allocation $b_m$.

Concluding from the above two cases, all D2D pairs experience equal or higher interference after any exchange identified by the T-REX mechanism. Therefore, all exchanges in the T-REX mechanism are beneficial exchanges according to Definition 1, and the convergence of the T-REX mechanism in multiple service areas is guaranteed by Theorem 2.

![Fig. 3. An example of the T-REX mechanism](image-url)

![Fig. 4. Flow Chart of T-REX mechanism](image-url)

<table>
<thead>
<tr>
<th>Preference</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) D2D 1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>D2D 2</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>D2D 3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Trader 1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Trader 2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

![Algorithm 1 T-REX Mechanism](algorithm-url)

The complexity of the T-REX mechanism with a given $F_i^m(\cdot)$ is $O(|B|^2)$, and the complexity of the T-REX mechanism is $O(|B|F_i^m(\cdot))$. This comes from the fact that at least one vertex is removed from the graph at each iteration (Line 7 to 21), and it takes at most $|G| \leq |B|$ steps to update the edges and $O(F_i^m(\cdot))$ to update the preferences of traders in each iteration. Therefore, when $O(F_i^m(\cdot))$ is polynomial, the complexity of the T-REX mechanism is...
The primary operation of the CYC preference is to ensure that when an incomplete cycle $\omega$ with trader $t_1^{m_1}$ as the tail vertex exists, the trader $t_1^{m_1}$ always chooses the RBG possessed by the head D2D pair of the incomplete cycle $\omega$ as her most preferred RBG in that round. A new directed edge is connected from the trader $t_1^{m_1}$ to the head D2D pair, and the incomplete cycle $\omega$ is now complete. With the CYC addition, all D2D pairs in the incomplete cycle will derive their most preferred RBGs. In cases where there is no incomplete cycle with tail vertex as $t_1^{m_1}$, the trader $t_1^{m_1}$ just randomly chooses a RBG $j \in B_{m_1}$ as her preferred RBG.

When multiple incomplete cycles end at the same trader, a reasonable choice for the CYC preference is to choose the largest incomplete cycle. With this choice, we greedily maximize the number of D2D pairs receiving their preferred RBGs. We define the set of incomplete cycles with tail vertex $t_1^{m_1}$ in round $l$ as $\Omega_{m_1,l}$, and the set of incomplete cycles with $n$ vertices as $\Omega_{m_1,l}^n \subset \Omega_{m_1,l}$. The trader preference function $F_{i,CYC}$ is given by (12), where the head vertex of $\omega$ is $\text{head}(\omega)$.

Unfortunately, a T-REX mechanism with CYC preference is not strategy-proof. An example of cheating is shown in Fig. 5. In this D2D service area, D2D pair 2 prefers RBG 4 most, which is held by Trader 1. Her second preferred RBG is RBG 1, which is held by D2D pair 1. However, the largest incomplete cycle ending at Trader 1 is $\{d_1, d_3, t_1\}$. According to the CYC preference, Trader 1 will choose RBG 1 as her most preferred RBG. D2D pair 2 does not have the chance to exchange with either Trader 1 or D2D pair 1. Nevertheless, it can be seen that if D2D pair 2 sends a forged CQI report to choose RBG 2 as her most preferred RBG, a new incomplete cycle $\omega'$ = $\{d_2, d_1, d_3, t_1\}$ is formed. In the manipulated resource exchange graph, Trader 1 will choose RBG 2 as her most preferred RBG, and D2D pair 2 can exchange with D2D pair 1 to get her second preferred RBG, which is better than the results in the original resource exchange graph. Therefore, D2D pair 2 has the incentive to cheat when CYC preference is applied. In conclusion, the T-REX mechanism with CYC preference is not strategy-proof.

D. Sufficient Conditions of Strategy-proofness

We now discuss the sufficient conditions of the trader preference function to make the T-REX mechanism strategy-proof. As observed in the previous section, the primary problem with the CYC preference is that the preferences of traders are related to the preferences of D2D pairs. This results in the possibility for that D2D pairs could cheat in the game by influencing the preferences of traders. Based on this observation, we now propose the sufficient conditions for a strategy-proof T-REX mechanism.

Theorem 4. When the preferences of traders are unrelated to the preferences of D2D pairs, the T-REX mechanism with the implemented trader preference function is strategy-proof.

Proof: Since the trader preferences are not related to the preferences of D2D pairs, the problem is equivalent to an allocation problem with $D'_{m_1} = \{D_{m_1}, T_m\}$, $B_{m_1} = B$. In this equivalent problem, all nodes are considered as D2D pairs with independent preferences.

We first denote the cycle found in round $k$ of the procedure as $C_k$, the D2D pair set in $C_k$ as $N_k$, and the set of RBGs exchanged in this round as $B_k$. Assume that a D2D pair $d_{m}^r$ has a CQI $\psi_i$. Without losing generality, we assume $d_{m}^r \in N_k$ when reporting $\psi_i$.

Let $b_m$ and $b'_m$ be the allocation return by the T-REX mechanism when $d_{m}^r$ reports $\psi_i$ and $\psi_i' \neq \psi_i$, respectively. Also, let $N_1, N_2, ..., N_k, N'_1, N'_2, ...$, be the corresponding cycles formed in round 1, 2, ... given $d_{m}^r$ reporting $\psi_i$ and $\psi_i'$, respectively. First we show that it is not possible for a $d_{m}^r \in N_k$ to break into $C_{r + 1}$. For $r = 1, 2, ..., k$ by reporting $\psi_i'$. Since a $d_{m}^r \in N_k$, no edge $e'(t', i)$ exists $\forall d_{m}^r \in \cup_{r < k} N_r$. Thus, given any $\psi'' \in R'_r$, $N_r = N'_r \forall r < k$ and $d_{m}^r \notin \cup_{r < k} N'_r$. So $d_{m}^r$ cannot derive any RBG in $\cup_{r < k} B_r$ by reporting $\psi_i'$. However, since $b'_m$ is the RBG $d_{m}^r$ derived by reporting $\psi_i'$, the constructed preference $\succ_i$ has already chosen the most preferred RBG in $B - \cup_{r < k} B_r$. Thus $b'_m \succeq_i b_m$. This completes the proof for strategy-proofness.

In addition to the strategy-proofness, we see that the final RBG allocation of Algorithm 1 is Pareto optimal.

Theorem 5 (Pareto Optimal). Given the trader preference $\succ_{tr}$, the allocation returned by Algorithm 1 is Pareto optimal when $\succ_i$ is strict for all $d_{m}^r \in D_{m}$.

Proof: We prove this by contradiction. Let $b_m$ be the output allocation of Algorithm 1. We assume that there exists a set of D2D pairs $D_0 \subset D_m$ which can form an exchange sequence and derive a new allocation $b'_m$ that $\forall d_{m}^r \in D_0$, $b'_m \succeq_i b_m$, and $\exists d_{m}^r \in D_0$, $b'_m \succ_i b_m$. Without losing generality, let $i = 1, 2, ..., |D_0|$, $d_{m}^r \in N_{k_i}$, $k_i \geq k$, when $i \geq t'$. 

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19 hexagonal topology
23dBm
100 m
15 (if not specified)
6 (if not specified)

We check each D2D pair’s possessed RBG in \( b_m \). For \( d_{it}^m \), since it belongs to \( N_{ki} \), it has chosen the most preferred RBG in \( \{ b_i \} | d_{it}^m \in \cup_{j=k_i,k_i+1,...,N_r} \} \). In addition, \( \forall d_{it}^m \in D^m, \succ_i \) is strict. Thus, \( b_i^m = b_i^m \). We can repeat this statement from \( d_{i}^m \) to \( d_{it}^m \) and conclude that \( b_i^m = b_i^m, \forall d_{it}^m \in D^m \). We reach a contradiction here. Thus, there exists no D2D pairs that can get better RBGs than in the allocation \( b_m \) without harming others. In short, the allocation \( b_m \) is Pareto optimal.

### E. Randomized Preference

We now propose a strategy-proof trader preference function: RANDomized preference (RAN). In the RAN preference, each trader randomly generates her preference on RBGs. Let the set that contains all possible preferences on RBG set \( B \) be \( P(B) \). The trader preference function of the RAN preference is defined as:

\[
F_{i,RAN}^m(B) = \text{RAND}(P(B)).
\]  

(13)

Theorem 4 guarantees that the RAN preference is strategy-proof, since the preferences of traders are not related to the preferences of traders.

Nevertheless, since the preferences of traders are randomly chosen, it is possible that traders may choose each other’s RBGs as their most preferred RBGs. In such a case, an inter-trader exchange will occur. But it is meaningless to the system because both traders in fact belong to the same eNodeB. This also eliminates the possibility of D2D pairs exchanging with these traders, leading to an inefficient RBG allocation.

To enhance the efficiency while maintaining strategy-proofness, we propose the modified RAN algorithm, which we call D2D-preferred RANDomized preference (DRAN). Recall that \( B_m(b^0_m) \) represents the RBGs allocated to D2D pairs in the initial allocation \( b^0_m \). We use these RBGs to determine the first \( n^\text{th} \) highest preferred RBGs for all traders. The rest of the unallocated RBGs are then randomly chosen as the \((n+1)^\text{th}\) to \( L^\text{th}\) highest preferred RBGs for all traders. With this modified preference, we eliminate the possibility of traders exchanging RBGs with each others. The trader preference function of DRAN preference is

\[
F_{i,DRAN}^m(b^0_m, B) = \{ \text{RAND}(P(B_m(b^0_m))) \}
\]  

(14)

\( \succ_i \) is mainly caused by those D2D pairs served in different areas. This mechanism represents the case that D2D pairs have very limited information about the preferences of other pairs and therefore it is not possible to have an exchange sequence with more than two pairs involved. We measure the efficiency of each mechanism with the interference experienced by D2D pairs only. This can be implemented in a distributed way through the D2D-Tiggered mode in our framework or by using TTCA algorithm. It represents the case that the eNodeB generally is not involved in the resource re-allocation. In the Couple Only mechanism, an exchange occurs only when both pairs have lower interference immediately after the exchange. This mechanism represents the case that D2D pairs have very limited information about the preferences of other pairs and therefore it is not possible to have an exchange sequence with more than two pairs involved. We measure the efficiency of each mechanism with the interference experienced by D2D pairs in their possessed RBGs.

We first evaluate the impact of number of D2D pairs on the efficiency of the T-REX mechanism. We preserve 15 RBGs and adjust the number of D2D pairs from 6 to 15 in the simulation. The simulation results are shown in Fig. 6(a). We first observe

\[
F_{i,CYC}^m(\Omega_{i,m}) = \{ \text{head}(\text{RAND}(\omega)) \succ_i \text{jump}(\omega), \omega \in \Omega^m_{i,m}, n_l = \max \{ j \} \}
\]  

(12)

12 contributions [?]. The proposed simulator is implemented in Matlab while the source codes will be released publicly if published.

The preference of RBGs is based on the D2D pairs’ measurements on the interference in each RBG. The interference is mainly caused by those D2D pairs served in different areas. We assume that the D2D pairs in the same area measure the interference at the same time. Therefore, their measurements do not include the interference from the D2D pairs in the same area.

Then, we simulate the system in multiple rounds. In each round, we randomly choose a service area and apply the simulating resource allocation mechanism. If the applied mechanism does not alter the allocation in all service areas, the simulation goes to the next round and the process repeats. The loop process terminates when there exists no service area that would like to alter its allocation under the simulating mechanism.

### A. Interference Mitigation

We measure the average system interference experienced by D2D pairs under the T-REX mechanism with two strategy-proof preferences (RAN and DRAN), as well as the greedy cycle-complete preferences (CYC). We compare the T-REX mechanism with the Random, Local Exchange, and Couple Only mechanisms. The Random mechanism, in which all RBGs are randomly assigned to D2D pairs, is considered as a baseline with no optimization applied. In Local Exchange mechanism, D2D pairs exchange with the RBGs held by other D2D pairs only. This can be implemented in a distributed way through the D2D-Tiggered mode in our framework or by using TTCA algorithm. It represents the case that the eNodeB generally is not involved in the resource re-allocation. In the Couple Only mechanism, an exchange occurs only when both pairs have lower interference immediately after the exchange. This mechanism represents the case that D2D pairs have very limited information about the preferences of other pairs and therefore it is not possible to have an exchange sequence with more than two pairs involved. We measure the efficiency of each mechanism with the interference experienced by D2D pairs in their possessed RBGs.

We first evaluate the impact of number of D2D pairs on the efficiency of the T-REX mechanism. We preserve 15 RBGs and adjust the number of D2D pairs from 6 to 15 in the simulation. The simulation results are shown in Fig. 6(a). We first observe
that the T-REX mechanism significantly outperforms the Random, Local Exchange, and Couple Only mechanisms in terms of average interference. The Couple Only mechanism has a little improvement in interference compared to the Random mechanism, while the Local Exchange mechanism has better performance than the Couple Only one.

Nevertheless, all T-REX mechanisms perform much better because of the granting of unallocated RBGs from the BSs to the D2D pairs through traders. We also observe that all T-REX RAN, DRAN, and CYC mechanisms perform similarly. This suggests that when the T-REX mechanism converges, the resulting allocation is very close to (or is) the optimal one. Additionally, the strategy-proof T-REX RAN and DRAN mechanisms perform equally well with non-strategy-proof T-REX CY mechanism in terms of interference. We also observe that when the number of D2D pairs increases, there is an increase in the interference level under all T-REX mechanisms. The increase is due to the decrease of RBGs preserved by the BS. Since there are fewer RBGs for exchange, the room for improvements through the exchange is smaller. Additionally, we also observe that as the number of D2D pairs increases, the effect of trader preference functions becomes insignificant. This result comes from the decrease in available RBGs in the BS.

Finally, we simulate with 6 D2D pairs and adjust the number of available RBGs from 6 to 15. The results are shown in Fig. 6(b). We observe that when the number of available RBGs increases, the interference decreases in all schemes, and the interference mitigation of the T-REX mechanism from the Random scheme increases.

**B. Convergence**

Next, we compare the average convergence rounds of different mechanisms in the simulations. The resource exchange converges when no exchange occurs in any of 19 service areas. Here the Couple Only mechanism is implemented by D2D-triggered resource exchange only, where a shared RBG is used for all resource exchange requests. One of the key factors that influence the convergence of D2D-triggered algorithms is the contention for resource exchange request in the reserved shared RBG. A resource exchange request can be successfully delivered only when no collision is occurred. In order to prevent D2D pairs overuse this feature and brings unnecessary overhead here, we restrict D2D pairs to send their requests with a predetermined probability. In the updated simulation, we assume that the probability that one D2D pair in Couple Only algorithm sends a resource exchange request with a probability $p = 0.1$. The results are shown in Fig. 7. First, the Couple Only mechanism converges significantly faster rounds in all simulations since there is a limited number of D2D pairs that can exchange with this mechanism. For the Local mechanism, on the other hand, the convergence rounds increase to around $40 \sim 60$ rounds, which is significantly higher than those of the Couple Only mechanism. In return, her performance is also much better than that of the Couple Only mechanism, as we have seen in Fig. 6.

Then, we observe that T-REX mechanisms with different trader preference functions have different numbers of convergence rounds even if they perform similarly in terms of interference mitigation (Fig. 6). T-REX RAN has the largest number of convergence rounds in all simulations. This is due to the fact that inter-trader exchanges, which only occur in RAN, reduces the probability that a D2D pair possesses her desired RBG from the BS. This significantly slows down the convergence speed. For others, the T-REX DRAN and T-REX CYC mechanisms have similar numbers of convergence rounds. Additionally, the greedy cycle-complete method in T-REX CYC mechanism leads to less number of convergence rounds since no random process is involved in the T-REX CYC mechanism.

Additionally, we observe that the convergence round is convex for all T-REX mechanisms. The required convergence
round for all T-REX mechanisms is influenced by two factors: the number of D2D pairs and number of unallocated RBGs. The former determines the number of entities with specific preferences, while the latter determines the options can be offered by the eNodeB. When the number of D2D pairs increases, there are more D2D pairs who are expected to be unsatisfied with the current allocation. More exchanges requests are expected and the convergence round should increases in this case. On the other hand, when the number of unallocated RBGs decreases, eNodeB has fewer RBGs to exchange with. In such a case, those D2D pairs who have exchange requests must exchange with other D2D pairs, which could fail since other D2D pairs may already possess their preferred RBGs. Thus, the convergence round decreases since it is less likely to have valid exchange sequence in this case. These two contradictory effects occur simultaneously in all T-REX mechanisms when the number of D2D pairs increases while the total number of RBGs is fixed: more D2D pairs means less unallocated RBGs. The effect of increase in D2D pairs is more significant when the number of D2D pairs remains small. But eventually, the effect of unallocated RBGs dominates when there are only few RBGs unallocated. In both Local Exchanges and Couple Only algorithms, on the other hand, the unallocated RBGs does not have any effect on the convergence round since eNodeB does not exchange with any D2D pairs in these two algorithms. Therefore the convergence round generally increases with the number of D2D pairs in these cases.

We further investigate how the proposed algorithms perform when D2D pairs are in mobility. We simulate with D2D pairs moving around within the service area following Random Way-Point model. We fixed the number of D2D pairs in each service area to 6, while the number of preserved RBGs is 15. The CQI reporting period is 80 ms. The maximum speed of D2D pairs is adjusted from 5 m/s to 20 m/s, while distance between D2D devices of the same pair remains the same among the movement. Random, Couple Only, and T-REX CYC mechanisms are applied in the simulations. The average interference per D2D pairs under different mobility over time is shown in Fig. 7(b).

We observe that the performance of both Random and Couple Only schemes are heavily affected by the mobility of D2D pairs, while T-REX CYC mechanism maintains the best and relatively stable performance under all mobility scenarios. When we further check the ratio of time reaching a stable allocation within the simulation time, which is shown in Fig. 7(c), we observe that T-REX CYC mechanism actively adjusts the RBG allocation according to the received CQI reports and seldom enters the stable state. In contrast, D2D pairs in Couple Only mechanism seldom exchange their resources. This phenomenon suggests that when signaling overhead between devices and eNodeB is not a concern, T-REX CYC mechanism maintains a better and stable performance by adjusting the RBG allocation dynamically when D2D pairs are in mobility. Nevertheless, when the signaling overhead is of concern, Couple Only scheme still provides some performance enhancement with much less signaling/resource exchanges and more stable RBG allocation.
through designing the trader preference functions. This design is critical to the convergence speed, as has been shown in the simulations. Through game-theoretic analysis, we also proved that when the trader preference functions are properly designed, the T-REX mechanism is strategy-proof. This prevents the eNodeB from receiving forged CQI reports from rational D2D devices and users. Finally, we evaluated the performance of the T-REX mechanism through simulations. The simulations with the parameters suggested in the latest 3GPP technical contribution showed that the T-REX mechanism significantly mitigates the interference experienced by D2D devices.

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