Matching with Peer Effects for Context-Aware Resource Allocation in D2D Communications

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***Abstract*—In this letter, we investigate the context-aware resource allocation for device-to-device communications accounting for the quality-of-service (QoS) requirements and priorities of different applications based on users' requests. We formulate a context-aware optimization problem and implement the matching theory to solve the problem. We propose a novel algorithm where the D2D user equipments and resource blocks (RBs) act as two opposite sets of players and interact with each other to obtain the optimal matching. We analytically prove that the algorithm converges to a two-sided exchange stability within limited number of swap operations. We also demonstrate that the proposed algorithm significantly outperforms the context-unaware resource allocation algorithm by around 62.2%.**

***Index Terms*—Context awareness, device-to-device communications, many-to-one matching, and resource allocation.**

I. INTRODUCTION

With the recent proliferation of smartphones and tablets nowadays, a huge amount of multimedia services, such as content dissemination and social networking, are becoming available among users in the proximity of each other. Device-to-device (D2D) communications is considered as a key technology to take advantage of the physical proximity of communicating devices [1, 2]. However, to provide smooth operation and high flexibility to the multitasking D2D user equipments (UEs) introduces new challenges, including more efficient resource allocation approaches according to different UEs' *context* information.

The concept of *context awareness* was introduced in the area of computer science, and has attracted considerable attention in wireless communications [3]. However, the work on context awareness is still novel in D2D communications [4, 5]. In [4], the authors proposed a social-aware approach which accounted for the social ties among the D2D users, where the system data rate was increased. In [5], the context information, including channel state information (CSI), service requirements and priority information, was exploited, reducing the number of required RBs to support service requirements.

With the rapid growth in the number of multi-tasking devices in cellular networks, it is desirable to meet the quality-of-service (QoS) requirements of different applications. Moreover, the priorities of applications with respect to UEs' requests need to be distinguished. For example, for users of tablets, the HD video streaming is often with the highest priority, followed by the file transmission which always runs as the background application. Therefore, it is worth considering the intelligent allocation of resources corresponding to different priorities of UEs' requests for applications to improve the network efficiency. However, in the existing literature on D2D communications [4, 5], there is a lack of a systematic approach for investigating context-aware resource allocation problems in terms of the priorities of applications based on UEs' requests. Therefore, in this work, we adopt a new utility function (UF) which captures the priorities and QoS, e.g., data rate, packet error rate (PER), and delay, of different applications.

The main contributions of this paper are summarized in the following. *First*, we formulate a novel context-aware RB allocation problem for D2D communications, where different priorities of applications with respect to UEs' requests are taken into consideration. *Second*, to solve the formulated problem, we propose a novel algorithm based on the many-to-one matching with *peer effects*, where the action of each D2D pair is affected by the decisions of its peers. This is in contrast to most existing works on matching theory for wireless networks [6, 7]. In [6], peer effects were not taken into consideration because of the difficulty to analyze the stability. In [7], a one-to-one matching model with peer effects was discussed, for which the complexity for analyzing stability is much lower than the many-to-one matching. In our work, we show that the proposed algorithm allows the D2D pairs and RBs interact and converge to a stable matching with manageable complexity. Simulation results demonstrate that the proposed algorithm outperforms the traditional Gale-Shapley (GS) algorithm, the one-to-one matching algorithm as well as the context-unaware algorithm.

II. SYSTEM MODEL

In this work, a single-cell uplink scenario with multiple users is considered. Both the eNB and UEs are equipped with single omni-directional antennas. The locations of cellular UEs and D2D transmitters are set in a random manner and traversing the whole cell. The receiver of each D2D pair follows a uniform distribution inside a region with the distance L from the corresponding transmitter. We assume that multiple D2D pairs can share the same RB, while each D2D pair can use no more than one RB for transmission. The set of D2D pairs is represented by $\{D_1, ..., D_m, ..., D_M\}$, and the set of RBs is denoted by $\{RB_1, ..., RB_n, ..., RB_N\}$. The set of cellular UEs is represented by $\{C_1, ..., C_n, ..., C_N\}$. It is assumed that each RB is allocated to a cellular UE in a random manner. The received signal-to-noise-plus-interference-ratio (SINR) at the receiver of D_m on RB_n is given by

$$\gamma_m^n = \frac{P_m G_m}{P_n G_{nm} + \sum_{m' \neq m} \alpha_{m'n} P_{m'} G_{m'm} + \sigma^2}, \qquad (1)$$

where P_m and P_n are the transmission power of the transmitter of D_m and C_n, respectively. G_m, G_{nm}, $G_{m'm}$ are the channel gains between the transmitter and receiver of D_m, that between C_n and the receiver of D_m, and that between the transmitter of $D_{m'}$ and the receiver of D_m, respectively. σ^2 is the additive white Gaussian noise power. α_{mn} indicates a RB is allocated to a D2D pair or not. If RB_n is allocated to D_m, $\alpha_{mn} = 1$; otherwise, $\alpha_{mn} = 0$. Similarly, the received SINR at the eNB on RB_n is given by

$$\gamma_n = \frac{P_n G_{nB}}{\sum_m \alpha_{mn} P_m G_{mB} + \sigma^2}, \qquad (2)$$

where G_{nB} and G_{mB} are the channel gains between C_n and the eNB, and that between the transmitter of D_m and the eNB, respectively. Based on the Shannon-Hartley theorem, the data rate of D_m on RB_n is $R_m^n = \alpha_{mn} B \log_2(1+\gamma_m^n)$, and the data rate of C_n is $R_n = B \log_2(1+\gamma_n)$. Here, B is the bandwidth of a RB.

The probability of packet error during the transmission between the transmitter and receiver of a D2D pair can be expressed as a function of the SINR. For uncoded quadrature amplitude modulation (QAM), this PER is given by [8]

$$PER_m(\gamma_m^n) = \begin{cases} a_m \exp(-b_m \gamma_m^n), & \text{if } \gamma_m^n \geq \gamma_m^{thr}; \\ 1, & \text{otherwise,} \end{cases} \qquad (3)$$

where a_m, b_m are packet-size dependent constants and γ_m^{thr} is the minimum SINR threshold which guarantees the correct demodulation. For ease of analysis, we do not consider the retransmission of the packets which are erroneously received.

We consider the UEs' *context* in terms of priorities of their requests for different active applications. On the one hand, the priorities of applications vary with respect to different UEs. On the other hand, for different active applications, the minimum QoS requirements, including data rate, PER, and delay, which guarantees the successful transmission are different. To this end, we consider three types of UEs, i.e., UE1, UE2, and UE3; and four types of applications, i.e., HD video streaming, multi-user gaming, audio streaming, and file transmission. We assume that the set of active applications of D2D pair D_m is $\mathcal{K}_m = \{1, ..., K_m\}$, where the applications are ordered in descending order with respect to their priorities. For example, for UE1, the HD video streaming is with the highest priority, followed by the file transmission which is the background application. For UE2, the audio streaming is the main application and given the highest priority to transmit, but HD video streaming is with lower priority.

Inspired by the proposed context model, where the priorities of applications with respect to D2D UEs' requests are different, D2D pair D_m is able to discriminate the traffic stream of each application. Then, D_m gives each traffic stream of the application k the k-th priority to transmit. We assume that the aggregated traffic of D_m is composed by packets of constant size generated using a Poisson arrival process with an average arrival rate of λ_m, where the arrival rate of each application is $\lambda_{m,k}$, and $\sum_{k=1}^{K_m} \lambda_{m,k} = \lambda_m$. We assume that the channel conditions are constant during the scheduling procedure, and thus we model the traffic at each D2D link as a priority-based M/D/1 queueing system, where the traffic requests are serviced according to the context dependent priorities. Thus, the average delay for the x-th priority stream of D2D pair D_m is given by

$$d_{m,x} = \frac{\sum_{k=1}^{K_m} \lambda_{m,k} \overline{T_m}^2}{2(1-\sum_{k=1}^{x-1}\rho_{m,k})(1-\sum_{k=1}^{x}\rho_{m,k})} + \frac{1}{R_m}, \qquad (4)$$

where $\rho_{m,k} = \lambda_{m,k}/R_m$ is the utilization factor for the k-th stream of D2D link D_m and $\overline{T_m}^2$ is the second moment of service time. We can see from (4) that the knowledge of context information enables D2D links to better prioritize application requests.

III. PROBLEM FORMULATION AND PROPOSED CONTEXT-AWARE RESOURCE ALLOCATION ALGORITHM

A. Problem Formulation

To capture characteristics of different applications and their priorities, our optimization problem is given as follows:

$$\max_{\alpha_{mn}} \sum_m UF_m(n), \qquad (5a)$$

$$s.t. \qquad R_m \geq \max_{k \in \mathcal{K}_m} R_k^{thr}, \quad \forall m, \qquad (5b)$$

$$d_{m,k} \leq d_k^{thr}, \quad \forall k, m, \qquad (5c)$$

$$PER_m \leq \min_{k \in \mathcal{K}_m} PER_k^{thr}, \quad \forall m, \qquad (5d)$$

$$\gamma_n \geq \gamma_n^{min}, \quad \forall n, \qquad (5e)$$

$$\alpha_{mn} \in \{0,1\}, \quad \forall m, n, \qquad (5f)$$

$$\sum_m \alpha_{mn} \leq q_{max}, \quad \forall n, \qquad (5g)$$

where $UF_m(n)$ is the utility function which is defined as

$$UF_m(n) = \frac{R_m(1-PER_m)}{\sum_{k=1}^{K_m} d_{m,k}}. \qquad (6)$$

This utility function captures the data rate and PER of D2D pair m given the achievable SINR γ_m^n on RB n. Moreover, the utility also properly accounts for the priorities of applications through the delay term $d_{m,k}$. R_k^{thr}, d_k^{thr}, and PER_k^{thr} are the minimum QoS requirements for the k-th application in terms of data rate, delay, and PER, respectively. (5b), (5c) and (5d) restrict these requirements. (5e) gives the SINR constraints of cellular UEs. (5f) shows that the value of α_{mn} should be either 0 or 1. (5g) means at most q_{max} D2D pairs can be allocated to each RB. This constraint is to restrict the interference on each RB, as well as reduce the implementation complexity.

The formulated problem here is a 0-1 integer program, which is one of Karp's 21 NP-complete problem [9]. Thus it is difficult to solve this problem via classical optimization approaches. Moreover, for a large-scale cellular network with D2D communications, it is desirable to develop a decentralized, self-organizing approach to make resource allocation decisions based on the local context information. Therefore, we invoke the many-to-one two-sided matching for obtaining a suboptimal solution in the next subsection.

B. Proposed Algorithm Using Matching Theory

The matching problem we formulate here is the many-to-one two sided matching between D2D pairs and RBs. The set of D2D pairs and RBs can be regarded as two opposite groups of selfish and rational players who try to enhance their own benefits during the matching process. To proceed with proposing the resource allocation algorithm, we first introduce some notations and basic definitions for the matching model.

Definition 1: In the many-to-one matching model, a *matching* Ω is a function from the set $\mathcal{RB} \cup \mathcal{D}$ into the set of all subsets of $\mathcal{RB} \cup \mathcal{D}$ such that 1) $|\Omega(D_m)| \leq 1, \forall D_m \in \mathcal{D}$, and $\Omega(D_m) = \emptyset$ if D_m is not matched to any RB; 2)

$|\Omega(RB_n)| \leq q_{max}$, $\forall RB_n \in \mathcal{RB}$, and $\Omega(RB_n) = \emptyset$ if RB_n is not matched to any D2D pair; 3) $D_m \in \Omega(RB_n)$ iff $RB_n = \Omega(D_m)$.

The utility of D2D pair m occupying RB n is given in (6), while the utility of RB n when choosing a set $\mathcal{S}$ of D2D pairs is the sum utility of D2D pairs $m \in \mathcal{S}$, which is expressed as

$$UF_n(\mathcal{S}) = \sum_{m \in \mathcal{S}} \frac{R_m(1 - PER_m)}{\sum_{k=1}^{K_m} d_{m,k}}. \tag{7}$$

Given these utilities, D2D pairs and RBs can set their own preference lists with the descending order of utilities. According to (1) and (6), the utility of D2D pair m depends not only on the cellular user it is matched with, but also on the set of D2D pairs that are matched to the same RB. In other words, the preference lists of D2D pairs and RBs change as the game evolves. This kind of interdependence among D2D pairs matched to the same RB is called *peer effects* [10]. To deal with peer effects, we enable *swap operations* between D2D pairs to exchange their matched RBs. A *swap matching* $\Omega_m^{m'}$ is expressed as

$$\Omega_m^{m'} = \{\Omega \setminus \{(m,n),(m',n')\}\} \cup \{(m,n'),(m',n)\}, \tag{8}$$

where $n = \Omega(m)$, and $n' = \Omega(m')$. A swap matching enables D2D pair D_m and $D_{m'}$ to switch their matched RBs while keeping other D2D pairs and RBs' matchings unchanged. Accordingly, a *swap-blocking* pair is defined as

Definition 2: $(D_m, D_{m'})$ is a *swap-blocking* pair if and only if i) $\forall x \in \{m, m', n, n'\}, U_x(\Omega_m^{m'}) \geq U_x(\Omega)$, and ii) $\exists x \in \{m, m', n, n'\}$, $U_x(\Omega_m^{m'}) > U_x(\Omega)$.

The above definition indicates that, if two D2D pairs want to switch their matched RBs, RBs must "approve" the swap. Condition (1) implies that the utilities of all the involved players should not be reduced after the swap operation between the *swap-blocking* pair $(D_m, D_{m'})$. Condition (2) indicates that at least one of the players' utilities is increased after the swap operation between the *swap-blocking* pair. This avoids looping between equivalent matchings where the utilities of all involved agents are indifferent.

Inspired by the work in [11], we propose a context-aware resource allocation algorithm for D2D communications (CARAD), where D2D pairs and RBs selfishly and rationally interact with each other to make matching decisions. The details of the algorithm is shown in Table 1. CARAD is composed of two main stages: Stage 1 initializes the matching state via the traditional GS algorithm. Stage 2 focuses on the swap-matching process. Particularly, in stage 1, D2D pairs and RBs first set up their own preference lists. Then, each D2D pair proposes to its most preferred RB, and each RB accepts the most preferred D2D pairs and rejects the others. Stage 1 terminates once each D2D pair is accepted by a RB or rejected by all its preferred RBs. Stage 2 enables D2D pairs to exchange their matched RBs to eliminate potential swap-blocking pairs, which ends when there is no more swap-blocking pairs.

As stated in [12], there is no longer a guarantee that a traditional "pairwise-stability" exists when players care about more than their own matching, and, if a stable matching does exist, it can be computationally difficult to find. The authors in [10] focused on the *two-sided exchange-stable matchings*, which is defined as follows:

Definition 3: A matching Ω is *two-sided exchange-stable* if there does not exist a *swap-blocking* pair.

TABLE I: Context-Aware Resource Allocation for D2D Communications (CARAD)

Stage 1: GS Algorithm-Based Initialization

a) D2D pairs and RBs construct their preference lists.
b) Each D2D pair proposes to its most preferred RB that has not rejected if before.
c) Each RB keeps the most preferred q_{max} D2D pairs and rejects the others.
d) Repeat b) and c) until each D2D pair is accepted by a RB or rejected by all its preferred RBs.

Stage 2: Swap-matching process

a) $\forall D_m \in \mathcal{D}$, it searches for another D2D pair $D_{m'} \in \{\mathcal{D} \setminus \{D_m\}, O\}$, where O is an open spot of RB's available vacancies.
b) If $(D_m, D_{m'})$ or $(D_m, \mathcal{O})$ is a swap-blocking pair, $\Omega \leftarrow \Omega_m^{m'}$. Else, keep the current matching state.
c) Repeat a) and b) until $\nexists (D_m, D_{m'})$ blocks the current matching.

End of the algorithm.

The *two-sided exchange stability* is a distinct notion of stability compared to the traditional notion of stability of [12], but one that is relevant to our situation where agents can compare notes with each other.

Theorem 1: The final matching Ω_{final} of CARAD is two-sided exchange stable. The proof is given as follows.

Proof: As shown in Table 1, the swap operations occur only when the utilities of players are strictly improved. After searching for all the possible swaps, the swap-matching phase terminates and there does not exist any swap matching to further improve the utilities for players in both sides of the current matching. Hence, we can say that the final matching is two-sided exchange stable. ☐

Lemma 1: The sum utility of D2D pairs increases after each swap operation.

Proof: Suppose a swap operation makes the matching state change from Ω to $\Omega_m^{m'}$. According to Table 1, a swap operation occurs only when $U_n(\Omega_m^{m'}) \geq U_n(\Omega)$ as well as $U_{n'}(\Omega_m^{m'}) \geq U_{n'}(\Omega)$. Given that $U_n(\mathcal{S}, \Omega) = \sum_{m \in \mathcal{S}} U_m(n, \Omega)$, we have

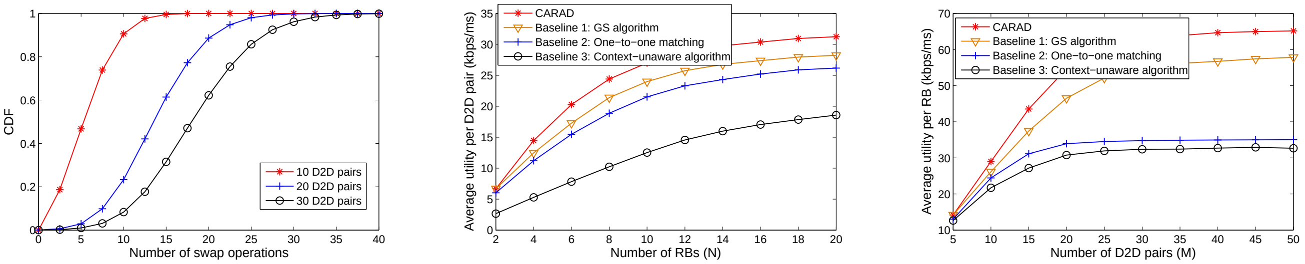
$$\begin{aligned} \Phi_{\Omega \to \Omega_m^{m'}} = &\sum\nolimits_n \sum\nolimits_m U_m(n, \Omega_m^{m'}) \\ &- \sum\nolimits_n \sum\nolimits_m U_m(n, \Omega) \geq 0. \end{aligned} \tag{9}$$

Therefore, the sum utility of D2D pairs is improved after each swap-matching process in Table 1. ☐

As shown in Table I, the complexity of the proposed algorithm mainly depends on the number of iterations in the swap-matching phase. As proved in Lemma 1, the sum utility increases with the swap operations going on. However, since the number of RBs and the maximum number of D2D pairs can be allocated to each RB are both limited, the sum utility has an upper bound. We denote the difference of the sum utilities of the final matching and the initial matching as $\Phi_{\Omega_0 \to \Omega_{final}}$, and the minimum increase of each swap operation as Δ_{min}. Thus, in the worst case, the computational complexity of the proposed algorithm is of the order $\mathcal{O}\left(\frac{\Phi_{\Omega_0 \to \Omega_{final}}}{\Delta_{min}}\right)$.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, numerical results are provided to demonstrate the performance of the proposed algorithm CARAD. The traditional GS algorithm, one-to-one matching algorithm and



(a) CDF of the number of swap operations, where $N = 10$.

(b) Average utility per D2D pair versus different number of RBs, where $M = 30$.

(c) Average utility per RB versus different number of D2D pairs, where $N = 10$.

Fig. 1: Performance analysis of the proposed CARAD algorithm.

context-unaware RB allocation algorithm are plotted as baseline 1, 2, and 3, respectively. Particularly, baseline algorithm 1 enables D2D pairs to apply for RBs, and get accepted or rejected via the GS algorithm. For baseline algorithm 2, D2D pairs and RB are matched via the one-to-one matching algorithm. For baseline algorithm 3, each D2D pair is associated with the RB that provides it with the highest SINR, without considering the context information. For the simulations, we set the cellular radius to 300 m, the bandwidth of each RB to 180 kHz, the cellular UEs' SINR threshold to 4 dB, σ^2 to -98 dBm, L to 50 m, and q_{max} to 4. The QoS parameters of popular wireless services are shown in Table II [13, 14].

TABLE II: QoS Requirements of Multimedia Applications.

Application	Data rate (kbps)	Delay (ms)	PER
HD video streaming	1800	40	0.05
Multi-user gaming	700	30	0.01
Audio streaming	320	20	0.08
File transmission	200	3000	0.1

Fig. 1(a) plots the CDF of the number of swap operations for the proposed algorithm. One can observe that the number of swap operations increases with the increased number of D2D pairs, which is due to the improved probability of the existence of swap-blocking pairs. The CDF also shows that the proposed matching algorithm converges within a reasonable number of iterations. For example, when there are 30 D2D pairs in the network, on average a maximum of 40 iterations is required to ensure the proposed algorithm to converge.

Fig. 1(b) plots the average utility per D2D pair versus different numbers of RBs. It is not surprising to see that the average utility per D2D pair increases with a slow rate with larger number of RBs due to the multi-user diversity gain. The proposed algorithm achieves a higher average utility of D2D users compared to baseline algorithm 1 since swap operations are enabled after the GS algorithm-based initialization. For baseline algorithm 2, the average utility is restricted due to the limited number of served D2D pairs in the one-to-one matching algorithm. Baseline algorithm 3 has the lowest average utility since it does not take the context information into consideration. In particular, the proposed algorithm improves the average utility by around 11%, 20%, and 63% compared to baseline 1, 2, and 3, respectively. Recall the definition of the utility of each D2D pair, the utility enhancement indicates that the proposed algorithm can jointly provide improved data rate, decreased PER and reduced delay.

Fig. 1(c) plots the average utility per RB versus different numbers of D2D pairs. Two main observations are as follows: 1) the average utility increases with the number of D2D pairs; and 2) the growth rate of the average utility is declined as the number of D2D pairs increases. This is due to the fact that the maximum number of D2D pairs that can be allocated to each RB is restricted. Moreover, the co-channel interference is enhanced when more D2D pairs occupy the same RB, which further limits the upper bound of the average utility.

V. CONCLUSIONS

In this paper, we have presented a novel approach for context-aware resource allocation in D2D communications. Formulating an optimization problem by maximizing the utilities of the D2D user equipments, we have proposed a novel algorithm based on the many-to-one matching game with peer effects. We have shown that the context-aware D2D transmission is capable of providing remarkable performance enhancement in terms of improved data rate, decreased packet error rate and reduced delay, compared to that of the context-unaware approach.

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