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Article

Efficiency Intra-Cluster Device-to-Device Relay Selection for Multicast Services Based on Combinatorial Auction

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Abstract: In Long Term Evolution-Advanced (LTE-A) networks, Device-to-device (D2D) communications can be utilized to enhance the performance of multicast services by leveraging D2D relays to serve nodes with worse channel conditions within a cluster. For traditional D2D relay schemes, D2D links with poor channel condition may be the bottleneck of system sum data rate. In this paper, to optimize the throughput of D2D communications, we introduce an iterative combinatorial auction algorithm for efficient D2D relay selection. In combinatorial auctions, the User Equipments (UEs) that fails to correctly receive multicast data from eNodeB (eNB) are viewed as bidders that compete for D2D relays, while the eNB is treated as the auctioneer. We also give properties of convergency and low-complexity and present numerical simulations to verify the efficiency of the proposed algorithm.

Keywords: device-to-device communication; multicast services; D2D relay; combinatorial auction

1. Introduction

The standard solution for supporting multicast services in Long Term Evolution-Advanced (LTE-A) networks suffers from severe inefficiencies [1], as the conventional cellular multicast performance is strictly bounded by the user with the poorest channel conditions. For this reason, researchers are active in studying solutions to enhance the multicast services performance in cellular systems [1]. Among many alternatives, another new paradigm within LTE-A systems, namely Device-to-Device (D2D) communications [2], has become a flourishing research field. D2D communication is about enabling direct flow of data among User Equipments (UEs) in close proximity, it holds merit of data offloading for the eNodeB (eNB), improving spectrum efficiency, and increasing system capacity [2–4], *etc.* These observations led us to the idea of bringing D2D communications into the cellular multicast services framework, and investigating the potentialities of adopting D2D communications to enhance the performance of conventional multicast services.

In LTE-A networks, UEs requesting the same data from eNB can be grouped into a cluster and eNB multicasts data to all UEs within the cluster. The major issue in cellular multicast transmissions is the different channel conditions for the multicast recipients. Alternatively in D2D-assisted networks, UEs with good channel conditions are enabled to act as relays to communicate the received multicast data from the eNB to the remaining UEs via D2D links, such that the eNB can multicast at a high data rate and the transmission efficiency is improved. Based on this idea, in [5] the authors proposed a cooperative multicast transmission scheme, *i.e.*, in which all successful multicast recipients participate in D2D relay transmissions by broadcasting their received data on the same resource. Because each D2D relay should serve all failed multicast recipients at a common rate selected according to the worst D2D link, it is unfavorable to improve the network throughput. In [6] the authors assumed a single predefined multicast recipient called cluster head which is responsible for D2D relay transmissions. Unfortunately the efficiency of this scheme is not guaranteed in case the predesignated recipient fails to receive multicast data and the eNB must participate in retransmissions. In [7] the authors proposed an adaptive D2D retransmission scheme exploiting the multi-channel diversity to improve spectrum, which adaptively selects the optimal number of D2D retransmitters and conducts the optimal sub-cluster partition. Furthermore, in [8] authors introduced relay based transmission into the multicast process so as to overcome transmission rate restriction caused by link heterogeneity, and a greedy heuristic algorithm was applied to select relay nodes. According to the these works, to improve the transmission quality of intra-cluster multicast service, a high efficient relay selection should be considered in the D2D cluster.

In this paper we consider an auction-based approach using game theory. A combinatorial auction (CA) model for resource management was introduced in [9]. Combinatorial auctions are multi-item or multi-bidder auctions in which bidders can form combinations called packages, rather than just bid individually. Furthermore, in the evolution auction mechanisms named iterative combinatorial auctions [10], the step of bid evaluation is executed multiple times, and the auctioneer computes provisional allocations in each auction round. Iterative CAs have already found applications in allocating radio spectrum for wireless communications [11]. The CAs motivate bidders to fully express their preferences, which is an advantage in improving system efficiency and auction revenues. Up to that point, we study an effective D2D relay selection for multicast services to further improve system efficiency based on the iterative CA. The whole system consists of the eNB, multiple successful multicast recipients, and multiple failed multicast recipients. Considering that an efficient exploitation of multi-channel diversity may bring large beneficial to system throughout, we formulate the problem as a CA game. By this way, the failed multicast recipients and the successful multicast recipients are regarded as bidders and goods, respectively, while the successful multicast recipients are goods waiting to be selected as relays. Each bidder has a valuation for the relays, and multiple bidders can form a package that share the same relay. During the auction, the bidders submit bids and the auctioneer, *i.e.*, the eNB decides the allocation of the relays. Furthermore, we propose an auction algorithm which runs iteratively until reaching an equilibrium state. We also discuss the properties of our algorithm and the simulation results show a good performance on the sum data rate and system efficiency.

The rest of the paper is organized as follows. In Section 2, a system model of intra-cluster D2D communication is introduced. Then we formulate the primary problem as a CA game in Section 3. Next, in Section 4, the CA algorithm for D2D relay selection is proposed, and the main properties of the proposed algorithm are discussed. In Section 5, we present the simulation results. Finally, we conclude this paper in Section 6.

2. System Model

We consider a single-cell multicast system where an eNB serves numerous UEs and the UEs in close proximity can group into a cluster to request the same data from eNB. The UEs within a cluster can not only communicate with eNB, but also directly communicate with each other via D2D links. Let us focus on one D2D cluster, as illustrated in Figure 1. Due to independent properties of cellular downlink channels, when the eNB multicasts data to all UEs within a D2D cluster at a certain rate, only a portion of the UEs can correctly receive and decode the data. The UEs that can and cannot successfully receive data are referred to as "ACK-UEs" and "NACK-UEs", respectively. In order to share the data from eNB in the whole cluster, ACK-UEs can be employed as relays to forward the received data to NACK-UEs via D2D links. In general, the underlined intra-cluster relay transmissions can be accomplished via D2D multicast. Meanwhile, to avoid the interference between D2D communication and cellular communication, orthogonal resources should be allocated to them.

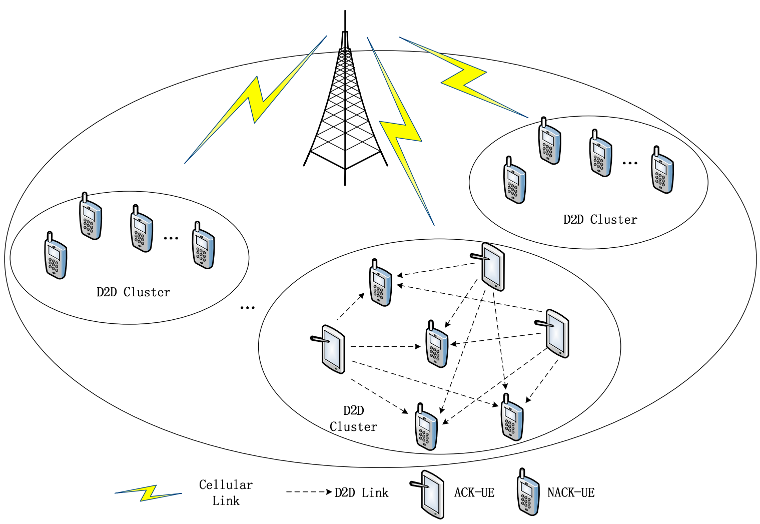

Figure 1. D2D clusters with ACK-UEs and NACK-UEs in the cellular network.

In the paper, we only consider both large-scale path-loss attenuation and smallscale fading characterized by Rayleigh fading, and thus the channel response follows the independent complex

Gaussian distribution. In addition, the free space propagation path-loss model, $P = P_0 \cdot (d / d_0)^{-\alpha}$, is used where P_0 and P represent signal power measured at d_0 and d meters away from the transmitter, respectively. α is a path-loss exponent. We simplify the received power at $d_0 = 1$ equals the transmit power. Hence, the received power of each D2D link can be expressed as.

$$P_{r,ij} = P_i \cdot h_{ij}^2 = P_i \cdot \left(d_{ij}\right)^{-\alpha} \cdot h_0^2 \tag{1}$$

where $P_{r,ij}$ and d_{ij} are the received power and the distance of the *i–j* link. P_i represents the transmit power of UE i, and h_0 is the complex Gaussian channel coefficient that obeys the distribution $\mathcal{CN}(0,1)$. Given the power spectral density of the additive Gaussian noise σ^2 and system bandwidth W_c, according to Shannon formula, the channel rate of UE *j* can be obtained by.

$$R_{i,j} = \log_2\left(1 + \frac{P_i h_{ij}^2}{W_c \sigma^2}\right) \tag{2}$$

We define $\mathcal{N}_{\text{NACK}}$ is the set of NACK-UEs and $\mathcal{N}_{\text{ACK}}$ is the set of ACK-UEs. The numbers of NACK-UEs and ACK-UEs in the cluster are denoted as N_{NACK} and N_{ACK}, respectively. Besides, inspired by [7], we assume there are L ACK-UEs acting as relays. For a given relay, the achievable D2D multicast rate depends on the worst link among all links connecting it with all NACK-UEs. By optimizing selecting of a D2D relay, the system sum data rate can be defined as

$$\mathcal{R}_{\text{opt}} = \max_{\substack{n_i \in \mathcal{N}_{\text{ACK}}, i=1,\ldots,L \\ n_1 \neq n_2 \neq n_3 \neq \cdots n_L \\ \mathcal{N}_{n_1} \cup \cdots \cup \mathcal{N}_{n_L} = \mathcal{N}_{\text{NACK}}}} \sum_{i=1}^{L} \sum_{j \in \mathcal{N}_{n_i}} \min_{j \in \mathcal{N}_{n_i}} R_{n_i,j} \tag{3}$$

where n_i $(i = 1, 2, \ldots, L)$ stands for the index of an ACK-UE acting as the *i*-th D2D relay. The optimal D2D relay selection is performed under constraints $n_i \in \mathcal{N}_{\text{ACK}}, n_1 \neq n_2 \neq \cdots n_L$, and $\mathcal{N}_{n_1} \cup \cdots \mathcal{N}_{n_L} = \mathcal{N}_{\text{NACK}}$, to guarantee that each NACK-UE in the cluster should be served by one relay. Although Equation (3) gives a generic solution, this optimization problem is very complicated in general. Therefore, it is necessary to design a relay selection mechanism that is not only computationally tractable, but also able to sustain high system efficiency.

3. Problem Formulation

In the proposed D2D cluster, system sum data rate is considered as the central optimization problem. As ACK-UEs are selected as relays to serve NACK-UEs, the contributions to system data rate are various due to heterogeneity of the D2D links between relays and NACK-UEs. Therefore, in order to optimize the system performance, we focus on the how NACK-UEs are effectively allocated to ACK-UEs for the sake of relay services.

In this section, based on Equation (3), we can model the D2D relay selection process as a CA game. In this auction, NACK-UEs are considered as the bidders who bid to get a certain item, *i.e.*, ACK-UE, while the eNB is the auctioneer. Since multiple NACK-UEs can be served by one D2D relay, the packages of NACK-UEs can form combinatorial bidders. We denote $\mathcal{N}_{\text{NACK}} = \{b_1, b_2, \ldots, b_N\}$ as the set of bidders participating in the auction $(|\mathcal{N}_{\text{NACK}}| = N)$ and denote $b_k \in \mathcal{N}_{\text{NACK}}$ as a specific bidder. Similarly, we denote $\mathcal{N}_{\text{ACK}} = \{i_1, i_2, \ldots, i_M\}$ as the set of items to be auctioned $(|\mathcal{N}_{\text{ACK}}| = M)$ and denote $i_m \in \mathcal{N}_{\text{ACK}}$ as a specific item. We also denote the set of all possible NACK-UEs packages by $\mathcal{D} = \{\mathcal{D}_1, \mathcal{D}_2, \ldots, \mathcal{D}_M\}$, in which an element package is expressed as $\mathcal{D}_m, m = 1,2,...,M$ in correspondence with the *m*-th ACK-UE. The possible packages are subsets of NACK-UEs. By using $\mathcal{D}$, we can transform the optimization problem in Equation (3) into a package assignment process. We consider a set of binary variables $\{x^{\{b_k\}}(\mathcal{D}_m)\}$ to define the allocation, $x^{\{b_k\}}(\mathcal{D}_m) \in \{0,1\}$. $x^{\{b_k\}}(\mathcal{D}_m) = 1$ indicates that NACK-UE b_k bidding for ACK-UE i_m is assigned into package $\mathcal{D}_m$. In the auction, the goal of the eNB is to maximize the total revenue by selling ACK-UEs. Meanwhile, each NACK-UE targets at purchasing the item to maximize its own package utility.

In order to describe the allocation outcome intuitively, we give the definition below.

Definition 1. *The result of the auction is an allocation denoted by* $X = (\mathcal{D}_1, \mathcal{D}_2, ..., \mathcal{D}_M)$, *which allocates a corresponding bidder package to every item. And the allocated packages are not intersect:* $\forall i, j, \mathcal{D}_i \cap \mathcal{D}_j = \varnothing$.

To motivate the bidders to reveal their true preferences, we express NACK-UE b_k's valuation for ACK-UE i_m as channel data rate R_{b_k,i_m}. Then, the private valuation of package $\mathcal{D}_m$ can be expressed as:

$$\begin{aligned} &\upsilon^{\{b_k\}}(\mathcal{D}_m) = |\mathcal{D}_m| * \min_{b_k \in \mathcal{D}_m} \left[\log_2 \left(1 + \frac{P_{b_k} h_{b_k,i_m}^2}{W_c \sigma^2} \right) \right], \\ &\{b_k\} = \{b_1, ..., b_k, ...b_K\}, \forall k, K \in \{1,2,...,N\} \end{aligned} \tag{4}$$

Although the NACK-UEs obtains D2D data rate by getting a D2D relay service of ACK-UE, there exists some cost such as control signals transmission and information feedback during the relay selection process. We define the cost as a pay price. For ACK-UE i_m, the pay price by the NACK-UE b_k in package $\mathcal{D}_m$ is written as $p_{b_k}(\mathcal{D}_m)$. Based on Equation (4), the combinatorial utility of the bidder can be expressed as $\pi^{\{b_k\}}(\mathcal{D}_m, \mathcal{P}) = \upsilon^{\{b_k\}}(\mathcal{D}_m) - \sum_{b_k \in \mathcal{D}_m} p_{b_k}(\mathcal{D}_m)$, in which $\mathcal{P}$ is the price set, *i.e.*, $\mathcal{P} = \{p_{b_k}(\mathcal{D}_m), \forall m, b_k \in \mathcal{D}_m\}$. Then We define the allocation vector as $X = [x^{\{b_k\}}(\mathcal{D}_m) : \forall m, b_k \in \mathcal{D}_m]$, then the auctioneer (the eNB) revenue can be expressed as $\Pi(X, \mathcal{P}) = \sum_{b_k, \mathcal{D}_m} [x^{\{b_k\}}(\mathcal{D}_m) \sum_{b_k \in \mathcal{D}_m} p_{b_k}(\mathcal{D}_m)]$, which is usually considered to be the auctioneer's gain.

If given an allocation X, it can easily be shown that the overall gain, which includes the total gain of the auctioneer and all bidders does not depend on the pay prices, but is equal to the sum of the allocated packages' valuations [10], *i.e.*,

$$\begin{aligned} &\Pi(X, \mathcal{P}) + \pi_{all}(\mathcal{D}_m, \mathcal{P}) \\ &= \sum_{1 \le m \le M, b_k \in \mathcal{N}_{NACK}} \left[x^{\{b_k\}}(\mathcal{D}_m) \sum\nolimits_{b_k \in \mathcal{D}_m} p_{b_k}(\mathcal{D}_m) \right] + \sum_{1 \le m \le M} \pi^{\{b_k\}}(\mathcal{D}_m, \mathcal{P}) \\ &= \sum_{1 \le m \le M} \sum_{1 \le k \le N} \left[x^{\{b_k\}}(\mathcal{D}_m) \sum\nolimits_{b_k \in \mathcal{D}_m} p_{b_k}(\mathcal{D}_m) \right] + \sum_{1 \le m \le M} \sum_{1 \le k \le N} x^{\{b_k\}}(\mathcal{D}_m) \left[\upsilon^{\{b_k\}}(\mathcal{D}_m) - \sum\nolimits_{b_k \in \mathcal{D}_m} p_{b_k}(\mathcal{D}_m) \right] \\ &= \sum_{1 \le m \le M} \sum_{1 \le k \le N} x^{\{b_k\}}(\mathcal{D}_m) \upsilon^{\{b_k\}}(\mathcal{D}_m) \end{aligned} \tag{5}$$

As our original intention, we employ the CA to obtain an efficient allocation for D2D relays.

Definition 2. *An efficient allocation is an allocation that maximizes the overall gain. The efficient allocation is denoted by* $X^* = (\mathcal{D}_1^*, \mathcal{D}_2^*, ..., \mathcal{D}_M^*) = \{x^{\{b_k\}*}(\mathcal{D}_m)\}$.

Given the private valuations for all possible bidder packages in Equation (4), the efficient allocation can be obtained by solving the Combinatorial Allocation Problem (CAP) in CA games. Thus, the combinatorial NACK-UEs auction can be formulated as

$$X^{*}=\arg\max_{\{x^{\{b_k\}}(\mathcal{D}_m)\}}\sum_{1\le m\le M}\sum_{1\le k\le N}x^{\{b_k\}}(\mathcal{D}_m)\upsilon^{\{b_k\}}(\mathcal{D}_m)$$
$$\text{s.t.}\quad \sum_{1\le k\le N}x^{\{b_k\}}(\mathcal{D}_m)\le 1,\forall m\in\{1,2,...,M\},$$
$$\sum_{\mathcal{D}_m:b_k\in\mathcal{D}_m}\sum_{1\le m\le M}x^{\{b_k\}}(\mathcal{D}_m)\le 1,\forall k\in\{1,2,...,N\}. \tag{6}$$

We note that the first constraint ensures that at most one bidders package can be allocated to each ACK-UE. The second constraint guarantees that the bidder-overlapping packages can never be assigned. The CAP is also referred to as the winner determine problem, which has been proved that no polynomial time algorithm can be constructed for achieving the reasonable worst case guarantee [12], *i.e.*, the problem is NP hard. In the next section, instead of directly solving the NP-hard CAP in Equation (6), we introduce an approximate solution with a computationally tractable auction process to obtain the efficient NACK-UEs allocation.

4. Combinatorial Auction Algorithm

In this section, we first propose an iterative combinatorial auction mechanism, in which the bid allocation choices are determined by an iterative, multi-round auction process. Then, the auction-based algorithm is described in detail and important properties of the proposed algorithm are analyzed.

Algorithm 1 Algorithm for D2D relay selection

Initialize packages $\mathcal{D}_1,\mathcal{D}_2,...,\mathcal{D}_M$ to be empty set.
Set up the history function of bidder b_k for package is $h_{b_k}(\mathcal{D}_m)=0$, $b_k=b_1,b_2,...,b_N$, $\mathcal{D}_m=\mathcal{D}_1,\mathcal{D}_2,...,\mathcal{D}_M$.
for each $b_k := b_1 \to b_N$ **do**
for each $i_m := i_1 \to i_M$ **do**
    Calculate valuation R_{b_k,i_m} according to (2);
    Bidder b_k submits bids $\{b_k,i_m,R_{b_k,i_m}\}$ for item i_m;
    end for
end for
for each $b_k := b_1 \to b_N$ **do**
    Auctioneer finds the maximum valuation $R^{*}_{b_k,i_m}$ and sells the ACK-UE i^{*}_m to bidder b^{*}_k;
    Allocate b^{*}_k to package $\mathcal{D}_{m^*}$: $\mathcal{D}_{m^*}=\mathcal{D}_{m^*}\cup\{b^{*}_k\}$;
end for
Calculate combinatorial valuation of each package $\upsilon^{\{b_k\}}(\mathcal{D}_m)$ according to (4);
loop until $h_{b_k}(\mathcal{D}_m)=1,\forall b_k,m$:
Initialize $\delta=-\infty$, $\xi=0$;
    for each $b_k := b_1 \to b_N$ **do**
        if $h_{b_k}(\mathcal{D}_m)=1$ **then**
            break;
        else
            Find the package $\mathcal{D}_m$ that b_k is in;
Try to remove b_k from package $\mathcal{D}_m$, and calculate the consequent valuation $\upsilon'^{\{b_k\}}(\mathcal{D}_m)$;
            if $\upsilon'^{\{b_k\}}(\mathcal{D}_m)-\upsilon^{\{b_k\}}(\mathcal{D}_m)>\delta$ **then**

$b_{k^\dagger} \leftarrow b_k$, $\delta = \upsilon'^{\{b_k\}}(\mathcal{D}_m) - \upsilon^{\{b_k\}}(\mathcal{D}_m)$
end if
end if
end for
for each $i_{\widetilde{m}} := i_1 \to i_M, \widetilde{m} \neq m$ **do**
Bidder $b_{k^\dagger}$ submits bid $\{b_{k^\dagger}, i_{\widetilde{m}}, R_{b_{k^\dagger}, i_{\widetilde{m}}}\}$ for another item, the auctioneer calculate valuation $\upsilon'^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}})$;
if $\upsilon'^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}) - \upsilon^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}) > \xi$ **then**
$\mathcal{D}_{m^\dagger} \leftarrow \mathcal{D}_{\widetilde{m}}$, $\xi = \upsilon'^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}) - \upsilon^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}})$;
end if
end for
if $\delta + \xi > 0$ **then**
Update the provisional allocation: $\mathcal{D}_m = \mathcal{D}_m \setminus b_{k^\dagger}$, $\mathcal{D}_{m^\dagger} = \mathcal{D}_{m^\dagger} \cup \{b_{k^\dagger}\}$;
$h_{k^\dagger}(\mathcal{D}_{m^\dagger}) = h_{k^\dagger}(\mathcal{D}_{m^\dagger}) + 1$;
else
break;
end if
end loop

4.1. Algorithm for D2D Relay Selection

At the beginning of the auction, the eNB collects the location information of UEs and gets the channel state information (CSI) for all the links between UEs and the eNB. The bidders, *i.e.*, the NACK-UEs evaluate all their D2D links connecting to the ACK-UEs to obtain their valuations. In the first round, all bidders submit bids for each ACK-UE. Let $\{b_k, i_m, R_{b_k,i_m}\}$ denote the submitted bid by bidder b_k and $\mathcal{V}(b_k)$ the bid equal to its valuation for item k. The auctioneer finds the highest bid $\{b_k^*, i_m^*, R_{b_k,i_m}^*\}$, and sells the ACK-UE i_m^* to bidder b_k^*. Then b_k^* is added to package $\mathcal{D}_{m^*}$. The auction process moves on until all the bidders obtain an item. Then, the auction enters the second round.

In the auction, the ACK-UEs is allowed to be sold more than once, but the bidder can only be allocated one item. That means, at the end of the first round, we can get a provisional allocation $\{\mathcal{D}_1, \mathcal{D}_2, ..., \mathcal{D}_M\}$, in which each element corresponds to a bidder package (possibly empty). To improve the outcome of the first round, the auctioneer adjusts the auction results in the second round. Given each combinatorial valuation $\upsilon^{\{b_k\}}(\mathcal{D}_m)$ calculated according to Equation (2), the available adjustment strategies of the auctioneer and bidders are classified as follows

(1) Try to remove each bidder b_k $(k = 1, 2, ..., N)$ from its package $\mathcal{D}_m$ and calculate the consequent combinatorial valuation $\upsilon'^{\{b_k\}}(\mathcal{D}_m)$.
(2) Find the maximum value from the set $\{\upsilon'^{\{b_k\}}(\mathcal{D}_m) - \upsilon^{\{b_k\}}(\mathcal{D}_m), \forall k = 1, 2, ..., N\}$ and select the corresponding b_k which is marked as $b_{k^\dagger}$.
(3) Bidder $b_{k^\dagger}$ submits bid $\{b_{k^\dagger}, i_{\widetilde{m}}, R_{b_{k^\dagger}, i_{\widetilde{m}}}\}$, and then the auctioneer tries to add the bidder $b_{k^\dagger}$ into package $\mathcal{D}_{\widetilde{m}}$ $(\widetilde{m} \neq m, \widetilde{m} = 1, 2, ..., M)$ and calculates the consequent combinatorial valuation $\upsilon'^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}})$.

(4) Find the maximum value from the set $\{v'^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}) - v^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}), \forall \widetilde{m} = 1,2,...,M\}$ and select the corresponding $\mathcal{D}_{\widetilde{m}}$ which is marked as $\mathcal{D}_{m^\dagger}$.

(5) The auctioneer checks this adjustment for validity. If $v'^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}) - v^{\{b_{k^\dagger}\}}(\mathcal{D}_{\widetilde{m}}) + v'^{\{b_k\}}(\mathcal{D}_m) - v^{\{b_k\}}(\mathcal{D}_m) > 0$, then updates the provisional allocation, *i.e.*, $\mathcal{D}_m = \mathcal{D}_m \setminus b_{k^\dagger}$, $\mathcal{D}_{m^\dagger} = \mathcal{D}_{m^\dagger} \cup \{b_{k^\dagger}\}$, otherwise the above adjustment strategies are invalid.

(6) Combinations of items 1–5.

We define history function $h_{b_k}(\mathcal{D}_m)$, which represents, for every provisional allocation $\widehat{X}$ in the second round, the number of times that bidder b_k is adjusted into the package $\mathcal{D}_m$. Further, we also set a strategy constraint which does not allow each bidder is adjusted into the same package $\mathcal{D}_m$ for more than once, *i.e.*, $h_{b_k}(\mathcal{D}_m) \le 1, \forall b_k \in \mathcal{N}_{NACK}$. The proposed algorithm with a strategy constraint is summarized in Algorithm 1.

4.2. Convergence

Proposition 1: *The proposed algorithm based on the iterative CA with a strategy constraint has the convergence property that the number of the iterations is finite.*

Proof: According to the algorithm, in the first round, NACK-UEs are allocated sequentially. Let us focus on the combinatorial auction in the second round. Suppose that the algorithm does not converge after a limited number of iterations, i.e., after T (positive integer) iterations. In this regard, denoting by X^t the provisional allocation reached at the end of any iteration t, the outcome of proposed algorithm consists of an allocation sequence such as the following:

$$X^0 \to X^1 \to X^2 \to \cdots \to X^t \to \cdots \to X^T \tag{7}$$

According to the pigeonhole principle, there exists an allocation $\widehat{X} = \{\mathcal{D}_1, \mathcal{D}_2, ..., \mathcal{D}_m, ..., \mathcal{D}_M\}$ that occurs more than $T/|\mathcal{X}|$ times, where $\mathcal{X}$ denote the set of all possible allocations. Again, according to the pigeonhole principle, there exists a NACK-UE $b_k \in \mathcal{N}_{\text{NACK}}$ that is allocated to package $\mathcal{D}_m$ for more than $T/(|\mathcal{X}|N)$ times, where $\mathcal{D}_m \in \widehat{X}$. We suppose that $T = |\mathcal{X}|N$. Then after T iterations, a history function $h_{b_k}(\mathcal{D}_m)$ corresponding with the NACK-UE b_k satisfies

$$h_{b_k}(\mathcal{D}_m) > T/(|\mathcal{X}|N) \Rightarrow h_{b_k}(\mathcal{D}_m) > 1 \tag{8}$$

which contradicts our constraint. Thus in the second round, the proposed algorithm with a constraint must converge after T iterations, where T is a finite number.

4.3. Complexity

As mentioned before, a traditional CAP in fact is an NP hard problem, the number of items to be allocated is *M*, and the number of bidders is *N*. For an exhaustive optimal algorithm, an item can be allocated with *N* possible results. Thus, all the *M* items are allocated with N^M possible results. The complexity of the algorithm can be denoted by $\mathcal{O}(N^M)$. In the first round of the proposed algorithm, every channel is evaluated for all D2D pairs, resulting in a computation of $\mathcal{O}(NM)$. In the second round, since each NACK-UE can only be adjusted to the same package no more than once, the complexity is $\mathcal{O}(\sum_j^M N(M-j)) = \mathcal{O}(NM^2)$. Thus, the complexity of the proposed algorithm is $\mathcal{O}(NM^2)$. It is obvious that for sufficient large values of *M* and *N*, a finite number of *T*, a lower complexity is obtained by using the proposed iterative CA scheme. That is, $\mathcal{O}(N^M) > \mathcal{O}(NM^2)$.

4.4. Feedback and Signaling Overhead

In the D2D cluster, each cluster member should have the knowledge of $\mathcal{N}_{\text{ACK}}$ and $\mathcal{N}_{\text{NACK}}$. This can be achieved by employing one of the existing NACK-based feedback schemes [13]. At the same time, as periodical D2D channel probing and estimation are indispensable for any cluster setup and maintenance procedure, we assume that each cluster member is always made aware of the channel state information (CSI) of D2D links connecting itself and the others. The additional information needed in our scheme is CSI between ACK-UEs and NACK-UEs, which is much less than the full D2D CSI maintenance. Then, the following iteration process is all conducted at the eNB, and no signal overhead needs to be exchanged among the network nodes until the control signal forwarding. In addition, the future work on D2D relay selection could consider some mechanism that limits the number of NACK-UEs connecting to the same ACK-UE by distance constraint, sociality constraint, etc, which would obviously help to reduce the overhead.

5. Simulation Results and Discussions

In this section, we provide the simulation results to illustrate the performances of the proposed iterative combinatorial auction algorithm for relay selection (CARS). Besides, we give the necessary analysis for the results. A single cellular cell environment is considered. Without loss of generality, we consider that UEs within a D2D cluster are randomly distributed in the cell. Furthermore, mobility during the data sharing process is not considered in the simulations. The results are averaged over 1000 realizations. Main simulation parameters are listed in Table 1, which are inspired by [8].

Table 1. Main simulation parameters.

Parameter	Value
Cellular layout	one isolated cellular cell
System area	200 m × 200 m
UE distribution	randomly distributed
The exponent for D2D pathloss	4
D2D shadow fading std	6 dB
Noise spectral density	−174 dBm/Hz
UE antenna gain	0 dBi
Channel bandwith	5 MHz
D2D node Tx power	20 dBm
Cluster size	4~12
Realizations	1000

5.1. Performance of Different Algorithms

As a comparison, we compare the performance of our algorithm to other three algorithms. Figures 2–4 show the system sum rate for different relay selection algorithms. The curve marked EORS is simulated by the exhaustive optimal way for relay selection, which guarantees a theoretical top bound of the system sum data rate. The curve marked GHRS is the result of a greedy heuristic algorithm for relay selection in [8], in which each NACK-UE selects the ACK-UE with best D2D link between them as the relay. The complexity for the greedy heuristic is $\mathcal{O}(NM)$. Our algorithm has a higher complexity, but has a much better performance. The last one marked FSRS is the simulation result using the fixed single relay selection strategy in [6], where only one ACK-UE is selected as relay to participate in data retransmission. The selected relay, which can obtain the highest multicast rate amongst all ACK-UEs, multicasts data to all NACK-users.

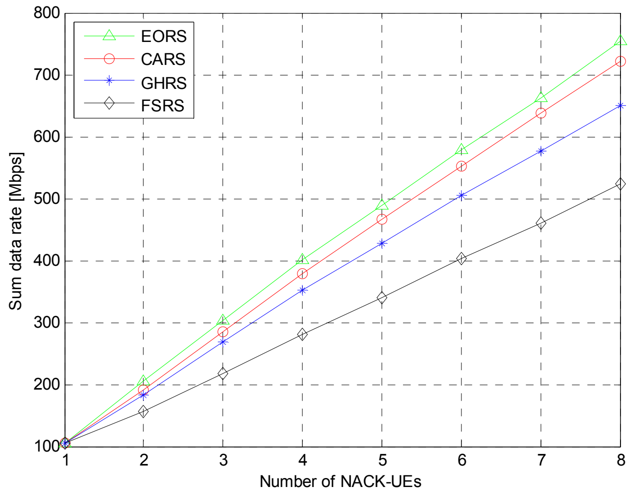

Figure 2. System sum data rate for different relay selection algorithms in the case of 4 ACK-UEs.

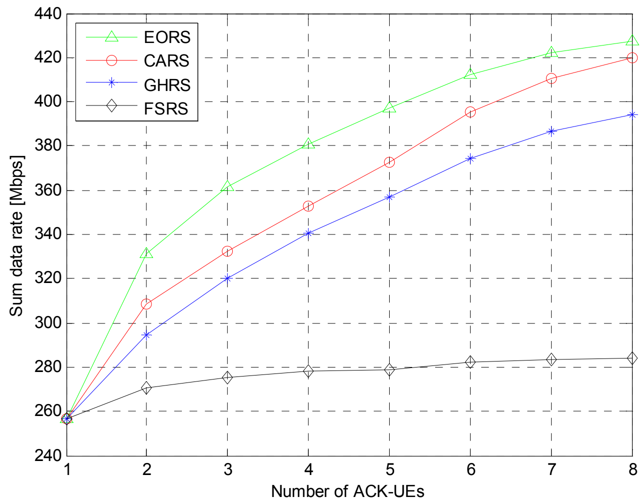

Figure 3. System sum data rate for different relay selection algorithms in the case of 4 NACK-Ues.

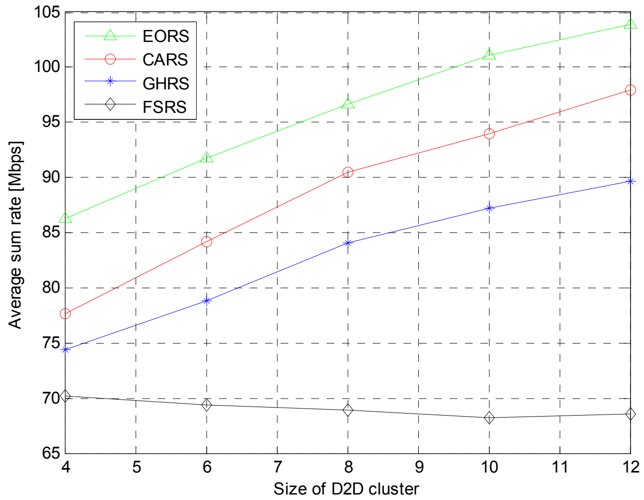

Figure 4. System mean data rate for different relay selection algorithms with different size of D2D cluster, where N_{ACK}:N_{NACK} = 1.

We plot the system sum date rate with different numbers of NACK-UEs and different numbers of ACK-UEs in Figures 2 and 3. Then, we observe that the system sum data rate goes up with both the number of NACK-UEs and the number of ACK-UEs increase. It is obvious as more NACK-UEs request for relays, rising D2D links lead to higher sum data rates. On the other side, as the amount of ACK-UEs increases, the probability of D2D links with better channel conditions being assigned to NACK-UEs enhances, an thus the performance of sum data rate is improved, even though the increase is slow as Figure 3 shows. This phenomenon is similar to the effect of multi-channel diversity. Definitely, ACK-UEs also contribute to the performance.

In addition, we can see that the proposed algorithm CARS is relatively much superior to the FSRS, and with the increase of NACK-UEs and ACK-UEs, the superiority becomes more evident. This is because in the FSRS algorithm, the multicast rate likely suffers a bottleneck due to poorer D2D links between the selected relay and its recipients, and the possibility is greater for the cluster with more NACK-users; while the CARS choose to use multi-relay with good channel conditions capable for high multicast rates, which enjoys more benefits from great independent variations in D2D channels by exploiting multi-channel diversity with more relays. From the simulation results, we also find that the CARS performs better than the GHRS and the absolute performance gap is obviously in the case of 4 ACK-UEs shown in Figure 3 and expands with more NACK-UEs. In other words, when the number of ACK-UEs becomes smaller relative to NACK-UEs, the range of choice of relays becomes narrow, which makes the GHRS suffer a setback. Whereas the CARS can fully exploit the multi-channel diversity gain by adaptively selecting the optimal relays, which contributes to the efficient data delivery. Meanwhile, as the theoretical optimum, the EORS results in the highest system sum rate, but the superiority compared to CARS is quite small, especially when the number of ACK-UEs increases as Figure 3 shows.

In order to further observe the impacts of cluster size on the performance of the proposed algorithm, Figure 4 shows the system mean data rate for different algorithm with various cluster sizes, where the number of ACK-UEs equals to the number of NACK-UEs, *i.e.*, $N_{ACK}:N_{NACK}=1:1$. As observed, all curves go up as the cluster size becomes larger except the OSRS, which indicates the larger cluster size is more beneficial to the proposed algorithm. Moreover, we can see that simulation results by the CARS algorithm are closer to the theoretical top bound than the GHRS algorithm, especially when the cluster size increases as Figure 4 shows. The reason for this phenomenon is that better multichannel diversity can be used to improve with the increase in cluster size, and thus the merit of the CARS algorithm over the other two algorithms becomes more evident.

5.2. System Efficiency

We define the system efficiency as $\mathcal{E} = \mathcal{R}/\mathcal{R}_{\text{opt}}$, where $\mathcal{R}_{\text{opt}}$ represents the exhaustive optimal sum data rate. Figure 5 gives the system efficiency with different numbers of NACK-UEs and different numbers of ACK-UEs. From the simulation result, we can see the lowest value of $\mathcal{E}$ is around 0.94 and the efficiency is stable above 0.94 over different parameters of NACK-UEs and ACK-UEs. It indicates that the proposed algorithm provides high system efficiency, and its performance is close to theoretical optimum. Moreover, the efficiency decreases slightly as the number of NACK-UEs increases. This is due to the limited number of adjustment for bidders such that the combinatorial auction is restricted to only achieving an approximate global optimization.

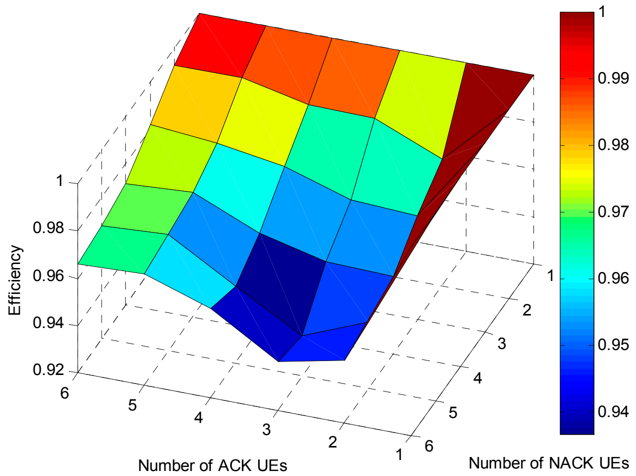

Figure 5. System efficiency: $\mathcal{E}$ with different numbers of NACK-UEs and different numbers of ACK-UEs.

6. Conclusions

D2D communication can be introduced into multicast services in cellular network to improve the transmission performance. In this paper, we investigated the problem of selecting an optimal number of D2D relays within a cluster to efficiently improve system sum data rate. We formulated the optimization problem as a combinatorial auction, and proposed an auction-based relay selection algorithm to allocate D2D relays for NACK-UEs. The proposed algorithm can converge in finite rounds and has low complexity. Simulation results show that the proposed algorithm achieves better performances than the greedy heuristic and the fixed single relay algorithm in terms of sum data rate and mean data rate. In addition, the results show that with different numbers of NACK-UEs and different numbers of ACK-UEs, the proposed algorithm provides high system efficiency.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Afolabi, R.O.; Dadlani, A.; Kim, K. Multicast scheduling and resource allocation algorithms for OFDMA-based systems: A survey. *IEEE Commun. Surv. Tutor.* **2013**, *15*, 240–254.
2. Doppler, K.; Rinne, M.; Wijting, C.; Ribeiro, C.B.; Hugl, K. Device-to-Device Communication as an Underlay to LTE-Advanced Networks. *IEEE Commun. Mag.* **2009**, *47*, 42–49.
3. Pyattaev, A.; Johnsson, K.; Andreev, S.; Koucheryavy, Y. Proximity based data offloading via network assisted device-to-device communications. In Proceedings of the 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), Dresden, Germany, 2–5 June 2013; pp. 1–5.
4. Hakola, S.; Chen, T.; Lehtomaki, J.; Koskela, T. Device-to-device (D2D) communication in cellular network-performance analysis of optimum and practical communication mode selection. In Proceedings of the 2010 IEEE Wireless Communications and Networking Conference (WCNC), Sydney, Australia, 18–21 April 2010; pp. 1–6.
5. Hou, F.; Cai, L.X.; Ho, P.H.; Shen, X.; Zhang, J. A cooperative multicast scheduling scheme for multimedia services in IEEE 802.16 networks. *IEEE Trans. Wirel. Commun*. **2009**, *8*, 1508–1519.
6. Spinella, S.C.; Araniti, G.; Iera, A.; Molinaro, A. Integration of ad-hoc networks with infrastructured systems for multicast services provisioning. In Proceedings of the International Conference on Ultra Modern Telecommunications, St. Petersburg, Russia, 12–14 October 2009; pp. 1–6.
7. Zhou, B.; Hu, H.; Huang, S.Q.; Chen, H.H. Intracluster device-to-device relay algorithm with optimal resource utilization. *IEEE Trans. Veh. Technol*. **2013**, *6*, 2315–2326.
8. Chen, N.; Tian, H.; Wang, Z.; Jiang, L. Intra-Cluster Device-to-Device Multicast Algorithm Based on Small World Model. In Proceedings of the 2014 IEEE 80th Vehicular Technology Conference (VTC Fall), Vancouver, BC, Canada, 14–17 September 2014; pp. 1–5.
9. Cramton, P.; Shoham, Y.; Steinberg, R. *Combinatorial Auctions*; MIT Press: Cambridge, MA, USA, 2005.
10. Pikovsky, A. Pricing and Bidding Strategies in Iterative Combinatorial Auctions. Ph.D. Thesis, Universität München, Germany, 2008.

11. Xu, C.; Song, L.; Han, Z.; Li, D.; Jiao, B. Resource allocation using a reverse iterative combinatorial auction for device-to-device underlay cellular networks. In Proceedings of the 2012 IEEE Global Communications Conference (GLOBECOM), Anaheim, CA, USA, 3–7 December 2012; pp. 4542–4547.
12. Sandholm, T. Algorithm for optimal winner determination in combinatorial auctions. *Artif. Intell.* **2002**, *135*, 1–54.
13. Seppala, J.; Koskela, T.; Chen, T.; Hakola, S. Network controlled Device-to-Device (D2D) and cluster multicast concept for LTE and LTE-A networks. In Proceedings of the 2011 IEEE Wireless Communications and Networking Conference (WCNC), Cancun, Mexico, 28–31 March 2011; pp. 986–991.