A Priced-Deferred Acceptance (p-DA) Technique for D2D Communication in Factories of the Future

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Abstract. The Deferred Acceptance (DA) algorithm has often been used to study spectrum sharing and to solve the assignment problem of Device-to-Device (D2D) links co-existing with traditional cellular users. We present a new reward-based DA algorithm denoted as priced-DA or (p-DA) to improve reuse gains in scenarios where there are variations in the number of cellular users and D2D links and when there are variations in the length of the preference lists. Interference coordination is implemented by jointly managing the power allocation and quality of service (QoS) admission control based on the inter-distances between devices. Simulation case studies demonstrate the advantages of the presented p-DA technique in comparison to other tested centralised approaches.

Keywords: Device-to-Device communication · Game theory · Deferred acceptance

1 Introduction

Device-to-Device (D2D) communication is a promising technology aiming to improve spectrum efficiency and to expand network capacity while adapting to the increasing growth of mobile services and data traffic demands. D2D links are usually in close proximity hence enabling increased data rate, lower latency and lower energy consumption [1]. This makes D2D links ideal to support industrial machine-type and vehicular communication applications [2]. D2D links sharing resources in cellular networks are attractive due to the reuse gain and scarcity of spectrum [3]. However, resource-sharing may result in mutual interference between cellular and D2D users. Centralised methods were investigated previously, where the evolved nodeB (eNB) coordinates interference among the users. The centralised schemes often require global acquisition of channel state information (CSI) which often incurs large signalling overheads and high complexity [4]. Many distributed approaches such as game theory which requires partial

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CSI were also explored. In particular, matching theory has been investigated for allocating cellular resources to D2D users. The deferred acceptance (DA) algorithm was applied to the stable matching problem (a variant of the matching game problem) for resource allocation of D2D users sharing cellular channels and for matching secondary users to primary user channels in cognitive radio networks [5–11]. The deferred acceptance solution to the stable matching problem is typically used for equally-sized opposite sides to be matched. However, the output of the matching may not be optimal in terms of resource sharing if there are variations in sizes of opposite sides and variations in the length of their preference lists.

As an extension to the work presented in [9], this paper studies resource allocation for D2D-links sharing resources with cellular users in a wireless industrial network for factories of the future (FoF). We present a matching game solution denoted as priced-DA (p-DA) which uses a reward-based mechanism to ensure stability and improve resource sharing. The p-DA technique is compared with centralised approaches where no optimisation is implemented in the matching process to reduce complexity and overheads.

The rest of the paper is organised as follows: we present the system model and problem formulation in Sect. 2. We discuss the resource allocation problem in Sect. 3. Examples of case studies and simulation results are presented in Sect. 4. Finally, the main conclusions are presented in Sect. 5.

2 System Model

We consider an industrial factory setting for the uplink of a D2D-enabled cellular network. The network comprises N cellular users (CUEs) denoted by set $C = \{c_1, \ldots, c_i, \ldots c_N\}$ and M D2D users (DUEs) and denoted by set $D = \left\{d_1, \ldots, d_j, \ldots d_M\right\}$ deployed with the coverage of the base station. A set of orthogonal sub-channels are available for spectrum allocation and pre-assigned to the CUEs but can be shared with the D2D links once the minimum QoS CUE-DUE resource-sharing partners are guaranteed. We assume spectrum reuse between DUEs and CUEs in uplink frequency division multiplexing (FDD).

The channel gain $g_{c,B}$, between CUE c_i and the base station, B can be expressed as follows:

$$g_{c,B}{=}C_1\gamma_{c,B}\chi_{c,B}d_{c,B}^{-\beta_1} \triangleq \zeta_{c,B}d_{c,B}^{-\beta_1} \tag{1}$$

where $\zeta_{c,B} = C_1\gamma_{c,B}\chi_{c,B}$, C_1 is the pathloss constant determined by system parameters, $\gamma_{c,B}$ is the small-scale fast fading gain due to multipath propagation and assumed to have an exponential distribution with unity mean. The large-scale fading is composed of pathloss with exponent β_1 and shadowing which has slow fading gain $\chi_{c,B}$ with log-normal distribution. $d_{c,B}$ is the distance between CUE c_i and base station B. The channel gain between DUE link d_j of transmitter d_T and receiver d_R is g_{d_T,d_R}, and channel gain of the interference link from d_T to the base station is $g_{d_T,B}$ and from CUE c_i to DUE d_j receiver is g_{c,d_R}.

The SINR at the received at base station B from CUE c_i and at the DUE d_j receiver d_R can be defined as follows:

$$\xi_{c_i} = \frac{P_{c_i} g_{c,B}}{\sigma^2 + \sum_{d_j \in D} \delta_j^i P_{d_j} g_{d_T,B}} \tag{2}$$

$$\xi_{d_j} = \frac{P_{d_j} h_{d_T,d_R}}{\sigma^2 + \sum_{c_i \in C} \delta_j^i P_{c_i} g_{c,d_R}} \tag{3}$$

where P_{c_i} and P_{d_j} are the transmit powers of CUE c_i and DUE d_j respectively, σ^2 is the power of additive white Gaussian noise of each channel. $\delta_j^i \in \{0, 1\}$ is the resource reuse indicator, $\delta_j^i = 1$ if DUE d_j reuses CUE c_i subchannel and is 0 otherwise.

The reliability of DUE d_j is expressed in terms of the maximum tolerable outage probability, p_0. The outage probability constraint, p_R, is given in (4) where P{.} denotes the probability of the input and $\xi_{d_j,\min}$ is the minimum target SINR for d_j.

$$p_R = \mathrm{P}\left(\xi_{d_j} \le \xi_{d_j,\min}\right) \le p_0 \tag{4}$$

The optimisation objective is to maximise the overall system throughput R. This is formulated as follows using Shannon capacity:

$$\max_{\delta_j^i, P_{c_i}, P_{c_j}} R = B_i\left(\sum\nolimits_{c_i \in C}\left(\log_2\left(1 + \xi_{c_i}\right) + \sum\nolimits_{d_j \in D^{\mathbb{A}}} \delta_j^i \log_2\left(1 + \xi_{d_j}\right)\right)\right) \tag{5}$$

subject to

$$\xi_{c_i} \ge \xi_{c_i,\min} \quad \forall c_i \in C \tag{5a}$$

$$\xi_{d_j} \ge \xi_{d_j,\min} \quad \forall d_j \in D^{\mathbb{A}} \tag{5b}$$

$$\delta_j^i p_R \le p_0 \quad \forall d_j \in D^{\mathbb{A}} \tag{5c}$$

$$\mathrm{P}_{c_i} \le \mathrm{P}_{c_i,\max} \quad \forall c_i \in C \tag{5d}$$

$$\mathrm{P}_{d_j} \le \mathrm{P}_{d_j,\max} \quad \forall d_j \in D^{\mathbb{A}} \tag{5e}$$

$$\sum\nolimits_{c_i \in C} \delta_j^i \le 1 \quad \forall d_j \in D^{\mathbb{A}} \tag{5f}$$

$$\sum\nolimits_{d_j \in \boldsymbol{D}^{\mathbb{A}}} \delta_j^i \le 1 \quad \forall c_i \in C \tag{5g}$$

where B_i is the bandwidth, $D^{\mathbb{A}}$ ($D^{\mathbb{A}} \subseteq D$) denotes the set of acceptable DUEs, $\xi_{c_i,\min}$ and $\xi_{d_j,\min}$ is the minimum SINR for c_i and d_j respectively. $\mathrm{P}_{c_i,\max}$ and $\mathrm{P}_{d_j,\max}$ denote the maximum transmit powers of c_i and d_j respectively.

The minimum QoS of the CUEs and DUEs are given in constraints 5(a)–5(c). The minimum SINR requirements for c_i and d_j respectively are defined 5(a) and 5(b). The reliability requirement for a valid matching between c_i and d_j is defined in 5(c). Constraints 5(d) and 5(e) are to ensure that the transmit of powers of c_i and d_j does not exceed the permitted limits. Constraints 5(f) and 5(g) guarantee a one-to-one pairing between CUEs and DUEs.

The optimisation problem in (5) is a Mixed Integer Non-linear Programming (MINLP) which is NP-hard and cannot solved directly. The solution to the problem is obtained by decomposing it into sub-problems as described in the section that follows.

3 The Resource Allocation Problem

3.1 QoS Admission and Power Allocation

The QoS admission and power allocation is similar to the joint admission and power control (JAPC) presented in [9]. For a CUE c_i to share resources with a DUE d_j, constraints 5(a) to 5(e) must be satisfied. Considering the inter-distances between the devices while relaxing the channel allocation constraints, (6) is obtained as follows.

$$\begin{cases} d_{d_T,B} \geq \left(\frac{P_{d_j} \xi_{c_i,\min} \zeta_{d_T,B}}{P_{c_i} \zeta_{c,B} - \sigma^2 \xi_{c_i,\min} (d_{c,B})^{\beta_1}} \right)^{\frac{1}{\beta_2}} \left(d_{c,B}\right)^{\frac{\beta_1}{\beta_2}} \\ d_{c,d_R} \geq \left(\frac{\xi_{d_j,\min} \left[P_{c_i} \zeta_{c,d_R} + \sigma^2 (d_{c,d_R})^{\beta_3} \right]}{P_{c_i} \zeta_{d_T,d_R}} \right)^{\frac{1}{\beta_4}} \left(d_{d_T,d_R}\right)^{\frac{\beta_3}{\beta_4}} \end{cases} \tag{6}$$

Setting $\beta_1 = \beta_2$ and $\beta_3 = \beta_4$, (6) implies the distance of the interfering link should be greater than the distance of the intended signal link. The power allocations for which (6) is valid are determined next. The power pair extrema values that can be assigned to c_i and d_j while satisfying (6) are given in 7a, 7b, 7c and 7d.

$$\mathrm{P}_{c_i,\min} = \frac{\xi_{c_i,\min}\left(\sigma^2 + g_{d_T,B} \mathrm{P}_{d_j,\max}\right)}{g_{c,B}} \tag{7a}$$

$$\mathrm{P}^{c}_{d_j,\max} = \frac{g_{c,B} \mathrm{P}_{c_i,\max} - \sigma^2 \xi_{c_i,\min}}{g_{d_T,B} \xi_{c_i,\min}} \tag{7b}$$

$$\mathrm{P}_{d_j,\min} = \frac{\xi_{d_j,\min}\left(\sigma^2 + g_{c,d_R} \mathrm{P}_{c_i,\max}\right)}{g_{d_T d_R}} \tag{7c}$$

$$\mathrm{P}^{d}_{c_i,\max} = \frac{g_{d_T d_R} \mathrm{P}_{d_j,\max} - \sigma^2 \xi_{d_j,\min}}{g_{c,d_R} \xi_{d_j,\min}} \tag{7d}$$

The set of transmit power extrema for c_i and d_j is represented by P_c and P_d respectively.

$$P_c = \left\{ \mathrm{P}_{c_i,\max}, \mathrm{P}^{d}_{c_i,\max}, \mathrm{P}_{c_i,\min} \right\} \tag{8a}$$

$$P_d = \left\{ \mathrm{P}_{d_j,\max}, \mathrm{P}^c_{d_j,\max}, \mathrm{P}_{d_j,\min} \right\} \tag{8b}$$

The set P_{cd} denotes the Cartesian product of P_c and P_d which gives the possible set of power pairs for c_i and d_j to share the same sub-channel. The invalid power pairs are eliminated from P_{cd}. A power pair is invalid if any of the transmit powers in the pair exceed maximum transmit power. $P^{\iota nv}_{cd}$ represent the set of invalid power pairs, P^v_{cd} denote the set of valid power pairs.

$$P^v_{cd} = P_{cd} - P^{inv}_{cd} \tag{9}$$

Next, we obtain the set of power pairs, $P^{\xi\min}_{cd}$, for which the minimum SINR threshold values for c_i and d_j are satisfied. The reliability constraint is then evaluated as the outage probability of DUE d_j conditioned on the selected CUE c_i and expressed as [12]. P^R_{cd} ($P^R_{cd} \subseteq P^{\xi\min}_{cd}$) is the set of power pairs for which minimum outage probability of d_j is satisfied. Therefore, CUE c_i and DUE d_j are potential resource-sharing partners if $P^R_{cd} \neq \emptyset$.

The optimal power allocation that maximises the sum throughput subject to the minimum QoS constraints is given as (10)

$$(P^*_{c_i}, P^*_{d_j}) = \arg \max_{(\mathrm{P}_{c_i}, \mathrm{P}_{d_j}) \in P^R_{cd}} B_i(\log_2(1 + \xi_{c_i}) + \log_2\left(1 + \xi_{d_j}\right)) \tag{10}$$

Having identified the resource-sharing CUE-DUE pairs that guarantees the minimum QoS requirements and the optimal power assignments to maximise sum rate, the optimal reuse partner for the CUEs $\forall c_i \in C$ is then determined. $S^d_{c_i}$ be the set of acceptable DUEs for CUE c_i and $S^c_{d_j}$ be the set of CUEs that d_j can share resources with. $C^{\mathbb{A}}$ and $D^{\mathbb{A}}$ is the set of all eligible CUEs and acceptable DUEs respectively.

3.2 Priced Deferred Acceptance Game Solution

The resource allocation problem is modeled using the structure of the Stable Marriage Problem (SMP), a one-to-one two-sided matching game approach. The players are a set of eligible CUEs $C^{\mathbb{A}}$ and a set of acceptable DUEs $D^{\mathbb{A}}$ with preference profiles with which they construct their lists of preference partners. The output of the game is the matching of a DUE to a CUE channel.

Utility Function and Preference Profile

The utility that $c_i \in C^{\mathbb{A}}$ generates from sharing its subchannel with DUEs $d_j \in S^d_{c_i}$, is its throughput and given as $u_{c_i}\left[d_j\right]$ whereas the utility that any eligible DUE $d_j \in D^{\mathbb{A}}$ obtains from reusing subchannel of CUE $c_i \in S^c_{d_j}$ is its throughput when paired with the CUE and denoted as $u_{d_j}[c_i]$. $\forall c_i \in C^{\mathbb{A}}$ define a strict preference relation $\succ_c$ over a set of DUEs $S^d_{c_i} \subseteq D^{\mathbb{A}}$ such that $d_1 \succ_{c_i} d_2 \Leftrightarrow u_{c_i}[d_1] > u_{c_i}[d_2]$ implies that c_i prefers d_1 to d_2. Similarly, $\forall d_j \in D^{\mathbb{A}}$, a strict preference relation $\succ_d$ is defined over a set of CUEs $S^c_{d_j} \subseteq C^{\mathbb{A}}$ such that $c_1 \succ_{d_j} c_2 \Leftrightarrow u_{d_j}[c_1] > u_{d_j}[c_2]$ implies that d_j prefers c_1 and c_2. $\forall c_i \in C^{\mathbb{A}}$ and $\forall d_j \in D^{\mathbb{A}}$ can construct their preference list $P\ell_{c_i}$ and $P\ell_{d_j}$ by ordering $S^d_{c_i}$ and $S^c_{d_j}$ respectively, giving precedence to ones that provides better utility.

Definition: For $n \neq m$, $\exists c_i \in C^{\mathbb{A}}$ for which $\left|P\ell_{c_i}\right| = 1 = \left\{d_j\right\}$ and $c_i \neq \max P\ell_{d_j}$, then $\mu(c_i) = \emptyset$. This implies that if there exist a CUE c_i with only one potential DUE partner d_j in its preference list, and c_i is not the most preferred by d_j then c_i will be unmatched at the output μ. Consequently, the output of the matching may not be optimal in terms of resource-sharing using the traditional DA method as some eligible CUE(s) might not be paired with a suitable partner. To address this challenge and maximise number of eligible CUEs sharing their sub-channels, a 'priced' Deferred Acceptance (p-DA) is presented.

It is assumed that each active UE is charged with a connection fee that corresponds to the achieved data rate. Denote Φ_{c_i} and Φ_{d_j} represent the price charged per connection for the CUEs and DUEs respectively.

$$\begin{cases} \Phi_{c_i} = \pi B_i \log_2(1 + \xi_{c_i}) \\ \Phi_{d_j} = \pi B_i \log_2(1 + \xi_{d_j}) \end{cases} \tag{11}$$

where π is the price per unit rate and assumed to be uniform for all the UEs. Therefore, the total revenue generated by the BS is given by (12).

$$u_B(\Phi) = \sum\nolimits_{c_i \in C} \Phi_{c_i} + \sum\nolimits_{d_j \in D^{\mathbb{A}}} \Phi_{d_j} \tag{12}$$

with $1 \leq i \leq N$ and $1 \leq j \leq D_{DA}$, where D_{DA} is the number of admitted DUEs.

To increase the number of CUE-DUE matching and DUE access rate, $d_j \in D^{\mathbb{A}}$ considers the size of the preference list $P\ell_{c_i}$, of $\forall c_i \in C^{\mathbb{A}}$ that proposes at each iteration round and gives precedence to the highest ranked CUE with the least length of $P\ell_{c_i}$. This is because the larger the length of $P\ell_{c_i}$, then $c_i \in C^{\mathbb{A}}$ will have more DUEs to propose to after being rejected in a previous round of proposals and vice versa. At iteration r, $\forall d_j \in D^{\mathbb{A}}$ will consider the proposal of the highest ranked CUE with least length of preference list at iteration $r+1$, $\left|P\ell_{c_i}^{(r+1)}\right|$, defined in (13)

$$\left|P\ell_{c_i}^{(r+1)}\right| = \left|P\ell_{c_i}^{(r-1)}\right| - d_j^{(r)} \tag{13}$$

The stability of the matching is ensured by using a reward-based mechanism to balance the utility loss of d_j. Since utility is in terms of the achieved rate, d_j will demand from the BS, a reduction in its price which is equivalent to its rate loss from being matched with c_i rather than $\mathrm{c}_i^{'}$ else d_j will deviate from the matching.

$R_{d_{j,}}[c_i]$ and $R_{d_{j,}}\left[\mathrm{c}_i^{'}\right]$ denote of the achieved rate from $(c_i d_j)$ and $\left(\mathrm{c}_i^{'} d_j\right)$ pairing respectively. The rate loss of d_j is given τ and the price of the rate loss is given as follows:

$$\tau = R_{d_{j,}}\left[\mathrm{c}_i^{'}\right] - R_{d_{j,}}[c_i] \tag{14}$$

$$\Phi_{\mathcal{L}} = \pi\tau \tag{15}$$

The p-DA algorithm is summarised as follows.

p-DA Algorithm

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Input $C^{\mathbb{A}}$, $D^{\mathbb{A}}$, $S^{d}_{c_i}$ $\forall c_i \in C^{\mathbb{A}}$, $S^{c}_{d_j}$ $\forall d_j \in D^{\mathbb{A}}$ and $(P^{*}_{c_i}, P^{*}_{d_j})$ for potential $(c_i, d_j)$ matching.
Set up the preference list of eligible CUEs, $P\ell_{c_i}$, by ordering the DUEs with
    $u_{c_i}[d_j] = B_i \log_2\left(1 + \frac{P^{*}_{c_i} g_{c,B}}{\sigma^2 + P^{*}_{d_j} g_{d_{T,B}}}\right), \forall c_i \in C^{\mathbb{A}}$
Set up the preference list of acceptable DUEs, $P\ell_{d_j}$, by ordering the CUEs with
    $u_{d_j}[c_i] = B_i \log_2\left(1 + \frac{P^{*}_{d_j} g_{d_T, d_R}}{\sigma^2 + P^{*}_{c_i} g_{c, d_R}}\right), \forall d_j \in D^{\mathbb{A}}$
Set up a list of unpaired CUEs $U_c = \{c_i : \forall c_i \in C^{\mathbb{A}}\}$
while $U_c \neq \emptyset$ do
    $c_i$ proposes and sends $\left|P\ell_{c_i}{}^{(r+1)}\right|$ to its highest ranked $d_j \in D^{\mathbb{A}}$ that it has not proposed to in its preference list, $\forall c_i \in U_c$
    if $\forall d_j \in D^{\mathbb{A}}$ that receives a proposal from $c_i \in U_c$, $c_i$ is the more preferred CUE with the least preference list, $\left|P\ell_{c_i}{}^{(r+1)}\right|$, compared to its current match $c''_i$ and $c'_i$ is the most preferred CUE then
        $d_j$ holds the proposal of $c_i$ and rejects $c'_i$ and $c''_i$;
        $U_c = U_c - c_i$;
        $U_c = U_c + c'_i$;
        $U_c = U_c + c''_i$;
        $d_j$ obtains its rate loss, $\tau = R_{d_{j,}}[c'_i] - R_{d_{j,}}[c_i]$;
    else
        $d_j$ rejects $c_i$ and remain matched to $c''_i$;
    end if
end while
output matching $\mu$
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4 Example Case Studies, Simulation Results and Discussion

The performance of the presented algorithm is verified for an industrial factory setting. The simulation scenario and channel models used is as depicted in [9]. It is assumed that CUEs have been pre-assigned a sub-channel each. The performance of the algorithm is evaluated using the achieved data rates and number of admitted DUEs (or DUE access rate) which is an indication of the number of shared channels. The random approach and the first feasible assignment (FFA) adopt a centralised approach in which the centralised controller matches a DUE to an eligible CUE once the minimum QoS criteria are met. No optimisation is considered in the matching. The Random approach matches a CUE to any random DUE while FFA matches a CUE to the first available DUE.

In Fig. 1, we compare the number of admitted DUEs, D_{AD}, for the three algorithms with $N = 50$ and varying M from 10% to 100% of N. D_{AD} remains constant when resource-sharing is not possible due to the violation of QoS requirements as illustrated at $M = 10$ and $M = 20$ for the three algorithms shown. D_{AD} increases as more valid CUE-DUE matchings are established. The p-DA algorithm achieves 12.5% to 14.28% increase in D_{AD} in comparison to the FFA scheme and 28.57% increase compared with random algorithms for $M > 30$ in particular. As the number of DUEs, M, increases, when $D_{AD} = N$, the network gets saturated and no DUE will be able to access a sub-channel as more DUEs are introduced to the system.

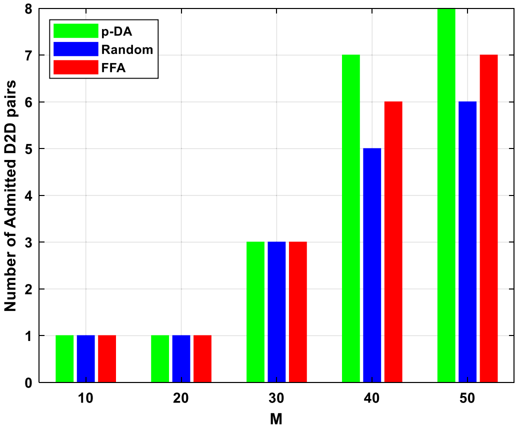

Fig. 1. The number of admitted DUEs, D_{AD} as a function of the number of DUEs, M in the network where $N = 50$, $\mathrm{P}_{c_i,\max} = 23$ dBm

The number of admitted DUEs, D_{AD}, directly influences the throughput performance. In Fig. 2, we show the total DUE throughput with respect to M. Random allocation achieves the least performance as expected followed by the FFA algorithm. The performance of p-DA is comparable to the centralised optimisation approach. The p-DA algorithm achieves 9.67% to 14.55% increase in DUE throughput in comparison to the FFA scheme and up to 28.02% random algorithms for $M > 30$ in particular.

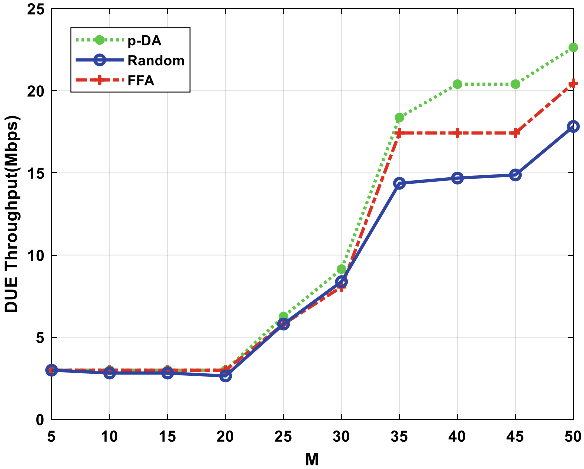

Fig. 2. The total DUE throughput with different number of DUEs, M in the network where $N = 50$, $\mathrm{P}_{c_i,\max} = 23$ dBm

In Fig. 3, it is shown that the overall system throughput performance increases with M. The p-DA approach achieves a better performance compared with the random and FFA approaches. The performance of p-DA and FFA algorithms are close however, significant differences are apparent as $M > 35$, where the p-DA scheme shows an improved system throughput.

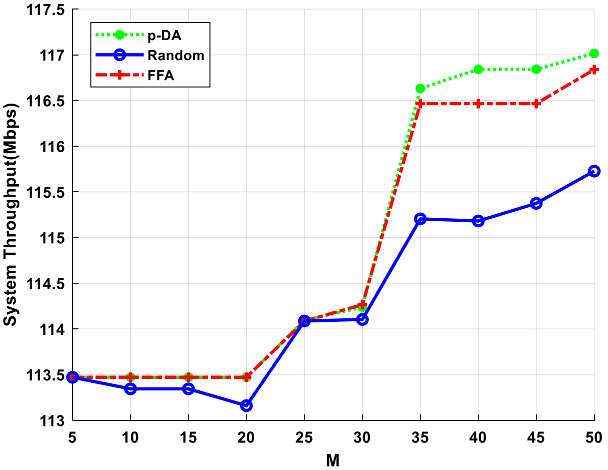

Fig. 3. System throughput with different number of DUEs, M in the network where $N = 50$, $\mathrm{P}_{c_i,\max} = 23$ dBm

5 Conclusions

In this paper, a priced-deferred acceptance (p-DA) algorithm was presented for a D2D-enabled cellular network targeting wireless industrial scenarios for factories of the future (FoF). The p-DA uses an incentive-based mechanism to ensure stability and improve resource-sharing between cellular and D2D links. Simulations results show that the presented p-DA scheme enhances the D2D throughput performance and reuse gain with lower complexity and signalling overhead compared to the FFA and random allocation schemes. This is because the latter techniques adopt a centralised approach which requires global acquisition of channel information while the p-DA scheme is a distributed approach which relies on local information. Our future work aims at comparing the performance of the presented p-DA game theoretic technique to machine learning approaches.

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