Performance Analysis of Online Matching Algorithms for D2D Communications

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***Abstract*—In this paper, we consider a Device-to-Device (D2D) cellular network in which idle users can work as relays between cell users and the base station to improve their data rate. The relaying induces a cost for the User Equipment Relays (UER), that should be compensated with a payment from the mobile operator so that UERs accept to offer the service. The problem hence arises for the operator to match cell users and UERs at a reasonable cost and increasing the data rate. In this context, we consider the requirements of truthfulness, budget feasibility and acceptance of online scenarios to compare ON algorithm, which considers all constraints, with other three algorithms that were not built to respect all of them, Hungarian, Threshold and Online Weighted Knapsack (OWK). We observed that ON algorithm is the best in terms of execution time; however, it does not scale well considering the number of matched edges, requiring modifications in its selection criteria. In addition, we noticed that OWK algorithm has appealing properties and, if it were modified to be truthful and to reduce its complexity, it would present the best results.**

I. Introduction

The usage of mobile devices such as smartphones and tablets for Internet access has increased significantly in the past few years and, by 2020, it is expected to reach 9 billion of devices [1]. Thereby, the number of mobile broadband subscriptions is also growing, and it should be greater than 7.7 billion by 2021, representing 85% of all broadband subscriptions [1]. Moreover, requirements such as the assurance of Quality of Service (QoS) and high data rates will become progressively important as the number of mobile users increases [2]. The development of social networks, in which everyone is an information source, tends to balance traffic in uplink and downlink, so that high uplink data rates are required.

The Fifth Generation Mobile Communication System (5G) is being developed to meet theses requirements [3]. When comparing to the current use of cellular networks approach, it is expected that it will present a volume of data transmission increased 1000 times and data rates 10 to 100 times higher [4]. An important 5G feature is the usage of Heterogeneous Cellular Networks (HetNet), which aims to provide larger coverage and higher user throughput [5]. One of its features is the use of cooperative relays to retransmit traffic of active users (UE - User Equipment) in the cell. Two different approaches have been studied in the past years to provide this type of communication, using fixed relays or idle users as relays. In this paper, we analyze algorithms that can be used in the second scenario, where a cooperative relay communication using idle users as relays. For this means, operator can deploy Device-to-Device (D2D) communication in its network. This technology is defined as the direct communication between two devices in a cell, without the Base Station (BS) intermediation [6]. Thus, a User Equipment Relay (UER) can be used to retransmit the data of other UE in the cell. With D2D communication as an underlay tier, we can improve the UE performance and also the cellular coverage [6].

In this paper, we analyze a scenario in which mobile devices called User Equipment Relay (UER) retransmit the uplink traffic of active cell users to the BS. We consider that each UER provides one channel for relaying, *i.e.* it can work as relay for a single UE at a time. The relaying is characterized by a single hop with a utility for the network and a cost for the UER. The utility represents the data rate improvement when considering the relay mode in respect to the direct mode. The cost indicates the resources used for retransmission, *i.e.* the energy consumed or an additional processing cost when relaying. In our model, the mobile network operator provides incentives for devices to act as UER by providing a payment for their relaying. The problem then arises for the operator to choose whether to match UERs to cell users or leave them permanently unmatched so that the global utility of the network increases at a reasonable cost. Further requirements are also important to calculate the final matching, such as truthfulness (UERs should report their true cost to the network), budget feasibility (the operator has a maximum budget for the payments) and the possibility to match UERs and UEs on the fly. Several algorithms have been proposed in the literature to calculate the matching of bipartite graphs in different contexts; however, few take into consideration all these requirements in a D2D communication. Vaze and Coupechoux in [7] propose an online algorithm called ON considering all requirements considering explicitly the context of D2D communication.

This paper formulates the D2D communication with UERs as a matching problem, and presents comparative analyses based on simulations of algorithms that consider different requirements when calculating the final matching. These algorithms are the Hungarian [8], Threshold [9], Online Weighted

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Knapsack [10] and ON [7] algorithms. These evaluations intend to verify the functionality of these algorithms in the specific scenario of D2D communication, as well as the influence of each requirement in the calculated matching and in the execution time performance. Moreover, we analyze ON algorithm actual advantages when compared to the other algorithms that do not consider all requirements. Final matching and scalability are analyzed for the comparison of the algorithms. The paper is structured as follows: related work is presented in section II, section III presents the different algorithms, section IV presents the system model, simulation results are shown in section V, and section VI concludes the paper.

II. Related Work

D2D communication has been analyzed to find solutions for some problems in today's cellular network. Several algorithms were proposed in order to validate this type of communication considering different requirements. Some of these algorithms were studied and simulated to understand their performance or to compare them to other algorithms. Nevertheless, algorithm studies considering different requirements in D2D communication have not been extensively evaluated.

Hungarian and Greedy algorithms are well-known algorithms for finding optimal or good matchings in bipartite graphs; therefore, there are many studies on their performance. Kim et al. compare in [11] Greedy, an improved Greedy and a modified Hungarian method. In addition, Niyato et al. analyze and compare in [12] Hungarian algorithm on the context of subcarrier and rate allocation in multirate Orthogonal Frequency-Division Multiple Access (OFDMA), verifying the performance in different scenarios, such as average total transmission rate, throughput and average delay.

In a crowdsourcing context, Goel et al. present UniformMechanism in [9], which was used as basis for Threshold algorithm by Vaze and Coupechoux in [7] for D2D communication. In these papers, they evaluate through simulations the algorithms performance both with simulated data and with realistic values resulting from a case usage, verifying the reported costs and the total utility of the matching.

Babaioff et al. present in [10] another matching algorithm, Online Weighted Knapsack algorithm, with the aim of solving the knapsack and secretary problems. They analyze it mathematically; however, the authors do not verify its complexity. In addition, they do not run simulations to test whether it works in realistic applications or not, and they do not verify its scalability considering its functionalities and execution time.

In [7] and [13], the authors apply the algorithms proposed to calculate the matching in the context of D2D communication when UER can be used to relay traffic of active users. Vaze and Coupechoux in [7] present mathematical studies to prove the algorithms performance; nevertheless, no simulations are run in order to verify its true functionality nor to compare it with other algorithms. Furthermore, Vaze in [13] simulates a new version of ON algorithm, which is called ON-TRUTH with improved competitive ratio, and he does not compare its results to ON.

III. Algorithms

The algorithms studied in this paper have been selected to verify the influence of three requirements that were proposed by Vaze et al. in [7]:

- Truthfulness: UERs do not misreport their cost;
- Budget feasibility: the total payment offered to UERs is at most the budget specified by the mobile network operators system;
- Online: the system does not have any information about UERs before their arrival in the cell.

Operators need a matching algorithm to select UERs or leave them permanently unmatched that can comply with all of these requirements so that they can guarantee that the budget is respected in a real-life scenario.

A. Hungarian Algorithm

The Hungarian algorithm [8] finds the matching that maximizes the total weight of a bipartite graph. D2D communication can use this algorithm to select the maximum matching considering utility as the graph weight. Moreover, we assume that the payment offered by the system is set as the UERs cost, but it is not considered when calculating the final matching.

It is an offline algorithm, *i.e.* we consider that it has information about the UERs at any time. In addition, it is not budget feasible, because it pays the UERs the same amount that it reported as its cost, and it is not possible to control whether UERs report their true cost or not.

B. Threshold Algorithm

Threshold algorithm [7] is based on UniformMechanism [9], and was built to calculate the matching of a complete bipartite graph with the highest utility, considering the budget constraint in an offline scenario. In addition, UERs cost is taken into account to calculate the optimal matching. It is truthful and budget feasible, but it is offline [7].

C. Online Weighted Knapsack Algorithm

The Online Weighted Knapsack (OWK) algorithm [10] is based on the knapsack secretary problem to find the optimal matching of a complete bipartite graph considering the edges and nodes weight, *i.e.* the utility and the cost. As in the secretary problem, it creates in the offline phase a selection criteria with the information of a set of UERs that will not be matched, and then applies it to the subsequent elements observed in the online phase. It was constructed to respect the budget constraint by selecting UERs that report cost under a virtual budget, as showed in [10]. As there is no payment in OWK, we allocate as a payment the reported cost. OWK is thus not truthful.

TABLE I
COMPARISON BETWEEN MATCHING ALGORITHMS.

Algorithm	Truthfulness	Budget Feasibility	Online
Hungarian	X	X	X
Threshold	$\surd$	$\surd$	X
Online Weighted Knapsack	X	$\surd$	$\surd$
ON	$\surd$	$\surd$	$\surd$

D. ON Algorithm

ON algorithm was developed by Vaze and Coupechoux in [7] to be an algorithm that finds the matching of a complete bipartite graph and respects the requirements of truthfulness, budget feasibility and acceptance of online scenarios. As an online algorithm, it also uses the paradigm of sampling a fraction of the UERs to use their information to define a selection criterion in the offline phase, which indicates whether the subsequent UERs arriving in the cell during the online phase should be selected or not. Therefore, it is composed of an offline (or learning) phase and an online phase. During its learning stage, it uses Threshold algorithm to calculate the selection criterion. Vaze and Coupechoux prove mathematically in [7] that ON is both truthful and budget feasible.

E. Comparison

Table I presents a comparison between the main characteristics of the analyzed algorithms. It compares them according to the constraints that are considered ($\surd$) or not (X) by the algorithms, as reported by literature.

The Hungarian algorithm does not take into account any of the requirements, being offline, not truthful nor budget feasible, although it maximizes utility sum; the Threshold algorithm is also offline, but it was constructed to be both truthful and budget feasible; the OWK algorithm is online and budget feasible, but it was not built to consider the truthfulness, and the ON algorithm is the only one that was constructed to respect all constraints. These four algorithms were chosen in order to verify the impact that each constraint has on the matching, execution time, total cost and total utility.

IV. SYSTEM MODEL

A. D2D Relaying

We consider the retransmission with one relay of uplink traffic in a single cell served by a BS b. Let U be the set of active users in the cell, *i.e.* UEs willing to transmit data to the BS. The set U is known to the operator. Let R be the set of UERs, who are potential D2D relays for the cell users in U (they have registered to the operator for this service). We assume that a UER can retransmit the data of a single UE at a time to the BS. In an offline setting, the set R is known to the operators system, which is performing the matching. In an online setting, UERs arrive in the cell sequentially in time and the system matches (or not) UERs at their time arrival without any delay.

If a UER $r \in R$ is matched to a UE $u \in U$, it uses its own resources; thus, we consider that relaying induces a cost c_r. This cost is a private information and is independent on the UE to which it is matched, for instance, it can be the power a UER would provide for relaying. In order to create incentives for its service, the operator offers r a payment p_r greater or equal to its cost, $p_r \geq c_r$. This payment can be represented by a monetary transfer or other commercial benefits for the UER. Furthermore, the operator has a maximum budget B for its service, so that the sum of all payments is less or equal to B, $\sum p_r \leq B$.

In this paper, we consider that the UER uses a single channel for retransmission. Therefore, the D2D communication system is modeled as a bipartite graph $G(R \cup U, E)$, where E is the set of edges $e = \{(u,r), u \in U, r \in R\}$ and represents possible connections between active UEs and UERs in the cell. Each of these edges has a weight represented by a utility w_{ur}.

B. Relaying Model

Considering a single relay channel involving an active user u as a source, a UER r that relays its traffic and a BS b as a destination, the data rate of the direct transmission R_{ub} and the data rate R_{ur} of a D2D relayed transmission can be calculated as [14]:

$$R_{ub} = f\Big(P'_u/\sigma^2\Big), \tag{1}$$

$$\begin{aligned} R_{ur} = \max_{0 \leq \alpha \leq 1} \min \Bigg\{ & f\Big(\alpha g_{ur} P_u/\sigma^2\Big), \\ & f\Big((P'_u + P'_r + 2\sqrt{(1-\alpha)P'_u P'_r})/\sigma^2\Big)\Bigg\} \end{aligned} \tag{2}$$

where $f(x) \triangleq \frac{1}{2}\log_2(1+x)$, $g_{ij} = 1/pl_{ij}$ is the channel gain between $i \in \{u,r\}$ and $j \in \{r,b\}$, pl is the path loss, σ^2 is the noise power, $P'_u = P_u g_{ub}$, $P'_r = P_r g_{rb}$, and P_u and P_r are the transmit powers of UE u and UER r, respectively. Relaying is efficient if and only if $R_{ur} - R_{ub} \geq 0$.

C. Utility and Cost Models

The utility w_{ur} of an edge $e = (u,r) \in E$ is used in the algorithms as the graph weight. It represents the advantage of using the D2D relaying rather than the direct communication. If $R_{ur} - R_{ub} \leq 0$, utility is of course null. Otherwise, there are several approaches to define utility. In this paper, without loss of generality, we define utility as follows:

$$w_{ur} = \max\{0, 1/R_{ub} - 1/R_{ur}\}. \tag{3}$$

This can be interpreted as a reduction in the cell load for the operator, or, alternatively, as a gain in delay for the UE.

Again without loss of generality, we define the cost for UER r as follows:

$$c_r = P_r, \tag{4}$$

where P_r is in dBm. What is important here is the fact that this cost does not depend on the UE to which r is matched and that P_r is freely chosen by the UER.

TABLE II
SIMULATION PARAMETERS.

Parameter		Value
Cell radius		200 m
Spectrum bandwidth		20 MHz
Power Spectral density		-174 dBm/Hz
UER power / UER cost		[0;23] dBm
UE power		23 dBm
Total budget		$10.5N_r$ dBm
Final matching simulation	UEs	10
	UERs	10
Truthfulness simulation	UEs	10
	UERs	10
Scalability simulation	UEs	10 to 110
	UERs	10 to 110

V. SIMULATIONS

The Hungarian, Threshold, OWK and ON algorithms were implemented and simulated on MATLAB to analyze and compare the results of each one.

A. Simulation Parameters

We consider the uplink of a small cell covering a disk of radius $R_C = 200$ m. Two types of communication used in the system: user-to-BS and user-to-user. The first comprises the communication between UE or UER and BS, and we can assume that the propagation model for this communication is the Long Term Evolution (LTE) model. From [15], we have that the path loss (PL) in dB for the user-to-BS communication on a Urban Micro (UMi) NLOS hexagonal cell layout is given by (5).

$$PL = 36.7\log_{10} d + 22.7 + 26\log_{10} f_c \quad (5)$$

where d is the distance between user and base station that should be $10\text{m} < d < 2000\text{m}$, and $f_c = 2.6\text{GHz}$ is the carrier frequency. The user-to-user communication propagation model is taken from [16] and the PL in dB can be calculated by (6).

$$PL_{ur} = \max\{PL_1(d), PL_2(d)\} \quad (6)$$

where $PL_1(d) = 19.38 + 23\log_{10}(f_c) + 5.83\log_{10}(h_{BS}) + (44.9 - 6.55\log_{10}(h_{BS}))\log_{10} d$, $h_{BS} = 1.5$ m [17], $PL_2(d) = 46.4 + 20\log_{10} d + 20\log_{10}(f_c/5)$ [18].

The system bandwidth is $W = 20$ MHz and its noise power is calculated by $\sigma^2 = N_0 W$, where N_0 is the power spectral density, set as -174 dBm/Hz in simulations. UEs and UERs are uniformly distributed in the cell. UEs transmit at maximum power $P_u = P_{\max} = 23$ dBm. UERs may choose not to use their maximum power to relay the traffic of UEs. Hence, UERs transmit power is randomly and uniformly selected in the range $[0, P_{\max}]$. We set the maximum budget to $B = 10.5N_r$ dBm, where $N_r = |R|$ is the number of UERs (the budget scales with the number of UERs). We ran with MATLAB on a CPU Intel Core i5, its RAM has 8GB running with 64-bit Windows 8.1.

The simulation parameters are summarized in Table II.

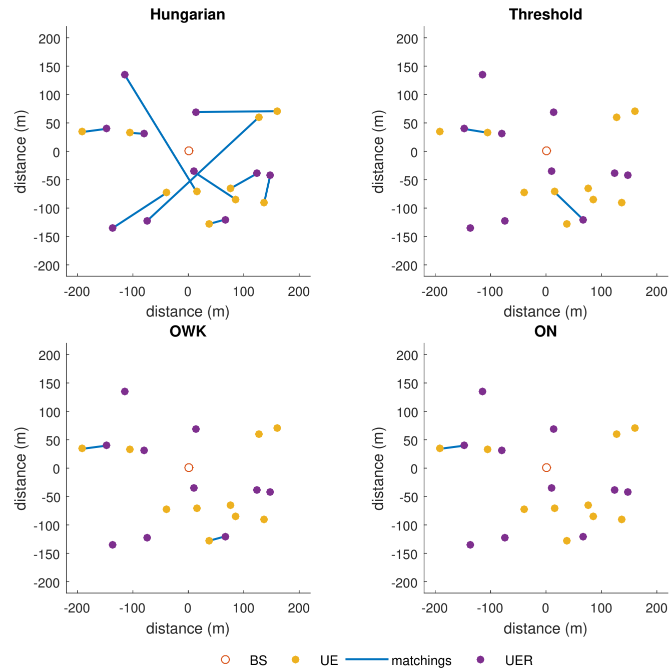

Fig. 1. Final matching obtained by matching algorithms.

B. Simulation Results

To compare algorithms, we analyzed for a fixed number of UEs and UERs the final matching, the truthfulness and the scalability by varying number of UEs and UERs.

1) Final Matching: we first show in Fig. 1 the final matching obtained by the algorithms when 10 UEs (diamonds) and 10 UERs (squares) are uniformly distributed in the cell. The lines represent the matchings.

Hungarian algorithm is the one that matches the most UEs and UERs, because it calculates the maximum weighted matching in the offline setting. Comparing it with the other offline algorithm, Threshold, we observe that respecting the budget and truthfulness constraints has reduced the number of edges in the final matching, dropping from 10 to 2 matched edges. When analyzing the two online algorithms, there is a reduction on the matching when the constraint of budget feasibility is considered in algorithm ON. Therefore, it is possible to infer that truthfulness, although a very important requirement for implementation success, does not have so much influence on the matching and that the constraint that affects mostly the result is the budget feasibility.

2) Truthfulness: we verify in Fig. 2 the truthfulness of the algorithms by simulating an increasing misreport of a UER's cost (in each iteration the cost is increased by 5 dBm) and by observing the payment provided. A scenario with 10 UEs and 10 UERs uniformly distributed in the cell is considered.

As expected, Hungarian algorithm is not truthful, since the system always pays the UERs the cost they reported. The same is observed in OWK: although after a threshold, the UER is not matched anymore, the payment first follows the reported cost, so that OWK is not truthful. According to literature, Threshold

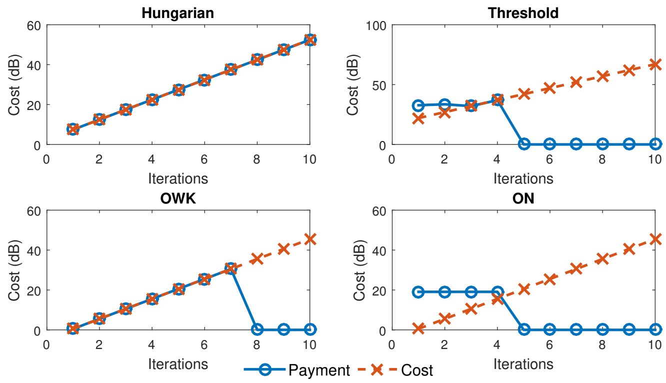

Fig. 2. Truthfulness study: Reported cost vs. payment.

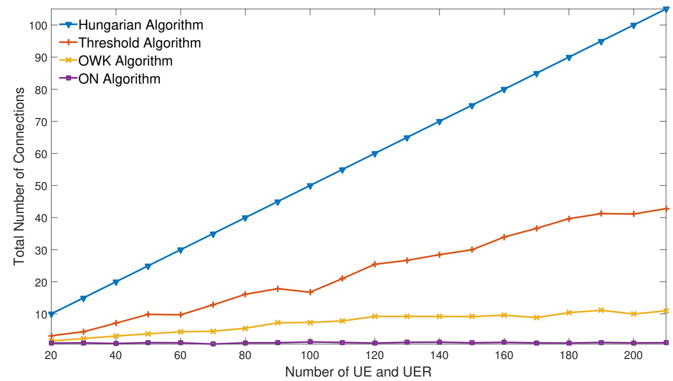

Fig. 4. Number of connections as a function of the number of UEs and UERs.

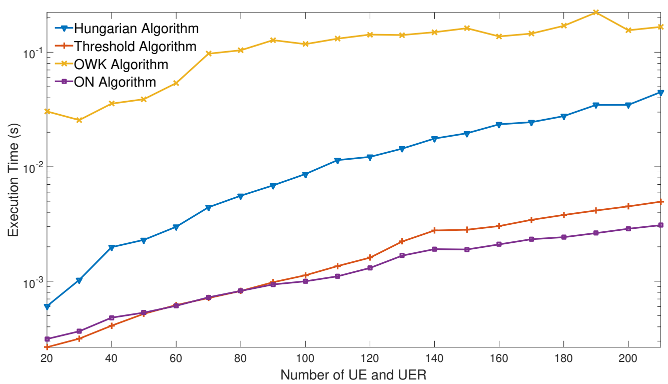

Fig. 3. Execution time as a function of the number of UEs and UERs.

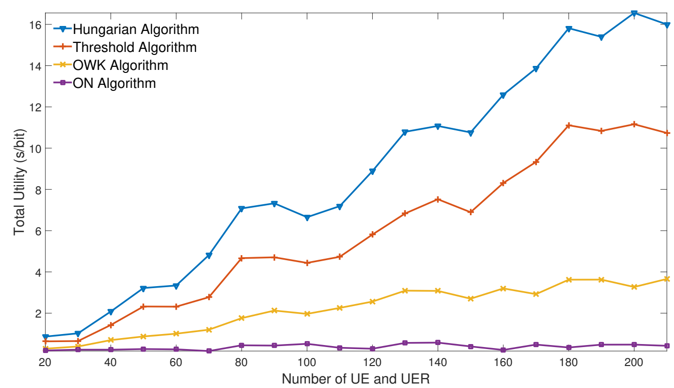

Fig. 5. Total utility as a function of the number of UEs and UERs.

algorithm should be truthful; however, the simulation shows that it allows the UER to misreport its cost and it also increase its payment. ON algorithm is the only one that is actually truthful. We observe that even if it allows the UER to report a higher cost, it does not increase the payment, and when the cost becomes higher, it is not selected anymore.

3) Scalability: We now study the scalability of the algorithms by varying the number of UEs and UERs from 20 to 210. Every point is an average of 50 random locations of UEs and UERs.

Fig. 3 presents the time variation when the number of UEs and UERs increases. Analyzing the running time scalability of the offline algorithms, we notice that it does not scale as well as Threshold, even if both are solvable in polynomial time [9]. This fact is observed because Threshold iterates a lower number of nodes when compared to Hungarian algorithm to find the solution thanks to the bisection method. Moreover, ON algorithm presents an execution time similar to Threshold; however, we observe that the rate at which the algorithm increases its execution time is lower. ON algorithm has an execution time similar to Threshold, however, it scales slightly better. This happens because Threshold is used in the learning phase over half of the set of UERs and that is the most time consuming step. In conclusion, ON has a better scalability. Lastly, OWK is the one that scales the best, even if its execution time is lower than the others.

Fig. 4 illustrates the number of D2D connections and Fig. 5, the variation of the total utility when the number of UEs and UERs increases. Results are correlated since the total utility depends on the number of matched edges. When observing these graphs, the influence of each constraint is clear: the more requirements are taken into consideration, the less matched edges there are, and the lower is the total utility of the matching. Hungarian algorithm does not consider any of these constraints, it simply finds the maximum weight matching considering the utility of the edges. Therefore the number of connections increases linearly, and its utility is always the highest. Moreover, both offline algorithms connect more devices and thus exhibit higher utility than online algorithms. The reason is that with online algorithms, a subset of UERs is used to created the selection criteria and are never matched. Subsequently, it is also possible to notice that the number of connections selected by ON algorithm is always very low, independently on the number of UEs and UERs, resulting in a very low total utility. This characteristic is a result of a very restrictive selection rule. This rule is indeed based on the best achievable rate among half of the UERs. This rate is often much better than the rate achieved by UERs arriving during the matching phase.

Lastly, Fig. 6 presents the total payment as a function of the number of UEs and UERs. The solid line increasing linearly represents the budget for the quantity of UEs and

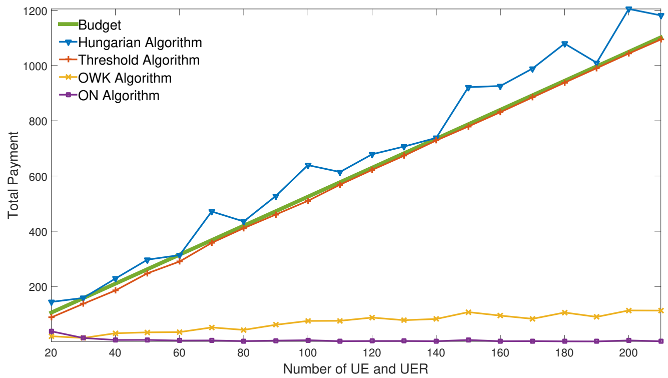

Fig. 6. Total payment as a function of the number of UEs and UERs.

UERs. This simulation illustrates whether the algorithms are budget feasible or not. As expected, Hungarian algorithm is frequently over the limit. Thus it is not budget feasible since it does not take into consideration the cost nor the budget when calculating the matching. Threshold algorithm's result is very close to the budget limit, but it is always under the continuous curve, showing that it is budget feasible. Online Weighted Knapsack algorithm is also always below the budget, following the theoretical guarantee presented in the literature. ON algorithm results prove that it is budget feasible. It is frequently very low though, being a consequence to the low number of matched edges presented in the graph of Fig. 4.

In terms of execution time, ON is the best algorithm; nevertheless, it requires modification in its selection criterion because of the very low number of connections. On the other hand, we infer that OWK is the best algorithm in practice, although not considering truthfulness. It has very appealing properties compared to other algorithms as long as the number of UEs and UERs is not too high, because, even if its scalability is good, note that it takes almost a second to calculate the matching when there are 60 users. It indeed respects the budget constraint and scales the best in terms of number of D2D connections and utility. Regarding the requirements presented in this paper, only truthfulness is missing. Modifying OWK payments to achieve this requirement and reducing the algorithm complexity are interesting research challenges.

VI. Conclusion

This paper analyzes a D2D network, in which UERs serve as relays for cellular users in order to improve their uplink data rate. Helping a UE generates a cost, but UERs are retributed by a payment from the network. We study the budget feasible matching problem and compare four algorithms – Hungarian, Threshold, Online Weighted Knapsack and ON – in the context of D2D communication. Three requirements have been considered: truthfulness, budget feasibility, and acceptance of online scenario. Among these constraints, budget feasibility was verified to be the one that affects the most the final result, albeit truthfulness is the more important. Moreover, when analyzing the comparison of algorithms scalability, it is clear that the more requirements are considered, the lower is the number of matched edges and the total utility, as expected. Also, it illustrates the fact that OWK, although not truthful, has very appealing properties and had the best results among the online algorithms. Lastly, it was possible to notice that the ON algorithm presents some problems: the amount of matched edges is always low and even if it presents the average payment under the budget. It is then an interesting topic of research to propose changes in this algorithm to improve the selection criterion calculation during its learning phase.

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