On Stable Many-to-Many Matching for Distributed Medium Access with Reuse of Spectral Resources

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***Abstract*—Recently, direct device-to-device (D2D) communication has gained broad attention. This paper studies a distributed model for the assignment of transmitter-receiver links to frequency resources within a D2D network. We present a novel and low-complex protocol based on the game-theoretic framework of stable many-to-many matching. In this model, several links can share the same resource and each link can use several resources for communication. In order to promote fairness in the system, the resource assignment is restricted through matching quotas. Although spectral reuse is allowed, we ensure reliable transmissions on every resource by an appropriate power allocation scheme based on conservative interference assumptions. The power allocation of each device takes SINR goals into consideration while incorporating an energy-efficient use of the resources. Simulation results evaluate the performance of our distributed algorithm against a centralized resource allocation scheme.**

***Index Terms*—Resource allocation; Distributed medium access; Spectral reuse; Network-assisted D2D; Stable matching**

I. Introduction

Direct communication among wireless devices in proximity to each other provides a number of benefits over infrastructure-based communication [1]. It enables low end-to-end latencies due to short-range paths of the device-to-device (D2D) links, a reduced number of communication hops and less processing. Proximity links may improve the spectral efficiency by a more efficient utilization of radio resources. Besides, energy efficiency can be greatly improved. 3GPP is currently introducing concepts for proximity-based services within cellular networks on the basis of D2D communication, see Long Term Evolution (LTE) Rel. 12 and beyond [2]. Here, a network-assisted D2D operation mode assumes the split of control and user planes. While control data is routed via a coordinator entity, e.g. the LTE base station, the devices exchange user data directly. There are manifold application areas for D2D connectivity, e.g. cellular traffic offloading, direct content sharing, fallback public safety networks and machine-type communications (MTC). In the context of 5G, mission-critical MTC in wireless automation systems is an especially challenging use case for D2D communication due to high reliability requirements and a considerable number of sensor and actuator nodes [3]. Hence, medium access schemes need to guarantee the required transmission quality of the links, e.g. in terms of given signal to interference and noise ratios (SINRs), while being scalable.

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In this paper, we discuss the allocation of frequency resources in an assisted D2D setup when spectrum reuse is allowed. We assume a dynamic and flexible resource allocation rather than a static scheme with periodically reserved resources. In order to reduce the overhead in the control channels, we study a distributed protocol for the medium access where each device has only local channel state information (CSI) available. We intend few information exchange and minor coordination effort. A set of active devices may negotiate the allocation of the resource pool among each other based on individual utilities. The D2D coordinator is provided with as little global information as needed to coordinate the negotiation. We utilize the framework of stable matching [4], [5] to a give low-complex and fast terminating medium access algorithm. Moreover, we apply a many-to-many version of stable matching to incorporate resource budgets of transmitter-receiver pairs on the one hand and spectrum reuse, i.e. multiple D2D links per resource, on the other hand. The frequency resources shall be matched sufficiently fair in the sense that the finally allocated resource budgets are almost equal among the D2D links. Furthermore, the decision-making process shall be driven by energy efficiency metrics and satisfy SINR constraints on resources. Here, the energy efficiency will be determined by each device based on the transmit power needed to reach the target SINR for a reliable transmission.

A. *Related Work*

In the context of wireless communications, many-to-many stable matching was rarely applied up to now. It was recently used in [6] for distributed CSI selection in MIMO interference channels. Besides, some variants of many-to-one stable matchings were proposed for distributed medium access in cognitive radios, see [7]–[10]. In a cognitive radio, secondary communication links can be operated as an underlay to a primary network, i.e. a spectral resource is shared with a known primary user. In [9], a truncated matching algorithm is used for resource allocation in cognitive networks. Here, truncation implies that the applied stable matching algorithm terminates after a given number of negotiation rounds, giving an almost stable allocation only. In [10], the secondary system is a D2D underlay to a cellular network. A multi-stage stable matching scheme is applied that incorporates matching under both resource requirements (lower matching quotas) and resource budgets (upper matching quotas) of the D2D links.

B. *Outline of the Paper*

The outline of this work is as follows: Section II presents the system model and a formulation of our resource allocation problem based on multiple objectives. In Section III, we define the stable many-to-many matching and give an algorithm for its distributed implementation. We discuss the local utilities of the D2D links and the utility functions of the D2D coordinator in Section IV. Finally, simulation results are presented in Section V for an indoor D2D network.

II. Problem Statement

We consider a set of D2D links $d \in \mathcal{D}$ between transmitter d_T and receiver d_R. The D2D pairs are to be matched to a set of frequency resources $r \in \mathcal{R}$ based on utility functions $u_d(r)$ and $u_r(d)$ which are use case specific, see Section IV. From the utility functions, strict preference relations over favorable assignments are to be defined for each set of agents. We denote by $M(d)$ the set of resources matched to D2D link d and by $M(r)$ the set of D2D links matched to resource r. Further, we allow a many-to-many matching, i.e. frequency reuse with a factor $q_r^{\text{reuse}} \leq |\mathcal{D}|$ per resource, $q_r^{\text{reuse}} \in \mathbb{N}$, and multiple resources per D2D link. Further, our aim is to achieve resource-fairness through an *almost uniform* distribution of the resources allocated to D2D links over many realizations, aiming for the average score

$$p = \frac{\sum_{r=1}^{|\mathcal{R}|} q_r^{\text{reuse}}}{|\mathcal{D}|} \,, \tag{1}$$

which is bounded by the integers

$$\underline{p} = \lfloor p \rfloor \in \mathbb{N} \,, \; \overline{p} = \lceil p \rceil \in \mathbb{N} \,. \tag{2}$$

Hence, we seek $\mathbb{E}[|M(d)|] \approx p$, $\forall d$.
A realization of our two-sided matching problem can be stated as a multi-objective binary programming (MOBP) problem [11]:

$$\underset{\mathbf{x}}{\text{maximize}} \;\; \mathbf{f}(\mathbf{x}) = \left[f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_N(\mathbf{x})\right]^T \tag{3a}$$

$$\text{subject to} \;\; \mathbf{x} \in \mathcal{X} \,, \tag{3b}$$

where $\mathcal{X} \subseteq \{0,1\}^{|\mathcal{R}|\,|\mathcal{D}|}$ is the set of feasible points in the binary domain, see the refinement in (4), and N is the number of objectives. In the following, we formulate (3) as a weighted sum utility optimization given by

$$\underset{\mathbf{x}}{\text{maximize}} \quad \sum_{r\in\mathcal{R}} \sum_{d\in\mathcal{D}} \Big(\omega_d\, u_d(r) + \omega_r\, u_r(d)\Big)\, x_{rd} \tag{4a}$$

$$\text{subject to} \quad \underline{p} \leq \sum_{r\in\mathcal{R}} x_{rd} \leq \overline{p}, \; \forall d \in \mathcal{D}, \tag{4b}$$

$$\sum_{d\in\mathcal{D}} x_{rd} \leq q_r^{\text{reuse}}, \; \forall r \in \mathcal{R}, \tag{4c}$$

$$x_{rd} \in \{0,1\}, \; \forall (r,d) \in \mathcal{R} \times \mathcal{D} \,, \tag{4d}$$

where ω_d, $\omega_r \in [0,1]$ are weights to adjust the operating point and $\sum_{d\in\mathcal{D}} \omega_d + \sum_{r\in\mathcal{R}} \omega_r = 1$. Note, that (4) is a linear assignment problem (AP) which can be efficiently solved by centralized algorithms provided that all necessary information

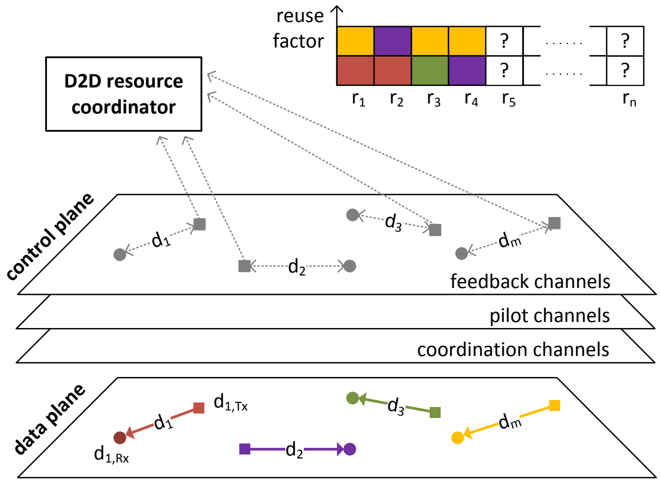

Fig. 1: D2D network with frequency reuse: In order to get frequency resources assigned for data transmission over direct peer-to-peer links, the D2D users communicate with each other over control channels supported by a coordinator.

is globally available, see Section V-B. In general, the weighted utility maximization ends up in an operating point on the convex hull of the achievable utility region and, hence, serves as an upper bound for the proposed distributed matching implementation in Section III.

III. Distributed Medium Access Scheme

A. *Stable Many-to-Many Matching*

We distributively solve the AP on the basis of locally available information, using two-sided stable matching [4], [5]. Stable matching is a game-theory inspired framework to solve decision-making problems with multiple agents based on a stable outcome of the system. The goal is to terminate in a state in which each agent is assigned a partner (or a set of partners) which is considered its best mutually beneficial choice. Hence, it is impossible to strictly improve the performance of all agents jointly. Below, we give some definitions in order to define stability in the context of many-to-many matchings for our setup with upper matching quotas q_r $\forall r$ and q_d $\forall d$. The quotas q_d will be associated with $\overline{p}$ later on. We assume non-negative real-valued utilities, i.e., $u_d(\cdot) \in \mathbb{R}_+$ and $u_r(\cdot) \in \mathbb{R}_+$.

Definition 1: Two agents are *mutually acceptable* for a matching if $u_d(r) > 0 \wedge u_r(d) > 0$ for $(r,d) \in \mathcal{R} \times \mathcal{D}$.

Definition 2: [5] The matching M is *individually rational* if $u_d(r^\star) > u_d(d)$, $r^\star \in M(d)$, for some $d \in \mathcal{D}$ or $u_r(d^\star) > u_r(r)$, $d^\star \in M(r)$, for some $r \in \mathcal{R}$.
Accordingly, individually rational matching ensures that no agent would prefer being matched to himself than with its current matching.

Definition 3: [5], [12] The matching M is *blocked* if there exists a mutually acceptable pair $(r,d) \in \mathcal{R} \times \mathcal{D}$ which is unmatched, $r \notin M(d)$, $d \notin M(r)$, and

- **(i)** the agents prefer each other over their matched partners, i.e., $u_d(r) > u_d(r^\star)$ for some $r^\star \in M(d)$ and $u_r(d) > u_r(d^\star)$ for some $d^\star \in M(r)$,
- **(ii)** the agents prefer each other to an unfilled position, i.e., $|M(d)| < q_d$ or $|M(r)| < q_r$.

A matching is *pairwise stable* if it is individually rational and not blocked by any pair of agents.[1]

B. *Distributed Implementation*

Algorithm 1 D2D-proposing stable matching with almost uniform outcome.

Initial Phase:

Proposals: Every D2D $d \in \mathcal{D}$ sends to coordinator the index of its $\overline{p}$ most preferred resources (via coordination channels). These indices are cleared from preference list l_d.

Decision: Coordinator accepts at most q_r^{reuse} proposals per resource $r \in \mathcal{R}$ subject to preference list l_r and rejects proposals when the reuse factor is overfulfilled.

Iterative Phase:

while $\exists\, d \in \mathcal{D} : l_d \neq \emptyset$ (not yet proposed to all resources) and $|M(d)| < \overline{p}$ (undersubscribed) **do**

Proposals: D2D d sends to coordinator the index of next $\overline{p} - |M(d)|$ preferred resources. These indices are cleared from preference list l_d.

Decision: Same as in intial decision phase.

end while

We apply the matching algorithm presented in [15] and adopt it to meet our system model. For that reason, we seek to achieve a pairwise stable matching that involves uniformity as far as possible, meaning that constraint set (4b) of allocating between $\underline{p}$ and $\overline{p}$ resources per D2D link is envisaged, however, it may be underfulfilled. Therefore, we set $q_d = \overline{p}\ \forall d$ to target $|M(d)| \leq \overline{p}$. The proposed matching algorithm fulfills constraint set (4c) with equality, giving $|M(r)| = q_r^{\text{reuse}}\ \forall r$. We assume that the device pairs d rank their preferred resources in descending order in lists l_d based on $u_d(r)$. Similar, the coordinator managing the resources holds preference lists l_r over the D2D links based on $u_r(d)$. Basic assumptions are: (i) only agents that both find each other acceptable appear on the preference lists, (ii) agents are not indifferent in their preferred matches and (iii) $|l_d| \geq \overline{p}$ is satisfied for each $d \in \mathcal{D}$. We give the uniform many-to-many matching approach in Algorithm 1, where each D2D pair proposes at most once to be matched to a resource from its list. Thus, the complexity of the algorithm is $\mathcal{O}(|\mathcal{D}||\mathcal{R}|)$ in terms of the number of proposals.

[1]Note, that pairwise stability is different from group stability which requires that a matching is not blocked by any coalition of agents. A coalition might consist of multiple D2D links and/or resources. Group stability was first defined in the context of many-to-one matchings [5] and later on extended for many-to-many matchings, see the definition of setwise stability in [12], [13] and credible group stability in [14]. In general, the relation between the stability concepts is: group-stable sets $\subseteq$ setwise-stable sets $\subseteq$ credibly group-stable sets $\subseteq$ pairwise-stable sets. In this paper, we do not consider preference strategies (utilities) over coalitions and, hence, stick to pairwise stability.

In the following, we show some theorems and their proofs for Algorithm 1 as discussed in [15].

Theorem 1: Algorithm 1 gives a pairwise stable matching which is D2D-optimal, i.e., the best feasible stable matching for the D2D links.

Proof: The proof will be provided in Appendix A. ∎

Theorem 2: If Algorithm 1 gives a stable matching where at least one D2D link obtains an unfulfilled resource score $\underline{p}$, then no stable matching exists in which *every* D2D link is assigned $\underline{p}$ or $\overline{p}$ resources.

Proof: The proof will be provided in Appendix B. ∎

IV. Utility Functions

A. *D2D Utilities – Local CSI*

We consider SISO transmission between the transmitter-receiver pairs in the network. Furthermore, the transmission is subject to the following requirements:

- Each D2D link d shall adjust its power budget for transmission at a *target SINR*, as long as this is achievable under peak power constraints. In this way, we ensure reliable communication.
- Each D2D link d shall optimize its *energy efficiency (EE)*, see [16], under the given SINR and peak power constraints. Using this measure, the devices aim for an efficient use of their battery power and an extended battery life.

1) SINR Requirements in the Assignment Problem: In the analysis below, our assumption is that interference can be treated as noise. The SINR calculation for the link d between receiver d_R and transmitter d_T depends on the assignment $\mathbf{x}$ of other devices on the same resource and is given for time instance t on resource r as

$$SINR_d^{[r]}\big(\mathbf{x}(t)\big) = \underbrace{\frac{|h_{d_R d_T}^{[r]}(t)|^2}{\sigma_n^2 + I_{d_R}^{[r]}\big(\mathbf{x}(t)\big)}}_{\gamma_d^{[r]}(\mathbf{x}(t))} P_{d_T}^{[r]}(t) \geq \beta_d^{[r]}\,, \tag{5}$$

where the required SINR $\beta_d^{[r]}$ shall be satisfied per resource. We target $\beta_d^{[r]} = \beta = \text{const.}, \forall d \in \mathcal{D}, \forall r \in \mathcal{R}$, to allow a unified interface for resource block association on higher layers and a simplified physical layer modulation and coding scheme selection. The extension to different SINR targets is straightforward.
Above, $|h_{d_R d_T}^{[r]}(t)|^2$ is the instantaneous channel gain between Tx and Rx of D2D link d, including pathloss and the respective fading model, while $P_{d_T}^{[r]}(t)$ is the transmit power, including antenna gains. σ_n^2 accounts for the noise floor which is affected by thermal noise and the Rx noise figure. For the moment, we assume perfect channel knowledge for the link $h_{d_R,d_T}^{[r]}$. By introducing

$$\gamma_d^{[r]}\big(\mathbf{x}(t)\big) = \frac{|h_{d_R d_T}^{[r]}(t)|^2}{\sigma_n^2 + I_{d_R}^{[r]}\big(\mathbf{x}(t)\big)}\,, \tag{6}$$

we summarize the part of the SINR term which is independent of the device's own transmit power. The interference term in Eq. (6) is

$$I_{d_R}^{[r]}\big(\mathbf{x}(t)\big) = \sum_{d'\in\mathcal{D}\setminus\{d\}} P_{d'_T}^{[r]}(t)\left|h_{d_R d'_T}^{[r]}(t)\right|^2 x_{rd'}\,. \tag{7}$$

Here, $|h_{d_R d'_T}^{[r]}(t)|^2$ denotes the instantaneous gain of the interference channel between Tx $d' \neq d$ and Rx d, and $P_{d'_T}^{[r]}(t)$ is the transmit power of interferer d'. The interference depends on the final resource assignment vector $\mathbf{x}$ at time instance t. It is the interdependence of the SINR and the assignment decision that makes a resource allocation extremely difficult and not solvable by efficient assignment mechanisms. Below, we discuss one way to approach the resource allocation problem taking into account a specific interference metric.

2) Worst Case Interference:
It is feasible to apply a pilot scheme in the D2D network in order to measure channel state information (CSI) prior to the medium access. The pilot scheme runs on specifically defined control channels with well-defined pilot powers. We assume the use of perfectly orthogonal codes, e.g. Walsh-Hadamard sequences, to identify the pilot tones of each device.[2] Thus, receiver d_R knows the channel gains of the links $h_{d_R d'_T}^{[r]}$. By using this local CSI, a conservative estimation of interference can be performed. In the worst scenario, the transmitted data seen on the interference links comes with the *maximum peak power* $\hat{P}_{d'_T}$ per resource. In this work, we assume that the total transmit power limitation per device is uniformly spread over all resources. Also, we assume $\hat{P}_{d'_T}$ to be equal for all devices in the network for the sake of simplicity. Consequently, the worst case interference is

$$\hat{I}_{d_R}^{[r]}(t) = \sum_{d'\in\mathcal{I}^{[r]}} \hat{P}_{d'_T}\left|h_{d_R d'_T}^{[r]}(t)\right|^2, \tag{8}$$

where $\mathcal{I}^{[r]}$ is the set of the $(q_r^{\text{reuse}}-1)$ strongest interferers $d' \neq d$ on resource r in the considered instance t. Using (8), we ensure to fulfill (or overfulfill) the target SINR. The conservatively presumed SINR term is

$$\gamma_d^{[r]}(t) = \frac{|h_{d_R d_T}^{[r]}(t)|^2}{\sigma_n^2 + \hat{I}_{d_R}^{[r]}(t)} = \hat{\gamma}_d^{[r]}(t)\,. \tag{9}$$

3) Power Allocation:
Each D2D transmitter computes the transmit power $P_{d_T}^{\star[r]}$ it would allocate on the resources $r \in \mathcal{R}$. The power allocation is determined by the fulfillment of the target SINR and, furthermore, an energy-efficient transmission. The power budget $P_{d_T}^{\text{opt-EE}}$ needed to operate on an EE-optimal point is considered only if it exceeds the required minimum transmit power $P_{d_T}^{\text{req-SINR}}$. In time instance t, we have

$$P_{d_T}^{\star[r]}(t) = \min\left\{\max\left\{P_{d_T}^{\text{req-SINR}}(t), P_{d_T}^{\text{opt-EE}}(t)\right\}, \hat{P}_{d_T}\right\}. \tag{10}$$

[2]Such pilot schemes may not be scalable in large D2D networks.

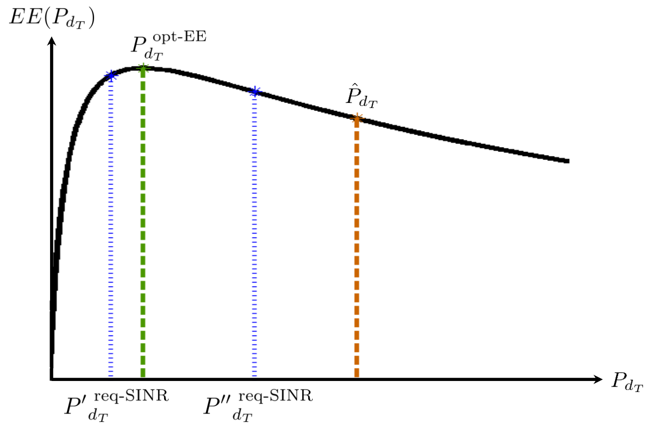

Fig. 2: Different operating points for the transmit power P_{d_T} on a schematic energy efficiency curve, following the function $EE(P_{d_T}) = \log_2(1+k_1 P_{d_T})/(k_2 P_{d_T}+k_3)$. Here, k_1, k_2, k_3 is a choice of constants being further described in the paper.

The maximum peak power $\hat{P}_{d_T}$, which applies per resource as described in paragraph *2)*, may limit the finally achievable SINR of the devices. Moreover, the following equations hold:

$$P_{d_T}^{\text{req-SINR}}(t) = \frac{\beta}{\hat{\gamma}_d^{[r]}(t)}\,, \tag{11}$$

and

$$P_{d_T}^{\text{opt-EE}}(t) = \frac{\lambda - 1}{\hat{\gamma}_d^{[r]}(t)}\,, \tag{12}$$

where

$$\ln\lambda = 1 + W_0\left(e^{-1}\left(\hat{\gamma}_d^{[r]}(t)\frac{P_{d,\text{HW}}^{[r]}}{\alpha_d} - 1\right)\right). \tag{13}$$

Above, W_0 denotes the principal branch of the Lambert W function, see [17]. It is $W_0(x) \geq -1$ for $x \geq e^{-1}$ and, hence, $\ln\lambda \geq 0$ or $\lambda \geq 1$ respectively. $P_{d_T}^{\text{opt-EE}}(t)$ is the closed-form solution to the problem

$$\frac{\partial EE_d^{[r]}(t)}{\partial P_{d_T}^{[r]}(t)} = 0 \tag{14}$$

and maximizes the energy efficiency that is stated in Eq. (15) below. Further explanation on (12)–(14) can be found in [18]. Fig. 2 gives a schematic overview of the different operating points on a generalized EE curve.

4) Energy Efficiency:
We give the EE in [bit/Joule] as the ratio of the achievable communication rate in [bit/s] and the power spent. In time instance t, the transmitter-receiver pair d calculates its energy efficiency on resource r as follows:

$$EE_d^{[r]}(t) = BW\,\frac{\eta\,\log_2\left(1+\gamma_d^{[r]}(t)\,P_{d_T}^{\star[r]}(t)\right)}{\alpha_d P_{d_T}^{\star[r]}(t) + P_{d,\text{HW}}^{[r]}}\,. \tag{15}$$

Above, $\alpha_d \geq 1$ accounts for amplifier non-idealities. $P_{d,\text{HW}}^{[r]}$ is the power consumed by hardware components, e.g. DA/AD converters and modulation filters, which is to be scaled-down on resource level, i.e., $P^{[r]}_{d,\text{HW}} = P_{d,\text{HW}}/|\mathcal{R}|$. Besides, BW is the bandwidth of the frequency resource and η is a scaling factor to consider signaling overhead and other rate-deducting effects.

We define the utility of the D2D links $d \in \mathcal{D}$, from which the individual matching preferences over the resource pool are derived, see Algorithm 1, by their resource-wise EE. Consequently, we have

$$u_d(r) = EE^{[r]}_d(t)\,. \tag{16}$$

B. *Coordinator Utilities – Globally Collected Information*

We assume that the coordinator receives from each D2D pair d a subset of the locally available information, e.g. only the applicable power budgets per resource or the resource-wise energy efficiency measure.
In the following, we imply the global collection of the latter parameter. Then, we define the utility of the resources $r \in \mathcal{R}$ managed by the coordinator by a prioritization of the communicated EE values. With user priority ρ_d, e.g. according to buffer queues or tariffs, we have

$$u_r(d) = \rho_d\, EE^{[r]}_d(t)\,. \tag{17}$$

Based on (17), the coordinator defines for each resource the preference ranking over the D2D links.

V. Simulation Assumptions and Results

Next, we describe the studied indoor environment and give the parameterization used for our simulations. We compare the results of the distributed medium access algorithm with a centralized scheme.

A. *D2D Network Layout and Channel Model*

We simulate a network with $|\mathcal{D}| = 8$ D2D SISO links that compete for $|\mathcal{R}| = 25$ orthogonal frequency resources over a 5 MHz band. Each of the reused resource blocks (RBs) has a bandwidth of 180 kHz plus guard band.
The considered simulation scenario corresponds to an industrial hall with dimensions shown in the area plot in Fig. 3. We use the indoor path loss model presented in [19] for 5.2 GHz. It is given by $PL_{[dB]}(x) = 70.28 + 25.9 \log_{10}(x_{[m]}/15)$, where x is the distance in [m]. Also, we apply additional geo-correlated shadow fading with $\sigma_{\text{SF}} = 6$ dB. The transmitter-receiver pairs have a communication distance between 5 m and 8 m. Other simulation parameters are listed in Table I.
The simulations are averaged over 10^3 random channel realizations. We consider a block-fading channel model, where the multipath fading is according to the ITU indoor office tap-delay model ('channel A') with flat Doppler spectrum, see [20].[3]

[3]This model is exemplarily chosen due to a lack of representative tapped-delay-line parameters for industrial indoor environments.

Parameter	Value
Scenario	Industrial indoor environment
Carrier frequency	5.2 GHz
D2D Tx-Rx pairs	8
Frequency resources	25 resource blocks (RBs)
BW per RB	180 kHz
Tx power limitation per device	23 dBm
$\hat{P}_{d_T}$ per RB	9 dBm
Rx noise figure	9 dB
Thermal noise spectral density	-174 dBm/Hz
η	0.6
$P_{d,\text{HW}}$	10 dBm
α_d	1.3

TABLE I: Basic configuration of the performed simulations.

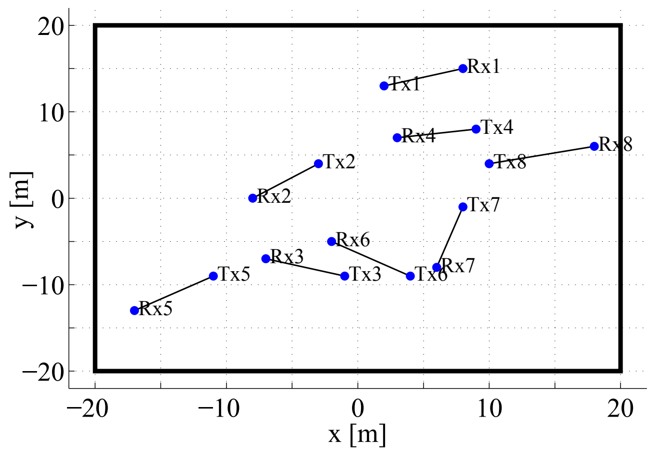

Fig. 3: Layout of an industrial building with an indoor D2D network of 8 transmitter-receiver pairs.

B. *Centralized Solution of the Linear AP*

We use the solver tool GLPK[4] [22] to find an efficient (near-optimal) solution for the binary program in (4). For a fair comparison with the proposed distributed algorithm, we fulfill (4c) with equality and distinguish between two cases of the binary constraint set (4b), namely:

(Almost) Uniform Resource Distribution	Relaxation
$\underline{p} \leq \sum_{r\in\mathcal{R}} x_{rd} \leq \overline{p},\ \forall d \in \mathcal{D}$	$\sum_{r\in\mathcal{R}} x_{rd} \leq \overline{p},\ \forall d \in \mathcal{D}$

The centralized relaxation delivers an upper bound to our distributed solution which may violate the lower quotas $\underline{p}$ as well. Hence, both schemes are well comparable. However, the centralized uniform scheme that incorporates $\underline{p}$ finds a solution on the actual domain of (4). Due to its circumscribed feasible solution space, the performance of the centralized uniform scheme may be or may not be better than the performance of the distributed solution. In the observed D2D network, the

[4]Please refer to [21] for a general performance comparison between GLPK and other noncommercial solvers for mixed-integer linear programming.

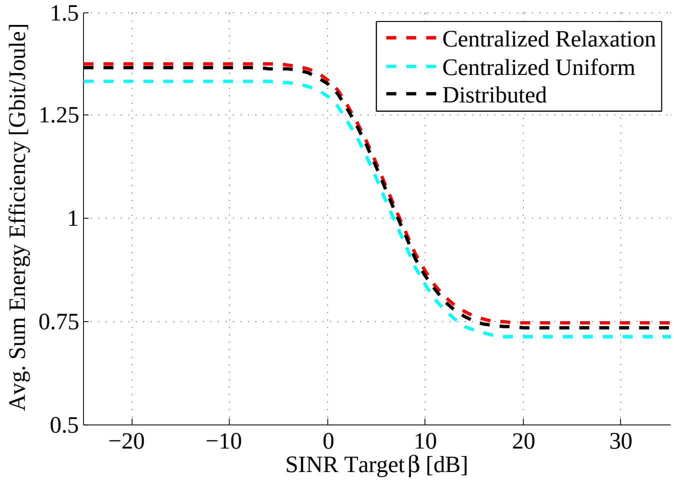

Fig. 4: Predicted sum EE in the D2D network acc. to *worst case interference* assumptions over β for reuse factor 2.

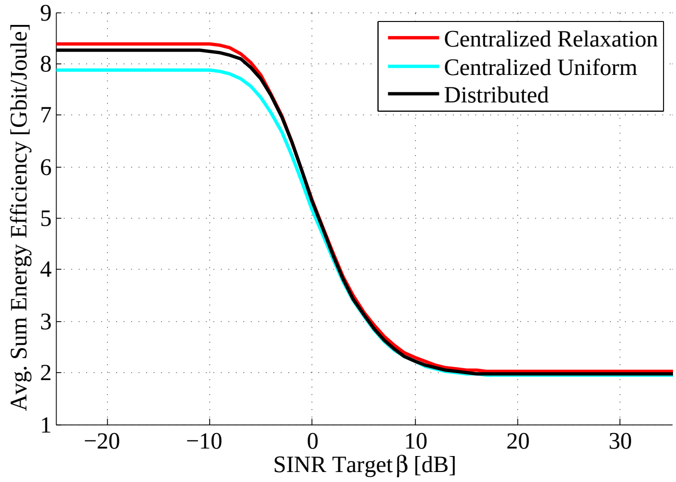

Fig. 6: True sum EE in the D2D network acc. to the *actual interference* after the assignment decision over β for reuse factor 2.

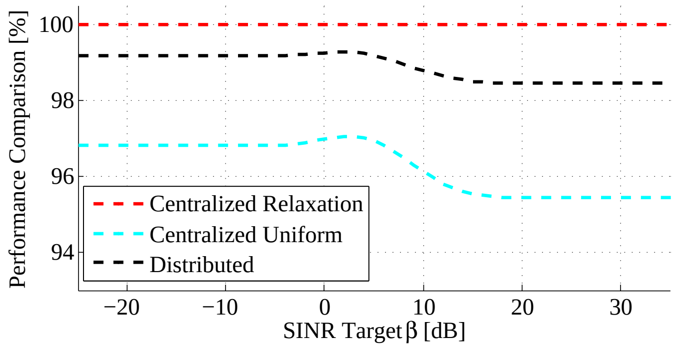

Fig. 5: Comparison of the distributed medium access scheme to centralized solutions based Fig. 4.

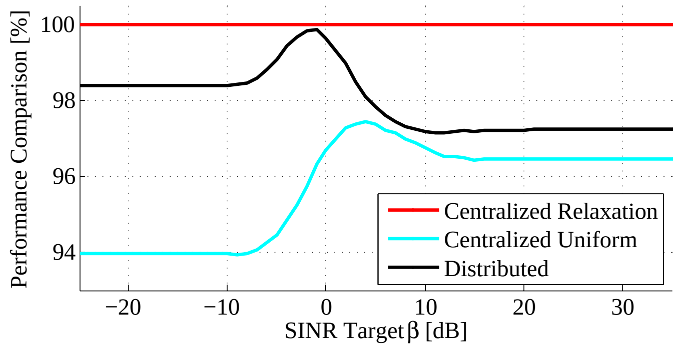

Fig. 7: Comparison of the distributed medium access scheme to centralized solutions based Fig. 6.

distributed medium access scheme outperforms the centralized uniform scheme for the price of violating (4b), see also Fig. 5 and Fig. 7 provided in the next paragraph. Note that a centralized resource allocation requires extensive global knowledge of the network.

For reasons of simplification, we assume $\rho_d = 1 \ \forall d$ herein. Then, the utilities of the D2D links and the coordinator are based on the same energy efficiency measure $EE_d^{[r]}$. For this specific case, the weights in (4a) can be dropped.

C. Simulation Results for the Distributed Stable Matching

We evaluate the performance of the distributed medium access scheme using the sum utility achieved by the resource allocation for a reuse factor $q_r^{\text{reuse}} = 2 \ \forall r$. Fig. 4 shows the average sum EE in the D2D network based on Eq. (15) with worst case interference assumptions of (8) and (9). As discussed before, the distributed solution is upper-bounded by the centralized relaxation but its performance reaches up to 99 % of the optimum, see Fig. 5. The true energy efficiency performance in the D2D network shows much higher values, see Fig. 6, since the real interference is less than the assumption. The actually assigend resources might give (i) better interference channels and (ii) fewer transmit power than the assumed peak power of other devices on these channels. Having its own transmit power decided, this allows higher than expected SINR and more transmitted bits for a device. Fig. 7 shows that, in reality, the distributed performance might even reach the centralized solution.

In general, the sum EE decreases with increasing β. It is limited for high SINR targets by the $\hat{P}_{d_T}$-constraint on the power allocation (Fig. 10) that restricts the achievable rate and by the increasing interference from high-power transmissions of other devices. It occurs, that the target SINR cannot be reached anymore for high β, see Fig. 9.

In Fig. 8-11, we present performance results for different frequency reuse factors, where we assume that the same q_r^{reuse} applies on all resources. We observe that the sum EE decreases with increasing spectral reuse, i.e. the increased interference scenario causes a less efficient use of each bit. The overall communication rate in the network is increasing due to more available resources. However, the speed of the sum rate increase will drop with very high reuse in the network. Also, strong interference let the SINR success probability shrink, i.e. the SINR target β cannot be satisfied in much of the allocated resources anymore. Fig. 9 provides information about the trade-off between SINR requirement, SINR success rate (or reliability) and spectral reuse in the system.

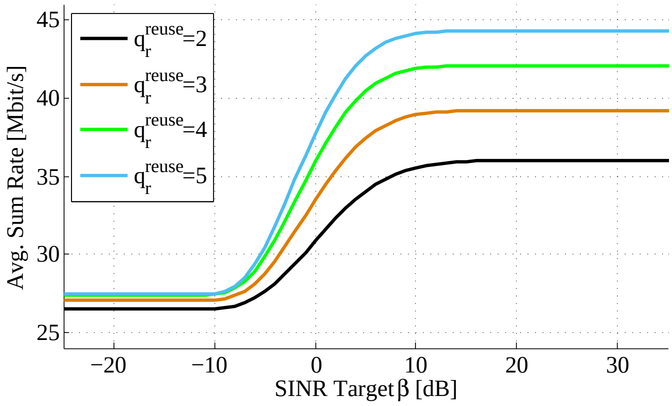

Fig. 8: Distributed medium access: Sum rate performance in the D2D network acc. to the actual interference over β for different reuse factors.

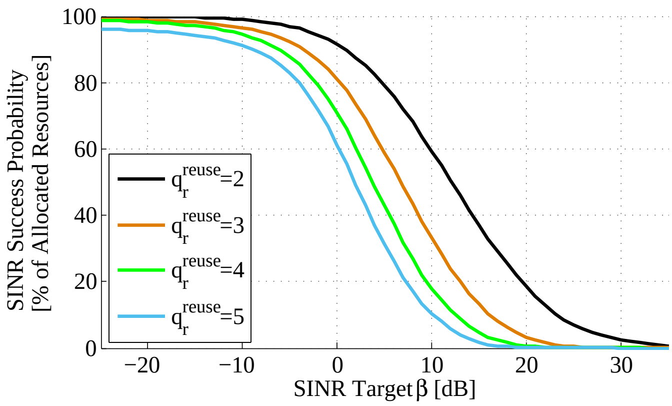

Fig. 9: Distributed medium access: Average number of fulfilled SINR requirements in the allocated resources over increasing β for different reuse factors.

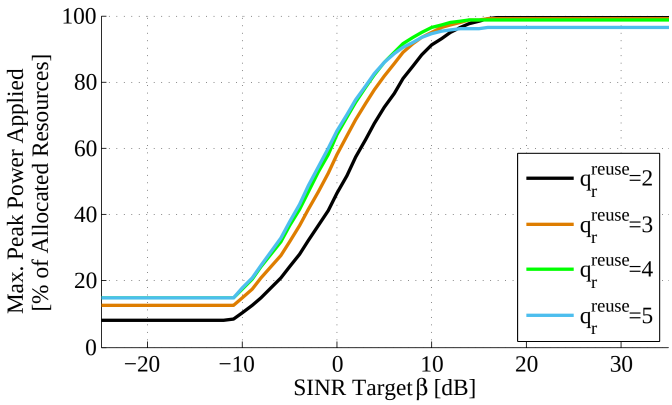

Fig. 10: Distributed medium access: Average number of applied max. peak powers in the allocated resources over increasing β for different reuse factors.

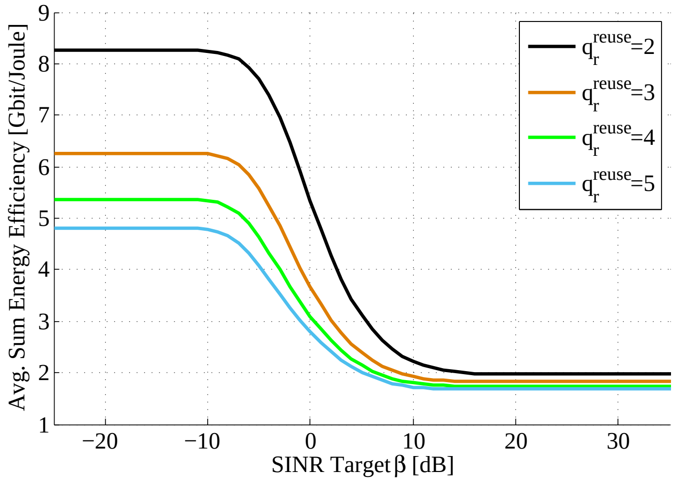

Fig. 11: Distributed medium access: Sum EE performance acc. to the actual interference over β for different reuse factors.

VI. Conclusion

In this paper, we presented a framework for distributed medium access in a network-assisted D2D setup where spectrum reuse is allowed and resource-fairness is a goal. The framework is based on many-to-many stable matching. Analytical proofs on stability for the proposed matching algorithm are given as well as the utility functions needed to derive the individual matching preferences. The utilities are based on a power allocation scheme that implies an energy-efficient use and reuse of resources under the condition of SINR requirements. Hence, our medium access framework facilitates reliable communication among device-to-device pairs. System-level simulations for an exemplified D2D indoor network are presented and the results of the distributed implementation are compared to a centralized solution of the resource allocation problem. We evaluate the performance of our distributed access scheme for different frequency reuse factors.

Appendix A
Proof of Theorem 1

The following proof is from [15].

Pairwise stability: Assume a blocking pair (r, d), $r \notin M(d)$, $d \notin M(r)$, and (i) $\exists\, r^{\star} \in M(d) : u_d(r) > u_d(r^{\star})$ and (ii) $\exists\, d^{\star} \in M(r) : u_r(d) > u_r(d^{\star})$. Then, two cases are to be discussed:

- d never proposed to r. It means that $u_d(r)$ is worse than the utility over any matched resource in $M(d)$ which contradicts (i). Thus, (r, d) cannot be a blocking pair.
- d proposed to r but was finally rejected. It means that r preferred other q_r^{reuse} D2D links (and traded d for a more preferable one) which contradicts (ii). Thus, (r, d) cannot be a blocking pair.

D2D optimality: Assume an alternative matching M' which is better for some D2D link d and assume $\exists\, r' \in M'(d)$, $r' \notin M(d)$ and $\exists\, r \in M(d)$ such that $u_d(r') > u_d(r)$. Then, again, either d never proposed to r' which contradicts the mechanism of Algorithm 1 or r' rejected the proposal to achieve a more preferable stable trade. Hence, M' cannot be stable and M is the best stable matching for the D2D links.

APPENDIX B
PROOF OF THEOREM 2

The following proof is from [15].

Assume a stable matching M with a D2D link d for which $|M(d)| < \underline{p}$. Also, assume a stable matching M' where d fulfills $\underline{p}$, i.e. $|M'(d)| = \underline{p}$. Then, all $r \in M'(d)$ are strictly better off than (at least) one resource in $M(d)$. However, this contradicts the argument that M is D2D-optimal which implies that d is best possibly matched in M, see Theorem 1.

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