Investigation of Decision Metrics for Reuse Link Selection in Device-to-Device Communication

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Abstract—Device-to-Device (D2D) communication is envisioned to enhance the functionality of future cellular networks. Dynamic frequency reuse in D2D enhanced networks can increase the frequency reuse factor beyond one and has achieved much attention in the last years. To leverage frequency reuse, a proper reuse link selection must be performed. We investigate a core problem of reuse link selection, namely how to find the maximum number of reuse links in a network. Efficient, optimal solutions for this problem have not been found over a decade in arbitrary wireless network scenarios. We investigate different decision metrics for reuse link selection under dynamic power control and propose a metric that outperforms the known state of the art solutions.

I. INTRODUCTION

For future cellular networks, the possibility of direct communication between user equipments (UEs) has been proposed to enhance network functionality. Such direct communication, referred to as device-to-device (D2D) communication, is considered to offload local traffic from the cellular base station and has achieved increased attention among network researchers [1], [2]. One of the potential use cases is that D2D-communication might leverage the proximity of devices and perform a dynamic frequency reuse, which allows pushing the frequency reuse factor beyond one [3]. However, the management of dynamic frequency reuse is a challenging task, due to the increased interference added to the system.

Frequency reuse has attracted much attention in academia, where the case of D2D with reuse is referred to as the underlay scenario. In this scenario some UEs, called C-UEs, participate in cellular communication sessions towards the base station and other UEs, the D-UEs, in D2D sessions. D-UEs are allowed to reuse channels of C-UEs, provided that the created interference is within defined bounds. The task is then to find appropriate pairs of D-UEs and C-UEs such that some metric is optimized, which typically is the sum-rate or energy efficiency. This problem is often also combined with mode selection, scheduling decisions, power control, or a full cross-layer optimization. A common assumption is that the number of D2D-links which are allowed to reuse a certain channel is upper bounded by one or two, to keep the complexity low.

In this paper, we consider a core problem of frequency reuse, the problem of how to activate as many links as possible on a single resource such that each link achieves a certain desired minimal signal quality. We believe that when we know how to find the maximal number of reusing links, we can use this knowledge to further optimize the network, e.g., by directly increasing the reuse factor or scheduling links while allowing reuse. Activating as many links as possible is rarely investigated as standalone in D2D-related literature. On the other hand, similar problems have been considered in other wireless networking context. For this reason, we relate mostly to literature which is out of context while still being aware of the current state-of-the-art for D2D, which is described e.g., in the surveys [1], [2].

The idea of reusing frequencies has attracted research for more than two decades already, although in different use-cases. Especially power control and call admission control techniques consider problems that are similar to the ones investigated in current research on D2D-reuse but have found little attention in the D2D context so far. Power control answers the question how to tune the transmission powers of all transmitters such that certain minimum quality of service (QoS) constraints are fulfilled for all links. Decentral, efficient solutions that will find adequate powers whenever they exist have been proposed as early as 1993 [4]. Call admission control, on the other hand, goes one step further and considers which links should be selected such that the power control problem has a solution. If the links are selected such that the power control problem is not solvable, reuse cannot have a satisfactory result for all links. Although designed for uplink cellular networks, the latter problem clearly relates to the reuse link selection problem of D2D networks. However, efficient optimal solutions for it have not been found yet. In this paper, we map the call admission control problems to a D2D reuse use-case and propose a heuristic that outperforms state-of-the-art solutions.

II. MODEL AND BASICS

We consider a single cell set-up as is illustrated in Figure 1. A C-UE within the cell uses a certain transmission resource for uplink or downlink transmission and needs a certain quality
guarantee. A random number of D2D-Links, that also require minimum transmission qualities, are scattered in the cell. The question is which links should reuse the resource of the C-UE such that the reuse factor is maximized, under the condition that all quality guarantees are met. Problems of this type occur as sub-problems for, e.g., resource allocation and cause high complexity due to the complex interference situations. We abstract the set-up and consider a set \( \mathcal{L} \) of \( N \) wireless links. One of the links is engaged in a cellular up-/downlink transmission, and the others are D2D links. We consider that the sender of link \( j \in \mathcal{L} \) transmits with a power \( P_j \) and the receiving power at the receiver of link \( i \) is \( h_{ij} P_j \), where \( h_{ij} \) is a channel gain that takes account for path-loss and fading effects. We further consider the interference-limited case, i.e., assume that the signal and interference power at each link is large enough such that receiver noise can be neglected. The signal to interference ratio (SIR) of link \( i \) then is:

\[
SIR_i = \frac{h_{ii} P_i}{\sum_{j \neq i} h_{ij} P_j}, \quad j = 1, 2, \ldots, N
\]

We assume that each link needs to achieve a certain QoS metric which is strictly increasing with its SIR. Then, any minimum QoS constraint is equivalent to a constraint of the form \( SIR_i \geq \gamma_i \) for given minimum SIRs \( \gamma_i \). A valid QoS condition is, e.g., a minimum Shannon Capacity, \( C_i = \log_2(1 + SIR_i) \geq C_{i,\text{min}} \). This can be transformed into \( SIR_i \geq 2^{C_{i,\text{min}}} - 1 = \gamma_i \), because it is strictly increasing. The question we are interested in is how to maximize the number of active links such that all of them can achieve their SIR constraints at the same time, assuming dynamic power control. There are known power control algorithms [4]–[6] which are proven to find transmission powers that satisfy all SIR constraints whenever they exist. So the considered problem reduces to finding a set of links such that the power control problem remains feasible, because if it is not feasible reuse cannot be done with a satisfactory result. We now use the existing literature on power control [7]. Let \( \mathcal{A} \subseteq \mathcal{L} \) be the set of active links, i.e., the C-UE and all links that have been chosen to reuse its transmission resource, and let \( ||\mathcal{A}|| = M \leq N \). Then it is known that the \( M \) SIR-constraints of the links in \( \mathcal{A} \) can be rewritten to

\[
P_i \geq \sum_{j \neq i} \gamma_i h_{ij}/h_{ii} P_j
\]

or, in matrix form:

\[
\vec{P} \geq \mathbf{F}_A \vec{P},
\]

where \( \vec{P} = [P_1, \ldots, P_M]^T \) is the vector of transmission powers and \( \mathbf{F}_A \) is the Foschini-Matrix of all active links with \( (i, j) \) entry \( f_{A}^{(i,j)} = \gamma_i h_{ij}/h_{ii} \) if \( i \neq j \) and 0 otherwise. In (2) and further on, the inequalities on vectors are taken element-wise. The elements \( f_{A}^{(i,j)} \) can be seen as indicators of how severe the interference from link \( j \) to link \( i \) is, considering the desired SIR, interference path gain and signal path gain. Hence, the row sum \( \sum_{j=1}^{M} f_{A}^{(i,j)} \) is an indicator for the severity of the overall interference that link \( i \) is exposed to. The column sum \( \sum_{i=1}^{M} f_{A}^{(i,j)} \) indicates, how severe the interference is that link \( i \) produces.

If the SIR constraints of all active links can be satisfied at the same time, equation (2) has a solution. As all channel gains and SIR-constraints are nonnegative, so are the entries of \( \mathbf{F}_A \), hence \( \mathbf{F}_A \) is a nonnegative matrix. According to the Perron-Frobenius Theorem for nonnegative matrices [7], (2) has a solution if and only if the spectral radius of \( \mathbf{F}_A \), i.e., its maximum modulus eigenvalue, \( \rho(\mathbf{F}_A) \leq 1 \). Assume a matrix \( \mathbf{F}_C \), which is the Foschini-Matrix when all links are activated. Then, any matrix \( \mathbf{F}_A \) is a sub-matrix of \( \mathbf{F}_C \), i.e., is created from \( \mathbf{F}_C \) by deleting the rows and columns of all inactive links. Whenever an inactive link is activated, both a row and a column of entries is added to \( \mathbf{F}_A \). When a link is deactivated, its row and column are deleted from \( \mathbf{F}_A \). From this perspective, we can formulate the considered reuse link selection problem as:

\[
\max ||\mathcal{A}|| \quad s.t. \quad \rho(\mathbf{F}_A) \leq 1.
\]

The problem here is that the exact influence of adding or removing rows and columns on the maximal eigenvalue of \( \mathbf{F}_A \) cannot be captured by an analytical expression. For this reason, the reuse link selection problem has a combinatorial nature that leads to a high complexity. In fact, the problem is considered to be NP-complete [8], although a formal proof for this is missing in literature. Anyhow the complexity is large enough that designing an optimal scheme is out of the scope of this paper, which is why we focus on heuristic criteria.

A. State of the Art

The state-of-the-art which we consider concentrates on research in arbitrary wireless networks but also contains refer-
ences to D2D communication. In general, reuse link selection can be performed by merging link sets, i.e., increasing the number of active links, as well as by removing link sets [8]. With link sets, either single links or groups of links can be merged/removed. In [5], J. Zander proposes a stepwise removal algorithm (SRA), where the link with the largest maximum of both, row sum and column sum of $F_A$ is removed. As we have stated already, the row and column sum have a tight connection to the severity of received and created interference. Andersin et al. propose the SMART criterion in [8], which removes those links step-by-step, that will reduce interference. Xiao et al. propose the call admission control scheme $\Delta$-CAC, in which inactive links use low-power probing tones to determine whether they can become active [9]. Links are therein activated if a certain discriminant, $\Delta$, is larger than zero. Chen et al. [10] propose a decentralized two-phase link selection algorithm that extends [9]. In this algorithm, the dynamics of the distributed constrained power control (DCPC) [6] are used to determine a first feasible set, which is then extended by repeatedly executing the $\Delta$-CAC algorithm with random links. The focus of [10] is not to provide an optimal solution but to create a completely decentralized algorithm. Finally, Lee et al. use a heuristic for D2D reuse link selection in [11] where those links are removed, whose column vectors in $F_A$ have a maximal 2-norm. For this last work, however, the performance of the link selection is not in focus and hence not evaluated. In general, D2D related work performs larger optimizations and does not investigate our problem as standalone, which is why [11] is the only comparable reference with D2D context that we found.

III. PROPOSED CRITERIA

A. Criteria Derivation

We now derive our proposed criteria for reuse link selection. As stated the investigated problem is, mathematically spoken, the problem how to create a submatrix $F_A$ of $F_C$ with maximal dimensionality, such that $\rho(F_A) \leq 1$. A close relation exists between $\rho(F_A)$ and the so-called power iteration, which we give in the following lemma:

**Lemma 1 (Power Iteration):** Assume a sequence of vectors, $\bar{P}[k]$, that evolves according to the power iteration, i.e., $\bar{P}[k+1] = F_A \bar{P}[k]$. Then it is true that [12]:

$$\lim_{k \to \infty} \bar{P}[k] = \lim_{k \to \infty} F_A \bar{P}[0] = \rho(F_A) \bar{v}_p c, \quad (4)$$

where $\bar{v}_p$ is the eigenvector with unit norm corresponding to $\rho(F_A)$ and $c > 0$ is a constant. $\bar{v}_p$ is also called dominant eigenvector of $F_A$.

It is known that $(F_A \bar{P})_i = \gamma_i / \text{SNR}_i$, which is the basis of several dynamic power control algorithms [4]–[6]. Those can be run in a decentralized fashion and will find power vectors that fulfill (2), if they exist. From Lemma 1 we derive the following corollary:

**Corollary 1 (Diminishing Power Values):** Consider two reuse link sets, $A$ and $A'$ and assume that $\rho(F_A) < \rho(F_{A'})$. Then, using the power method, there exists a $K > 0$ such that:

$$\bar{P}[k] = F_A^k \bar{P}[0] < F_{A'}^k \bar{P}[0] = \bar{P}'[k] \quad \forall k \geq K. \quad (5)$$

**Proof:** Let $\bar{v}_p$ be the dominant eigenvector of $F_A$ and $\bar{v}_p'$ be the one of $F_{A'}$. As all eigenvectors are determined up to constants $c, c'$, we have according to Lemma 1 that:

$$\lim_{k \to \infty} \bar{P}[k] = \rho(F_A) k \bar{v}_p c; \quad \lim_{k \to \infty} \bar{P}'[k] = \rho(F_{A'}) k \bar{v}_p' c' \quad (6)$$

Combining this with (5), we get the condition

$$\rho(F_A) < \rho(F_{A'}) \sqrt{\min_{i} \left\{ \frac{\bar{v}_p'^t c'}{\bar{v}_p c} \right\}} \forall k \geq K, \quad (7)$$

which is true because $\sqrt{\left( \cdot \right)}$ monotonically converges to one with increasing $k$.

We note that, as all inequalities on vectors are taken element-wise, if Corollary 1 is true, then also

$$\sum_{i=1}^M P_i[k] < \sum_{i=1}^M P_i'[k] \quad \forall k \geq K \iff \rho(F_A) < \rho(F_{A'}). \quad (8)$$

Assuming that we choose $\bar{P}[0] = \bar{1}$, where $\bar{1}$ is a vector containing only ones, by writing out the matrix-vector product, we get that (8) corresponds to:

$$\begin{align*}
\sum_{s_0=1}^M P_{s_0}[k] &= \sum_{s_0=1}^M \sum_{s_1=1}^M f_A(s_0, s_1) P_{s_1}[k - 1] \\
&= \sum_{s_0=1}^M \cdots \sum_{s_1=1}^M \prod_{l=1}^k f_A(s_{l-1}, s_l) P_{s_l}[0] \\
&= \sum_{s_0=1}^M \cdots \sum_{s_k=1}^M f_A(s_0, s_k) \\
&= \sum_{s_0=1}^M \cdots \sum_{s_k=1}^M f_A(s_{k-1}, s_k). \quad (9)
\end{align*}$$

Fig. 2. Graph showing the interference coupling for $N = 4$ Links.
Algorithm 1 General Link Mergence Algorithm

1: Set $\mathcal{A}$ to contain only C-UE
2: Choose Criterion $\mathcal{M} \in \{2$-Circle, Signal-Flow, $\ldots\}$
3: Gather all channel gains and create $\mathcal{F}_A$.
4: while $\rho(\mathcal{F}_A) \leq 1$ do
   5: Find $l = \arg \min_{k \in (\mathcal{L} \setminus \mathcal{A})} \mathcal{M}(l, \mathcal{A} \cup l)$.
   6: $\mathcal{A} := \mathcal{A} \cup l$
   7: Create $\mathcal{F}_A$, Calculate $\rho(\mathcal{F}_A)$.
8: end while
9: Output $(\mathcal{A} \setminus l) $

Algorithm 2 General Link Removal Algorithm

1: Set $\mathcal{A} = \mathcal{L}$
2: Choose Criterion $\mathcal{R} \in \{2$-Circle, Signal-Flow, $\ldots\}$
3: Gather all channel gains and create $\mathcal{F}_A$.
4: while $\rho(\mathcal{F}_A) > 1$ do
   5: Find $l = \arg \max_{l \in \mathcal{A}} \mathcal{R}(l, \mathcal{A})$.
   6: $\mathcal{A} := \mathcal{A} \setminus l$
   7: Create $\mathcal{F}_A$, Calculate $\rho(\mathcal{F}_A)$.
8: end while
9: Output $\mathcal{A}$

Each summand of (9) is in fact a product of elements from $\mathcal{F}_A$, which are chosen such that the indices form a “chain”. This can be interpreted in the following fashion: Consider a graph $\mathcal{G}_A = (\mathcal{V}, \mathcal{E})$, shown in Figure 2, where the vertices are formed by the set of active links, i.e., $\mathcal{V} = \mathcal{A}$, and that has edges between any vertices $v_i$, $v_j$, if and only if $i \neq j$. Let any edge $(i, j)$ be weighted by $f_A^{(i,j)}$. Further, we define a weight function for any path $p$ on $\mathcal{G}_A$ as $w(p) = \prod_{(s_{l-1},s_l) \in p} f_A^{(s_{l-1},s_l)}$. Then, (9) sums up the weights of all paths with length $k$ in $\mathcal{G}_A$.

This interpretation gives us an interesting insight into the coupling of interference. The graph can be interpreted as a “signal flow” that represents the evolution of the power method. Any input signal $P_i[k]$ is forwarded via all outgoing edges and amplified by $f_A^{(i,j)}$. The sum of all incoming, weighted signals of vertex $v_i$ form the input $P_i[k + 1]$ for the next iteration. When $\rho(\mathcal{F}_A) > 1$, i.e., reuse is infeasible, then the amplification will be unstable and tend to infinity for any arbitrary small input. In the other case, it will be stable and tend to zero for any arbitrary large input. Assume that the interference situation is infeasible and that a link needs to be removed. Then it should be the link that reduces $\rho(\mathcal{F}_A)$ most, because we want to come as close to feasibility as possible. When adding a link to a feasible set, on the other hand, the added link should be the one that increases $\rho(\mathcal{F}_A)$ least. From Corollary 1 and equation (8), the link that reduces $\rho(\mathcal{F}_A)$ most, or increases it least, is also the one that reduces (9) most or increases it least, respectively. This is the one whose impact on the overall amplification is largest/second largest. Evaluating the full impact of a link removal or addition to $\mathcal{A}$ is clearly very hard because (9) contains an exponentially increasing number of summands, of which not all are influenced when adding/removing a single link. Any heuristic that does not optimally solve the problem needs to at least capture the dominant aspects of the interference situation. The state-of-the-art approaches presented in Section II mainly depend on the weights of $\mathcal{F}_A$. From our graph perspective in (9), the weights themselves only capture part of the interference situation. The full severity of interference is captured by all combinations that the weights can form, i.e., the paths on the graph $\mathcal{G}$. With this perspective, it makes sense to propose the following two criteria in addition to the existing ones:

Criterion 1 (Sum of 2-Circles):
Add/Remove the link $i$ for which
$$\sum_{m=1}^{M} \left( \sum_{j=1}^{M} f_A^{(m,i)} f_A^{(i,j)} \right)$$
is minimal/maximal.

Criterion 2 (Sum of Signal Flows):
Add/Remove the link $i$ for which
$$\sum_{m=1}^{M} \left( \sum_{j=1}^{M} f_A^{(m,i)} f_A^{(i,j)} \right) = \left( \sum_{m=1}^{M} f_A^{(m,i)} \right) \left( \sum_{j=1}^{M} f_A^{(i,j)} \right)$$
is minimal/maximal.

As indicated by the subtitles of the criteria, Criterion 1 removes the link $i$ for which the sum of all amplifications over circles with size 2 through $i$ is largest. This captures the mutual interference amplification among all link pairs but neglects amplifications of longer paths. Criterion 2 removes the link for which the sum of amplifications over all possible paths through $i$ is largest. We stress that these criteria are not optimal. For example, it might happen that $f_A^{(m,i)} f_A^{(i,j)}$ is very large but all $f_A^{(l,m)} f_A^{(m,i)} f_A^{(i,j)}$ is very small $\forall l$. Then, link $i$ will probably be chosen for removal by both criteria but the influence on $\rho(\mathcal{F}_A)$ might be small. However, we will show that these criteria capture the influence of links better than the state-of-the-art.

B. Criteria Implementations

The criteria that we propose induce both an algorithm for link mergence and link removal. The algorithms are summarized as Algorithms 1 and 2. In the mergence case there is an active link set $\mathcal{A}$, and any link that is not in $\mathcal{A}$ will evaluate the selected criterion with respect to all active links. The link
with the lowest value is added to $\mathcal{A}$. In the removal case, all links in $\mathcal{A}$ evaluate the considered criterion and the one with the largest value is removed from $\mathcal{A}$.

The proposed algorithms are both centralized and need knowledge of the full channel gain matrix. It has been shown in [13], that the acquisition of the gain matrix for $M$ links needs $\Omega(M)$ transmission time intervals (TTIs) and produces control traffic of $\Omega(M^2)$ bytes. $\Omega(*)$ is the landau symbol indicating a lower bound for an order of increase. A semi-decentralized feasibility check, on the other hand, can be performed with a constant number of TTIs and control traffic of $\Omega(M)$ bytes [13]. Both proposed algorithms can also have a potential semi-decentralized implementation that we are aware of, but that we cannot publish here due to space restrictions. The best semi-distributed implementation for the Signal Flow criterion (Criterion 2) we could design needs three TTIs for decision per addition/removal step and produces $\Omega(|A|)$ bytes control traffic per step for the removal case, or $\Omega(|L\setminus A|)$ bytes for the addition case. The best implementation of the 2-Circle criterion (Criterion 1) that we could design needs $\Omega(|A|)$ TTIs for decision per removal step, $\Omega(|L\setminus A|)$ TTIs per addition step and produces a similar amount of bytes control traffic. Assume that $K$ addition or removal steps are necessary to reach the found maximal set. At each step, the size of the candidate set ($A$ for removal and $L\setminus A$ for addition) reduces by one. Then the Signal-Flow criterion needs $\Omega(K)$ TTIs to find the maximal set and produces control traffic in the order of $\Omega((K+1)(M-K/2))$ byte. The 2-Circle criterion needs $\Omega((K+1)(M-K/2))$ TTIs to find the set and produces an equal magnitude of byte for control traffic. This order is smaller than $\Omega(M^2)$, grows sub-linearly with $K$ but is significantly larger than both, $K$ and $M$. Comparing this with the values for channel gain collection, we conclude that a semi-distributed implementation will produce less control traffic but not necessarily be faster than a centralized implementation. We consider the central implementation for the simulative analysis, due to its ease of implementation.

### IV. Simulation

We now investigate the quality of the proposed criteria and compare them with the state-of-the-art. In particular, we are interested in two aspects: (1) What is the largest average reuse set found by the criteria and (2) is there a performance gap between link mergence and link removal? We compare the proposed criteria 2-Circle and Signal-Flows with SMART [8] and 2-Norm [11] from literature.

#### A. Simulation Setup

The simulation is implemented using SimuLTE [14], which is based on OMNeT++ [15]. SimuLTE uses a realistic channel model based on ITU-R M.2135-1 that includes shadowing and fading. We use a circular cell, with a radius chosen such that the coverage area is $10^6$ $m^2$. The eNodeB is located in the center of the cell and the only cellular UE is placed randomly within the cell. The number of active D2D links and their locations inside the cell follow a poisson point process with density $\lambda$. The eNodeB gathers the exact channel information between all links in a centralized fashion, creates $F_L$ and then determines the maximal set of feasible D2D links, according to the algorithms 1 and 2. Table I shows chosen parameter settings of the simulation.

#### B. Simulation Results

First, we analyze the performance difference of removing and merging links. For each criterion, we vary the density of D2D-links $\lambda$ and evaluate the mean number of active links after simulation for both removal and mergence. We calculate the mean difference of feasible links by subtracting the results of link mergence from those of link removal.

Figure 3 shows the performance differences of removal and mergence for the selected criteria. There is only a small performance difference between link removal and link mergence for the SMART and 2-Circle criteria. However, for the Signal-Flows criterion, with increasing link density, link mergence on average outputs slightly more feasible links than link removal. This effect becomes a little more dominant with increasing link density. On the other hand, for the 2-Norm criterion, link removal always achieves a larger number of feasible links than link mergence. Also, the performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Maximal Transmission Power</td>
<td>26 dBm</td>
</tr>
<tr>
<td>Cell Radius</td>
<td>550 m</td>
</tr>
<tr>
<td>D2D Distance Range</td>
<td>0 – 50 m</td>
</tr>
<tr>
<td>Target SINR</td>
<td>5 dB</td>
</tr>
<tr>
<td>Expected Number of Links (Mean)</td>
<td>10, 20,..., 60</td>
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<tr>
<td>Number of Simulations per Round</td>
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</tr>
<tr>
<td>Confidence Level</td>
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![Fig. 3. Difference of mean feasible link density between link removal and link mergence comparing each criterion. The mean of link mergence is subtracted from that of link removal.](image-url)
gap becomes larger when the total link density increases. However, compared to the total link densities, the performance differences are not dominant. We conclude that in most cases, the performance gap between link removal and link mergence is on the edge of being negligible. This has an impact on the chosen implementation for the semi-distributed case: In general, when the algorithm becomes distributed, the active link set slowly increases or decreases. Then, link mergence is preferable over link removal because smaller, suboptimal feasible combinations will be found earlier. In the process of accepting more D2D links into the feasible set, the whole system will also remain feasible with high probability, so data or control packets can be sent already by all active links while the link selection is still in progress.

Now we take the absolute performance of each criterion into consideration, which is shown in Figure 4. We select the version of each criterion, removal or mergence, that yields the better results. The confidence intervals of a 99% confidence level are also shown for each curve. For lower total link density, from 10 to 20, the difference between 2-Circle and Signal-Flows and the difference between SMART and 2-Norm are both very small, considering the overlapping of confidence intervals. However as the density increases, even though all curves encounter difficulty of keeping a linear rate of growth, the performance difference among them becomes obvious. 2-Circle remains the best, while 2-Norm performs worst. When the total active link density reaches 60, 2-Circle produces 20 more feasible links than 2-Norm. This is a performance increase of nearly 70%! The Signal-Flows-criterion also produces more feasible links than the two from literature, with performance gains from 20% to 50%. For all criteria, larger link densities lead to larger confidence intervals.

V. CONCLUSION

We conclude the paper by commenting on its main aspects. We investigated the question how to maximize the reuse of a single transmission resource, considering a set-up with a single uplink and a random number of D2D links. We recognized a cross-relation to a part of literature that has found little attention so far, namely call-admission-control with dynamic power control. Putting the problem into a standard form, we presented an alternative formulation that can be interpreted from a graph perspective. This formulation allowed us to propose two new criteria for reuse link selection, the 2-Circle criterion and the Signal-Flow criterion. With simulations we investigated their impact on link mergence/link removal strategies and found that: (1) Link mergence and link removal perform nearly the same, for any considered criterion. (2) Both our proposed criteria produce significantly (up to 70%) higher reuse sets than the compared ones. We further find that apparently, the assumption of one or two links reusing a resource in a cell, which is often found in literature, is much too conservative. Our simulations show that the maximally possible reuse set can be in the order of ten-fold to forty-fold reuse, depending on the desired signal quality. A main enabler for this reuse increase seems to be dynamic power control, because it is able to reduce interference significantly.

REFERENCES