Abstract—It has been postulated in literature that three gain types are introduced into the radio access part of cellular networks by device-to-device communication, namely the proximity gain, hop gain and reuse gain. These gain types have further been shown to be captured by a resource efficiency metric. We investigate the influence of mode selection and scheduling on the resource efficiency gains in the D2D overlay case. We formulate mode selection as a resource efficiency maximization problem and find that for proper mode selection, the achieved resource efficiencies of schedulers must be anticipated correctly. Because this is very complex, we propose a simple, channel state based mode selection scheme and investigate how well it performs using different schedulers. We show that our proposed scheme is optimal for schedulers that do not leverage frequency diversity and optimizes a tight lower bound for those that do leverage diversity. Simulations show that in any case, our scheme produces higher D2D-gains than the state of the art.

I. INTRODUCTION

Device-to-Device (D2D) communication, i.e., direct communication between user equipments, is envisioned to enhance the functionality of future cellular networks. The D2D concept has achieved increased attention in both, academia and industry due to its potential to increase the spectral and energy efficiency, to offload traffic from the core network and enable proximity aware networking on a new scale [1]–[3]. In an early work on design aspects of D2D communication [2], Fodor et al. postulated the existence of three gain types that are introduced with D2D communication on the radio access network (RAN), compared to realizing all traffic with cellular communication. The proximity gain denotes that, due to the expected spatial proximity of devices, higher data rates can be achieved by D2D communication, with lower delay and energy consumption. The hop gain is a gain in terms of used transmission resources, which are less for D2D communication because only one hop is used, compared to one uplink and downlink hop in the cellular case. The reuse gain accounts for the fact that a dynamic reuse of transmission resources can be performed with D2D communication, increasing the effective number of usable resources.

Mode selection considers the question, by which communication mode a certain flow should be realized in the cellular network. In general, there are three possible modes: (1) The cellular mode (CM), in which a flow uses the uplink and downlink hop, i.e., is relayed by the base station. (2) The dedicated D2D mode (DM). Here, the communication is direct but uses dedicated transmission resources. (3) The reuse D2D mode (RM), sometimes also shared mode, is a direct communication where resources are allowed to be reused within a cell. The DM is also referred to as overlay D2D, whereas the RM is known as underlay. In general, the decision of CM versus direct communication can be seen as a routing problem because the flow will either be routed directly or through the infrastructure. The decision of DM versus RM is, on the other hand, a scheduling problem that depends on interference properties in the network. Consequently, underlay mode selection is often combined with scheduling and power control problems or reuse link selection. In literature, a large variety of use cases and mode combinations are considered, so a full review is out of the scope of this paper. We refer the interested reader to Mach et al. [4], which contains a well summarized state of the art analysis.

In [5], Kluegel et al. motivated that the RAN-gains proximity-, hop- and reuse-gain can be captured by a flow-based resource efficiency metric. The resource efficiency of a communication flow is therein the number of its end-to-end transported bits, divided by the resources used by the flow on all hops of its communication path. When the overall resource efficiency of a flow is formulated, the factor by which D2D communication is more efficient than cellular communication decomposes into three sub-factors, which can be interpreted as proximity-, hop- and reuse-gain [5]. This formulation gives a concrete analytical measure for Fodors’ gains and has an immediate impact on mode selection. In this work we aim at choosing the communication mode such that the D2D-Gain is maximized. However, our simulations show that the actually achieved resource efficiency strongly depends on the scheduling mechanism used by the network operator. The resource efficiency achieved with different communication modes is...
We propose a channel state based mode selection scheme and investigate how well it performs for different types of schedulers. We find it to optimize a lower bound for all schedulers that leverage frequency diversity and to be optimal for those that do not. We further show that in any case, our proposed scheme produces higher D2D gains than state of the art schemes.

II. SYSTEM DESCRIPTION

We consider the overlay D2D case of an LTE cell, as illustrated in Figure 1. A random number of D2D links are present in a cell and produce local traffic. The eNodeB needs to decide, with respect so some chosen metric, which of the links are offloaded to D2D communication. Afterwards, the eNodeB schedules the ongoing transmissions in an overlay manner, i.e., without frequency reuse.

For mathematical tractability, we describe the system similarly to the systems investigated in [6], although we use a different notation. We model a set of mobile nodes $N$ that contains both user equipments (UEs) and the eNodeB. The UEs form pairs, among each of which a single communication flow arises that we consider as a commodity $c \in C$. From the nodes, a set of medium access control (MAC) layer wireless links $L \subseteq N \times N$ are available for transmission and are referred by the set $\mathcal{R} = \{PRB_t\}$, which contains all usable PRBs. $\mathcal{R}$ consists of a uplink PRB set $\mathcal{R}_{ul}$ and a downlink set $\mathcal{R}_{dl}$, that are meant to be used by the corresponding communication types only. We assume transmissions on different PRBs to be non-interfering.

Each wireless transmission uses a subset of $\mathcal{R}$ that has been assigned by the scheduler. The overall resource structure is divided into consecutive time frames of fixed duration $T$, that we index with $t \in \{1, 2, \ldots \}$. The PRBs are unique within a time frame and the PRB structure repeats with each new frame. For each link $l \in L$ and each $PRB_t \in \mathcal{R}$, there is a channel state $q^{(t)}_{l,r}$ per time frame that denotes the channel quality for link $l$ on $PRB_t$ during this frame. The input domain of $q^{(t)}_{l,r}$ contains the integer valued channel quality indicators (CQIs), which we assume constant during one frame. The system wide channel state at frame $t$ is then described by the matrix $Q^{(t)} \in \mathbb{R}^{[L] \times |\mathcal{R}|}$. We consider that each commodity $c$ can be routed over a path that contains a sequence of links. The path is described by the column vector $\vec{p}_c \in \{0, 1\}^{[L]}$ of which element $p_{c,l}$ is one if the link $l$ is in the path of $c$ and zero otherwise. Each node $n$ in the path of commodity $c$ has a buffer for $c$, whose backlog at time frame $t$ we denote with $b^{(t)}_{n,c}$. Accordingly, the matrix of all backlogs is $B^{(t)} \in \mathbb{R}^{[N] \times |C|}$.

We assume that the behavior of the scheduler at the eNodeB is defined by a set of rules that assigns a transmit power and modulation and coding scheme (MCS) on each PRB to each link. Depending on the channel state $Q^{(t)}$, this assignment will result in a number of bits which can be transmitted error free. We assume that the number of bits can be calculated when $Q^{(t)}$ is known. In this case, there is a maximum number of bits, $s^{*(t)}_{l,r}$, that can be transmitted on each PRB $r$ by a link $l$, when the power and MCS are chosen optimally. We assume that the scheduler knows these optimal choices and hence, scheduling can be reduced to assigning a number of bits for transmission on a resource. The schedule itself is then a number of admitted bits per link and PRB. The scheduler is re-run at every time frame, so the resulting schedule can be different for different $t$. The schedule is represented by the matrix $S^{(t)} \in \mathbb{R}^{[L] \times |\mathcal{R}|}$. We model the scheduler itself as a function which maps the system state and queue backlogs to a schedule, i.e., $S^{(t)} = S(Q^{(t)}, B^{(t)})$. When the schedule is fixed, the number of bits delivered over an arbitrary link $l$ in frame $t$ is

$$d^{(t)}_l = \min\{\sum_{r=1}^{|\mathcal{R}|} s^{(t)}_{l,r}, \sum_{c \in C} p_{c,l} b^{(t),c}_l\}. \tag{1}$$

That is, the link will transmit the minimum of the scheduled bits and the amount in its buffers. We adopt the concept of resource measure introduced in [5]. According to this concept, there is an “amount” of resource used by each link, which is its lebesgue measure (volume) in the resource space. Further, when resources are reused, all links occupy it with equal parts. The amount of resource used by link $l$ on $PRB_t$ and frame
The numerator term is one when PRB frequency size of a PRB and \(|A_c|\) is the size of the cell area, i.e., the area in which a PRB may not be reused in the overlay case. The total term is one when \(PRB_k\) is used by link \(l\) and the denominator term counts how often a PRB is used in total. Together, these terms create resource usage metric in which the time-frequency-space usage of a PRB is equally divided by all nodes in a cell using that PRB. The total amount of resource used by a link is then the sum of resource usage over all scheduled PRBs:

\[
\sum_{l=1}^{[L]} \left| PRB \right| \left| A_c \right| \frac{\text{sgn}(s_{l,k}^{(t)})}{\sum_{m=1}^{[C]} \text{sgn}(s_{m,k}^{(t)})} = \frac{\bar{c}_l^{(t)} \cdot \bar{r}_l^{(t)}}{r_l^{(t)}} \tag{3}
\]

We define \(\bar{c}_l^{(t)} = \left| PRB \right| \left| A_c \right| \sum_{r=1}^{[R]} \text{sgn}(s_{l,s}^{(t)})\), which we call the apparent resource usage of link \(l\), and its counterpart \(\bar{r}_l^{(t)}\), the effective reuse factor experienced by link \(l\), a parameter which is such that \(\bar{c}_l^{(t)} / \bar{r}_l^{(t)} = r_l^{(t)}\).

If several commodities share a link, they share its resources by their achieved percentage of link rate. In the considered setup, there is at most one commodity transported over each link, so the rate that \(c\) achieves on link \(l\) in frame \(t\) and the resources it uses are equal to \(d_l^{(t)}\) and \(\bar{r}_l^{(t)}\), respectively.

### A. Resource Efficiency and D2D-Gain

The resource efficiency of a flow has been defined in [5] as the number of end-to-end transported bits, divided by the number of resources used on its communication path. Consider that a commodity \(c\) is routed over a path and consider its last link to be \(l_c\). Then the end-to-end delivered bits in time frame \(t\) is equal to \(d_l^{(t)}\). The number of resources used by \(c\) in frame \(t\) on path \(p_c\) is

\[
r_c^{(t)} = \sum_{l \in \mathcal{L}} p_{c,l} r_l^{(t)} = \sum_{l \in \mathcal{L}} p_{c,l} \bar{r}_l^{(t)}/\bar{r}_l^{(t)}. \tag{4}
\]

We now assume a certain observation time that contains a frame interval \([t_i, t_u]\) of \(\Delta t\) time frames. The resource efficiency achieved by commodity \(c\) in this observation time is:

\[
RE_c^{(C)} ([t_i, t_u]) = \frac{\sum_{t=t_i}^{t_u} d_l^{(t)} - \sum_{t=t_i}^{t_u} s_l^{(t)}}{\sum_{t=t_i}^{t_u} r_c^{(t)}} = \frac{TP_c([t_i, t_u])}{R_c([t_i, t_u])}). \tag{5}
\]

\(TP_c([t_i, t_u])\) is the average throughput of commodity \(c\) per time frame and \(R_c([t_i, t_u])\) the average resource usage per time frame, both achieved during the observation time. When we let \(t_u\) go towards infinity, the averages turn into mean values that we denote with \(TP_c\) and \(R_c\), respectively.

Assume now that a flow \(c\) can be realized in the network using either the CM or a D2D mode, and assume both choices to achieve a resource efficiency of \(RE^{(CM)}_c\) and \(RE^{(D2D)}_c\). Then the increase factor of efficiency by D2D has been defined as the D2D-Gain [5]. Combining equations (4) and (5) gives:

\[
G_{c,D2D} = \frac{RE^{(D2D)}_c}{RE^{(CM)}_c} = \frac{TP^{(D2D)}_c}{TP^{(CM)}_c}. \tag{6}
\]

Analog to \(\bar{r}_l^{(t)}\), we define \(\bar{R}_c = \sum_{l=1}^{[L]} \sum_{0 \leq t \leq [T]} p_{c,l} \bar{r}_l^{(t)} / (T \cdot \Delta t)\) as the average apparent resource usage of flow \(c\). \(\bar{R}_c\) is the average effective reuse factor experienced by \(c\), a parameter such that \(\bar{R}_c / \bar{R}_c = \sum_{l=1}^{[L]} \sum_{0 \leq t \leq [T]} p_{c,l} \bar{r}_l^{(t)} / (T \cdot \Delta t)\).

By equation (6), the D2D gain decomposes into three factors. The first one captures the throughput increase of D2D communication, compared with the CM, and can be seen as the proximity gain. The second is the factor by which D2D uses less resources than the CM, i.e., is the hop gain. The third one captures the increase of reuse factor when D2D is used, compared to CM and hence is the reuse gain introduced by D2D. Finally, we define the Resource efficiency of a whole network as:

\[
RE_{total} = \sum_{c \in C} \frac{TP_c}{R_c} = \sum_{c \in C} \frac{R_c}{R_{total}} RE_c = \sum_{c \in C} \eta_c RE_c, \tag{7}
\]

where \(R_{total} = \sum_{c \in C} R_c\) is the total resource usage and \(\eta_c = R_c / R_{total}\) is the percentage of resources used by flow \(c\).

### III. Proposed Mode Selection

We aim at maximizing Fodor’s gains proximity- and hop-gain, assuming an overlay D2D communication scenario. We want to choose the DM only when it leverages the D2D gains, i.e., when it achieves a higher resource efficiency than the CM. As stated already, overlay mode selection can be interpreted as a routing problem. The choice is between the cellular path \(\bar{p}^{(CM)}_c\), which contains one uplink and one downlink hop, and the direct path \(\bar{p}^{(D2D)}_c\), which has one hop only. Formally we aim at solving the problem

\[
\max_{\bar{p}_c} RE_{total} \text{ s.t. } \bar{p}_c \in \{\bar{p}_c^{(CM)}, \bar{p}_c^{(D2D)}\} \forall c. \tag{8}
\]
To optimally solve (8) it must be evaluated what resource efficiency a flow will experience for both, CM and DM. The efficiency depends on the used scheduler, buffer status and the channel qualities of all links and hence is hard to predict before a mode switch. We propose a simple heuristic that uses the achievable rates of the direct and cellular links as an input. While this is simpler, it is not clear how well the resource efficiency of a flow can be predicted from the achievable rates, because the dynamics of the scheduler are ignored. We will discuss this issue in detail in Section IV. Let $ul, dl, d2d \in L$ denote the uplink, downlink and direct link of a potential D2D flow and let $\hat{d}_l = \sum_{r \in R} s^l_{t,r}$ be the maximal available link rate on link $l$, that is achieved when $l$ uses all available resources within a frame. Further, let $RE_l$ be the resource efficiency achieved when $\hat{d}_l$ is scheduled, i.e., $\hat{d}_l$ divided by all resources. The capacity of the direct path is $C_{c}^{(DM)} = \hat{d}_{d2d}$, where we assume that D2D is allowed to use both, uplink and downlink resources. The capacity of the direct path is $C_{c}^{(CM)} = \min \{d_{ul}, d_{dl}\}$. We can calculate the amount of resources necessary to achieve the capacity as:

$$r_{c}^{(DM)} = \frac{|PRB||A_c||R|}{C_{c}^{(DM)}},$$

$$r_{c}^{(CM)} = C_{c}^{(CM)} \left( \frac{1}{RE_{ul}} + \frac{1}{RE_{dl}} \right).$$

The DM path requires all resources to achieve its capacity. On the CM path, however, each hop will use only the percentage of resources necessary to achieve $C_{c}^{(CM)}$, which is less than $|R_{ul/dl}|$ in general. The proposed mode selection scheme is:

**Mode Selection 1 (Resource Efficiency Mode Selection):** Choose DM for flow $c$, if

$$RE_{c}^{(DM)} = \frac{C_{c}^{(DM)}}{r_{c}^{(DM)}} > \frac{C_{c}^{(CM)}}{r_{c}^{(CM)}} = RE_{c}^{(CM)} \tag{9}$$

Else, choose CM.

Mode Selection 1 does not depend on the used scheduler but performs a rather simple evaluation of link qualities, aiming at resource efficiency maximization. For comparison, we consider a mode selection that is prototypical for schemes found in literature:

**Mode Selection 2 (General Mode Selection):** Choose DM, if

$$C^{(DM)} = \hat{d}_{d2d} > \alpha \cdot \min \{\hat{d}_{ul}, \hat{d}_{dl}\} = \alpha \cdot C^{(CM)} \tag{10}$$

for $\alpha \geq 0$. Else, choose CM.

We note that many mode selection schemes found in literature take the form of the General Mode Selection scheme. For $\alpha = 0$, DM is chosen whenever there is a connectivity among the D-UEs. This is typically referred to as the ForceD2D scheme [7]–[9]. With $\alpha = 1$, DM is chosen whenever the D2D capacity is larger than the cellular link capacity, which we call the Capacity scheme [9], [10]. When the CM throughput is corrected to be half of the cellular capacity to account for the hop-gain [8], [11], which we call the Rate scheme, $\alpha = 0.5$. Compared with these, the Resource Efficiency mode selection takes a similar form but has an $\alpha$ that differs per link.

### IV. Efficiency of Schedulers

Because the resource efficiency metric depends on the scheduled rates, the scheduler has a major influence on the average achieved resource efficiency. Most end-to-end throughputs can be realized by a multitude of schedules of which some will be more resource efficient than others.

Schedulers are often designed to maximize the sum-throughput of a network, its energy efficiency or user fairness but not to maximize its resource efficiency. Hence, it is not even clear to what extent popular schedulers are actually suited to create D2D gains. Further, the ability of a mode selection scheme to leverage the D2D-gains depends on its ability to predict the efficiency increase experienced by the scheduler in DM. The proposed Resource Efficiency scheme is independent of used schedulers, so the question arises whether it can predict the more efficient mode correctly. To clarify this, we start with a short investigation of the impact of schedulers on resource efficiency in this section. For particular comparison, we consider three known schedulers whose scheduling rules are:

**Scheduler 1 (Proportional Fairness Scheduler [12]):** Let $R_0$ be the set of unused PRBs, $\hat{d}_l = \sum_{r \in R_0} s^l_{t,r}$ be the maximal achievable rate by link $l$ on $R_0$, $\bar{d}_l$ the long-term average rate of $l$ and let the set $B = \{ l : \sum_{c \in C} b_{l(t),c} > 0 \}$ contain all MAC-layer links with backlogged data. Then, satisfy all demands of link $k \in B$ for which $d_{k/l} \geq \hat{d}_l/\bar{d}_l \forall l \in B$. If resources are left afterwards, remove $k$ from $B$, adapt $R_0$ and re-run.

**Scheduler 2 (Maximum C/I Scheduler [13]):** Let $B = \{ l : \sum_{c \in C} b_{l(t),c} > 0 \}$ be the set of all MAC-layer links with backlogged data. Then, assign each PRB $r$ to link $k \in B$, for which $s^l_{k,r} \geq s^l_{t,r} \forall l \in B$.

**Scheduler 3 (Backpressure Scheduler [14]):** Let $B = \{ l : \sum_{c \in C} b_{l(t),c} > 0 \}$ be the set of all MAC-layer links with backlogged data. Then, define the backpressure of link $k$ on PRB $r$ as $BP_{k,r} = s^l_{k,r} + \sum_{c \in C} (b_{l(k),c} - b_{r(k),c})$. Assign each PRB $r$ to link $k \in B$, for which $BP_{k,r} \geq \bar{d}_l \forall l \in B$.

While the Proportional Fair Scheduler aims at achieving fair rates, the Maximum C/I Scheduler is known to maximize the sum-rate of a network under the infinite backlog assump-
tion. The Backpressure Scheduler is proven to stabilize all network queues whenever the input rates are within the so-called stability region [6], i.e., the transport layer capacity region.

We start our investigation by relating throughput maximization and resource efficiency. Consider the sum-throughput of a network, which is, from (7):

\[ TP_{tot} = \sum_{c \in C} TP_c = RE_{tot} \sum_{c \in C} R_c = RE_{tot} R_{tot}. \]  

(11)

This formulation shows us two ways how the sum-throughput can be maximized: By increasing the resource usage, \( R_{tot} \), or by increasing the resource efficiency, \( RE_{tot} \). Because in real networks, the number of usable resources is limited, we must assume \( R_{tot} \) to be upper bounded by some \( \hat{R}_{tot} \). So we see the following relation between maximizing the sum throughput and maximizing the resource efficiency:

**Proposition 1:** Assume a schedule \( S^* \) that maximizes the sum-throughput of a network. Then, the same schedule will also solve the problem:

\[ \max RE_{tot} \text{ s.t. } R_{tot} = \hat{R}_{tot}. \]  

(12)

**Proof:** Assume that when using \( S^* \), \( R_{tot} < \hat{R}_{tot} \). Then, some usable resources are unused. By using those resources, \( TP_{tot} \) could be increased, leading to a contradiction on the assumed throughput optimality of \( S^* \). Consequently, when using \( S^* \), \( R_{tot} = \hat{R}_{tot} \). Assume now that \( S^* \) does not maximize the resource efficiency among all schedules with \( R_{tot} = \hat{R}_{tot} \). Then, there is a schedule \( S' \) with \( R_{tot} = \hat{R}_{tot} \) but \( RE_{tot} > RE_{tot}' \). From equation (11), \( S' \) will achieve a larger sum-throughput than \( S^* \), leading again to a contradiction on the throughput optimality of \( S^* \). So \( S^* \) also maximizes the resource efficiency.

This result seems intuitive but does in fact not come naturally. Especially in lightly loaded networks, throughput optimal schedulers will schedule all PRBs to some link, even if their CQI is low and hence their use inefficient. Anyhow, Proposition 1 makes us optimistic that indeed, throughput maximizing schedulers are somewhat suitable to achieve a good resource efficiency, at least in the cases when the network load is large enough that all resources need to be used.

We can classify the schedulers by considering whether they leverage frequency diversity or not. For this we define \( \pi_{l,k} \) to be the percentage of frames in which link \( l \) is scheduled on PRB\( k \). Then we define to classes of schedulers:

**Definition 1 (Diversity-leveraging schedulers):** Assume two CQI-values \( q_{l,k}, q_{l,m} \) on different PRBs. Then, the set of diversity-leveraging schedulers is

\[ S_L = \{ S : s_{l,k} \in \{0, s^*_{l,k} \} \cap (\pi_{l,k} > \pi_{l,m} \Leftrightarrow q_{l,k} > q_{l,m}) \}. \]

**Definition 2 (Diversity-agnostic schedulers):** The set of diversity agnostic schedulers is

\[ S_A = \{ S : s_{l,k} \in \{0, s^*_{l,k} \} \cap (\pi_{l,k} = \pi_l \ \forall k) \}. \]

Both, diversity leveraging and diversity agnostic schedulers will always schedule the optimal amount of bytes on a PRB to a link. With diversity leveraging schedulers, a link will be assigned PRBs with larger CQI more often. For diversity agnostic schedulers, the PRB allocation is independent of CQI. The considered schedulers Maximum C/I and Backpressure leverage channel diversity, whereas the Proportional Fair scheduler is diversity agnostic, because it does not consider the channel states per PRB. We now observe the following:

**Lemma 1 (Efficiency is invariant to scaling):** Assume that a scheduler \( S^{(1)} \) schedules all links on PRBs with certain percentages \( \pi_{l,k}^{(1)} \), and a second scheduler \( S^{(\alpha)} \) with \( \pi_{l,k}^{(\alpha)} = a\pi_{l,k}^{(1)} \) for an \( a > 0 \). We call \( S^{(\alpha)} \) a scaled version of \( S^{(1)} \). Then both, throughput and resource usage of \( S^{(\alpha)} \) will be by the factor \( a \) larger than those of \( S^{(1)} \), but both achieve the same efficiency:

\[ RE_{tot}(S^{(\alpha)}) = \alpha \sum_{c \in C} R_{c}^{(\alpha)} = \frac{\sum_{c \in C} aTP_{c}^{(1)}}{\sum_{c \in C} aR_{c}^{(1)}} = RE_{tot}(S^{(1)}). \]

By the definition of diversity agnostic schedulers, we realize that on each link, all diversity agnostic schedulers are scaled versions of each other, hence they achieve the same efficiency per link. By re-considering the proposed Resource Efficiency mode selection, it becomes clear that it is based on the resource efficiency of a diversity-agnostic scheduler, because the \( d_l \) correspond to the achieved rates when \( \pi_{l,k} = 1 \ \forall k \). By Lemma 1 it will correctly estimate the efficiency gain of any diversity-agnostic scheduler, hence it is optimal when used with such schedulers, e.g., the Proportional Fair scheduler. The question arises, whether the Resource Efficiency mode selection is also suitable for use with diversity leveraging schedulers. We investigate this with the following Theorem:

**Theorem 1 (Leveraging diversity improves efficiency):** Let \( S_L \in S_L \) and \( S_A \in S_A \). Then, \( RE_{tot}(S_L) \geq RE_{tot}(S_A) \) for traffic demands within the stability region.

**Proof:** Consider an arbitrary link \( l \). For any \( S_A \), we can imagine a scaled version \( S_A^{(\alpha)} \) that assigns as many resources to \( l \) as \( S_L \). Recall that we consider the overlay case with no PRB reuse. Then, from (3) and because all PRBs are scheduled to link \( l \) in \( \pi_{l,k} \) percent of time frames,

\[ \frac{r_{l}^{(L)}}{|PRB|A_{c}} = \sum_{k \in R} \pi_{l,k}^{(L)} = \sum_{k \in R} \pi_{l,k}^{(\alpha)} = \frac{r_{l}^{(\alpha)}}{|PRB|A_{c}}, \]

where \( r_{l}^{(\alpha)} \) denotes the average resource use for link \( l \). For the
Theorem 1 tells us that although Resource Efficiency Mode Selection assumes a diversity-agnostic scheduler, it also optimizes a tight lower bound of diversity-leveraging schedulers, when operated within their stability region.

V. SIMULATION

We now investigate the interplay of the considered schedulers and mode selection schemes with simulations. We use the open source simulator SimuLTE [15], which is based on the known network simulator OMNeT++ [16]. SimuLTE implements major parts of the LTE stack, including the LTE PDCP layer, the RLC layer and the MAC layer. On RLC layer, the transparent mode (TM), unacknowledged mode (UM) and PDCP layer, the RLC layer and the MAC layer. On RLC layer, the transparent mode (TM), unacknowledged mode (UM) and

The dotted lines represent scenarios with fading turned off. e.g., IP, TCP or UDP protocols, traffic generation, etc. were included using the INET framework for OMNeT++.

Our simulations consider the single cell overlay D2D set-up illustrated in Figure 1. A random number of UE-pairs are deployed in a single cell, whose number and positions follow a poisson point process with density 20 km−2. A data flow, modeled by a video transmission, appears between each of the UE pairs. The eNodeB decides, according to a chosen mode selection scheme, which of the flows will be offloaded to DM and which reside in CM. After all decisions have been made, the transmissions continue for 20 seconds simulation time. During simulation, the overall number of transmitted byte and the PRB usage are recorded for uplink, downlink and direct links. We simulate each combination of the schedulers Proportional Fair, Maximum C/I and Backpressure with the mode selection schemes ForcedD2D, ForceCellular, Capacity, Rate and Resource Efficiency. We vary the input data rate used for video transmission at each link from 0.8 kbit/s to 3.2 Mbit/s in exponential steps and perform 1000 runs for each configuration. After each run it is evaluated whether the required rates were within the stability region of the scheduler. If this was not the case for at least one combination, we neglect the run. In that case, different schedulers will operate on different rate points within the throughput region, which we do not want to compare.

In Figure 2 we compare the network wide resource efficiencies (i.e., Transported Byte per PRB and Cell) achieved by different schedulers after using the Resource Efficiency mode selection scheme. We calculate the efficiencies according to eq. (7). Similar results are achieved using the other mode selection schemes, which is why we do not explicitly show them. We show two cases, one with fading turned off and one with fading turned on. In general, fading reduces the channel quality independently on each channel, i.e., no fading means no frequency diversity. It can be seen in Figure 2 that
with frequency diversity, the diversity leveraging schedulers *Maximum C/I* and *Backpressure* achieve a larger resource efficiency than the diversity agnostic scheduler *Proportional Fair*. This had been predicted by Theorem 1. It also gives a notion that the efficiency roughly increases with the throughput optimality of the schedulers. On the other hand, without frequency diversity, all schedulers achieve the same resource efficiency, which is the equality case of Theorem 1.

We also compare the resource efficiencies produced by different mode selection schemes in combination with all schedulers. The comparison is qualitatively the same for all schedulers, which is why we show only those of the *Backpressure* scheduler. The input rate versus average resource efficiencies after mode selection with different schemes are shown in Figure 3. The proposed scheme, *Resource Efficiency*, produces the largest resource efficiency inside the stability region, followed by *Capacity*. For small input rates, all *Resource Efficiency*, *ForceCellular* and *Rate* scheme perform equally well. However, *Rate* is overtaken by *ForceCellular* as the input rates increase and for large rates *ForceCellular* performs equally well as *Capacity*. The *ForceD2D* scheme performs worst throughout the whole parameter space. The reason is that in our simulation set-up, this scheme produces a high amount of D2D links with low channel qualities, which can only be scheduled inefficiently. In general, the *Rate* scheme over-estimates the hop-gain (it assumes that DM uses half the resource of CM) and will tend to choose the DM too often, which produces more serious drawbacks for larger input rates. The *Capacity* scheme, on the other hand, does not consider the hop-gain at all and hence is too conservative with offloading.

**VI. Conclusion**

We considered an overlay D2D scenario and modeled the behavior of wireless links and dynamic schedulers. We derived an expression for the resource efficiency, which has been shown in literature to capture Fodors’ D2D gains. The interpretation of mode selection as routing for resource efficiency maximization led to the proposition of a mode selection scheme, the *Resource Efficiency* mode selection. The impact of scheduling on the resource efficiency metric was discussed and it was shown that (1) a loose coupling exists between the throughput optimality of a scheduler and its achieved resource efficiency, (2) the proposed scheme is optimal for diversity agnostic schedulers and optimizes a tight lower bound for diversity-leveraging schedulers. By means of simulation, we showed that the proposed mode selection outperforms the state of the art in terms of resource efficiency and hence better leverages the proximity- and hop-gain. These gains can directly be transformed into either a larger network throughput or low resource usage, if the used scheduler is able to leverage them. However, popular schedulers seem only partly suited to do so. The design of a dynamic scheduler that is fully capable of leveraging the D2D-gain is an interesting challenge for future work.

**REFERENCES**


