Floating Band D2D: Exploring and Exploiting the Potentials of Adaptive D2D-enabled Networks

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***Abstract*—In this paper, we propose *Floating Band D2D*, an adaptive framework to exploit the full potential of Device-to-Device (D2D) transmission modes. We show that *inband* and *outband* D2D modes exhibit different pros and cons in terms of complexity, interference, and spectral efficiency. Moreover, none of these modes is suitable as a *one-size-fits-all* solution for today's cellular networks, due to diverse network requirements and variable users' behavior. Therefore, we unveil the need for going beyond traditional single-band mode-selection schemes. Specifically, we model and formulate a general and adaptive *multi-band mode selection* problem, namely *Floating Band D2D*. The problem is NP-hard, so we propose simple yet effective heuristics. Our results show the superiority of the *Floating Band D2D* framework, which dramatically increases network utility and achieves near complete fairness.**

I. Introduction

There have been extensive research efforts in both academia and industry to explore D2D techniques [1]. D2D communications have been considered for a large variety of use-cases such as cellular offloading [2], mobile relaying [3], and video streaming [4]. These studies indicate the potential outstanding gain of D2D communications in cellular networks. Indeed, the high performance gain motivated leading telecommunication companies such as Qualcomm to perform experimental studies on this paradigm using early stage prototypes [5]. Standardization bodies such as 3GPP have also joined this front by considering D2D communications as a public safety feature in the next release of LTE-A [6]. These efforts from academia, industry, and standardization bodies confirm that the society regards D2D communications as a crucial feature for next generation networks. Nevertheless, there is still no concrete agreement on D2D operational details such as which medium access control to adopt, or which spectrum allocation schemes, connection setup, and resource management protocols are to be implemented. Initial proposals for D2D communications aimed at re-using the same resources that are used for conventional cellular communications (i.e., *inband underlay* D2D mode) [7]. The significance of the D2D gain had led to proposals in which a part of the cellular resources is dedicated only to D2D communications (i.e., *inband overlay* D2D mode). Finally, the scarcity and the high price of cellular spectrum motivated some researchers to explore D2D communications over the unlicensed band (i.e., *outband* D2D mode). These D2D modes are schematically illustrated in Fig. 1.

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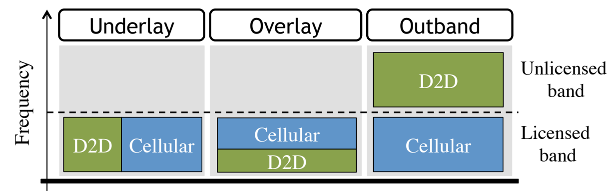


Fig. 1. Schematic representation of overlay inband, underlay inband, and outband D2D for cellular scenarios.

The majority of the existing studies on D2D communications select one of the aforementioned modes, then propose a method for resource allocation/interference management in order to handle the resulting complications, and finally illustrate the achievable performance improvement [2], [3], [7]–[9]. However, single mode D2D significantly limits the system performance to the interference profile of the network. Existing multi-mode D2D systems only focus on inband D2D modes, i.e., fully dependent on cellular spectrum. Other proposals focus on joint scheduling and mode selection [10], [11], although they are extremely complex (more complex than scheduling, which is already proven to be NP-hard for cellular systems such as LTE [12]) and introduce unnecessarily frequent mode selection decisions.

Interestingly, while some researchers limit D2D communications to cellular spectrum, the standards have a more liberal view of D2D. In fact, 3GPP defines D2D as "the communication between two users in proximity using a direct link between the devices without traversing the eNB(s) or the core network" [6]. We also remark that network-assisted outband D2D is accounted for in 3GPP proximity-based services (ProSe) [13]. Although both inband and outband D2D are considered valid options for ProSe services, there is no indication on how to select between the two. Hence, given the fast-track emergence of D2D communications in cellular networks, the need for an adaptive D2D mode selection scheme is beyond question.

In this paper, we propose a flexible framework to adaptively select D2D mode or operating band and technology. In particular, we first discuss the practical implications of each D2D mode based on the latest standard releases of LTE-A and WiFi-Direct. This discussion clarifies that *there is no superior D2D mode* and the potential of each mode is highly scenario/use-case dependent. After discussing practical implementation issues of D2D-enabled networks, we provide analytical insights into the mode selection problem in an innovative multi-mode multi-band setup, which accounts for both achieved *throughput* and *energy costs*. We call such a novel approach *Floating Band D2D*, because D2D transmissions can occur on either inband or outband modes. The problem is formulated as a non-linear integer programming problem. Given the NP-hardness of the problem and time-stringent requirements of future cellular networks, e.g., 5G networks, we propose three practical heuristics with near-optimal performance and low complexity. Finally, we evaluate the performance of the proposed heuristics in a multi-cell scenario using a realistic setup designed based on the ITU-R guidelines for evaluating IMT-Advanced networks [14]. Our results confirm that the coexistence of D2D modes immensely ameliorates the performance of the system in terms of the key performance factors such as throughput and utility (up to one order of magnitude), and near complete fairness.

II. Device-to-Device in cellular networks

As mentioned, 3GPP's definition does not restrain D2D implementations to a specific technology or spectrum. To date, the available commercialized technologies that suit D2D communications are either in the family of 3GPP standards such as LTE-A or in the family of IEEE standards such as WiFi. The former are suitable candidates for inband D2D and the latter match the requirements of outband D2D. Indeed, the feasibility of D2D communications with the aforementioned technologies has recently been theoretically proven [15], [16].

A. Definitions

We refer to users that communicate with the eNB as *cellular users* and to those who communicate with other neighboring users as *D2D users*. The following describes the list of D2D modes available for D2D users [1], as illustrated in Fig. 1:

- Underlay inband: D2D communications occur over the same licensed spectrum simultaneously used for legacy cellular communications.
- Overlay inband: A fixed fraction of the licensed spectrum is reserved for D2D users.
- Outband: D2D users exploit unlicensed spectrum to communicate with each other.

Note that inband D2D users are allowed *to share the same resource* (i.e., simultaneously transmit over the same frequency), while outband D2D users adopt a WiFi MAC and contend for channel access. The differences among available D2D modes pose advantages and disadvantages for each mode, as summarized in Table I. For completeness, we also include legacy cellular communication in the table. Interestingly, none of the available D2D modes can simultaneously guarantee features like controlled interference, spectrum efficiency, and QoS. So, when it comes to electing a specific mode for implementing D2D in a network, there is no clear winner.

B. Which D2D mode is the best?

Looking at the pros and cons of the available D2D modes, one can observe that none of the available D2D modes is ideal. So the question remains: *Which D2D mode is the best?*

Let us look at a few examples to better address this question. The use of underlay in micro cell scenarios, where users are in short range, results in intolerable co-channel interference to cellular users. In such scenarios, overlay and outband modes better facilitate D2D communications. On the other hand, using overlay in a macro cell with many cellular users can result in underutilization of network resources if the number of D2D users is small. Here, underlay and outband potentially perform better because of the sufficient distance among users. Finally, places with high occupancy of unlicensed band are not suitable for outband mode, due to well known congestion problems of contention-based MAC protocols.

TABLE I
Pros and cons of each D2D mode

	Underlay	Overlay	WiFi	Cellular
Interference between D2D and cellular users	✓	×	×	×
Interference among D2D users	✓	✓	×	×
Needs dedicated resources for D2D users	×	✓	×	×
Controlled interference environment	✓	✓	×	✓
Simultaneous D2D and cellular transmission	×	×	✓	×
Increased spectral efficiency	✓	✓	✓	×
Requires additional wireless interface	×	×	✓	×
QoS guarantee	✓	✓	×	✓
Energy cost	Eq.(3)	Eq.(3)	Eq.(5)	Eq.(2)

One can observe that an eNB may face the above-mentioned scenarios on a daily basis, e.g. as different groups of users (workers/students, residents, shoppers, etc.) become dominant at particular times of the day. Thus, *an adaptive scenario-independent D2D-enabled system cannot be tied to a specific mode or band*. Indeed, we propose a multi-band mode selection scheme in order to facilitate such high level of adaptiveness in real implementations.

III. System model

In this section, we describe our reference system, our proposed mode selection approach, and its practical implications.

A. System

We consider a hexagonal multi-cell LTE-A network with a reference cell in the center and its first-tier neighbors as shown in Fig. 2. The cell consists of N users labelled as $n \in \mathcal{N} := \{1, 2, \ldots, N\}$. Downlink and uplink channels are separated and each one has a fixed bandwidth. Users may communicate with other users in the cell or with those outside the cell. If a user wants to communicate with another user in her proximity, she can use D2D communications. Inband D2D communications use uplink cellular spectrum [6]. It is assumed that each user communicates with (at most) one user at any given time. Each connection between users n and m is referred to as (n, m), $\forall n, m \in \mathcal{N}$. For notational convenience, the eNB is addressed as user $N + 1$. In this paper, the outband D2D exploits WiFi Direct technology. With the above, we use four communication modes operating as described in Section II-A:

- Mode 0 $\leftrightarrow$ cellular;
- Mode 1 $\leftrightarrow$ inband underlay D2D;
- Mode 2 $\leftrightarrow$ inband overlay D2D;
- Mode 3 $\leftrightarrow$ outband D2D (WiFi).

Our system operates in discrete time units and the eNB is in charge of mode selection and scheduling. The eNB makes the scheduling decisions on a per-frame basis. Each *frame*

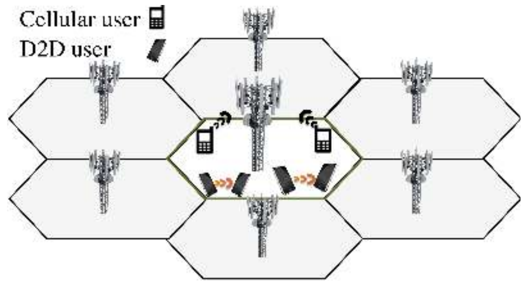


Fig. 2. Our system model that consists of a cell with its first-tier neighbors.

consists of 10 *subframes* and the length of a frame is 10 ms. In each subframe, only one cellular user is scheduled, while the number of concurrent D2D transmissions is not limited *a priori*. Therefore, there is no interference among cellular users (i.e., mode 0), but underlay users (i.e., mode 1) interfere with the cellular and other underlay users (i.e., modes 0 and 1). Overlay users only interfere with each other, while outband D2D users simply contend for the WiFi channel. A fixed portion of cellular bandwidth is dedicated to overlay D2D users. This portion is released to cellular and underlay users if there is no user in overlay mode.

B. Mode selection and scheduling

As mentioned, mode selection and scheduling decisions by nature require decision making schemes with a different time-scale resolution. Thus, we propose to decouple the mode selection and scheduling problems. The decoupling is mainly inspired by the fact that D2D connections last more than a few frames in a real world scenario and scheduling them on a per-frame basis is unnecessary and possibly inefficient. The inefficiency is due to the high signaling overhead, which is caused by such a high resolution mode selection (see Subsection III-C). Moreover, the channel quality of D2D links is potentially less time variant in comparison to that of the cellular links due to the short-range nature of D2D communications. The decoupling also simplifies the integration of D2D communications into current cellular systems as it minimizes the changes to the scheduler. Although mode selection and scheduling are decoupled, they are still highly intertwined. On one hand, the scheduling is affected by the interference, which is unknown before mode selection. On the other hand, mode selection depends on the set of cellular users scheduled along with D2D users. Hence, we choose the eNB to perform mode selection, because it is already in charge of scheduling.

We propose a mechanism in which the eNB handles these decisions in two steps: (i) mode selection and (ii) scheduling. First, in mode selection, each D2D pair is assigned a mode (modes 1 to 3), and the assignment is repeated at regular *mode intervals* of length T seconds. The eNB selects D2D modes with the assumption of a worst-case interference scenario. This approach helps to reduce the system complexity and to avoid disruptive co-channel interference. Second, in the scheduling phase, the eNB schedules users and assigns them a Modulation and Coding Scheme (MCS). Mode selection and scheduling both rely on the accuracy of Channel State Information (CSI) data gathered at the eNB, which can be challenging in terms of signaling overhead and scheduling.

C. Practical implications

In a D2D-enabled network, the eNB requires CSI between each pair of users (i.e., user-to-user CSI) in addition to user-to-eNB CSI in order to perform MCS assignment and scheduling. However, the existing cellular technologies do not have the means to obtain user-to-user CSI. Hence, we need a mechanism to obtain and send this information to the eNB efficiently because the addition of user-to-user CSI imposes high signaling overhead to the system.

CSI measurement. In LTE, the eNB-to-user CSI is estimated by active measurements from the received signal strength. However, there is no signaling message exchange between the users. Therefore, some researchers propose probing techniques to perform CSI estimation among users [10]. This approach imposes even higher signaling overhead to the system. In contrast, we propose an adaptive passive CSI estimation between users as explained in what follows. In LTE, each user has a unique ID (i.e., C-RNTI [17]) and this ID is included in the frame header. Thus, the users can detect the ID of the source of interference at each frame. Alternatively, the user can read C-RNTIs from the broadcasted scheduling map to identify the interfering user's ID. The latter does not require users to sniff and decode other users' frame headers. The CSI is then reported to the eNB. The eNB builds an interference table, whose elements $I_{n,m} \geq 0$ represent the interference caused by user n to user m $(\forall n, m \in \mathcal{N} \cup \{N+1\})$. In case two users do not detect each other for physical/timing reasons, the failure only causes an interruption on a millisecond scale. Once an interruption occurs, the user will report it to the eNB which will update the interference matrix. As for outband D2D, each user reports the last achieved rate over WiFi. In case of an inaccurate report due to long inactivity period, the users can send an updated report before the next mode interval.

Signaling overhead. The maximum number of CSI reports in LTE-A (with wideband CSI reporting [17]) is equal to N. This number increases to $N + 2|\mathcal{N}_d||\mathcal{N}_c| + |\mathcal{N}_d|\left(|\mathcal{N}_d| - 1\right)$ in a D2D-enabled network, where $\mathcal{N}_c$ and $\mathcal{N}_d$ are the sets of cellular and D2D users, respectively. For instance, a D2D-enabled network with 4 cellular and 6 D2D users may require up to 88 CSI reports, which is almost 9 times higher than its equivalent in a legacy system. Fortunately, the CSI feedbacks can be considerably reduced using the state-of-the-art feedback reduction techniques [18]. Moreover, we will see in Section VI that the D2D signaling overhead is negligible as compared to the resulting gain. This overhead is further reduced by our proposal because we decouple scheduling from mode selection, hence the D2D related CSIs are obtained less frequently.

IV. Floating Band D2D Framework

In this section we describe our proposed Floating Band D2D framework and formulate the problem of mode selection at the beginning of each mode interval j, i.e., each T seconds. The utility function in our problem formulation depends on throughput and energy costs, for which we provide a general model in which specific schedulers can be plugged in. Note that, although the general model can be used with specific schedulers to evaluate the performance of various strategies, the formulation of the problem does not depend on the scheduler actually implemented, and is not affected by resource allocation strategies for either cellular or D2D connections.

Throughput and energy costs. The transmitted data $\theta^i_{n,m}(j)$ for a connection (n,m) in mode $i \in \{0,1,2\}$ during mode interval j is formulated as follows:

$$\theta^i_{n,m}(j) = B^i_{n,m}(j) R^{i,\text{CSI}}_{n,m}(j), \tag{1}$$

where $B^i_{n,m}(j)$ is the number of Resource Blocks (RBs) allocated to connection (n,m) in mode interval j. $R^{i,\text{CSI}}_{n,m}(j)$ is the number of transmitted bits per RB of connection (n,m) in mode i during mode interval j, computed based on the channel gain between users n and m, and the interference matrix $\mathbf{I}$.

The energy consumption of a cellular user $E^0_{n,m}(j)$ and the energy consumption of a D2D pair $E^i_{n,m}(j)$ in inband mode $i \in \{1,2\}$ are given by:

$$E^0_{n,m}(j) = \beta_{lte} + p^{0,\text{TX}}_n \cdot t_{B^0_{n,m}}(j) \qquad m = N+1, \tag{2}$$

$$E^i_{n,m}(j) = 2\left(\beta_{lte} + \beta^{\texttt{WiFi}}_{idle}\right) + \left(p^{i,\text{TX}}_n + p^{i,\text{RX}}_m\right) t_{B^i_{n,m}}(j), \tag{3}$$

where β_{lte} and $\beta^{\texttt{WiFi}}_{idle}$ are the baseline energy consumed in a mode interval by an active cellular interface and an idle WiFi interface, respectively. The WiFi interface is kept idle in inband modes to speed up WiFi connection setup. Here, $p^{i,\text{TX}}_n$ and $p^{i,\text{RX}}_m$ are the energy consumed for transmission and reception in one subframe, respectively. $t_{B^i_{n,m}}(j)$ is the duration of $B^i_{n,m}(j)$. Here, we do not calculate the energy per RB, because it is shown that the transmission/reception power mainly depends on time rather than bandwidth [19].

The expression of transmitted data $\theta^3_{n,m}(j)$ and the energy consumption $E^3_{n,m}(j)$ for connection (n,m) under outband mode (i.e., mode 3) in mode interval j is as follows:

$$\theta^3_{n,m}(j) = T \cdot R^{3,\text{CSI}}_{n,m}(j), \tag{4}$$

$$E^3_{n,m}(j) = 2(\beta_{lte} + \beta^{\texttt{WiFi}}_{active}) + \left(p^{3,\text{TX}}_n + p^{3,\text{RX}}_m\right) \theta^3_{n,m}(j), \tag{5}$$

where $R^{3,\text{CSI}}_{n,m}$ is the WiFi rate and $\beta^{\texttt{WiFi}}_{active}$ is the baseline WiFi energy consumed by a user in a mode interval. $p^{3,\text{TX}}_n$ and $p^{3,\text{RX}}_m$ are the energy consumed by user m per transmitted/received bit. Note that the energy consumption as defined here can incorporate both the consumption due to transmission/reception and packet processing (see [3]). The β_{lte} is due to the dependence of outband users to the eNB signaling.

We define a utility function for connection (n,m) under mode i in mode interval j as follows:

$$U^i_{n,m}(j) = \theta^i_{n,m}(j) - \alpha E^i_{n,m}(j), \tag{6}$$

where α is the relative cost of energy. The utility accounts for both throughput and energy consumption. The value of α determines whether the system is biased towards higher throughput or lower energy consumption. In our model, the impact of schedulers is summarized in $B^i_{n,m}$ and $t_{B^i_{n,m}}$. Those parameters have to be computed in each mode interval and for each possible mode selection decision.

Problem formulation. Let $\mathcal{L}(j)$ be the set of all existing connections during mode interval, j, $\{Y^i_{n,m}(j)\}$ be the set of binary decision variables, and γ_n be the tolerable interference threshold that allows for a non-zero reception rate by user n. We formulate the problem of mode selection for mode interval j as a binary programming problem (the dependency on j is omitted for readability):

$$\begin{cases} \max \quad U_{sum} := \sum_{i=0}^{3} \sum_{(n,m)\in\mathcal{L}} U^i_{n,m} Y^i_{n,m} \ \forall (n,m) \in \mathcal{L} \\ \text{s.t. } \sum_{i=0}^{3} \sum_{n|(n,m)\in\mathcal{L}} Y^i_{n,m} \le 1 \quad \forall m \in \mathcal{N} \\ \quad \sum_{i=0}^{3} \sum_{m|(n,m)\in\mathcal{L}} Y^i_{n,m} \le 1 \quad \forall n \in \mathcal{N} \\ \quad \sum_{(n,m)\in\mathcal{L}} Y^1_{n,m} I_{n,x} \le \gamma_x \quad \forall x \in \mathcal{N}_c \cup \{N+1\} \\ \quad \sum_{i\in\{0,1\}} \sum_{(x,y)\in\mathcal{L}\setminus\{(n,m)\}} Y^i_{x,y} Y^1_{n,m} I_{x,m} \le \gamma_m \\ \quad \sum_{(x,y)\in\mathcal{L}\setminus\{(n,m)\}} Y^2_{x,y} Y^2_{n,m} I_{x,m} \le \gamma_m \ \forall (n,m) \in \mathcal{L} \end{cases} \tag{7}$$

Problem (7) maximizes the sum of utilities U_{sum} over all possible combinations of users and modes. Our assumption on single instantaneous connectivity is enforced with the first and second constraints (the eNB, which is labeled as $N+1$, is an exception). The third constraint ensures that the co-channel interference from underlay users to cellular users and to the eNB is kept below the threshold. The fourth constraint limits the interference from cellular and inband underlay users to other inband underlay users. The interference of overlay transmissions is limited by the fifth constraint.

Complexity. Problem (7) is NP-hard and non-linear since it can be reduced to the *longest path problem* (e.g., for a weighted directed and possibly disconnected graph), which is NP-hard [20]. This reduction is obtained when we consider Problem (7) for a single mode $i = 3$ (outband), in which the objective is to activate D2D pairs so as to achieve the maximum utility possible with the two restrictions on at most one incoming and at most one outgoing transmission for every user. Problem (7) requires the computation of $\{U^i_{n,m}\}$, which is based on Signal to Noise and Interference Ratios (SINRs) and its optimal solution can be achieved by brute force: exploring the consequences of assigning modes 1, 2, or 3 to any of the $\frac{|\mathcal{N}_d|}{2}$ D2D pairs. Hence, the resulting complexity is $O(N \cdot 3^{\frac{|\mathcal{N}_d|}{2}})$, which grows exponentially with the number of D2D pairs. The optimal solution to the above maximization problem is computationally expensive and practically unfeasible in dense networks. However, the non-linear constraints can be linearized so that the problem can be solved relatively efficiently by standard approaches, such as Branch & Bound [21]. Nevertheless, we deem such an approach impractical as the system requires a solution in milliseconds. Thereby, we propose efficient heuristics in what follows.

V. Heuristics

The exact solution to Problem (7) is computationally expensive and does not allow for a fast and scalable mode selection. Given the similarity of the problem to the longest path problem and the knapsack problem, we propose three practical heuristics. These heuristics explore the achievable utilities of the users in an iterative manner. Note that these utilities are computed assuming that the system is fully utilized

Algorithm 1 `Social`

Input:
1: $\mathcal{N}_{d,\text{TX}}$: set of D2D transmitters (randomized order).
2: $I_{n,x}$: interference between each pair of users.
Output: $Y^i_{(n,m)}, \forall n \in \mathcal{N}_{d,\text{TX}}$
3: initialize: $\mathbf{Y} = \mathbf{Y}_{old} = \emptyset$; $Y^0_{(c,N+1)} = 1, \forall c \in \mathcal{N}_c$; $Y^3_{(n,m)} = 1, \forall n \in \mathcal{N}_{d,\text{TX}}$; $\max = U_{sum}$
4: **while** $\mathbf{Y} \neq \mathbf{Y}_{old}$ **do**
5: $\quad\mathbf{Y}_{old} = \mathbf{Y}$
6: $\quad$**for** $n \in \mathcal{N}_{d,\text{TX}}$ **do**
7: $\quad\quad$**for** $j \in \{1,2,3\}$ **do**
8: $\quad\quad\quad$Calculate: $U_{sum}|n$ is in mode j
9: $\quad\quad\quad$**if** $U_{sum} > \max$ **then**
10: $\quad\quad\quad\quad\max = U_{sum}$
11: $\quad\quad\quad\quad Y^j_{(n,m)} = 1$; $Y^k_{(n,m)} = 0, k \in \{1,2,3\} \setminus \{j\}$
12: $\quad\quad\quad$**end if**
13: $\quad\quad$**end for**
14: $\quad$**end for**
15: **end while**

Algorithm 2 `Greedy`

Input:
1: $\mathcal{N}_{d,\text{TX}}$: set of D2D transmitters (randomized order).
2: $I_{n,x}$: interference between each pair of users.
Output: $Y^i_{(n,m)}, \forall n \in \mathcal{N}_{d,\text{TX}}$
3: initialize: $\mathbf{Y} = \emptyset$; $Y^0_{(c,N+1)} = 1, \forall c \in \mathcal{N}_c$; $Y^3_{(n,m)} = 1, \forall n \in \mathcal{N}_{d,\text{TX}}$; $\max_i = U_{(i,m)}$; $exit = False, \mathcal{D} = \emptyset$
4: **while** $exit = False$ **do**
5: $\quad$**for** $i \in \mathcal{N}_{d,\text{TX}}$ **do**
6: $\quad\quad$**for** $j \in \{1,2,3\}$ **do**
7: $\quad\quad\quad$Calculate: $U^j_{(i,m)}|i$ is in mode j
8: $\quad\quad\quad$**if** $U^j_{(i,m)} > \max_i$ **then**
9: $\quad\quad\quad\quad\max_i = U^j_{(i,m)}$
10: $\quad\quad\quad\quad Y^j_{(i,m)} = 1$; $Y^k_{(i,m)} = 0, k \in \{1,2,3\} \setminus \{j\}$
11: $\quad\quad\quad$**end if**
12: $\quad\quad$**end for**
13: $\quad$**end for**
14: $\quad dec$ = Index of current $\mathbf{Y}$
15: $\quad$**if** $dec \in \mathcal{D}$ **then**
16: $\quad\quad$exit = True
17: $\quad$**end if**
18: $\quad$Add dec to $\mathcal{D}$
19: **end while**

Algorithm 3 `Ranked`

Input:
1: $\mathcal{N}_{d,\text{TX}}$: set of D2D transmitters (randomized order).
2: $I_{n,x}$: interference between each pair of users.
Output: $Y^i_{(n,m)}$
3: initialize: $\mathbf{Y} = \emptyset$; $Y^0_{(c,N+1)} = 1, \forall c \in \mathcal{N}_c$; $Y^3_{(n,m)} = 1, \forall n \in \mathcal{N}_{d,\text{TX}}$

PHASE 1: Sorting D2D pairs based on their utility

4: **for** $i \in \mathcal{N}_{d,\text{TX}}$ **do**
5: $\quad$**for** $j \in \{1,2,3\}$ **do**
6: $\quad\quad$Calculate $U^j_{(i,m)}$
7: $\quad$**end for**
8: $\quad\text{mode}_i = \arg\max\{U^j_{(i,m)}; j \in \{1,2,3\}\}$
9: **end for**
10: sort the $\mathcal{N}_{d,\text{TX}}$ based on utilities $U^{\text{mode}_i}_{(i,m)}$ & store in $\mathcal{N}^{(\text{ranked})}_{d,\text{TX}}$.

PHASE 2: Executing `Greedy` heuristic

11: Do `Greedy` with $\mathcal{N}_{d,\text{TX}} = \mathcal{N}^{(\text{ranked})}_{d,\text{TX}}$.

(i.e., users' queues are fully backlogged) so that they do not require the knowledge of the actual user's offered load.

a) Heuristic 1. `Social`*:* The eNB iterates over the set of D2D transmitters $\mathcal{N}_{d,TX}$, and it selects the mode that maximizes the aggregate utility (lines 7-13 in Algorithm 1). Note that the mode for user i is selected based on the modes selected for the precedent users. Initially, all D2D pairs are assigned to mode 3 (outband), to minimize the impact on cellular users. For better fairness [5], the order of users in $\mathcal{N}_{d,TX}$ is randomized at any mode interval. The mode selection repeats until the algorithm converges to a decision. We name this heuristic as `Social` because it decides based on social welfare. Since the utility of `Social` cannot decrease with mode selection decisions, the heuristic always converges.

b) Heuristic 2. `Greedy`*:* The `Greedy` heuristic is similar to `Social`. Unlike `Social`, `Greedy` selects the mode which maximizes the user's individual utility (line 10 in Algorithm 2). The drawback of `Greedy` is that it might not converge. However, we can index each decision since the algorithm is running in the eNB. Once a duplicate index (stored in $\mathcal{D}$) is found, the algorithm stops the iteration.

c) Heuristic 3. `Ranked`*:* Both `Social` and `Greedy` operate on a list of D2D transmitters with a randomized order. In contrast, `Ranked` heuristic sorts this list based on the achievable utility of each user without considering the impact of other users (PHASE 1). In PHASE 2, the pre-ordered list $\mathcal{N}^{(\text{ranked})}_{d,\text{TX}}$ is evaluated using `Greedy`, which makes the heuristic *greedier* than `Greedy`. This helps to evaluate the ability of our approach to withstand unfair conditions. Algorithm 3 illustrates the pseudocode of the heuristic.

d) Complexity Analysis: Our proposed heuristics compute $N - |\mathcal{N}_{d,\text{TX}}|$ utilities $\{U^i_{n,m}\}$ for each mode and for every D2D transmitter in a sequential manner, i.e., $3\left(N|\mathcal{N}_{d,\text{TX}}| - |\mathcal{N}_{d,\text{TX}}|^2\right)$ utilities per round of evaluation. In each mode interval, the evaluation cycle is repeated r_i times, $r_i \geq 1$, until the algorithm converges to a decision. Therefore, the complexity of `Social` and `Greedy` is $O\left(3r_iN|\mathcal{N}_{d,\text{TX}}|\right)$, $i \in \{1,2\}$. `Ranked` has an additional sorting procedure before the mode selection in which the utility of each D2D pair is computed in isolation. Thus, the algorithm only needs to compute $3|\mathcal{N}_{d,\text{TX}}|$ utilities in PHASE 1, which can be neglected with respect to the number of utilities to be computed in PHASE 2. Hence, the complexity of `Ranked` is $O\left(3r_3N|\mathcal{N}_{d,\text{TX}}|\right)$. Therefore, the three proposed heuristics have the same complexity, except for a constant factor r_i that we will quantify experimentally later.

VI. Evaluation

In this section, we use numerical simulations to evaluate the performance of our proposed heuristics. The evaluation scenario consists of a hexagonal multi-cell network with a reference cell in the middle and its first-tier neighbors (see Fig. 2). The results reported in this paper pertain to the reference cell, and the neighboring cells model the impact of inter-cell interference. Error bars in the results are the 95% confidence intervals. Although our approach can be tested with any scheduler, here we refer to the Proportional Fair (PF) scheme for scheduling cellular users, since it represents the state of the art for schedulers used in real implementations [12], [22]. In addition to our heuristics, we evaluate three benchmark schemes, namely, `Forced-LTE`, `Forced-WiFi`, and `Optimal`. In `Forced-LTE`, D2D users are forced to use legacy cellular communications (i.e., mode 0). In `Forced-WiFi`, D2D users are forced to communicate over WiFi (i.e., mode 3). `Optimal`

TABLE II
THE PARAMETERS USED IN THE EVALUATION

Parameter	Value
Cellular	
Cellular uplink bandwidth	20 MHz
Cell radius	250 m
eNB, cellular user TX power	44 dBm, 24 dBm
Thermal noise power	-174 dBm/Hz
Mode interval length T	2 s
Fading, shadowing, pathloss	Reyleigh, 6 dB, UMa [14]
Buffer size	500 packets
β_{lte}	1288.04 mW
WiFi	
WiFi bandwidth	22 MHz
WiFi effective range	150 m
WiFi TX power	20 dBm
$\beta^{\texttt{WiFi}}_{active}$, $\beta^{\texttt{WiFi}}_{idle}$	132.86 mW, 77.2 mW
D2D	
Underlay max bandwidth	20 MHz
Overlay resource portion	30%
D2D maximum distance	20 m
D2D inband TX power	10 dBm
Relative cost of energy α	1 bit/Joule

results are based on the exact solution to Problem (7). The benchmarks allow to compare our proposals with the legacy cellular system, to measure the gain due to extra WiFi bandwidth, and to see how far the heuristics are from the optimum.

A. Simulation setup

User placement follows the uniform distribution. The number of D2D users is on average 30% of the cell population. The simulation parameters are chosen according to the evaluation guidelines of ITU-R [14] which are reported in Table II. In the simulation, we show both the packet simulation results (i.e., performance under finite offered load and in the presence of probabilistic arrival processes) and the achievable performance (i.e., performance at capacity-level utilization, under infinite offered load conditions). Unless otherwise specified, the default values for α and overlay resource portion are those reported in Table II, with an aggregate D2D and cellular load of 30 Mbps and 90 Mbps, respectively. Since the D2D capacity is higher than the cellular one, due to proximity of D2D users and availability of outband resources, we deemed fair to impose higher load to D2D users. Note that the default value of α is selected based on a rough estimate of the current relative price of bit per Joule (b/J) in the market.

Besides the values of Table II, we investigate the impact of user density N, overlay resource portion, relative cost of energy α, and D2D load on the system performance. Moreover, we shed light on the convergence time of our heuristics and their flexibility in different environments.

B. Simulation results

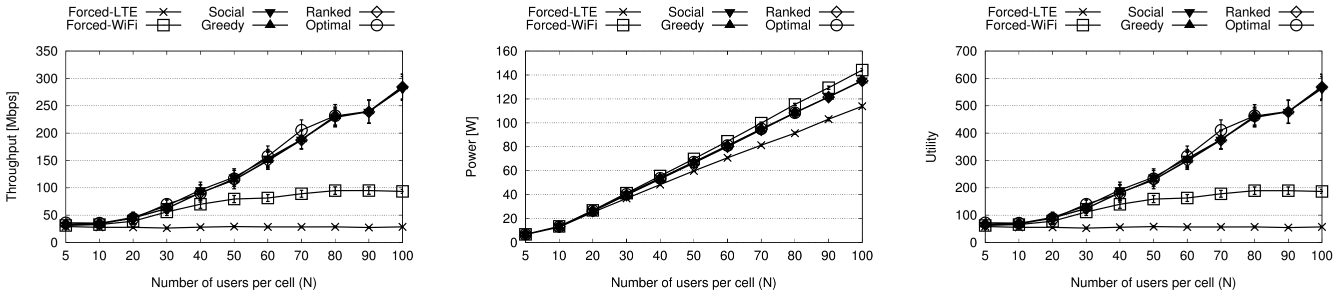
Impact of the number of users N. Fig. 3 illustrates the impact of N on achievable system performance. We can observe the achievable throughput in Fig. 3(a). The aggregate throughput has a negligible change with N under `Forced-LTE` because the distribution of channel qualities in the cell remains the same for different density of users, and therefore the average aggregated throughput. The throughput of the rest of schemes increases with N because there are probabilistically more D2D pairs in a denser cell, hence D2D throughput is higher. In `Forced-WiFi`, the throughput grows slowly due to the contention-based nature of WiFi, in which the MAC overhead increases with the number of contending users. Since some of the outband D2D pairs do not interfere with each other (i.e., they are more distant than 150 m), the aggregate throughput of `Forced-WiFi` in our experiments reaches up to 98 Mbps. More importantly, not only the simple proposed heuristics greatly outperform `Forced-LTE` and `Forced-WiFi`, but they also perform very close to `Optimal` (due to the computational complexity of such an ideal scheme, we only have the results up to 80 users).

In terms of energy cost, the aggregate cell power increases with N, as shown in Fig. 3(b), mainly due to the baseline energy consumption of wireless interfaces. `Forced-WiFi` has higher energy consumption because outband users have to maintain two active wireless interfaces instead of one.

Fig. 3(c) shows that the trend for system utility is similar to that of throughput because the throughput is the dominant factor with the current value of α. Our results show that, with a reasonable population, say 100 users per cell, the aggregate throughput gain over `Forced-LTE` is tenfold. This gain comes from both the frequency re-use of inband modes and additional spectrum provided by the outband mode. The significant contribution of both outband and inband modes to this gain highlights the importance of Floating Band D2D. Moreover, this gain can easily compensate for the infrequent D2D CSI feedbacks sent to the eNB (user-to-user CSI). Note that in LTE-A systems with millisecond feedback reporting, the CSI contributes to less than 20% of the total bandwidth.

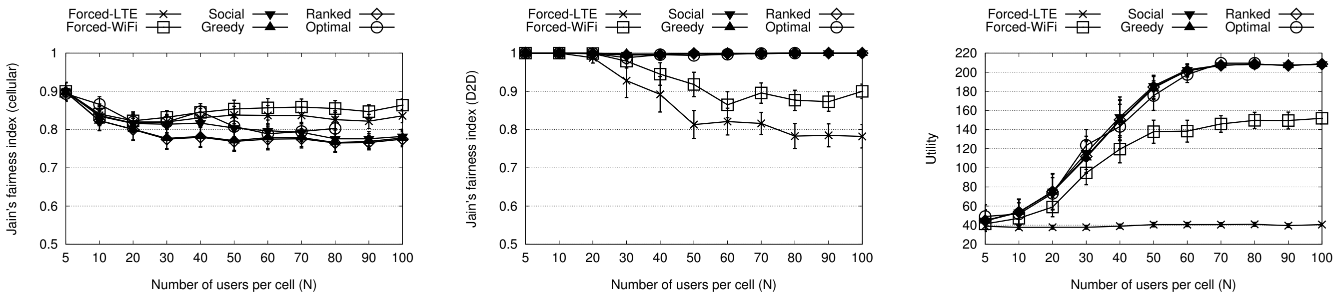
In Fig. 4, we can observe the accuracy of our mode selection and its performance using packet simulation. Fig. 4(a) shows that cellular users have comparable throughput performance under all schemes due to PF scheduling. If the data rate of a cellular user degrades due to co-channel interference, the PF compensates for it by allocating more resources to that user. In Fig. 4(b), it is observed that the fairness among D2D users drops under `Forced-LTE` and `Forced-WiFi`. Under `Forced-LTE`, D2D users are scheduled as cellular users, hence they achieve similar fairness performance as cellular users (but not equal because their fairness is computed over a different set and their load is different). The fairness reduction under `Forced-WiFi` is due to topologically uneven distribution of contending outband users. In Fig. 4(c), we can observe that utilities of all D2D-enabled schemes grow until N reaches 50. The reason for this behavior is that the network operates under saturation up to this point. In fact, one can observe in Fig. 3(a) that the achievable throughput with 50 users or less is below 120 Mbps which is equal to the total offered load (i.e., $30+90$) in the scenario of Fig. 4(c). For $N>50$, the utility in the packet simulation is limited by the adopted load.

Impact of overlay resource portion. Here, the number of users per cell is fixed to 50. Fig. 5(a) shows that the utilities of multi-band schemes increase with the overlay bandwidth. This



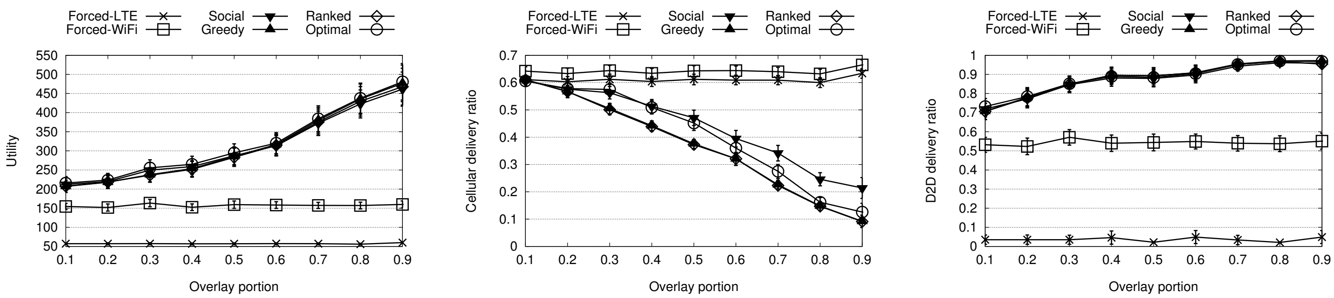
(a) Aggregate cell throughput. (b) Aggregate cell power. (c) Aggregate cell Utility.

Fig. 3. The impact of user population on the system performance with fully backlogged queues (*achievable performance*).



(a) Fairness among cellular users. (b) Fairness among D2D users. (c) Aggregate cell Utility.

Fig. 4. The impact of user population on the system performance evaluated through packet simulation.



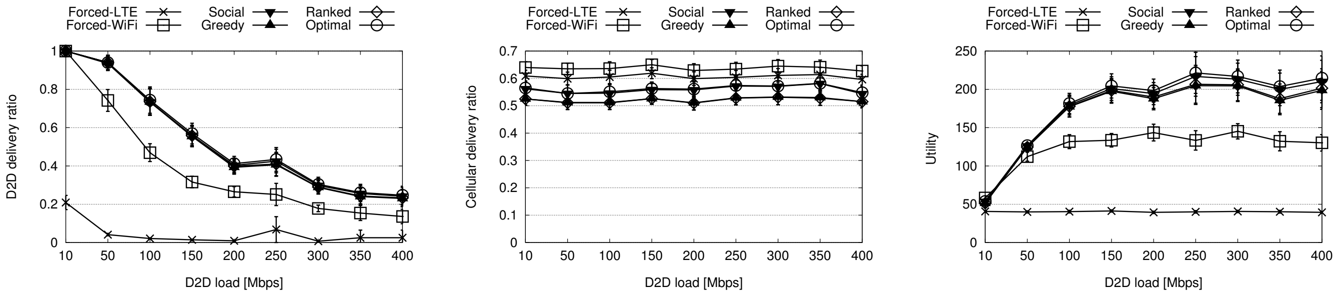
(a) Aggregate achievable utility. (b) Average delivery ratio of cellular users. (c) Average delivery ratio of D2D users.

Fig. 5. The impact of overlay portion on system performance ($N = 50$).

increment is due to throughput improvement under mode 2. This implies that D2D users tend to receive more interference from cellular users than from other D2D users, hence, the spectral efficiency is higher in overlay than underlay. As mentioned, the overlay portion is given to modes 0 and 1 if there are no overlay users. As a result, the utilities of `Forced-LTE` and `Forced-WiFi` remain unchanged here.

Although the aggregate utilities are improved, we should also investigate the impact of overlay bandwidth on cellular users. Fig. 5(b) illustrates that the delivery ratio of cellular users degrades as the overlay bandwidth grows because there is less bandwidth at their disposal. Fig. 5(b) also sheds light on the differences among multi-band schemes. Cellular users experience higher packet delivery ratio with `Social`. Indeed, `Social` is the only scheme that aims to maximize the aggregate utility, which includes the utility of cellular users. Finally, Fig. 5(c) shows how the delivery ratio of D2D users approaches 1 with higher overlay bandwidths, as expected.

Impact of D2D load. The impact of D2D load is shown in Fig. 6 for $N = 50$. The packet delivery ratio for D2D users drops as the load increases, as shown in Fig. 6(a). This is the expected behavior of systems in saturation. However, as we see in Fig. 6(b), our schemes are designed in such a way that saturation of D2D users does not impact the cellular users. This shows that our proposal can be a candidate for distributed D2D mode selection implementations in which *cellular users are protected from mode selection decisions of D2D users*. It is observed in Fig. 6(c) that system utility approaches its achievable limit (220) when the D2D load is almost 250 Mbps (see Fig 3(c), $N = 50$). In Fig 3(a), we observe that the achievable capacity for $N = 50$ is almost 120 Mbps. Indeed, by multiplying the packet delivery ratios (see Figs. 6(a) and 6(b)) with the aggregate network load (250 Mbps for D2D users and 30 Mbps for cellular users), we observe that the achieved throughput is almost 120 Mbps

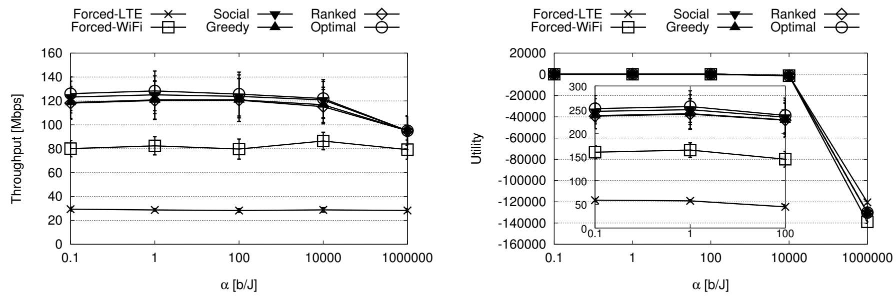


(a) D2D delivery ratio.

(b) Cellular delivery ratio.

(c) Aggregate utility.

Fig. 6. The impact of D2D load on system performance evaluated through packet simulation ($N = 50$).



(a) Aggregate achievable throughput.

(b) Aggregate achievable utility.

Fig. 7. The impact of α on system throughput and utility ($N = 50$).

(i.e., $250 \cdot 0.4 + 30 \cdot 0.6 = 118$). With similar calculations, one finds that `Forced-WiFi` saturates almost at 100 Mbps.

Impact of energy cost α. Recall that with the current relative energy cost α our system is biased towards throughput. Hence, we investigate the impact of α in Fig. 7, for $N = 50$. We start with Fig. 7(a), in which a 20% throughput reduction is observed at $\alpha = 10^6$ b/J. This shows the system's bias shifts towards energy minimization as α increases. In Fig. 7(b), the utility reduces as α grows, although the behavior of the curves is not linear at all. In particular, for very large values of α, our system prefers `Forced-LTE` (i.e., mode 0) because it only powers one interface. Since we disallow multi-band schemes to assign mode 0 to D2D users, `Forced-LTE` might achieve utilities higher than that of `Optimal` when α is very large (e.g., with $\alpha = 10^6$ b/J, which is too unrealistic as of today and for the near future due to the high cost of electricity).

Convergence. In Table III, we report the convergence of our proposed heuristics in terms of time and the number of iterations. The heuristics are tested on Mathematica™ on a machine with a 3.6 GHz processor and 8 GB memory. `Greedy` and `Social` have a very similar convergence time. `Greedy` is slightly slower than `Social` due to decision indexing. Interestingly, notwithstanding its ranking operations, `Ranked` has a better performance. This happens because `Ranked` converges to a decision with less iterations (which is what we have indicated as factor r_i in Section V-0d).

TABLE III
CONVERGENCE OF THE HEURISTICS ($N = 100$)

	`Social`	`Greedy`	`Ranked`
Average convergence time [s]	1.61	1.62	1.43
Average number of iterations r_i	2.69	2.80	1.46

Flexibility. As mentioned, Floating Band D2D is key to flexible D2D architectures. We emphasize this fact by evaluating our proposal in various cellular environments, according to ITU-R guidelines [14]. Table IV shows that, moving from micro-cell to rural macro-cell, the system relies more on the cellular spectrum as density reduces. As a consequence, the number of underlay connections increases. For denser environments, we observe that a significant part of connections is served using outband D2D.

TABLE IV
PERCENTAGE OF EACH MODE IN DIFFERENT ENVIRONMENTS ($N = 100$)

	Urban micro-cell	Urban macro-cell	Suburban macro-cell	Rural macro-cell
Inband underlay	4%	8%	29%	31%
Inband overlay	63%	66%	66%	67%
Outband	33%	26%	5%	2 %

VII. RELATED WORK

This section presents the most relevant mode selection schemes for inband/outband D2D communications and the joint scheduling and mode selection proposals. As of today, there is no proposal on multi-band D2D mode selection.

Zulhasnine *et al.* [8] address the problem of mode selection in cellular networks in which D2D users can either use underlay mode or legacy cellular communications. They formulate the problem as an optimization problem with SINR constraints. Next, they propose a greedy heuristic which reduces the interference by restraining underlay users to share resources only with cellular users experiencing the highest levels of channel quality. Moreover, differently from our approach, D2D users cannot share resources among them.

Asadi and Mancuso in [3] propose an outband D2D scheme in the framework of cellular relaying. In their proposal, cellular users can communicate directly with the eNB or indirectly through another cellular user with whom they have an outband D2D connection. There, users choose the communication mode by means of a coalitional game theory approach. That work does not leverage inband D2D modes.

In [23], Yu *et al.* formulate the problem of mode selection as a sum-rate maximization problem whose solution can be expressed in closed-form or searched through a finite set. However, the system model used in [23] is limited to a single cell network with one cellular and one D2D user.

Doppler *et al.* [10] propose a centralized mechanism for scheduling and mode selection that accounts for underlay, overlay, or legacy cellular transmissions. They propose active probing for CSI estimation among users. After probing, the eNB selects a mode for each D2D user, based on the reported SINRs. Unfortunately, active probing imposes high signaling overhead and suffers scalability issues (see Section III).

Phunchongharn *et al.* [11] propose a joint mode selection, scheduling and power control scheme for D2D communications. Specifically, D2D users are allowed to transmit using underlay, overlay, and cellular mode, or to remain silent. The problem is formulated as mixed integer programming, which is NP-complete, and no efficient heuristics are proposed.

To summarize, the available proposals on D2D mode selection: (i) assume D2D users cannot share resources between them, and/or (ii) propose to use a limited set of D2D users and modes, which restrain the adaptiveness of D2D communications, and/or (iii) propose complex solutions, which are either unscalable or too complex for millisecond decision making. In contrast, we formulate a multi-band mode selection problem, which allows to explore the full potential of D2D communications, and we have proposed simple and lightweight heuristics to adaptively exploit the advantages of multiple D2D modes. Specifically, a key practical advantage of our approach is that mode selection and scheduling are handled at substantially different time scales.

VIII. Conclusion

We have shown that the performance of D2D modes is highly scenario-dependent. To cope with this issue, we proposed the *Floating Band D2D* framework along with practical heuristics suitable for quick and adaptive mode selection in such a complex setup. Unlike existing schemes, we allow D2D users to communicate over inband or outband modes, depending on network load and channel conditions. Our results demonstrate the impressive potentials of multi-band mode selection. Remarkably, our simple heuristics result in fair operation and achieve near optimal performance by dramatically ameliorating network utility, which accounts for both throughput and energy consumption.

IX. Acknowledgements

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