Modeling Multi-mode D2D Communications in LTE

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ABSTRACT

In this work we propose a roadmap towards the analytical understanding of Device-to-Device (D2D) communications in LTE-A networks. Various D2D solutions have been proposed, which include *inband* and *outband* D2D transmission modes, each of which exhibits different pros and cons in terms of complexity, interference, and spectral efficiency achieved. We go beyond traditional mode optimization and mode-selection schemes. Specifically, we formulate a general problem for the joint per-user mode selection, connection activation and resource scheduling of connections.

1. INTRODUCTION

The booming growth in popularity of the cellular communications and the exponential rise of cellular data traffic pushed the technology manufactures to their limits in such a way that they could not keep pace with the current demand growth in mobile user's applications [4]. This made the cellular network industry open to new proposals more than ever. Among various proposals to ameliorate the cellular capacity shortcoming, Device-to-Device (D2D) communication stood out because it detected the paradigm shift in cellular data flow [2]. The cellular communication ends used to be distant a decade ago, while the emergence of new mobile applications into people's life (e.g., social networking) created significant traffic among nearby users. The literature on D2D communication is abundant. In fact both academia and industry have been actively exploring use-cases and techniques of D2D communications [2].

Academia proposes a wide range of use-cases for D2D communications such as relay [1], multicasting [8], and cellular offloading [3]. Initial D2D proposals focused on D2D communication underlaying cellular network transmissions, i.e., using the same spectral resources used for cellular communications [5]. Later, other D2D techniques have been proposed, which either fall under either *inband* or *outband* D2D communication. Inband D2D communications allow D2D users to communicate over the cellular spectrum, while outband schemes demands the D2D users to access unlicensed bands for D2D transmissions [2]. Each of these D2D operational *modes* poses its own merits and disadvantages in terms of interference management, implementation complexity, achievable spectral efficiency, and therefore in terms of performance guarantees. However, the available literature proposes solutions for efficiently implementing each mode in isolation, i.e., *mode selection* has not been addressed. Nevertheless, according to the definition provided by 3GPP standards, "D2D communication is the communication between two users in proximity using a direct link between the devices in order to bypass the eNB(s)[1] or core network" [7]. Therefore, any of these modes or perhaps all shall be used for D2D communications. Moreover, promising studies on D2D communication moved industry leaders such as Qualcomm to invest on future implementation of D2D communications, and 3GPP is considering to include generic D2D support in the next release of LTE-A standard as a public safety feature [7].

In such a framework, we believe that different D2D modes should not be treated as competitors but as complementary techniques. Co-existing D2D modes can immensely increase the system complexity because there should exist a mechanism to select the correct D2D mode according the overall system conditions.

2. SYSTEM MODEL

Our system consists of N users labelled as $n \in \mathcal{N} := \{1, 2, \ldots, N\}$ in a single-cell LTE network with 20MHz bandwidth eNB. For notational consistency, the eNB is labelled as $N+1$. Downlink/uplink channels are open separated bands (i.e., using an FDD scheme). Each LTE *subframe* (1ms) the eNB has 100 time-frequency Resource Blocks (RB)s for downlink and uplink transmission [6]. Users may communicate with other users in the cell or with those outside the cell. If a user wants to communicate with another user that is physically close to her, she can use D2D communication. We call such a pair of users a D2D pair. We assume that each user wants to communicate only with (at most) one user at any given time.

User states. The users are allowed to move, and therefore their availability for communication can change over time, so we will say that each user is in a particular *state* which can change over time. We will denote the state of user $n \in \mathcal{N}$ at time t by $X_n(t) \in \{0, 1, 2, \ldots, N+1\}$, where each state can be categorized in one of the following types (See Figure 1):

- **Dormant user (state 0)**: this is a user who either (i) has no data to transceive, or (ii) has a poor channel quality in which communication is not feasible.

[1] eNB is the 3GPP term referring to cellular base stations.

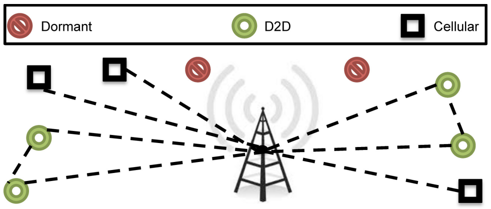


Figure 1: An illustration of a cell with dormant, cellular, and D2D users.

- **Cellular user (state $N+1$)**: this is a user who wants to communicate, and can only communicate with the eNB, labelled as $N+1$;
- **D2D user (states $1 \le m \le N$)**: this is a user who wants and can communicate with her D2D pair labelled m directly (i.e., she is in D2D reach of the user with whom she wants to communicate).

Consequently, the number of users in each state will vary in time. However, we assume that state changes occur (or are detected by the mode selection mechanism) at regular *mode intervals* of duration T seconds. We denote by $\mathcal{S}_m(j)$ the set of users in state $m \in \{0, .., N+1\}$ in mode interval j. Each cellular user and D2D pair is associated with a flow and each pair can only have one active flow at any given time. Moreover, the D2D communication is assumed to be symmetric, i.e., if user $n \in \mathcal{N}$ is in state $m \in \mathcal{N}$, then user m is in state n.

Graph model. We can map the network with N users and one eNB to a graph with $N+1$ nodes, where nodes 1 to N represent the users and node $N+1$ represents the base station. The location of nodes in the graph does not necessarily correspond to a physical position of the users (which are moreover allowed to move within a cell). The users' physical location and mobility affect the arcs of the graph rather than the nodes. An arc between two nodes represents the communication feasibility between the two nodes. Thus, at every given time, there is an arc between two nodes if these two nodes want to communicate and their physical channel allows a non-zero transmission rate. Thus, dormant users are isolated (without any arc), cellular users have an arc with eNB, and D2D users have an arc with their pairs and with eNB. In particular, if a user n is in state $m \in \mathcal{N}$, then there is an arc between users n and m and another one between user n and eNB $N+1$; if a user n is in state $N+1$, then there is an arc between user n and eNB $N+1$. Thus, the state of the user indicates her neighbour(s). See Figure 1 for an illustration. Due to users mobility and communication needs, which affect users' states, the arcs will change over time (which is fully captured by state changes each T seconds).

Note that there are at most $3N/2$ arcs in the graph, because each cellular user creates 1 arc and each D2D pair create 3 arcs. The arcs will be denoted by their end-nodes, (n, m). We will further denote the existence of arc (n, m) at time t by $Z_{n,m}(t) \in \{0, 1\}$.

Cellular mode. Users in state $N+1$ use normal cellular communication. We define this as mode 0.

D2D modes. Every D2D pair can communicate via any of the following modes (see Figure 2):

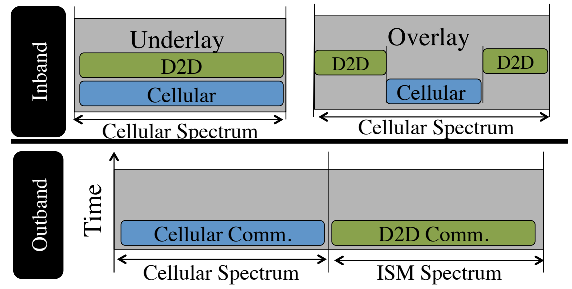


Figure 2: Schematic representation of overlay inband, underlay inband, and outband D2D.

Table 1: Cons and pros of each D2D mode

	Underlay	Overlay	Cellular	WiFi
Interference between D2D and cellular users	✓	×	×	×
Interference among D2D users	✓	✓	×	×
Requires dedicated resources for D2D users	×	✓	×	×
Controlled interference environment	✓	✓	✓	×
Simultaneous D2D and cellular transmission	×	×	×	✓
Increased spectral efficiency	✓	✓	×	✓
Energy cost	Eq.(1)	Eq.(1)	Eq.(1)	Eq.(3)

- Underlay inband (mode 1): D2D users reuse the RBs which are available to the cellular users (and therefore share resources with connections in mode 0).
- Overlay inband (mode 2): D2D communications occur over dedicated RBs, subtracted from cellular users.
- Outband (mode 3): D2D users switch to WiFi.

In both underlay and overlay modes, D2D pairs can use the same RBs used by other D2D pairs simultaneously as long as interference allows. Table 1 summarizes the merits and drawbacks of each method. Note that the major issue in inband is interference control, while outband D2D suffers from the power consumption of WiFi interface.

2.1 Joint scheduling and mode selection

At a given time, every existing arc represents a possible data transmission, and can be either active (allowed to transmit) or inactive (not allowed to transmit). We have to design a mechanism that selects the arcs to be used in each mode interval, and assign RBs to the arcs.

There are three tiers of decision making in our system:

- **Mode selection**: we have to decide about the operating mode for D2D pairs (modes 1 to 3);
- **Connection activation**: we have to decide which connections (arcs) are active given the interference constraints of the selected mode;
- **Connection scheduling**: we have to decide which connections transmit at what transmission rate (i.e., how the RBs are allocated).

The three tiers are intertwined, since the interference depends on mode selection but cannot be known before connection activation and scheduling. In turn, connection activation and scheduling depend on which connection is active and on which mode is used in each connection. For sake of tractability, we implement first mode selection, assuming a worst-case interference scenario for activating connections, and then we implement a conventional opportunistic cellular scheduler, Proportional Fair (PF) for connection scheduling at eNB. Specifically, scheduling priorities are computed on instantaneous or expected instantaneous channel quality of the users, and RBs allocated to inband overlay are fixed (they are used by users in mode 2, or released for modes 0 and 1 if no connection selects mode 2). In each *subframe* (lasting 1 ms), only one user is scheduled for direct communication to the eNB, while the number of concurrent D2D transmissions is not limited *a priori*. Therefore, mode 0 users do not interfere with each other, mode 1 users interfere with users in modes 0 and 1, and mode 2 only causes interference among users in mode 2.

Our system operates in discrete time units and there is a central *controller*, who schedules all the transmissions. For tractability, we build the model hierarchically. The controller observes the actual CQI (the LTE Channel Quality Indicator, which corresponds to a particular transmission rate) of each connection and takes the fundamental scheduling decisions every *frame* t_{frame} (consisting of 10 subframes, hence lasting 10 ms). All scheduled transmissions in each subframe occur simultaneously and use the maximal transmission rate permitted by the CQI observed by the eNB. A connection scheduled in a subframe will use all the RBs assigned to the specific mode selected.

The controller further estimates at the beginning of every *mode interval* T the future CQI of all possible connections (both WiFi and cellular), and decides upon the mode for the duration of the mode interval, which may imply setting up new connections or closing existing ones, i.e., changes the arcs of the graph. From the graphical point of view, there is hence a new random graph (on a fixed number of nodes N) at the beginning of every mode interval T. The controller also decides which of the arcs are active (allowed to transmit) over the mode interval. In practice, the random graphs will be strongly correlated, because the mode interval length has to be short enough (say, 200 frames) to prevent users to move and experience deep channel fading.

2.2 CQI and interference estimation

As mentioned above, CQI information is needed for each connection. We assume that the eNB can estimate the CQI of each connection by using the reports produced by the users, containing the signal strength they receive from each and all their neighboring transmitters. By extending this legacy LTE scheme, the interference can be estimated as well. Thus, the eNB can build the interference table, whose elements $I_{n,m}(j) \geq 0$ represent the interference caused by user n to user m ($\forall n, m \in \mathcal{N} \cup \{N+1\}$), in mode interval j. Hence, decisions upon connections (set up/close) can be made on the observations from previous mode intervals.

2.3 Centralized or Decentralized.

The main challenges faced by the majority of mode selection schemes is the channel quality and the interference estimation. In a centralized approach, the channel qualities and interferences power should be mapped between all mobiles in the networks. Assuming that mobiles use wideband or UE selected subband CQI reporting, the eNB in a network with N users requires a maximum of N CQI for to determine the SINR from eNB towards the UE. This value increases to The number of CQI reports for a D2D-enabled network would be $N + N_c \times N_{d2d} + \frac{N_{d2d}(N_{d2d}-1)}{2}$, where $N = N_c + N_{d2d}$. For instance D2D-enabled network with 4 cellular and 6 D2D UEs may require up to 49 CQI report. This value in the legacy network is upper bounded by 10, which is almost 5 fold smaller than the D2D-enabled scenario.

Although it is accepted to assume that the global CQI knowledge is available at the eNB, the complications and the feedback overhead of this assumption should not be overlooked. One method to reduce the number of reports is to use more efficient reporting schemes that send selective feedbacks based on user activities or eNB demands. Note that efficient CQI reporting schemes reduce the signaling overhead, but the eNB still remains under computational overhead of the mode selection procedure. The aforementioned issues are common defects of centralized systems.

Decentralizing complex cellular operations is an interesting method for reducing signaling and computational overhead at the eNB and the core network. Decentralization is not welcome by the operators because it may expose their infrastructure to security threads and it reduces operators' controlled over their spectrum. However, the advent of D2D communications introduced a new paradigm in which the operators can highly benefit from decentralization.

3. PROBLEM FORMULATION

We solve the problem hierarchically at the beginning of each mode interval j, i.e., each T seconds. Let $\mathcal{L}(j)$ be the set of all existing arcs during mode interval j, i.e., such that $Z_{n,m}(j) = 1$. For an active arc (n,m) under an LTE mode $i \in \{0,1,2\}$ in mode interval j we define the energy consumption $E^i_{n,m}(j)$ and the transferred data $\theta^i_{n,m}(j)$ (both per mode interval T) as follows:

$$E^i_{n,m}(j) = \frac{T}{t_{frame}} \left(p_n^{i,\mathrm{TX}} + p_m^{i,\mathrm{RX}}\right) B^i_{n,m}(j), \quad (1)$$

$$\theta^i_{n,m}(j) = \frac{T}{t_{frame}} B^i_{n,m}(j) R^{i,\mathrm{CQI}}_{n,m}(j), \quad (2)$$

where we do not consider the baseline energy consumed by a user in LTE in one mode interval, since it cannot be changed unless the node is switched off, $p_n^{i,\mathrm{TX}}$ and $p_m^{i,\mathrm{RX}}$ are the energy consumed by user m per transmitted and received RB, respectively, $B^i_{n,m}(j)$ is the number of RBs allocated to arc (n,m), and $R^{i,\mathrm{CQI}}_{n,m}(j)$ is the number of transmitted bits per RB of arc (n,m) under mode i during mode interval j.

For an active arc (n,m) under mode 3 (i.e., WiFi) in mode interval j we define the energy consumption $E^3_{n,m}(j)$ and the throughput $\theta^3_{n,m}(j)$ (both per mode interval) as follows:

$$E^3_{n,m}(j) = 2\beta^{\mathtt{WiFi}} + \left(p_n^{3,\mathrm{TX}} + p_m^{3,\mathrm{RX}}\right) \theta^3_{n,m}(j), \quad (3)$$

$$\theta^3_{n,m}(j) = T \cdot R^{i,\mathrm{CQI}}_{n,m}(j), \quad (4)$$

where $\beta^{\mathtt{WiFi}}$ is the baseline WiFi energy consumed by a user in one mode interval, and $R^{i,\mathrm{CQI}}_{n,m}$ is the WiFi rate. Note that the energy consumption as defined here can incorporate both the consumption due to transmission/reception and packet processing (see [1]).

The utility function for an active arc (n,m) under mode i in mode interval j is defined as follows:

$$U^i_{n,m}(j) = \theta^i_{n,m}(j) - \alpha E^i_{n,m}(j), \quad (5)$$

where α is a relative cost of energy.

3.1 Optimal solution

We use a set of binary decision variables $\{Y^i_{n,m}(j)\}$, to formulate the problem of mode selection for mode interval j, preceding the RB allocation procedure in the above described system (note that at mode selection time it is not yet possible to predict the exact interference caused by/to D2D users, so we account for the worst-case interference). The problem is formulated as follows (we omit the dependency on j from utilities, interferences, and decision variables):

$$
\begin{aligned}
\text{maximize} & \sum_{i=0}^{3} \sum_{(n,m)\in\mathcal{L}(j)} U^i_{n,m} Y^i_{n,m}; \\
\text{s.t.:} & \sum_{i=0}^{3} \sum_{n|(n,m)\in\mathcal{L}(j)} Y^i_{n,m} \le 1 \quad \forall m \in \mathcal{N}; \\
& \sum_{i=0}^{3} \sum_{m|(n,m)\in\mathcal{L}(j)} Y^i_{n,m} \le 1 \quad \forall n \in \mathcal{N}; \\
& \sum_{(n,m)\in\mathcal{L}(j)} Y^1_{n,m} I_{n,x} \le \gamma \quad \forall x \in \mathcal{S}_{N+1} \cup \{N+1\}; \\
& \sum_{i\in\{0,1\}} \sum_{(x,y)\in\mathcal{L}(j)\setminus\{(n,m)\}} Y^i_{x,y} Y^1_{n,m} I_{x,m} \le \gamma \quad \forall (n,m) \in \mathcal{L}(j); \\
& \sum_{(x,y)\in\mathcal{L}(j)\setminus\{(n,m)\}} Y^2_{x,y} Y^2_{n,m} I_{x,m} \le \gamma \quad \forall (n,m) \in \mathcal{L}(j);
\end{aligned}
$$

The formulated problem maximizes the sum of utilities over all possible combinations of users and modes. The first and second constraints ensure that at most one active connection can be allowed for each user (but for the eNB, which is labeled as $N+1$). The third constraint imposes that the interference caused by inband underlay D2D users to cellular users and to the eNB is below a threshold γ. The fourth constraint ensures that the interference caused by cellular and inband underlay transmissions to other inband underlay users is below a threshold. Finally, the fifth constraint ensures that the interference caused by inband overlay transmissions (mode 2) is below the threshold γ. The challenge to be tackled in future work consists in plugging the resource allocation scheme into the computation of $\theta^i_{n,m}$ and $E^i_{n,m}$, which, in turn, depend on mode selection and connection activation decisions through the resource allocation scheme.

Complexity. The complexity of the grows exponentially with the number of D2D pairs $N_{d2d} = \{|Z_{n,m}| : Z_{n,m} = 1, n \ne N+1, m \ne N+1\}$, $(O(3^{N_{d2d}}))$. The optimal solution to the above maximization problem is computationally expensive and practically unfeasible in dense networks.

3.2 Problem Linearization

The problem described above can be rewritten as an integer linear programming problem by introducing a set of additional binary decision variables $D^{i,l}_{x,y,n,m} := Y^i_{x,y} Y^l_{n,m}$ for $(i,l) \in \mathcal{I} := \{(0,1),(1,1),(2,2)\}$, while introducing a set of additional restrictions and replacing the quadratic restrictions, as formulated below. This is useful, because such a linearized problem can be effectively and quickly solved by the branch-and-bound algorithm implementing the simplex method.

$$
\begin{aligned}
\text{maximize} & \sum_{i=0}^{3} \sum_{(n,m)\in\mathcal{L}(j)} U^i_{n,m} Y^i_{n,m}; \\
\text{s.t.:} & \sum_{i=0}^{3} \sum_{n|(n,m)\in\mathcal{L}(j)} Y^i_{n,m} \le 1 \quad \forall m \in \mathcal{N}; \\
& \sum_{i=0}^{3} \sum_{m|(n,m)\in\mathcal{L}(j)} Y^i_{n,m} \le 1 \quad \forall n \in \mathcal{N}; \\
& \sum_{(n,m)\in\mathcal{L}(j)} Y^1_{n,m} I_{n,x} \le \gamma \quad \forall x \in \mathcal{S}_{N+1} \cup \{N+1\}; \\
& \sum_{i\in\{0,1\}} \sum_{(x,y)\in\mathcal{L}(j)\setminus\{(n,m)\}} Y^{i,1}_{x,y,n,m} I_{x,m} \le \gamma \quad \forall (n,m) \in \mathcal{L}(j); \\
& \sum_{(x,y)\in\mathcal{L}(j)\setminus\{(n,m)\}} D^{2,2}_{x,y,n,m} I_{x,m} \le \gamma \quad \forall (n,m) \in \mathcal{L}(j); \\
& D^{i,l}_{x,y,n,m} \le Y^i_{x,y} \quad \forall (i,l) \in \mathcal{I}, (n,m) \in \mathcal{L}(j), (x,y) \in \mathcal{L}(j) \setminus \{(n,m)\} \\
& D^{i,l}_{x,y,n,m} \le Y^l_{n,m} \quad \forall (i,l) \in \mathcal{I}, (n,m) \in \mathcal{L}(j), (x,y) \in \mathcal{L}(j) \setminus \{(n,m) \\
& Y^i_{x,y} + Y^l_{n,m} - 1 \le D^{i,l}_{x,y,n,m} \quad \forall (i,l) \in \mathcal{I}, (n,m) \in \mathcal{L}(j), (x,y) \in \mathcal{L}(
\end{aligned}
$$

3.3 Our Heuristics

We propose three simple heuristics for mode selection which reduces the complexity of the problem from exponential to linear. With proposed heuristics, the eNB performs mode selection according to patterns which result in near optimal results without the complexity of the optimal solutions. The complexity of our proposed heuristic is $O(3n)$ which even allows for online implementation of the algorithm.

3.3.1 Heuristic 1: social

The eNB creates the list of D2D pairs in which the order of pairs are decided randomly. Next, it computes the aggregate network utility for each mode for the first user. The first user is assigned the mode which provides the highest aggregate utility. This process is repeated for all D2D pairs. Note that in each round, the eNB takes into account the decision taken in the previous rounds. We name this heuristic as *social* because it takes decisions based on the social welfare. Algorithm 1 illustrates the Pseudocode of the heuristic.

Algorithm 1 Heuristic that considers the social welfare.

Require: $R^{CQI,i}_{n,m}$: $\forall n \in \mathcal{N}, \forall m \in (\mathcal{N} \cap N+1), i \in \{0,1,2,3\}$

$\mathcal{N}^{(TX)}_{d2d}$: set of D2D transmitters.

Ensure: $Y^i_{(n,m)}$

initialize: $Y^i_{(n,m)} = 0$, mode=0, $U^j_{max} = -\infty$

for $i \in \mathcal{N}^{(TX)}_{d2d}$ **do**
  for $j \in \{1,2,3\}$ **do**
    Calculate U^j_{total}
    if $U^j_{total} > U^j_{max}$ **then**
      $U^j_{max} = U^j_{total}$
      mode = j
    end if
  end for
  $Y^{mode}_{(i,m)} = 1$
end for

3.3.2 *Heuristic 2: greedy*

The eNB creates the list of D2D pairs in which the order of pairs are decided randomly. Next, it computes the utility for each mode for the first user. The selected mode for the user is the mode which provide the user with the the highest utility. This process is repeated for all D2D pairs. Note that in each round, the eNB takes into account the decision taken in the previous rounds. We name this heuristic as *greedy* because it takes decisions based on the users' individual welfare. Algorithm 2 illustrates the Pseudocode of the heuristic.

Algorithm 2 Heuristic with a greedy approach

Require: $R^{CQI,i}_{n,m}$: $\forall n \in \mathcal{N}, \forall m \in (\mathcal{N} \cap N+1), i \in \{0,1,2,3\}$
$\mathcal{N}^{(TX)}_{d2d}$: set of D2D transmitters.

Ensure: $Y^i_{(n,m)}$

initialize: $Y^i_{(n,m)} = 0$, mode=0, $U^j_{(i,max)} = -\infty$

for $i \in \mathcal{N}^{(TX)}_{d2d}$ **do**
    for $j \in \{1,2,3\}$ **do**
        if $U^j_{(i,m)} > U^j_{(i,max)}$ **then**
            $U^j_{(i,max)} = U^j_{(i,m)}$
            mode=j
        end if
    end for
    $Y^{mode}_{(i,m)} = 1$
end for

3.3.3 *Heuristic 3: Ranked*

In the social and the greedy heuristic algorithms, the order of mode assignments was random. In the first phase of the heuristic, the eNB evaluates the utility of each user for each mode. Next, the D2D pair list is sorted based on their utility in a descending order. In the second phase, the eNB creates the list of D2D pairs in which the order of pairs are decided randomly. Next, it computes the aggregate network utility for each mode for the first user. The first user is assigned the mode which provides the highest aggregate utility. This process is repeated for all D2D pairs. Note that in each round, the eNB takes into account the decision taken in the previous rounds. We name this heuristic as *ranked*. Algorithm 3 illustrates the Pseudocode of the heuristic.

Algorithm 3 Heuristic with smart D2D ranking

Ensure: $R^{CQI,i}_{n,m}$: $\forall n \in \mathcal{N}, \forall m \in (\mathcal{N} \cap N+1), i \in \{0,1,2,3\}$
$\mathcal{N}^{(TX)}_{d2d}$: set of D2D transmitters.

Ensure: $Y^i_{(n,m)}$

initialize: $Y^i_{(n,m)} = 0$, mode=0, $U^j_{(i,max)} = -\infty$

PHASE 1: Sorting D2D pairs based on their utility

for $i \in \mathcal{N}^{(TX)}_{d2d}$ **do**
    for $j \in \{1,2,3\}$ **do**
        Calculate $U^j_{(i,m)}$
    end for
    mode= $\max\{U^j_{(i,m)}\}, \forall j \in \{1,2,3\}$
    $Y^{mode}_{(i,m)} = 1$
end for
sort the $\mathcal{N}^{(TX)}_{d2d}$ based on utilities & store in $\mathcal{N}^{(TX)}_{sorted}$

PHASE 2: Executing greedy heuristic

for $i \in \mathcal{N}^{(TX)}_{sorted}$ **do**
    for $j \in \{1,2,3\}$ **do**
        if $U^j_{(i,m)} > U^j_{(i,max)}$ **then**
            $U^j_{(i,max)} = U^j_{(i,sm)}$
            mode=j
        end if
    end for
    $Y^{mode}_{(i,m)} = 1$
end for

4. EVALUATION

Let us study the performance of the aforementioned system using numerical simulation. We use brute-force method to illustrate the optimal solution to maximization problem introduced in subsection 3.1. Although the brute-force approach is not scalable and practical, it is used to show the upper bound. Next, the performance of the proposed heuristic is benchmarked against the optimal solution. In addition to the heuristic, we evaluate the performance of legacy cellular system and the performance of the system when only outband D2D is available. The latter is shown to confirm that the extra gain is not only due to additional WiFi bandwidth.

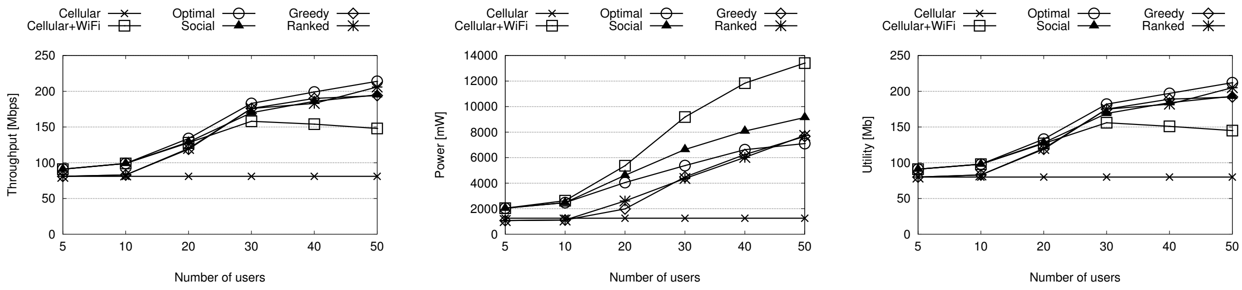
4.1 Simulation setup

We simulate a single cell LTE network with 20 MHz bandwidth, which is equality divided between uplink and downlink. The D2D communications occurs over uplink resources. Therefore, the maximum bandwidth for a D2D connection is 20 MHz. The simulation parameters can be found in Table 2.

Table 2: The parameters used in the evaluation.

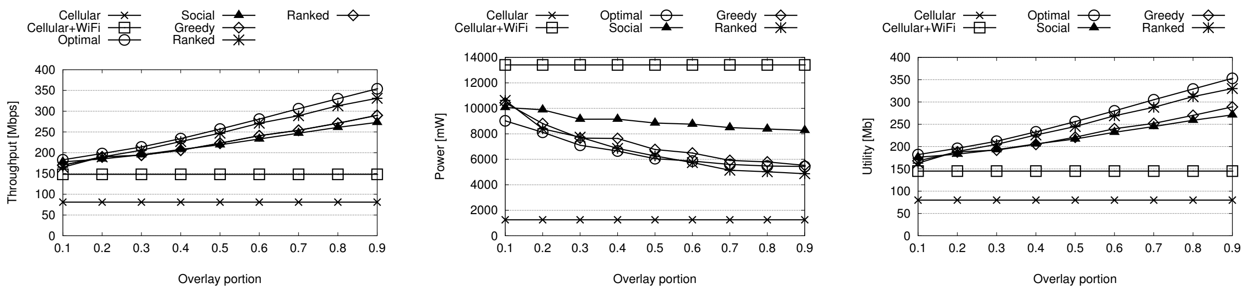
Parameter	Value
Cellular	
Cellular Bandwidth	20 MHz
Cell radius	100 m
eNB TX power	44 dbm
Cellular user TX power	24 dbm
Thermal Noise power	-174 dbm/Hz
Mode Interval	1 s
WiFi	
WiFi Bandwidth	22 MHz
WiFi TX power	20 dbm
WiFi effective range	50 m
D2D	
Underlay max bandwidth	20 MHz
Overlay max budget	30%
D2D maximum distance	20 m
D2D inband TX power	2 dbm
Minimum SINR for inband D2D	8.7 dbm (QPSK-4/5)
Minimum SINR for cellular	8.7 dbm (QPSK-4/5)
α	2

Figure 3 illustrates the system performance variations with respect to user density. The overlay portion is fixed to 30% and $\alpha = 2$. As shown in Figure 3(a), the throughput increases with the cell population because there are probabilistically more D2D pairs in a denser cell. All heuristics



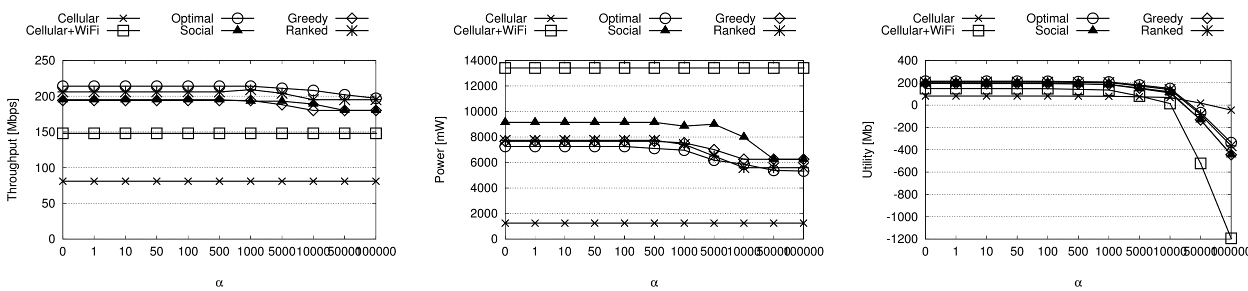
(a) Aggregate cell throughput (b) Aggregate cell Energy (c) Aggregate cell Utility

Figure 3: The impact of user population on the system performance.



(a) Aggregate cell throughput. (b) Aggregate cell power consumption. (c) Aggregate cell utility.

Figure 4: The impact of dedicated overlay bandwidth on the system performance.



(a) Aggregate cell throughput. (b) Aggregate cell power consumption. (c) Aggregate cell utility.

Figure 5: The impact of α on the system performance.

have close performance to the optimal decision. The throughput of Cellular+WiFi descends after 30 users because the WiFi throughput degrades in presence of more users contending for the channel. In terms of power consumption, Cellular+WiFi has the highest consumption because this scheme requires to maintain two wireless interfaces instead of one. The difference between other schemes depends on the number of outband D2D communications in the network (see Figure 3(b)). The trend in the system utility is very similar to the throughput because the impact of throughput is higher than power when $\alpha = 2$ (see Figure 3(c)). With the aforementioned configuration the network capacity can be improve up to 160% gain over conventional cellular network.

Figure 4 shows how the dedicated overlay bandwidth affects the system performance. We can see in Figure 4(a) that the aggregate throughput increases with the dedicated overlay bandwidth. Since the D2D users in mode 1 (i.e., underlay) should share the bandwidth with cellular users who have high transmission power, majority of D2D pairs have to use modes 2 and 3 in order to meet the minimum SINR requirements. Therefore, increasing the dedicated overlay bandwidth enhances the throughput of overlay D2D pairs which are more than underlay D2D pairs. As shown in Figure 4(b), increasing dedicated overlay bandwidth also improves the power consumption of the network because more users choose to use overlay mode rather than outband mode (i.e., WiFi). Note that power consumption of mobiles is lower in overlay mode than outband mode. Again, the trend in the system utility is very similar to the throughput because the impact of throughput is higher than power when $\alpha = 2$ (see Figure 4(c)). While all the heuristics have reasonable difference with the optimal solution, the ranked heuristic is very close to the optimal solution while providing much less complexity.

We can observe the impact of α on the system performance in Figure 5. With increasing the value of α, we prioritize energy over throughput. This is confirmed in Figures5(a) and 5(b). As α increases, the throughput reduces as well as the energy consumption. Finnally, as expected the value of utility drops by increasing the value of α.

5. CONCLUSIONS

In this paper, we studied the impact of using multi-mode D2D communications in cellular networks. We showed that allowing users to choose between different modes (i.e., cellular, underlay, overlay, and outband) results in significant improvement in the network performance. Moreover, we proposed a few heuristics with the capability to achieve high performances without the complexity of the optimal approach.

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