Modeling D2D Communications with LTE and WiFi

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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 using both LTE and WiFi resources.

1. INTRODUCTION

The booming growth in popularity of the cellular communications and the exponential rise of cellular data traffic pushed the high-tech manufactures to their limits in such a way that they could not keep pace with the current demand growth in mobile user's applications [5]. This made the cellular network industry open to new proposals more than ever. Among various proposals, Device-to-Device (D2D) communication stood out because it detected the paradigm shift in cellular data flow [3]. 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 for D2D communications [3].

Academia proposes a wide range of use-cases for D2D communications such as relay [2], multicasting [9], and cellular offloading [4]. Initial D2D proposals focused on D2D communication underlaying cellular network transmissions, i.e., using the same spectral resources used for cellular communications [6]. Later, other D2D techniques have been proposed, which either fall under either *inband* or *outband* D2D communications. 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 [3]. Each of these D2D operational *modes* has 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* with coexisting inband and outband 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" [8]. 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 [8].

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. For notational consistency, the eNB is labelled as $N + 1$. Downlink/uplink channels operate in two distinct 20 MHz band (i.e., using an FDD scheme). In each LTE *subframe* (1 ms), the eNB has 100 time-frequency Resource Blocks (RB)s for each transmission direction [7]. 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 the quality of the channels can change, 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:

- **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.
- **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** $1 \leq m \leq N$**)**: this is a user who wants and can communicate with her D2D pair la-

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

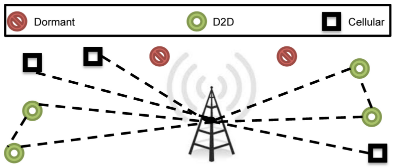

Figure 1: A cell with dormant, cellular, and D2D users.

belled m directly (i.e., she is in D2D reach of the user with whom she wants to communicate).

See Figure 1 for an illustration. 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. More details can be found in [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):

- 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 in the graph model 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*, 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.

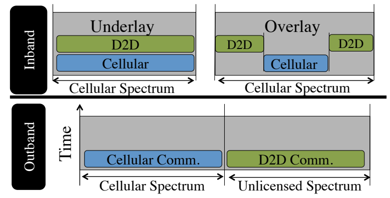

Figure 2: Schematic representation of overlay inband, underlay inband, and outband D2D.

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)

Our system operates in discrete time units and all the scheduling and mode selection decisions are made at the eNB. For tractability, we build the model hierarchically. The eNB observes the actual Channel State Information (CSI) of each connection and takes the fundamental scheduling decisions every *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 CSI observed by the eNB. A connection scheduled in a subframe uses all the RBs assigned to the selected mode .

At the beginning of every *mode interval* T, the eNB further estimates the future CSI of all possible connections (both WiFi and cellular), and decides upon the modes, which may imply setting up new connections or closing existing ones, i.e., changes the arcs of the graph. From a graph model 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 eNB also decides which of the arcs are active (allowed to transmit) over the mode interval.

2.2 CSI and interference estimation

As mentioned above, CSI information is needed for each connection. We assume that the eNB can estimate the CSI of each connection by using the reports produced by the users, containing the signal strength they receive from each and all their neighboring transmitters. 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.

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. For an active arc (n, m) under 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:

$$E^i_{n,m}(j) = \left(p^{i,\mathrm{TX}}_n + p^{i,\mathrm{RX}}_m\right) B^i_{n,m}(j), \quad (1)$$

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

where $p^{i,\mathrm{TX}}_n$ and $p^{i,\mathrm{RX}}_m$ are the energy consumed per RB by users n and m, 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. 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.

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:

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

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

where $\beta^{\mathtt{WiFi}}$ is the baseline WiFi energy consumed by a user in a 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 [2]).

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. 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):

$$\text{maximize} \sum_{i=0}^{3} \sum_{(n,m)\in\mathcal{L}(j)} U^i_{n,m} Y^i_{n,m};$$

$$\text{s.t.:} \quad \sum_{i=0}^{3} \sum_{n|(n,m)\in\mathcal{L}(j)} Y^i_{n,m} \le 1 \quad \forall m \in \mathcal{N};$$

$$\sum_{i=0}^{3} \sum_{m|(n,m)\in\mathcal{L}(j)} Y^i_{n,m} \le 1 \quad \forall n \in \mathcal{N};$$

$$\sum_{(n,m)\in\mathcal{L}(j)} Y^1_{n,m} I_{n,x} \le \gamma \quad \forall x \in \mathcal{S}_{N+1} \cup \{N+1\};$$

$$\sum_{i\in\{0,1\}} \sum_{(x,y)\in\mathcal{L}(j)\setminus\{(n,m)\}} Y^i_{x,y} Y^1_{n,m} I_{x,m} \le \gamma \quad \forall (n,m) \in \mathcal{L}(j);$$

$$\sum_{(x,y)\in\mathcal{L}(j)\setminus\{(n,m)\}} Y^2_{x,y} Y^2_{n,m} I_{x,m} \le \gamma \quad \forall (n,m) \in \mathcal{L}(j).$$

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 ensures 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.

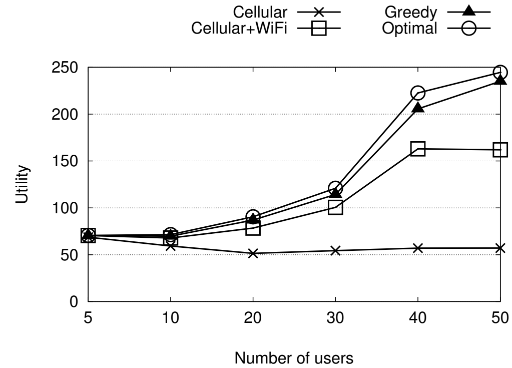

Figure 3: Aggregate Utility performance.

Figure 3 illustrates that the solution of the above described maximization problem ("Optimal" in the figure) can provide up to 400% gain over conventional cellular network (i.e., mode 0, "Cellular" in the figure). To clarify that this gain is not only due to extra WiFi bandwidth, we also include the throughput when only modes 0 and 1 are allowed ("Cellular + WiFi" in the figure). Here, the optimal solution is achieved using the brute-force method. However, as we can observe in the figure, our simple "Greedy" algorithm can achieve near-optimal results. It should be noted that the gain is so significant that there is high incentive to use suboptimal approaches with low complexity. More details on our Greedy heuristic can be found in [1].

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