Resource Allocation for Device-to-Device Communications in Multi-Cell LTE-Advanced Wireless Networks with C-RAN Architecture

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Introduction
Source: Cisco VNI Mobile, 2016
Billions of Devices

Source: Cisco VNI Mobile, 2016
Limitations and Constraints:

1. Frequency spectrum
2. Energy consumption
Mobile Core Network

Cell 1

Network Control

UE 1

D2D Communication

Cell 2

Network Control

UE 2

eNB 1

Mobile Core Network

eNB 2
D2D links reuse cellular channels. Hence, there is a need for interference management and control. In general, existing schemes:

- Assume a single insulated cell
- Ignore inter-cell interference
- Assume each D2D pair is situated in one insulated cell
- Assume each D2D pair uses only one channel
- Consider static power allocation to D2D pairs
We assume:

- We consider a multi-cell network with inter-cell interferences.
- We assume D2D pairs may be situated in different cells.
- We assign more than one channel at the same time to each pair to the extent possible.
- We assume no high speed movement.
Interference management is performed via proper allocation of resources (e.g., channels, transmit power levels, etc.).

Resource allocation is an optimization problem that can be solved either in a distributed or a centralized manner.

Distributed schemes are scalable, require less message passing, but are sub-optimal.

Centralized schemes have better performance, but require extensive message passing.

Multi-Cell D2D links require coordination between two cells, i.e., a centralized approach.
Cloud Radio Access Network (C-RAN) is a novel centralized architecture:

- The radio unit, called the remote radio head (RRH), is separated from the baseband unit (BBU),
- BBUs are pooled together in a cloud environment.
The objective is to allocate channels and transmit power levels:

- Maximize the number of active D2D pairs and reused channels
- Minimize the aggregate system uplink transmit power
- Maintain the QoS and transmit power constraints for all users.
System Model
We consider

- A multi-cell LTE-A network with C-RAN architecture,
- $\mathcal{N} = \{1, \ldots, N\}$ as the set of orthogonal uplink channels,
- $\mathcal{C} = \{1, \ldots, L\}$ as the set of CUs,
- $\mathcal{D} = \{1, \ldots, M\}$ as the set of D2D pairs,
- D2D pairs can reuse cellular uplink channels,
- $D_{\text{Tx}}$ and $D_{\text{Rx}}$ are not required to be in the same cell.
- $\overline{I}_l^c$: Maximum number of channels simultaneously used by CU $l$.
- $\mathcal{N}_l^c$ ($\mathcal{N}_l^c \subset \mathcal{N}$): Set of channels simultaneously used by CU $l$.
- $\xi_{l,n}^c, \hat{\xi}_{l,n}^c$: Actual SINR and required SINR of CU $l$ on channel $n$.
- $P_{l,n}^c, \overline{P}_{l,n}^c$: Actual transmit power and maximum transmit power of CU $l$ on channel $n$.
- $P_l^c, \overline{P}_l^c$: Actual aggregate transmit power and maximum aggregate transmit power of CU $l$ on all channels.

$$P_l^c = \sum_{n \in \mathcal{N}_l^c} P_{l,n}^c.$$

$$\overline{P}_{l,n}^c = \overline{P}_l^c - \sum_{j \in \mathcal{N}_l^c, j \neq n} P_{l,j}^c.$$
- $I^d_m$: Maximum number of channels simultaneously used by D2D pair $m$.
- $\mathcal{N}^d_m (\mathcal{N}^d_m \subset \mathcal{N})$: Set of uplink channels simultaneously used by D2D pair $m$.
- $\zeta^d_{m,n}, \hat{\zeta}^d_{m,n}$: Actual SINR and Required SINR of D2D pair $m$ on channel $n$.
- $P^d_{m,n}, \bar{P}^d_{m,n}$: Actual transmit power and maximum transmit power of D2D pair $m$ on channel $n$.
- $P^d_m, \bar{P}^d_m$: Actual aggregate transmit power and maximum aggregate transmit power of D2D pair $m$ on all channels.

\[
P^d_m = \sum_{n \in \mathcal{N}^d_m} P^d_{m,n}.
\]
\[
\bar{P}^d_{m,n} = \bar{P}^d_m - \sum_{j \in \mathcal{N}^d_m, j \neq n} P^d_{m,j}.
\]
Channel gain between CU $k$ and the receiver of CU $l$ (i.e., the base station to which CU $l$ is communicating) on channel $n$ is

$$g_{k,n,l}^{cc} = K\beta_{k,n,l}\zeta_{k,n,l}L_{k,n,l}^{-\alpha}.$$  

where

- $K$ is a constant that depends on system parameters,
- $\beta_{k,n,l}$ is the fast fading gain with exponential distribution,
- $\zeta_{k,n,l}$ is the slow fading gain with log-normal distribution,
- $\alpha$ is the path loss exponent,
- $L_{k,n,l}$ is the distance between CU $k$ and the receiver of CU $l$.

We assume AWGN noise in each channel.

- $\sigma_{l,n}^c$: Noise power at the receiver of CU $l$ in channel $n$,
- $\sigma_{m,n}^d$: Noise power at the receiver of D2D pair $m$ in channel $n$. 
Resource Allocation Problem
Two basic definitions:
1. An admissible D2D pair
2. A candidate reuse channel

Let
1. \( \mathcal{D}' (\mathcal{D}' \subseteq \mathcal{D}) \) be the set of all admissible D2D pairs.
2. \( \mathcal{R}_m \) be the set of candidate reuse channels for the D2D pair \( m \).
3. \( \mathcal{N}' \) be the union of all candidate reuse channels for all D2D pairs, i.e., \( \mathcal{N}' = \mathcal{R}_1 \cup \mathcal{R}_2 \cup \cdots \cup \mathcal{R}_M \).

Each uplink channel is reused by at most one D2D pair.

If D2D pair \( m \) reuses channel \( n \), then \( \rho_{m,n}^d \) is 1, otherwise it is 0.

We wish to
1. Maximize the number of admissible D2D pairs and reused channels.
2. Minimize the total transmit power for all users.
3. Maintain the QoS and transmit power constraints for all users.
Problem Formulation I

Determine \( \{ \rho_{m,n}^d, P_{m,n}^d, P_{l,n}^c \} \), \( \forall m \in D, \forall n \in N \),

To Maximize \( \sum_{m \in D} \sum_{n \in N} \rho_{m,n}^d \)

To Minimize \( \sum_{l \in C} \sum_{m \in D} \sum_{n \in N} (P_{l,n}^c + \rho_{m,n}^d P_{m,n}^d) \)

Subject to:

\[ \xi_{l,n}^c = \frac{g_{l,n,l}^c \cdot P_{l,n}^c}{\sigma_{l,n}^c + \sum_{k \in C \atop k \neq l} g_{k,n,l}^c \cdot P_{l,n}^c + \sum_{m \in D} \rho_{m,n}^d g_{m,n,l}^d \cdot P_{m,n}^d} \geq \hat{\xi}_{l,n}^c, \forall l \in C, \forall n \in N, \quad (1d) \]

\[ \xi_{m,n}^d = \frac{g_{m,n,m}^d \cdot P_{m,n}^d}{\sigma_{m,n}^d + \sum_{k \in C} g_{k,n,m}^d \cdot P_{k,n}^c} \geq \hat{\xi}_{m,n}^d, \quad \forall m \in D', \forall n \in N, \quad (1e) \]

\( \rho_{m,n}^d \in \{0, 1\}, \quad \forall m \in D, \forall n \in N, \quad (1f) \)
Problem Formulation II

\[
\sum_{m \in D} \rho_{m,n}^d \leq 1, \quad \forall n \in \mathcal{N}, \quad (1g)
\]
\[
1 \leq \sum_{n \in \mathcal{N}} \rho_{m,n}^d \leq \bar{I}_m^d, \quad \forall m \in \mathcal{D}', \quad (1h)
\]
\[
0 \leq P_{l,n}^c \leq \bar{P}_{l,n}^c, \quad \forall l \in \mathcal{C}, \forall n \in \mathcal{N}, \quad (1i)
\]
\[
0 \leq P_{m,n}^d \leq \bar{P}_{m,n}^d, \quad \forall m \in \mathcal{D}, \forall n \in \mathcal{N}, \quad (1j)
\]
\[
0 \leq P_l^c \leq \bar{P}_l^c, \quad \forall l \in \mathcal{C}, \quad (1k)
\]
\[
0 \leq P_m^d \leq \bar{P}_m^d, \quad \forall m \in \mathcal{D}. \quad (1l)
\]
Optimal Resource Allocation
• This problem is a mixed integer linear programming (MILP) problem, which is difficult to solve directly.

• We divide the optimization problem into two sub-problems:
  1. D2D Admissibility and Optimal Power Control
  2. Resource Allocation for Admissible D2D Pairs

• We solve each sub-problem separately, and combine the results via our proposed algorithm.
The D2D pair $m$ can reuse channel $n$ if

\[
\begin{align*}
\zeta_{l,n}^c &= \frac{g_{l,n,l}^{cc} P_{l,n}^c}{\sigma_{l,n}^c + \sum_{k \in C, k \neq l} g_{k,n,l}^{cc} P_{k,n}^c + g_{m,n,l}^{dc} P_{m,n}^d} \geq \hat{\zeta}_{l,n}^c, \quad \forall l \in C, \\
\zeta_{m,n}^d &= \frac{g_{m,n,m}^{dd} P_{m,n}^d}{\sigma_{m,n}^d + \sum_{k \in C} g_{k,n,m}^{cd} P_{k,n}^c} \geq \hat{\zeta}_{m,n}^d, \\
0 &\leq P_{l,n}^c \leq \bar{P}_{l,n}^c, \quad \forall l \in C, \\
0 &\leq P_{m,n}^d \leq \bar{P}_{m,n}^d.
\end{align*}
\]
In matrix form, the power constraints can be reformulated as

\[ 0 \leq \mathbf{p}_{m,n} \leq \mathbf{\bar{p}}_{m,n}, \]

where

\[ \mathbf{\bar{p}}_{m,n} = [ \, \mathbf{\bar{P}}_{1,n} \; \mathbf{\bar{P}}_{2,n} \; \cdots \; \mathbf{\bar{P}}_{L,n} \; \mathbf{\bar{P}}_{m,n} \, ]^T. \]

SINR constraints can be reformulated as

\[
\left\{ \begin{array}{l}
(g_{c,c,l}^c P_{c,l,n} - \sum_{\substack{k \in \mathcal{C} \atop k \neq l}} \hat{\xi}_{c,l,n} g_{k,n,l}^c P_{k,n}^c) - \hat{\xi}_{c,l,n} \sigma_{c,l,n}^c \geq \hat{\xi}_{c,l,n} \sigma_{c,l,n}^c, \forall l \in \mathcal{C}, \\
- \sum_{k \in \mathcal{C}} \hat{\xi}_{d,m,n} g_{k,n,m}^d P_{k,n}^c + g_{d,d,m}^d P_{m,n}^d \geq \hat{\xi}_{d,m,n} \sigma_{d,m,n}^d.
\end{array} \right.
\]
In matrix form SINR constraints can be reformulated as

\[ A_{m,n} p_{m,n} \geq \mu_{m,n}, \]

Where

\[
A_{m,n} = \begin{bmatrix}
g_{cc}^{1,n,1} & \cdots & -\hat{\xi}_{1,n} g_{cc}^{L,n,1} & -\hat{\xi}_{1,n} g_{dc}^{m,n,1} \\
\vdots & \ddots & \vdots & \vdots \\
-\hat{\xi}_{L,n} g_{cc}^{1,n,L} & \cdots & g_{cc}^{L,n,L} & -\hat{\xi}_{L,n} g_{dc}^{m,n,L} \\
-\hat{\xi}_{L,n} g_{cd}^{1,n,m} & \cdots & -\hat{\xi}_{L,n} g_{cd}^{L,n,m} & g_{dd}^{m,n,m}
\end{bmatrix},
\]

\[ p_{m,n} = \begin{bmatrix} P_{1,n}^c & P_{2,n}^c & \cdots & P_{L,n}^c & P_{m,n}^d \end{bmatrix}^T, \]

\[ \mu_{m,n} = \begin{bmatrix} \hat{\xi}_{1,n} \sigma_{1,n}^{c} & \cdots & \hat{\xi}_{L,n} \sigma_{L,n}^{c} & \hat{\xi}_{m,n} \sigma_{m,n}^{d} \end{bmatrix}^T. \]
The first sub-problem is

Minimize $\mathbf{1}_{L+1}^T \mathbf{p}_{m,n}$,

Subject to \[
\begin{align*}
A_{m,n} \mathbf{p}_{m,n} &\geq \mu_{m,n}, \\
0 &\leq \mathbf{p}_{m,n} \leq \bar{\mathbf{p}}_{m,n}.
\end{align*}
\]

This is a linear programming (LP) problem, and can be solved by the Simplex, the Active-Set or the Interior-Point algorithm.

If this sub-problem has a solution, we denote it by

$$\mathbf{p}^*_{m,n} = \begin{bmatrix} P^c_{1,n} & P^c_{2,n} & \cdots & P^c_{L,n} & P^c_{m,n} \end{bmatrix}^T.$$ 

In this situation

- D2D pair $m$ is admissible,
- Channel $n$ is a candidate reuse channel for D2D pair $m$,
- The minimum total transmit power of D2D pair $m$ and CUs on channel $n$ is

$$P^\text{sum}_{m,n} = \mathbf{1}_{L+1}^T \mathbf{p}^*_{m,n}.$$
When only CUs use channel \( n \) and no D2D pair reuses it, the power control problem for CUs is a similar LP problem.

In this case, the minimum aggregate transmit power of CUs in channel \( n \) is the sum of elements in vector \( \mathbf{p}^*_0, n \), i.e.,

\[
P_{0,n}^{\text{sum}} = \mathbf{1}_L^T \mathbf{p}^*_0, n.
\]

When the D2D pair \( m \) reuses channel \( n \) already in use by CUs, the increase in the aggregate transmit power of CUs and the transmitter of D2D pair \( m \) on channel \( n \) is

\[
P_{m,n}^{\text{inc}} = P_{m,n}^{\text{sum}} - P_{0,n}^{\text{sum}}.
\]
• When there is only one admissible D2D pair $m$ in all cells, its optimal reuse channel can be found via

$$n^*_m = \arg \min_{n \in \mathcal{R}_m} P^{inc}_{m,n}.$$  

• When there are multiple admissible D2D pairs, the problem of finding the optimal reuse channel for each admissible D2D pair is an assignment problem. This is our second sub-problem, formulated as

$$\min \left\{ \sum_{n \in \mathcal{N}'} \sum_{m \in \mathcal{D}'} \rho^d_{m,n} P^{inc}_{m,n} \right\},$$

subject to

$$\rho^d_{m,n} \in \{0, 1\},$$

$$\sum_{m \in \mathcal{D}'} \rho^d_{m,n} \leq 1, \forall n \in \mathcal{N'},$$

$$\sum_{n \in \mathcal{N}'} \rho^d_{m,n} = 1, \forall m \in \mathcal{D'}.$$
The Hungarian algorithm can be used to solve the second sub-problem efficiently.

In this way, one cellular channel is assigned to each admissible D2D pair.

When assigning more than one channel to each D2D pair is desired, the following algorithm is used.
Outline
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Resource Allocation Problem
Optimal Resource Allocation
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Conclusions

1: \( C \): The set of active CUs
2: \( D \): The set of D2D pairs
3: \( R_m \): The set of candidate reuse channels for D2D pair \( m \)
4: \( N \): The set of uplink channels
5: \( N^d_m \): The set of assigned channels to D2D pair \( m \)
6: Initialization:
   \[
   \begin{align*}
   \rho_{m,n}^d &= 0, \forall n \in N, \forall m \in D, \\
   N^d_m &= \emptyset, \forall m \in D, \\
   R_m &= \emptyset, \forall m \in D.
   \end{align*}
   \]
7: while \( N \neq \emptyset \) \& \( D \neq \emptyset \) do
8:   Calculate \( P_{c,l,n} \), \( \forall n \in N, \forall l \in C, \)
9:   Calculate \( P_{m,n}^d \), \( \forall n \in N, \forall m \in D, \)
10:   **Step 1**
11:   for \( \forall m \in D \) do
12:     for \( \forall n \in N \) do
13:       Calculate \( p_{m,n}^* \) by solving 1st sub-problem
14:       if 1st sub-problem has a solution then
15:         \( n \in R_m \)
16:       end if
17:     end for
18:     if \( R_m = \emptyset \) then \( D = D - m \)
19:     end if
20:   end for
21: \( N = R_1 \cup R_2 \cup \cdots \cup R_M \)
22: **end Step 1**

23: **Step 2**
24:   for \( \forall m \in D \) do
25:     for \( \forall n \in R_m \) do
26:       Calculate \( P_{m,n}^{inc} \)
27:     end for
28:   end for
29:   if \( |D| = 1 \) then
30:     Use the Hungarian algorithm to get \( n^*_m, \forall m \in D, \) 
31:     end if
32: **end Step 2**
33:   for \( \forall m \in D \) do
34:     \( R_m = \emptyset, \)
35:     \( N = N - n^*_m, \)
36:     if \( \sum_{n \in N^d_m} \rho_{m,n}^d = l^d_m \) then \( D = D - m \)
37:   end if
38: end for
39: **end while**
Simulation Results
We consider CUs are uniformly distributed in a fully loaded cellular network and each D2D pair is located in a uniformly distributed cluster with radius $r$.

we compare the performance of our proposed scheme with that in [9] which assumes a margin $k$ in each CU’s required SINR to take into account the interference caused by D2D transmitters.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius ($R$)</td>
<td>50, 100 m</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>1 MHz</td>
</tr>
<tr>
<td>AWGN power ($\sigma$)</td>
<td>-114 dBm</td>
</tr>
<tr>
<td>Pathloss exponent ($\alpha$)</td>
<td>3</td>
</tr>
<tr>
<td>Pathloss constant ($K$)</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Max. CU aggregate power ($\bar{P}_c^l$)</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Max. D_Tx aggregate power ($\bar{P}_m^d$)</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Req. SINR for a CU ($\xi_{l,m}^c$)</td>
<td>Uniform distribution in [0,20] dB</td>
</tr>
<tr>
<td>Req. SINR for a D2D pair ($\xi_{m,n}^d$)</td>
<td>Uniform distribution in [0,20] dB</td>
</tr>
<tr>
<td>Max. number of a CU’s channels ($\bar{I}_i^c$)</td>
<td>1</td>
</tr>
<tr>
<td>Max. number of a D2D pair’s channels ($\bar{I}_m^d$)</td>
<td>3</td>
</tr>
<tr>
<td>D2D cluster radius ($r$)</td>
<td>10, 30, 50, · · · , 90 m</td>
</tr>
<tr>
<td>Number of cellular channels ($N$)</td>
<td>32, 64</td>
</tr>
<tr>
<td>Number of cellular users ($L$)</td>
<td>32, 64</td>
</tr>
<tr>
<td>No. of D2D pairs ($M$)</td>
<td>0.25, 0.4375, · · · , 1 of $N$</td>
</tr>
<tr>
<td>Fast fading gain ($\beta$)</td>
<td>Exponential distribution with unit mean</td>
</tr>
<tr>
<td>Slow fading gain ($\zeta$)</td>
<td>Log-normal distribution with unit mean and standard deviation of 8 dB</td>
</tr>
<tr>
<td>SINR margin ($k$)</td>
<td>2 dB</td>
</tr>
</tbody>
</table>
Simulation metrics, each averaged for 200 realizations are:

1. **Channel reuse ratio**: The number of channels reused by D2D pairs divided by the total number of channels.

2. **D2D access ratio**: The number of admissible D2D pairs divided by the total number of D2D pairs.

3. **The increase in the total system uplink throughput** when D2D links are allowed as compared to the case in which D2D links are not permitted.
Conclusions
We proposed a novel optimal resource allocation scheme for D2D users in a multi-cell LTE-A network with C-RAN architecture that

- Increases the total capacity of the system,
- Maintains the required QoS in terms of SINR for all users,
- Considers both intracell and intercell interference,
- Permits the D2D transmitter and its receiver to be situated in different cells,
- Allows each D2D pair to simultaneously utilize multiple channels.

We divided the optimization problem into two sub-problems, solved each sub-problem separately, and combined the results via our proposed algorithm.

Simulation results demonstrate significant improvements in system performance.
Thank You