ITU Kaleidoscope 2016

ICTs for a Sustainable World

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

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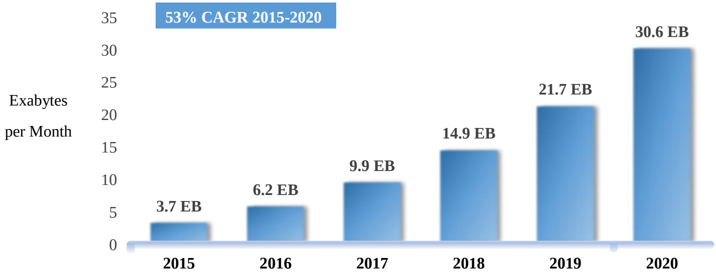
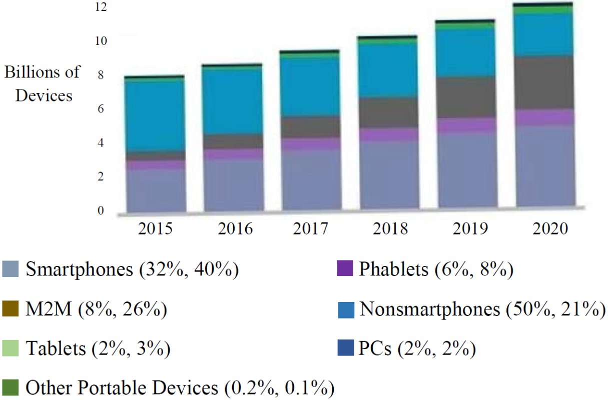
Introduction



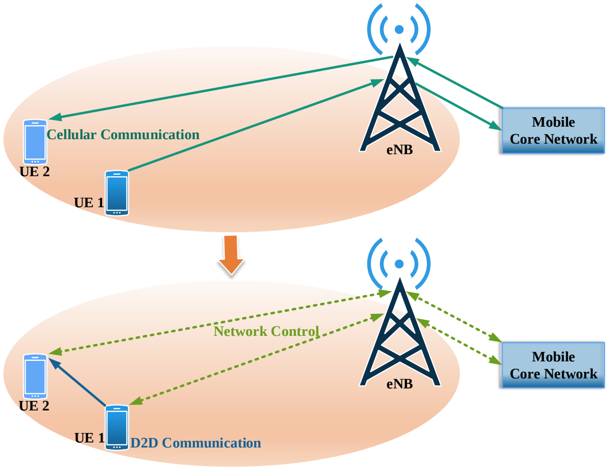
Source: Cisco VNI Mobile, 2016

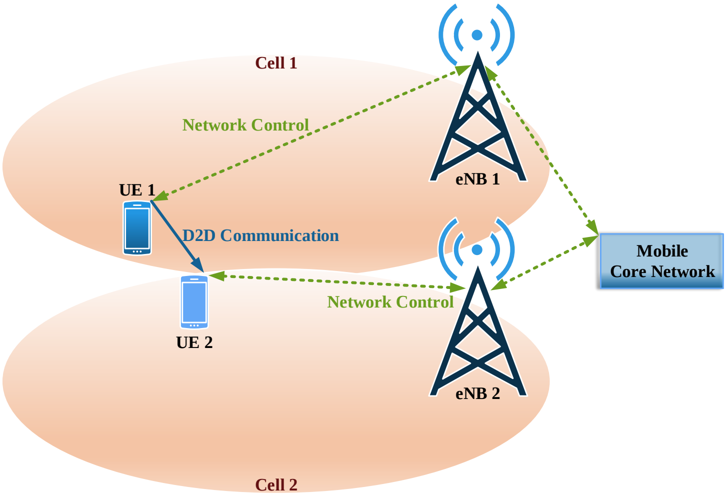


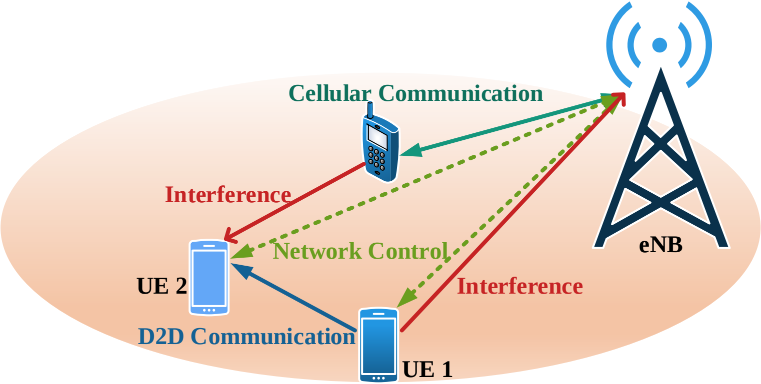
Source: Cisco VNI Mobile, 2016

Limitations and Constraints:

1. Frequency spectrum
2. Energy consumption


Mobile
Core Network
Cellular Communication
eNB
UE 2
UE 1
Network Control
Mobile
Core Network
eNB
UE 2
UE 1
D2D Communication


Cell 1
Network Control
eNB 1
UE 1
D2D Communication
Mobile
Core Network
Network Control
UE 2
eNB 2
Cell 2


Cellular Communication
Interference
Network Control
UE 2
D2D Communication
UE 1
Interference
eNB

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

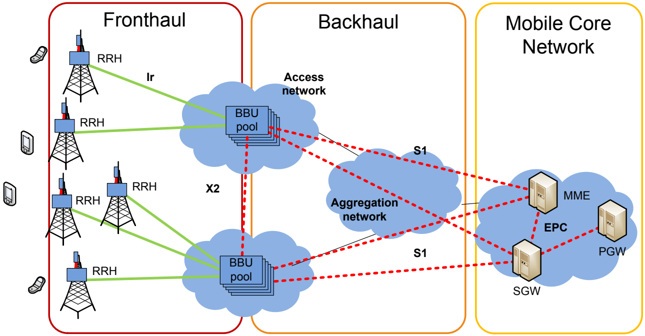
We assume:

- 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.



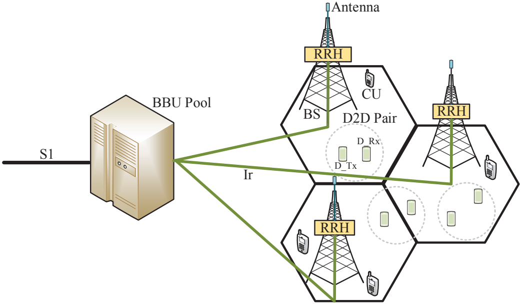
The objective is to allocate channels and transmit power levels:

- 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,
- $\mathcal{N} = \{1, ..., N\}$ as the set of orthogonal uplink channels,
- $\mathcal{C} = \{1, ..., L\}$ as the set of CUs,
- $\mathcal{D} = \{1, ..., M\}$ as the set of D2D pairs,
- D2D pairs can reuse cellular uplink channels,
- D_Tx and D_Rx are not required to be in the same cell.



- $\bar{I}_l^{\mathrm{c}}$: Maximum number of channels simultaneously used by CU l.
- $\mathcal{N}_l^{\mathrm{c}}$ ($\mathcal{N}_l^{\mathrm{c}} \subset \mathcal{N}$): Set of channels simultaneously used by CU l.
- $\xi_{l,n}^{\mathrm{c}}$, $\hat{\xi}_{l,n}^{\mathrm{c}}$: Actual SINR and required SINR of CU l on channel n.
- $P_{l,n}^{\mathrm{c}}$, $\bar{P}_{l,n}^{\mathrm{c}}$: Actual transmit power and maximum transmit power of CU l on channel n.
- P_l^{c}, $\bar{P}_l^{\mathrm{c}}$: Actual aggregate transmit power and maximum aggregate transmit power of CU l on all channels.
- $P_l^{\mathrm{c}} = \sum_{n \in \mathcal{N}_l^{\mathrm{c}}} P_{l,n}^{\mathrm{c}}$.
- $\bar{P}_{l,n}^{\mathrm{c}} = \bar{P}_l^{\mathrm{c}} - \sum_{j \in \mathcal{N}_l^{\mathrm{c}}, j \neq n} P_{l,j}^{\mathrm{c}}$.

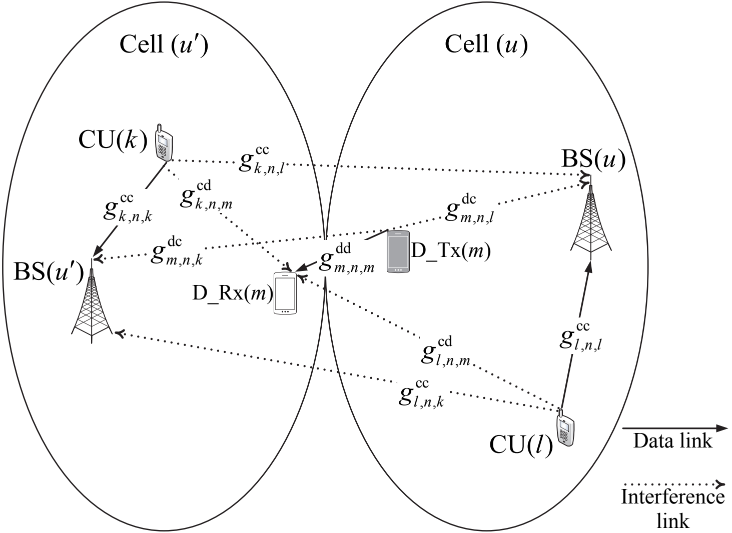
- $\bar{I}_m^{\mathrm{d}}$: Maximum number of channels simultaneously used by D2D pair m.
- $\mathcal{N}_m^{\mathrm{d}}$ ($\mathcal{N}_m^{\mathrm{d}} \subset \mathcal{N}$): Set of uplink channels simultaneously used by D2D pair m.
- $\zeta_{m,n}^{\mathrm{d}}$, $\hat{\zeta}_{m,n}^{\mathrm{d}}$: Actual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

- 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

$$g^{\mathrm{cc}}_{k,n,l} = K\beta_{k,n,l}\zeta_{k,n,l}L^{-\alpha}_{k,n,l}.$$

  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,
  - α 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.
  - $\sigma^{\mathrm{c}}_{l,n}$: Noise power at the receiver of CU l in channel n,
  - $\sigma^{\mathrm{d}}_{m,n}$: Noise power at the receiver of D2D pair m in channel n.



Cell (u')
Cell (u)
CU(k)
$g^{\text{cc}}_{k,n,l}$
BS(u)
$g^{\text{cd}}_{k,n,m}$
$g^{\text{cc}}_{k,n,k}$
$g^{\text{dc}}_{m,n,l}$
$g^{\text{dc}}_{m,n,k}$
$g^{\text{dd}}_{m,n,m}$
D_Tx(m)
BS(u')
D_Rx(m)
$g^{\text{cd}}_{l,n,m}$
$g^{\text{cc}}_{l,n,l}$
$g^{\text{cc}}_{l,n,k}$
CU(l)
Data link
Interference link

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 $\rho^{\mathrm{d}}_{m,n}$ 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

$$\text{Determine} \begin{cases} \rho^{\mathrm{d}}_{m,n}, & \forall m \in \mathcal{D}, \forall n \in \mathcal{N}, \\ P^{\mathrm{d}}_{m,n}, & \forall m \in \mathcal{D}, \forall n \in \mathcal{N}, \\ P^{\mathrm{c}}_{l,n}, & \forall l \in \mathcal{C}, \forall n \in \mathcal{N}, \end{cases} \tag{1a}$$

$$\text{To Maximize} \sum_{m\in\mathcal{D}} \sum_{n\in\mathcal{N}} \rho^{\mathrm{d}}_{m,n}, \tag{1b}$$

$$\text{To Minimize} \sum_{l\in\mathcal{C}} \sum_{m\in\mathcal{D}} \sum_{n\in\mathcal{N}} \left(P^{\mathrm{c}}_{l,n} + \rho^{\mathrm{d}}_{m,n} P^{\mathrm{d}}_{m,n}\right), \tag{1c}$$

Subject to:

$$\xi^{\mathrm{c}}_{l,n} = \frac{g^{\mathrm{cc}}_{l,n,l} P^{\mathrm{c}}_{l,n}}{\sigma^{\mathrm{c}}_{l,n} + \sum\limits_{\substack{k\in\mathcal{C} \\ k\neq l}} g^{\mathrm{cc}}_{k,n,l} P^{\mathrm{c}}_{k,n} + \sum\limits_{m\in\mathcal{D}} \rho^{\mathrm{d}}_{m,n} g^{\mathrm{dc}}_{m,n,l} P^{\mathrm{d}}_{m,n}} \geq \hat{\xi}^{\mathrm{c}}_{l,n}, \forall l \in \mathcal{C}, \forall n \in \mathcal{N}, \tag{1d}$$

$$\xi^{\mathrm{d}}_{m,n} = \frac{g^{\mathrm{dd}}_{m,n,m} P^{\mathrm{d}}_{m,n}}{\sigma^{\mathrm{d}}_{m,n} + \sum\limits_{k\in\mathcal{C}} g^{\mathrm{cd}}_{k,n,m} P^{\mathrm{c}}_{k,n}} \geq \hat{\xi}^{\mathrm{d}}_{m,n}, \qquad \forall m \in \mathcal{D}', \forall n \in \mathcal{N}, \tag{1e}$$

$$\rho^{\mathrm{d}}_{m,n} \in \{0, 1\}, \qquad \forall m \in \mathcal{D}, \forall n \in \mathcal{N}, \tag{1f}$$

Problem Formulation II

$$\sum_{m\in\mathcal{D}} \rho^{\mathrm{d}}_{m,n} \leq 1, \qquad \forall n \in \mathcal{N}, \tag{1g}$$

$$1 \leq \sum_{n\in\mathcal{N}} \rho^{\mathrm{d}}_{m,n} \leq \bar{I}^{\mathrm{d}}_{m}, \qquad \forall m \in \mathcal{D}', \tag{1h}$$

$$0 \leq P^{\mathrm{c}}_{l,n} \leq \bar{P}^{\mathrm{c}}_{l,n}, \qquad \forall l \in \mathcal{C}, \forall n \in \mathcal{N}, \tag{1i}$$

$$0 \leq P^{\mathrm{d}}_{m,n} \leq \bar{P}^{\mathrm{d}}_{m,n}, \qquad \forall m \in \mathcal{D}, \forall n \in \mathcal{N}, \tag{1j}$$

$$0 \leq P^{\mathrm{c}}_{l} \leq \bar{P}^{\mathrm{c}}_{l}, \qquad \forall l \in \mathcal{C}, \tag{1k}$$

$$0 \leq P^{\mathrm{d}}_{m} \leq \bar{P}^{\mathrm{d}}_{m}, \qquad \forall m \in \mathcal{D}. \tag{1l}$$

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

1. $$\begin{cases} \xi^{\mathrm{c}}_{l,n} = \dfrac{g^{\mathrm{cc}}_{l,n,l} P^{\mathrm{c}}_{l,n}}{\sigma^{\mathrm{c}}_{l,n} + \sum\limits_{\substack{k \in \mathcal{C} \\ k \neq l}} g^{\mathrm{cc}}_{k,n,l} P^{\mathrm{c}}_{k,n} + g^{\mathrm{dc}}_{m,n,l} P^{\mathrm{d}}_{m,n}} \geq \hat{\xi}^{\mathrm{c}}_{l,n}, \forall l \in \mathcal{C}, \\ \xi^{\mathrm{d}}_{m,n} = \dfrac{g^{\mathrm{dd}}_{m,n,m} P^{\mathrm{d}}_{m,n}}{\sigma^{\mathrm{d}}_{m,n} + \sum\limits_{k \in \mathcal{C}} g^{\mathrm{cd}}_{k,n,m} P^{\mathrm{c}}_{k,n}} \geq \hat{\xi}^{\mathrm{d}}_{m,n}, \end{cases}$$
2. $$\begin{cases} 0 \leq P^{\mathrm{c}}_{l,n} \leq \bar{P}^{\mathrm{c}}_{l,n}, \forall l \in \mathcal{C}, \\ 0 \leq P^{\mathrm{d}}_{m,n} \leq \bar{P}^{\mathrm{d}}_{m,n}. \end{cases}$$

- In matrix form, the power constraints can be reformulated as

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

where

$$\bar{\mathbf{p}}_{m,n} = \begin{bmatrix} \bar{P}^{\mathrm{c}}_{1,n} & \bar{P}^{\mathrm{c}}_{2,n} & \cdots & \bar{P}^{\mathrm{c}}_{L,n} & \bar{P}^{\mathrm{d}}_{m,n} \end{bmatrix}^{\mathrm{T}}.$$

- SINR constraints can be reformulated as

$$\begin{cases} \big(g^{\mathrm{cc}}_{l,n,l} P^{\mathrm{c}}_{l,n} - \sum\limits_{\substack{k\in\mathcal{C} \\ k\neq l}} \hat{\zeta}^{\mathrm{c}}_{l,n} g^{\mathrm{cc}}_{k,n,l} P^{\mathrm{c}}_{k,n}\big) - \hat{\zeta}^{\mathrm{c}}_{l,n} g^{\mathrm{dc}}_{m,n,l} P^{\mathrm{d}}_{m,n} \geq \hat{\zeta}^{\mathrm{c}}_{l,n} \sigma^{\mathrm{c}}_{l,n}, \forall l \in \mathcal{C}, \\ -\sum\limits_{k\in\mathcal{C}} \hat{\zeta}^{\mathrm{d}}_{m,n} g^{\mathrm{cd}}_{k,n,m} P^{\mathrm{c}}_{k,n} + g^{\mathrm{dd}}_{m,n,m} P^{\mathrm{d}}_{m,n} \geq \hat{\zeta}^{\mathrm{d}}_{m,n} \sigma^{\mathrm{d}}_{m,n}. \end{cases}$$

- In matrix form SINR constraints can be reformulated as

$$\mathbf{A}_{m,n}\mathbf{p}_{m,n} \geq \boldsymbol{\mu}_{m,n},$$

Where

$$\mathbf{A}_{m,n} = \begin{bmatrix} g^{\mathrm{cc}}_{1,n,1} & \cdots & -\hat{\zeta}^{\mathrm{c}}_{1,n} g^{\mathrm{cc}}_{L,n,1} & -\hat{\zeta}^{\mathrm{c}}_{1,n} g^{\mathrm{dc}}_{m,n,1} \\ \vdots & \ddots & \vdots & \vdots \\ -\hat{\zeta}^{\mathrm{c}}_{L,n} g^{\mathrm{cc}}_{1,n,L} & \cdots & g^{\mathrm{cc}}_{L,n,L} & -\hat{\zeta}^{\mathrm{c}}_{L,n} g^{\mathrm{dc}}_{m,n,L} \\ -\hat{\zeta}^{\mathrm{d}}_{m,n} g^{\mathrm{cd}}_{1,n,m} & \cdots & -\hat{\zeta}^{\mathrm{d}}_{m,n} g^{\mathrm{cd}}_{L,n,m} & g^{\mathrm{dd}}_{m,n,m} \end{bmatrix},$$

$$\mathbf{p}_{m,n} = \begin{bmatrix} P^{\mathrm{c}}_{1,n} & P^{\mathrm{c}}_{2,n} & \cdots & P^{\mathrm{c}}_{L,n} & P^{\mathrm{d}}_{m,n} \end{bmatrix}^{\mathrm{T}},$$

$$\boldsymbol{\mu}_{m,n} = \begin{bmatrix} \hat{\zeta}^{\mathrm{c}}_{1,n}\sigma^{\mathrm{c}}_{1,n} & \cdots & \hat{\zeta}^{\mathrm{c}}_{L,n}\sigma^{\mathrm{c}}_{L,n} & \hat{\zeta}^{\mathrm{d}}_{m,n}\sigma^{\mathrm{d}}_{m,n} \end{bmatrix}^{\mathrm{T}}.$$

- The first sub-problem is

$$\text{Minimize } \mathbf{1}_{L+1}^{\mathrm{T}}\mathbf{p}_{m,n},$$
$$\text{Subject to} \begin{cases} \mathbf{A}_{m,n}\mathbf{p}_{m,n} \geq \boldsymbol{\mu}_{m,n}, \\ \mathbf{0} \leq \mathbf{p}_{m,n} \leq \bar{\mathbf{p}}_{m,n}. \end{cases}$$

- 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

$$\mathbf{p}_{m,n}^{*} = \begin{bmatrix} P_{1,n}^{\mathrm{c}^*} & P_{2,n}^{\mathrm{c}^*} & \ldots & P_{L,n}^{\mathrm{c}^*} & P_{m,n}^{\mathrm{c}^*} \end{bmatrix}^{\mathrm{T}}.$$

- In this situation
  - D2D pair m is admissible,
  - Channel n is a candidate reuse channel for D2D pair m,
  - The minmum total transmit power of D2D pair m and CUs on channel n is

$$P_{m,n}^{\mathrm{sum}} = \mathbf{1}_{L+1}^{\mathrm{T}}\mathbf{p}_{m,n}^{*}.$$

- 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.,

$$P^{\text{sum}}_{0,n} = \mathbf{1}^{\text{T}}_{L+1}\mathbf{p}^*_{0,n}.$$

- 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

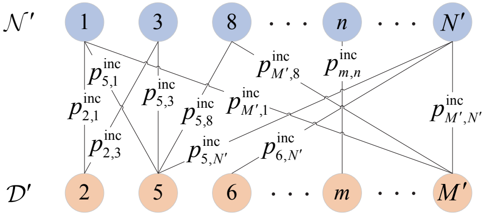
$$P^{\text{inc}}_{m,n} = P^{\text{sum}}_{m,n} - P^{\text{sum}}_{0,n}.$$

- When there is only one admissible D2D pair m in all cells, its optimal reuse channel can be found via

$$n_m^* = \underset{n \in \mathcal{R}_m}{\arg\min}\, P_{m,n}^{\mathrm{inc}}.$$

- 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

$$\min_{\rho_{m,n}^{\mathrm{d}}} \left\{ \sum_{n \in \mathcal{N}'} \sum_{m \in \mathcal{D}'} \rho_{m,n}^{\mathrm{d}} P_{m,n}^{\mathrm{inc}} \right\},$$
$$\text{subjectto} \begin{cases} \rho_{m,n}^{\mathrm{d}} \in \{0, 1\}, \\ \sum_{m \in \mathcal{D}'} \rho_{m,n}^{\mathrm{d}} \leq 1, \forall n \in \mathcal{N}', \\ \sum_{n \in \mathcal{N}'} \rho_{m,n}^{\mathrm{d}} = 1, \forall m \in \mathcal{D}'. \end{cases}$$



A bipartite graph for channel assignment problem.

- 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.

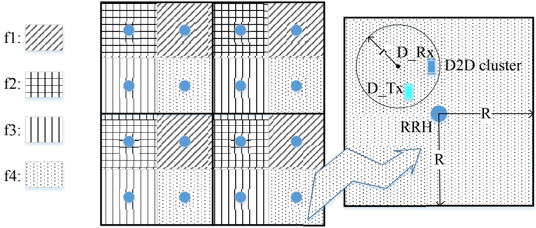
$\mathcal{C}$: The set of active CUs
$\mathcal{D}$: The set of D2D pairs
$\mathcal{R}_m$: The set of candidate reuse channels for D2D pair m
$\mathcal{N}$: The set of uplink channels
$\mathcal{N}_m^{\mathrm{d}}$: The set of assigned channels to D2D pair m
Initialization: $\begin{cases} \rho_{m,n}^{\mathrm{d}} = 0, \forall n \in \mathcal{N}, \forall m \in \mathcal{D}, \\ \mathcal{N}_m^{\mathrm{d}} = \emptyset, \forall m \in \mathcal{D}, \\ \mathcal{R}_m = \emptyset, \forall m \in \mathcal{D}. \end{cases}$
while $\mathcal{N} \neq \emptyset$ & $\mathcal{D} \neq \emptyset$ **do**
    Calculate $\bar{P}_{l,n}^{\mathrm{c}}, \forall n \in \mathcal{N}, \forall l \in \mathcal{C}$,
    Calculate $\bar{P}_{m,n}^{\mathrm{d}}, \forall n \in \mathcal{N}, \forall m \in \mathcal{D}$,

    Step 1
    for $\forall m \in \mathcal{D}$ **do**
        for $\forall n \in \mathcal{N}$ **do**
            Calculate $\mathbf{p}_{m,n}^{*}$ by solving 1st sub-problem
            if 1st sub-problem has a solution **then**
                $n \in \mathcal{R}_m$
            end if
        end for
        if $\mathcal{R}_m = \emptyset$ **then** $\mathcal{D} = \mathcal{D} - m$
        end if
    end for
    $\mathcal{N} = \mathcal{R}_1 \cup \mathcal{R}_2 \cup \cdots \cup \mathcal{R}_M$
    end Step 1

    Step 2
    for $\forall m \in \mathcal{D}$ **do**
        for $\forall n \in \mathcal{R}_m$ **do**
            Calculate $P_{m,n}^{\mathrm{inc}}$
        end for
    end for
    if $|\mathcal{D}| = 1$ **then** $\begin{cases} n_m^{*} = \arg\min\limits_{n \in \mathcal{R}_m} P_{m,n}^{\mathrm{inc}} \\ \rho_{m,n_m^{*}}^{\mathrm{d}} = 1 \\ \mathcal{N}_m^{\mathrm{d}} = \mathcal{N}_m^{\mathrm{d}} + n_m^{*} \end{cases}$
    else Use the Hungarian algorithm
        to get $n_m^{*}, \forall m \in \mathcal{D}$, & then
        $\begin{cases} \rho_{m,n_m^{*}}^{\mathrm{d}} = 1, \forall m \in \mathcal{D} \\ \mathcal{N}_m^{\mathrm{d}} = \mathcal{N}_m^{\mathrm{d}} + n_m^{*}, \forall m \in \mathcal{D} \end{cases}$
    end if
    end Step 2

    for $\forall m \in \mathcal{D}$ **do**
        $\mathcal{R}_m = \emptyset$,
        $\mathcal{N} = \mathcal{N} - n_m^{*}$,
        if $\sum\limits_{n \in \mathcal{N}_m^{\mathrm{d}}} \rho_{m,n}^{\mathrm{d}} = \bar{I}_m^{\mathrm{d}}$ **then** $\mathcal{D} = \mathcal{D} - m$
        end if
    end for
end while

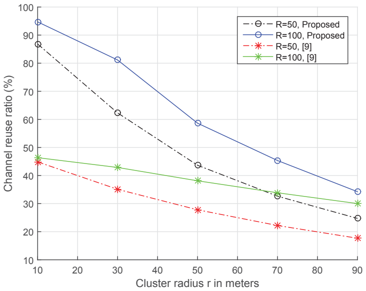
Simulation Results

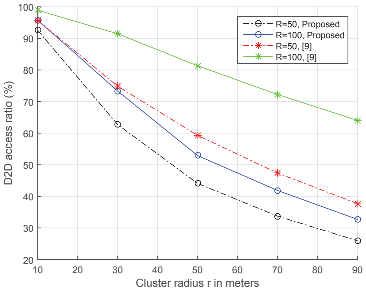


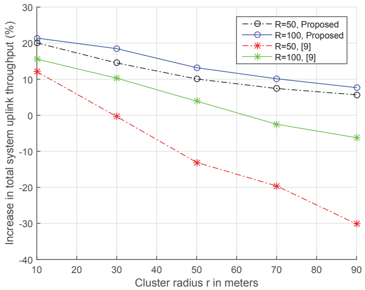
- We consider CUs are uniformly distributed in a fully loaded cellular network and each D2D pair is located in a uniformly distributed cluster with radius r.
- we compare the performance of our proposed scheme with that in [9] which assumes a margin k in each CU's required SINR to take into account the interference caused by D2D transmitters.

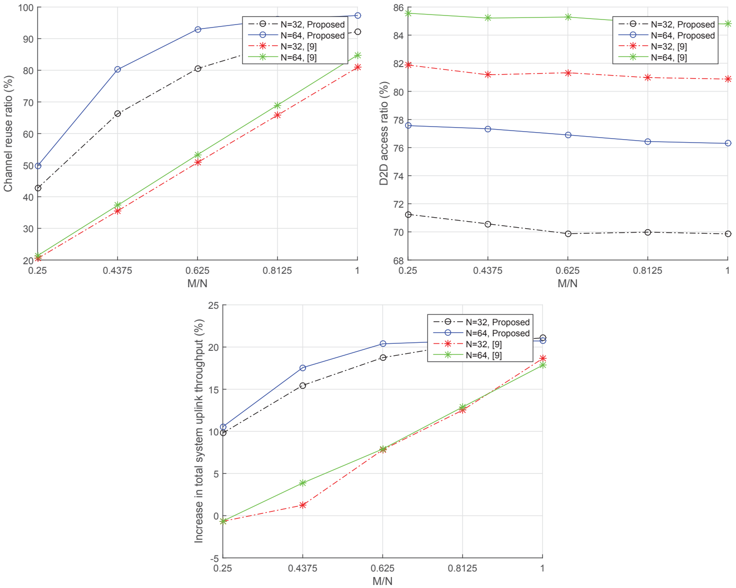
Parameter	Value
Cell radius (R)	50, 100 m
Channel bandwidth	1 MHz
AWGN power (σ)	-114 dBm
Pathloss exponent (α)	3
Pathloss constant (K)	10^{-2}
Max. CU aggregate power ($\bar{P}_l^{\mathrm{c}}$)	20 dBm
Max. D_Tx aggregate power ($\bar{P}_m^{\mathrm{d}}$)	20 dBm
Req. SINR for a CU ($\hat{\xi}_{l,n}^{\mathrm{c}}$)	Uniform distribution in [0,20] dB
Req. SINR for a D2D pair ($\hat{\xi}_{m,n}^{\mathrm{d}}$)	Uniform distribution in [0,20] dB
Max. number of a CU's channels ($\bar{I}_l^{\mathrm{c}}$)	1
Max. number of a D2D pair's channels ($\overline{I_m^{\mathrm{d}}}$)	3
D2D cluster radius (r)	10, 30, 50, $\cdots$, 90 m
Number of cellular channels (N)	32, 64
Number of cellular users (L)	32, 64
No. of D2D pairs (M)	0.25, 0.4375, $\cdots$, 1 of N
Fast fading gain (β)	Exponential distribution with unit mean
Slow fading gain (ζ)	Log-normal distribution with unit mean and standard deviation of 8 dB
SINR margin (k)	2 dB

- 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.


Channel reuse ratio (%)
Cluster radius r in meters
R=50, Proposed
R=100, Proposed
R=50, [9]
R=100, [9]


D2D access ratio (%)
Cluster radius r in meters
R=50, Proposed
R=100, Proposed
R=50, [9]
R=100, [9]


Increase in total system uplink throughput (%)
Cluster radius r in meters
R=50, Proposed
R=100, Proposed
R=50, [9]
R=100, [9]


Channel reuse ratio (%)
M/N
N=32, Proposed
N=64, Proposed
N=32, [9]
N=64, [9]
D2D access ratio (%)
M/N
N=32, Proposed
N=64, Proposed
N=32, [9]
N=64, [9]
Increase in total system uplink throughput (%)
M/N
N=32, Proposed
N=64, Proposed
N=32, [9]
N=64, [9]

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