Incentive Compatible Mode Selection and Spectrum Partitioning in Overlay D2D-Enabled Network

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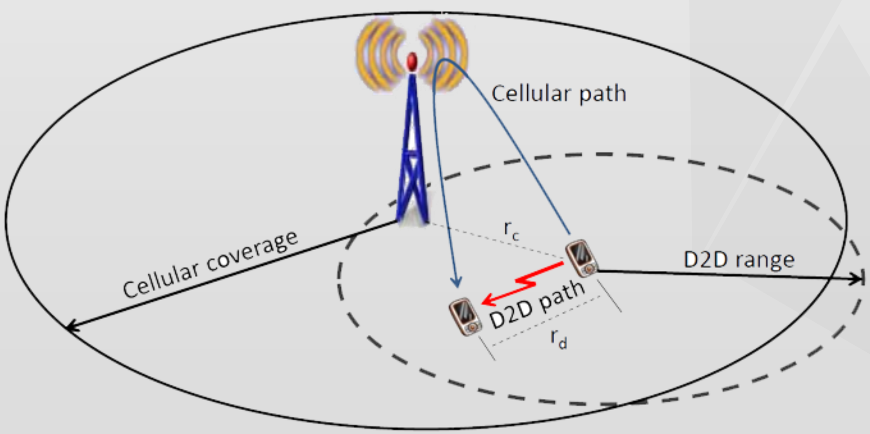
Background

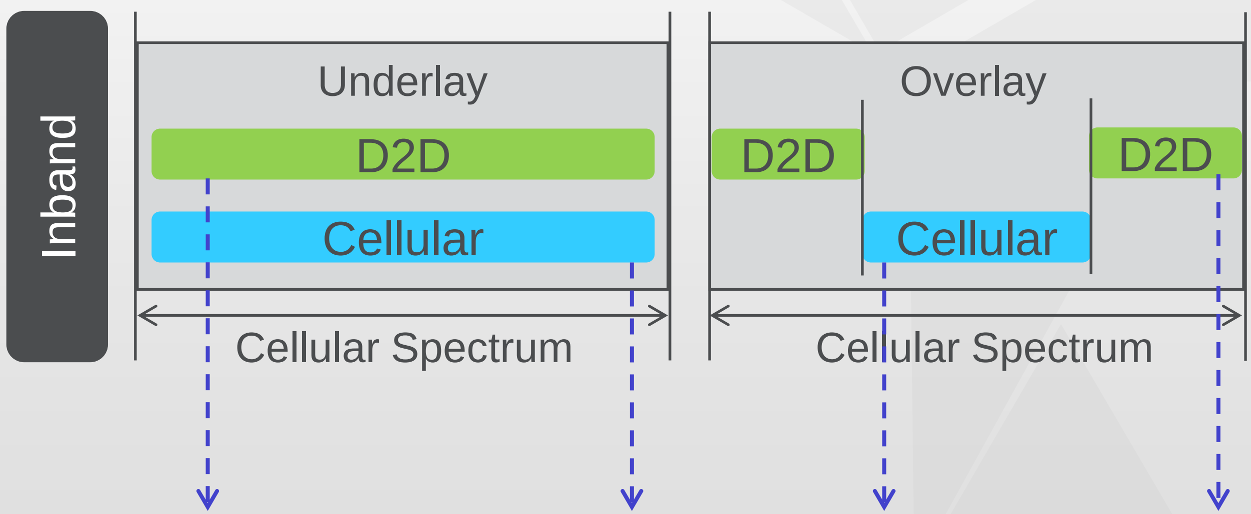
With the large expected demand of wireless network communication, *Device-to-Device (D2D) communication* has been proposed as a promising technology to enhance network performance.

One of the most challenging issues in integrating D2D communication into conventional cellular system is the *spectrum assignment* on both D2D links and cellular links.



Background

Two main approaches:
- *Overlay* spectrum access
- *Underlay* spectrum access



Reused mode
(uplink resources)

Cellular mode

Dedicated mode

Background

Mode Selection:

Potential D2D users make selection between cellular mode and D2D mode.

Selfish nature: they select their communication mode selfishly, which is difficult to be handled.

Specially under overlay spectrum access,

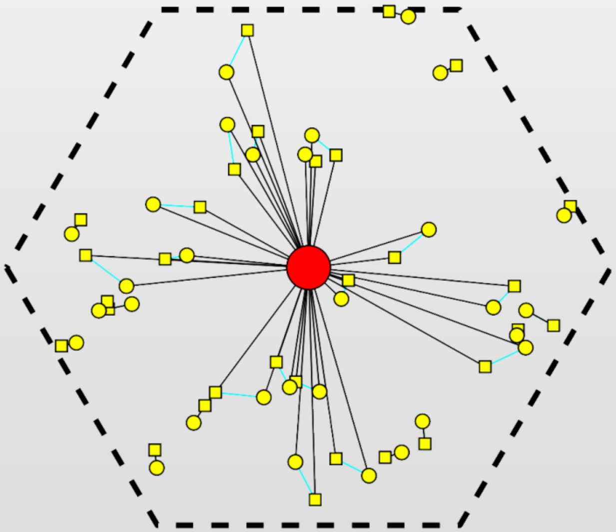
Spectrum Partitioning:

How to partition dedicated spectrum for D2D communication only.

System Model

We consider:

1. A D2D-enabled cellular system with one cell and multiple UEs.
2. Some of UEs are potential D2D users.



3. Potential D2D users have formed transmitter-receiver pairs in advance, called *potential D2D pairs*.
4. Other pairs, which can only communicate through BS in conventional way, are denoted as *cellular pairs*.
5. The D2D-enabled cellular system is under overlay spectrum access only.

System Model

List of Key Notation

Notation	Definition
$\mathcal{U}, \mathcal{U}_c, \mathcal{U}_d$	{Total, cellular, potential D2D} UE pair set
N_c	The number of cellular UE pairs, $N_c = \lvert\mathcal{U}_c\rvert$
N_d	The number of potential D2D pairs, $N_d = \lvert\mathcal{U}_d\rvert$
N	The number of all UE pairs, $N = N_c + N_d = \lvert\mathcal{U}\rvert$
● W	Total bandwidth in one macro D2D-enabled network
● p	Proportion of bandwidth reserved for D2D communication
w_c	bandwidth allocated to one cellular pair for either downlink or uplink
w_d	bandwidth allocated to one D2D pair
● m	The number of potential D2D pairs in D2D mode

System Model

Under overlay D2D communication, the proposed system supports either of the two D2D modes (dedicated) :

(1) **Divided D2D mode**:

Dedicated spectrum allocated for D2D communication is equally divided for each D2D pair. $[w_d = \frac{Wp}{m}]$

(2) **Shared D2D mode**:

All D2D pairs share the whole dedicated D2D spectrum. $[w_d = Wp]$

Cellular mode: for either downlink or uplink $[w_c = \frac{W(1-p)}{2(N-m)}]$

System Model

Mode selection vector :

$$\mathbf{X} = [x_i], \quad x_i \in \{0,1\}, \quad i \in \mathcal{U}_d$$

For potential D2D pair $i \in \mathcal{U}_d$,

define $r_{i,d}$ and $r_{i,c}$ as *network utility* (logarithmic function to achievable rate) in each mode:

(1) **Choose D2D mode** [$x_i = 1$]:

$$r_{i,d} = \log(w_d \log(1 + \frac{\mathrm{SINR}_{i,d}}{\Gamma}))$$

(2) **Choose cellular mode** [$x_i = 0$]:

$$\begin{aligned} r_{i,c} &= \log(w_c \log(1 + \frac{\mathrm{SINR}_{i,c}}{\Gamma})) \\ &= \log(w_c \log(1 + \frac{\min\{\mathrm{SINR}_{i,up}, \mathrm{SINR}_{i,down}\}}{\Gamma})) \end{aligned}$$

System Model

Due to the selfish nature of potential D2D pairs, we would like to propose a pricing-based mode selection and spectrum partitioning framework for integrating overlay D2D communication into exiting conventional cellular network.

Our goal is to maximize total network utility of the D2D-enabled cellular system.

Stackelberg Game

We propose a two-stage Stackelberg game to manage the system:

leader

followers

Stage I: BS determines spectrum partitioning p, announces additional price π for D2D communication

Stage II: Potential D2D pairs determine whether or not to choose D2D mode, report x_i to BS

Price π here is the *additional payment* for D2D communication.

Each pair starts to communicate after playing this game. (one shot game)

For next, we will analyze the Stackelberg game following standard backward induction process in divided D2D mode setting.

Stackelberg Game

Mode selection in Stage II

For potential D2D pair $i \in \mathcal{U}_d$, its utility:

$$u_i = \begin{cases} r_{i,d} - \pi, & x_i = 1. \\ r_{i,c}, & \text{else.} \end{cases}$$

Each potential D2D pair's objective is to maximize their own utility:

$$x_i = 1 \text{ if and only if } r_{i,d} - r_{i,c} - \pi > 0$$

Introduce parameters:

$$a_{i,d} = \log(W \log(1 + \frac{\text{SINR}_{i,d}}{\Gamma}))$$
$$a_{i,c} = \log(W \log(1 + \frac{\text{SINR}_{i,c}}{\Gamma}))$$

$$\Rightarrow x_i^* = \begin{cases} 1, & \text{if } a_{i,d} - a_{i,c} - [\pi - \log \frac{2p(N-m)}{m(1-p)}] > 0. \\ 0, & \text{otherwise.} \end{cases}$$

This is the *incentive compatible conditions* for potential D2D pairs to follow the specific mode selection strategy.

Stackelberg Game

Spectrum Allocation and Pricing Strategy in Stage I

Network utility:

cellular pairs

$$\Pi_c = \sum_{i \in \mathcal{U}_c} r_i$$

potential D2D pairs

$$\Pi_d = \sum_{i \in \mathcal{U}_d} x_i r_{i,d} + \sum_{i \in \mathcal{U}_d} (1 - x_i) r_{i,c}$$

The goal of the BS is to maximize total network utility:

$$\max_{X,m} \{\Pi = \Pi_c + \Pi_d\}$$

$N_c = |\mathcal{U}_c|$, $N_d = |\mathcal{U}_d|$ and $m = \sum_{i \in \mathcal{U}_d} x_i$

$$\Pi = \sum_{i \in \mathcal{U}_d} x_i (a_{i,d} - a_{i,c}) + \sum_{i \in \mathcal{U}_c} a_i + \sum_{i \in \mathcal{U}_d} a_{i,c} + m \log \frac{p}{m} + (N - m) \log \frac{(1-p)}{2(N-m)}$$

The BS would like to solve the optimization problem under the incentive compatible constraint.

Stackelberg Game

Spectrum Allocation and Pricing Strategy in Stage I

Primal-Dual Pricing Update Method:

The coupling constraint $m = \sum_{i \in \mathcal{U}_d} x_i$ motivates us to turn to the Lagrangian dual decomposition method to handle the optimization problem.

We introduce a *dual variable* μ :

$$D(\mu) = \sum_{i \in \mathcal{U}_d} x_i(a_{i,d} - a_{i,c}) + \sum_{i \in \mathcal{U}_c} a_i + \sum_{i \in \mathcal{U}_d} a_{i,c} + m \log \frac{p}{m} + (N-m) \log \frac{(1-p)}{2(N-m)} + \boxed{\mu(m - \sum_{i \in \mathcal{U}_d} x_i)}$$

To solve the dual optimization problem, we decouple it into two sub-problems:

$$\mathbf{D} : \min_{u} D(\mu) = f_{\mathbf{X}}(\mu) + g_m(\mu)$$

where $f(\mu) = \max_{\mathbf{X}} \{ \sum_{i \in \mathcal{U}_d} x_i(a_{i,d} - a_{i,c} - \mu) \}, \ \mathbf{X} = [x_i]$

$$g(\mu) = \max_{m} \{ \sum_{i \in \mathcal{U}_c} a_i + \sum_{i \in \mathcal{U}_d} a_{i,c} + m \log \frac{p}{m} + (N-m) \log \frac{(1-p)}{2(N-m)} + m\mu \}$$

Stackelberg Game

Spectrum Allocation and Pricing Strategy in Stage I

Primal-Dual Pricing Update Method:

When p and μ are fixed,

(1) $$g(\mu) = \max_{m}\{\sum_{i\in\mathcal{U}_c} a_i + \sum_{i\in\mathcal{U}_d} a_{i,c} + m\log\frac{p}{m} + (N-m)\log\frac{(1-p)}{2(N-m)} + m\mu\}$$

By linear integer search algorithm $\Rightarrow$ $m^* = \arg\max_{m} g(u), \quad m \in [0, N_d]$

(2) $$f(\mu) = \max_{\mathbf{X}}\{\sum_{i\in\mathcal{U}_d} x_i(a_{i,d} - a_{i,c} - \mu)\}, \ \mathbf{X} = [x_i]$$

$$\Rightarrow \quad x_i^* = \begin{cases} 1, & \text{if } a_{i,d} - a_{i,c} - \mu > 0. \\ 0, & \text{otherwise.} \end{cases}$$

Recall the incentive compatible conditions for potential D2D pairs:

$$x_i^* = \begin{cases} 1, & \text{if } a_{i,d} - a_{i,c} - [\pi - \log\frac{2p(N-m)}{m(1-p)}] > 0. \\ 0, & \text{otherwise.} \end{cases}$$

$\Rightarrow$ $$\pi = \mu + \log\frac{2p(N-m)}{m(1-p)}$$

virtual price

real price

Stackelberg Game

Spectrum Allocation and Pricing Strategy in Stage I

Primal-Dual Pricing Update Method:

Specially for shared D2D mode setting, we introduce SINR constraint for these potential D2D pairs in D2D mode:

$$x_i^* = \begin{cases} 1, & \text{if SINR}_{i,d} \geq K \text{ and } (a_{i,d} - a_{i,c} - \mu) > 0. \\ 0, & \text{else.} \end{cases}$$

According to subgradient method, virtual price μ is updated by

$$\mu_{t+1} = \mu_t - \delta_t (m - \sum_{i \in \mathcal{U}_d} x_i)$$

$\delta_t > 0$ is a dynamically chosen step size sequence.

t is the times of playing this Stackelberg game.

m and $\sum_{i \in \mathcal{U}_d} x_i$ act as supply and demand to the virtual price.

Stackelberg Game

Spectrum Allocation and Pricing Strategy in Stage I

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Dynamic Spectrum Partition Strategy

Here we relax the assumption that p is given in *Stage I*.

Observe that the original dual optimization function $D(\mu)$ is a differentiable concave function of given m and $\mathbf{X}$ fixed.

Thus, we check its first order differentiation:

$$\frac{m}{p^*} - \frac{N-m}{1-p^*} = 0 \quad \Longrightarrow \quad p^* = \frac{m}{N}$$

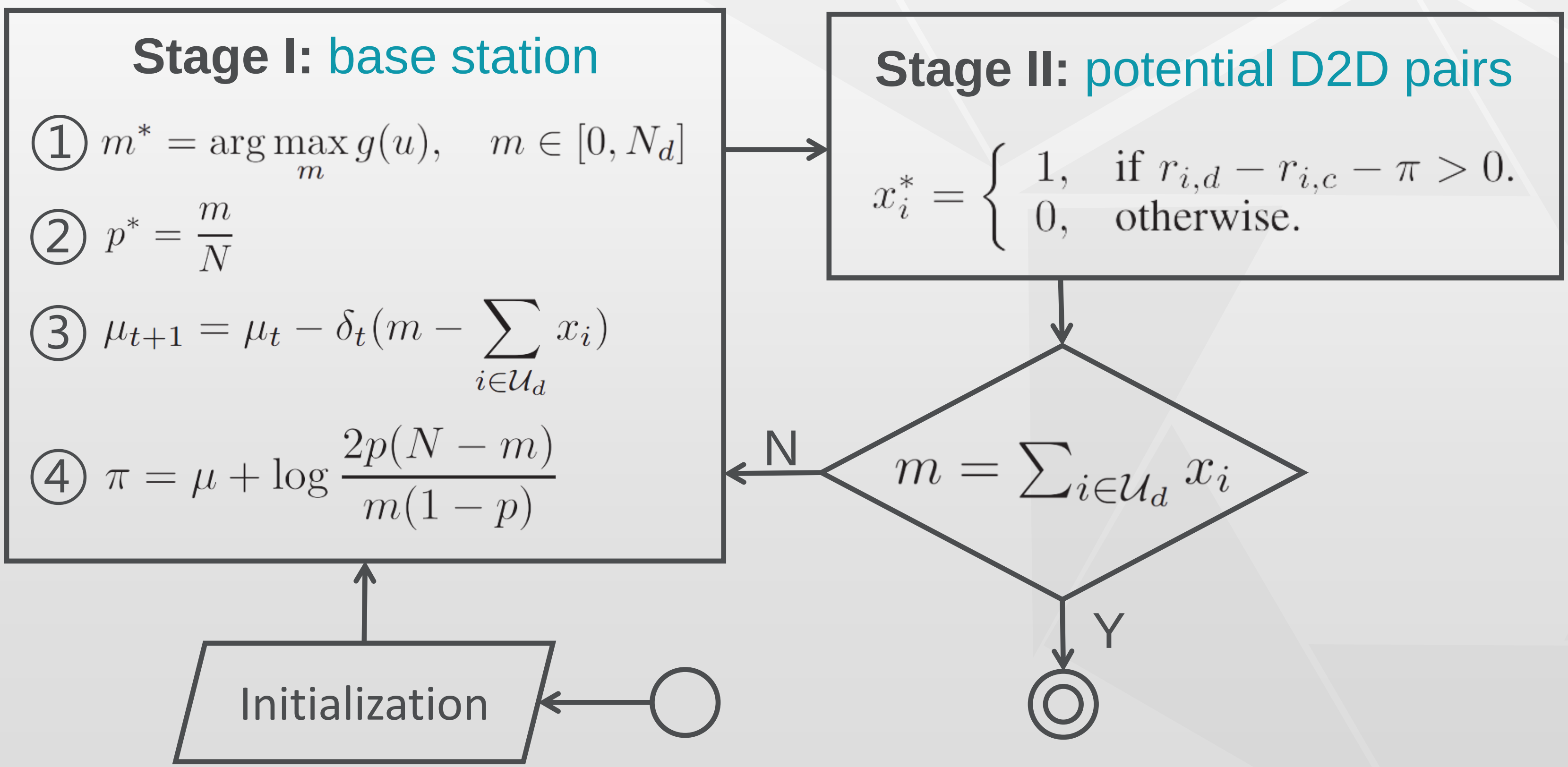
We proposed a dynamic spectrum partition strategy by applying p^*.

We observe that bandwidth $W\frac{m}{N}$ will be allocated to these m potential D2D pairs regardless of any mode selections they made.

Therefore, the service quality of cellular users and potential D2D pairs who stay in cellular mode will not be affected under the proposed D2D-enabled system.

Stackelberg Game

Algorithm: Primal-Dual Algorithm for Divided D2D Mode



Simulation Results

We evaluate the performance of proposed algorithms under either divided or shared D2D mode through simulations.

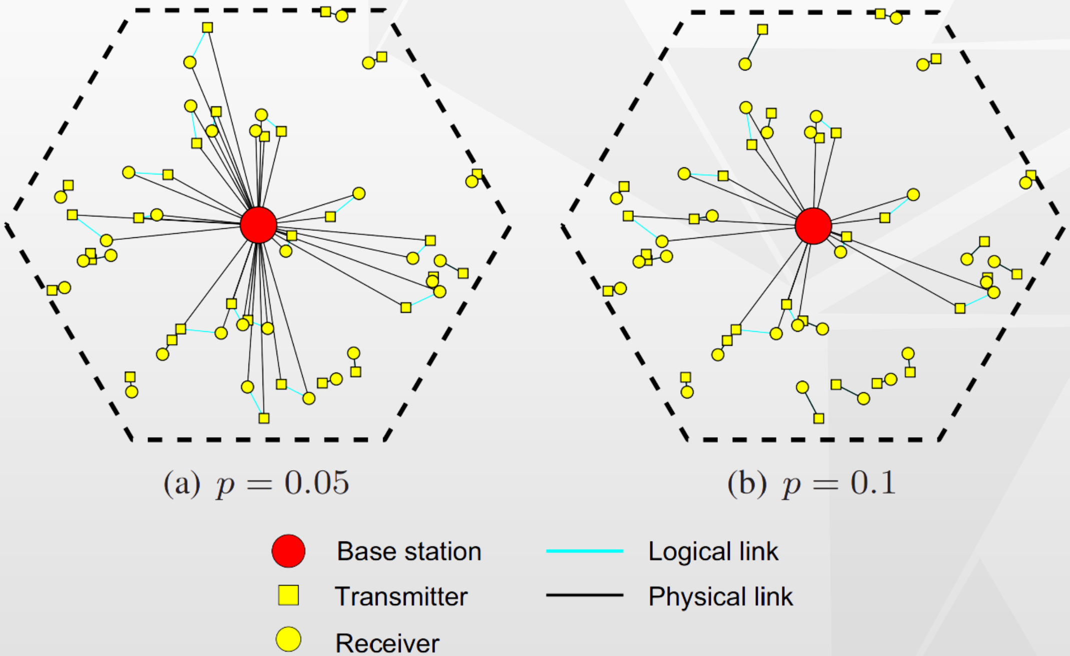
Simulation Parameters

ISD of Urban Macro (all UEs outdoor)	500m
Carrier Frequency	2GHz
System bandwidth, W	20MHz
BS Tx Power	46dBm
UE Tx Power	23dBm
Minimum distance between UE and BS	$>=$ 35m
Minimum distance between UEs	$>=$ 3m
Distribution range of potential D2D receiver	Within 50m of its corresponding transmitter
Default SINR constraint, K	6dB

All simulation settings, if not mentioned, follow the suggested value in 3GPP TR36.843.

Simulation Results

Effect of D2D Spectrum Partition Proportion



$N = 100$; $N_d = 30$; $N_c = 70$. (a) $p = 0.05$; (b) $p = 0.1$.

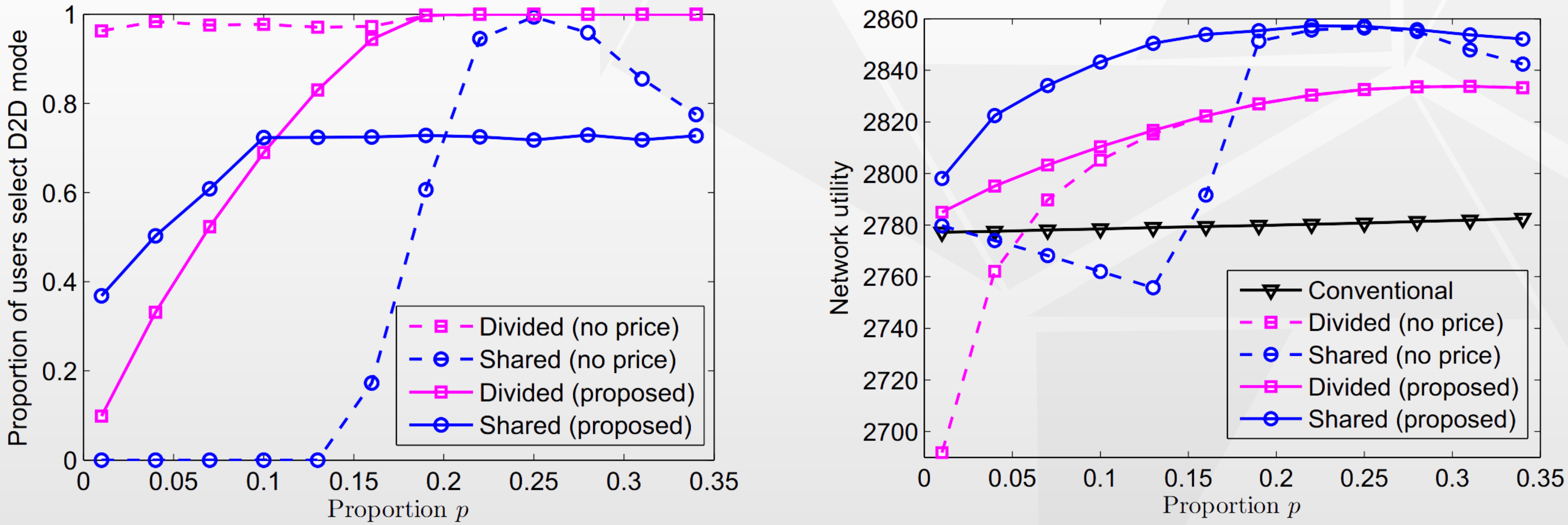
Behaviors performed by potential D2D pairs

Observation:

Potential D2D pairs are more likely to receive higher utility by choosing D2D mode with increasing p .

Simulation Results

Effect of D2D Spectrum Partition Proportion



$N = 200$; $N_d = 60$; $N_c = 140$; $K = 6$ dB.

Performance comparison among the conventional cellular system, the D2D-enbled system with no price and the proposed system

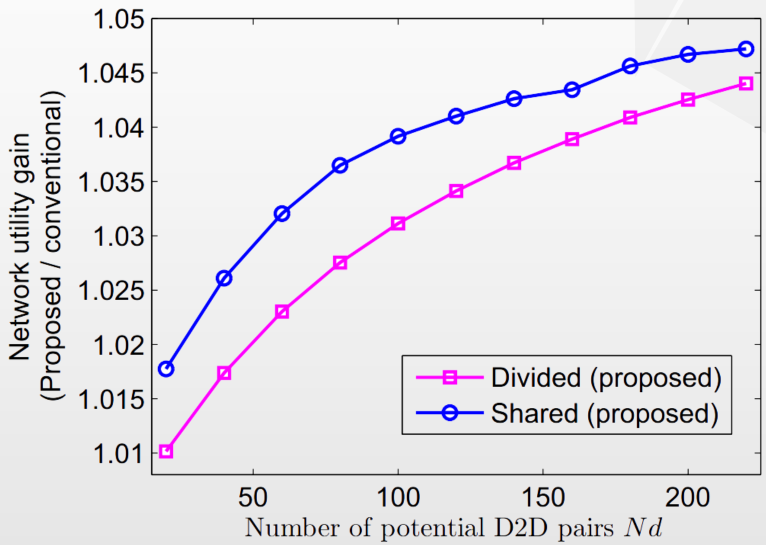
Observation:

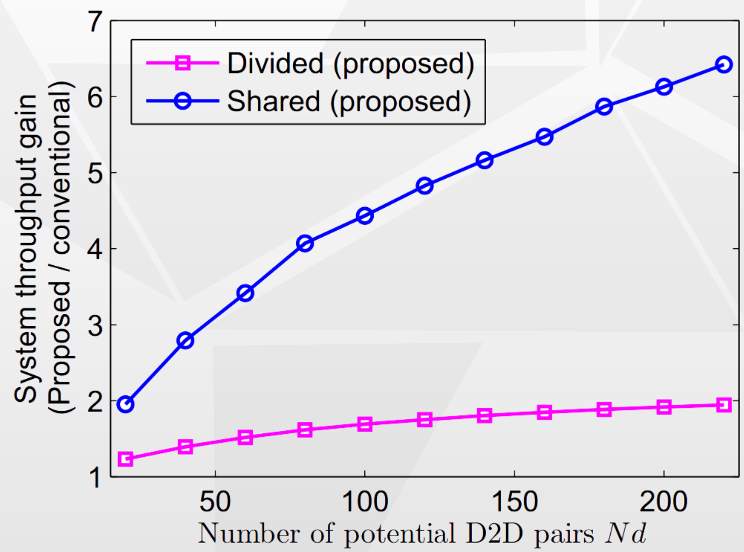
The interference reduces the incentive of potential D2D pairs to choose shared D2D mode.

Shared D2D mode performs significant better due to higher spectrum utilization efficiency from share spectrum.

Simulation Results

Dynamic Spectrum Partition Strategy





$N_c = 100$; $K = 6$ dB. (1) Network utility gain; (2) System throughput gain.

Observation:

In general, the overall system achieves better network utility gain with increased number of potential D2D pairs.

The performance of shared D2D mode is better than the divided D2D mode because of higher spectrum utilization efficiency.

The proposed system accordingly achieves high system throughput improvement for both of divided and shared D2D mode..

Conclusion

We presented a pricing-based Stackelberg game for optimal mode selection and spectrum partitioning for D2D communication.

The proposed pricing-based algorithm displays a significant performance improvement over conventional system and D2D-enabled system with no price applied.

The results showed that the BS can manage D2D-enabled network through the simple price design. Besides, both shared and divided D2D modes own their superiority in different environments.

The End

Thank you!