# D2D Routing Schemes and The Optimum Operating Points

Vinnu Bhardwaj and Chandra R. Murthy

SPC Lab

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# Outline

1. Recap (Downlink-inband D2D)
2. Routing Schemes
   - Fixed Rate Scheme
   - Fixed Power Scheme
3. Simulation Results
4. Optimum Operating Points
   - Fixed Rate Scheme
   - Fixed Power Scheme
5. Uplink inband D2D

# What is D2D

- Direct communication between devices without traversing the core cellular network
- *Inband* D2D: Communication over licensed spectrum
- *Outband* D2D: Communication over unlicensed spectrum

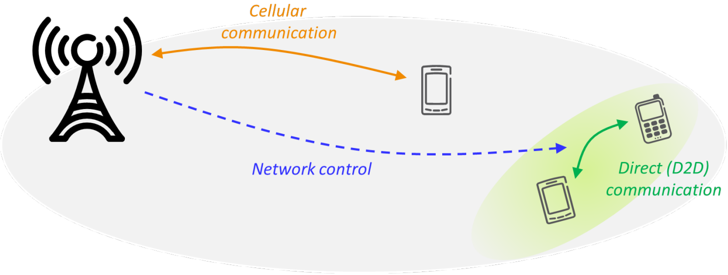
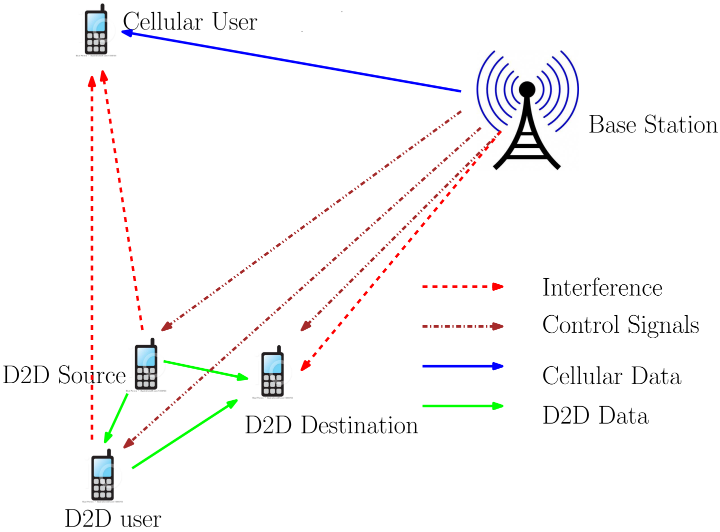



Figure: Simplest illustration of D2D communication

# System Model

- *Underlay Inband* D2D
- N BSs and M D2D devices
- D2D users reuse Downlink frequencies
- Two types of interference in the system :
  1. Base Station to D2D receiver
  2. D2D transmitter to cellular receiver
- Cellular users given priority
- Reliability($\gamma$,$\gamma_b$) and Interference constraints($\gamma_d$)
- D2D links rendered infeasible if they cause intolerable interference to the cellular users

# Model


Cellular User
Base Station
Interference
Control Signals
Cellular Data
D2D Data
D2D Source
D2D Destination
D2D user

# Feasible D2D links I

- All BSs assumed to transmit at the same power P
- Aim: To find all the feasible D2D pairs
- Algorithm
  1. Find the interference + noise power ($P_{int}^{d_R}$) at a D2D device ($d_R$)
  2. Find the transmit power required by $d_T$ to communicate reliably with $d_R$ and repeat for all $d_R$s and $d_T$s

$$P_{d_T}^{d_R} = P_{int}^{d_R} + \gamma + 10\alpha \log(d_{d_T}^{d_R})$$

  3. Find the region around the BSs in which the SNR for the cellular users is at least $\gamma_b$ dB.

$$P - 10\alpha \log(d) \geq \gamma_b$$

$$d_{max} = 10^{\left(\frac{P-\gamma_b}{10\alpha}\right)}$$

# Feasible D2D links II

4. Shut down all the D2D transmitters in the region
5. Find the max power that $d_T$ can use without causing intolerable interference to the cellular users

$$P^{max}_{d_T,BS_i} = \gamma_d + 10\alpha \log(D_{d_T,BS_i} - d_{max})$$

$$P^{max}_{d_T} = \min_{1 \leq i \leq N} P^{max}_{d_T,BS_i}$$

6. Declare the link $d_T \longrightarrow d_R$ *infeasible* if $P^{d_R}_{d_T} > P^{max}_{d_T}$.

- We have the feasible links and the transmit powers required for reliable communication on those links

# Illustration

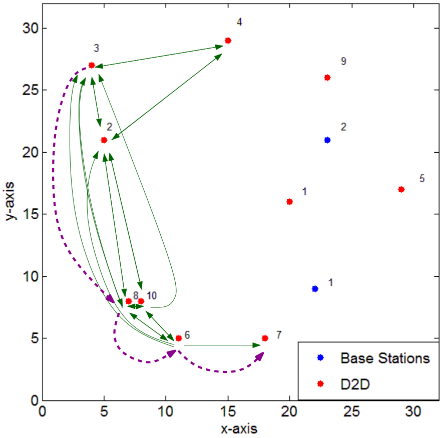



Figure: Feasible D2D links

We have the feasible D2D links.

# What's next ?

# The Problem

- Consider a device $d_S$ which has some data for some other device $d_D$ in the above system
- Data should reach the destination ASAP

D2D Routing schemes :

- Fixed Rate
- Fixed Power

# Fixed Rate Scheme

- The D2D SNR constraint $\gamma$ determines the rate of all the D2D links
- Effective rate on the link $d_S \longrightarrow d_D$

$$R_{\text{eff}} = \frac{\log(1+\gamma)}{\text{Number of hops}} \text{ bps/Hz}$$

- As $\gamma$ varies, the structure of the directed graph $G$ may also change.
- The shortest path $d_S \longrightarrow d_D$ may change

- Since the 'number of hops' term figures in the expression of $R_{eff}$, it is not true that as $\gamma$ increases, $R_{eff}$ should always increase.

- This motivates the problem:

  Find the ($\gamma_{opt}$) using which the devices $d_S$ and $d_D$ can communicate incurring the minimum delay.

# Fixed Power Scheme

- All D2D transmissions occur at the same power $P_D$
- Feasible D2D links using the algorithm
- Feasible D2D links achieve different rates depending upon the SINR at the receiver
- Shortest path is not the throughput maximizing path
- It can be shown that the maximum rate achieved by any path is the scaled harmonic mean of the rates of the links
- Throughput maximizing path is the path with the maximum scaled harmonic mean

- As $P_D$ increases
  - Rate of each feasible link increases
  - More D2D links might become infeasible
- This motivates the problem:

  Find ($P_D^{opt}$) using which the devices $d_S$ and $d_D$ can communicate achieving the maximum net throughput.

- Solution
  - Numerical Search
  - Analytical methods to find the optimum operating points

# Fixed Rate Scheme

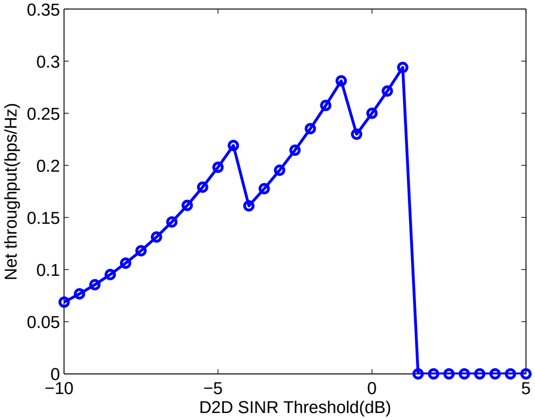



Figure: Fixed rate scheme: Illustration of the numerical search approach for finding the maximum achievable throughput.

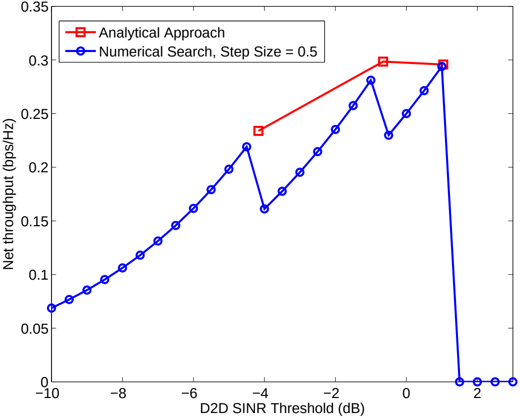



Figure: Fixed rate scheme: Numerical search approach vs Analytical approach

# Fixed Power Scheme

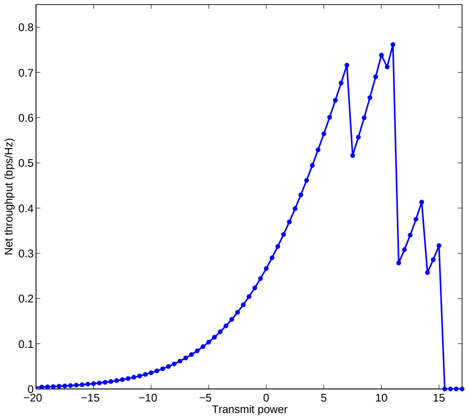



Figure: Fixed power scheme: Illustration of the numerical search approach.

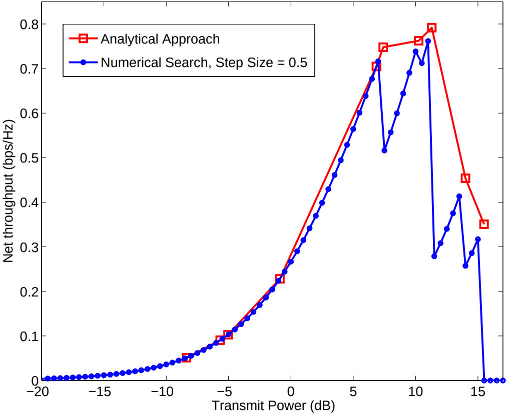



Figure: Fixed power scheme: Numerical search vs Analytical approach.

# Algorithm for Fixed Rate Scheme I

Step 1 Find the power ($P_{d_S}^{\max}$) at which the source $d_S$ is allowed to transmit. Find the corresponding SINR ($\gamma_{d_S}^{d_D}$) at $d_D$. Call this SINR $\gamma_1$.

Step 2 Consider the path $d_S \longrightarrow d_i \longrightarrow d_D$.
The maximum SINR at which some two-hop path will exist:

$$\gamma_2 = \max_{i \neq D,S} \left( \min(\gamma_{d_S}^{d_i}, \gamma_{d_i}^{d_D}) \right)$$

A peak exists here only if $\gamma_2$ is greater than $\gamma_1$.

Step 3 Repeat Step 2 for all possible three hop paths, and determine

$$\gamma_3 = \max_{i \neq D,S, j \neq D,S,i} \left( \min(\gamma_{d_S}^{d_i}, \gamma_{d_i}^{d_j}, \gamma_{d_j}^{d_D}) \right)$$

A peak exists here if $\gamma_3$ is greater than the previous $\gamma$ (i.e., $\gamma_2$, or $\gamma_1$ if $\gamma_2$ does not exist).

# Algorithm for Fixed Rate Scheme II

Step 4 Repeat with increasing number of hops, a point $\gamma_f$ is found such that when $\gamma > \gamma_f$, $d_S$ and $d_D$ are no longer connected in the graph $G_\gamma(V, E)$.

Note: The existence of $\gamma_f$ is guaranteed by the fact that the $G_{\gamma_j}(V, E)$ always has fewer links than $G_{\gamma_k}(V, E)$ for all $j$ and $k$ s.t. $j > k$.

Step 5 Set $\gamma_{\text{opt}} = \arg\max_{1 \leq i \leq M, \gamma_i \text{ exists}} R_{\text{eff}}(\gamma_i)$

# Fixed Rate Scheme

- The relationship between the rates on various links and $R_{\text{eff}}$ is not as simple as in the previous case
- Difficult to directly determine the $P_D$ values where the peaks occur.

Observations:

- As $P_D$ is increased, $R_{\text{eff}}$ increases until one of the D2D transmitters becomes infeasible.
- If the best path connecting $d_S$ and $d_D$ at that value of $P_D$ involves that D2D user, $R_{\text{eff}}$ drops, as an alternate path with lower $R_{\text{eff}}$ has to be used.

$$P_D^{\text{opt}} = \arg \max_{P_{d_T}^{\max}} R_{\text{eff}}(P_{d_T}^{\max})$$

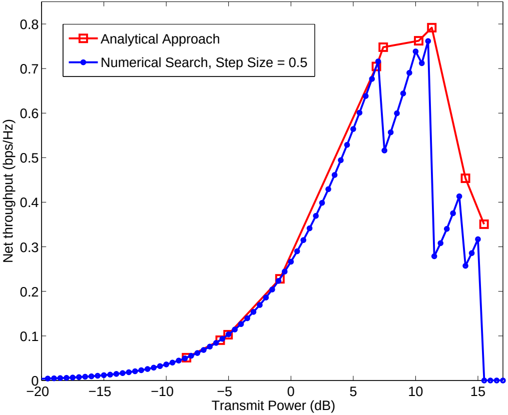



Figure: Fixed power scheme: Numerical search vs Analytical approach.

# Uplink inband D2D

- Uplink frequencies used for D2D communication
- Interference :
  - Cellular transmitters to the D2D receiver
  - D2D transmitter to the BS.
- Feasible D2D links:
  - Modified version of the algorithm presented earlier
  - Approach not conservative

# Fixed Rate Scheme

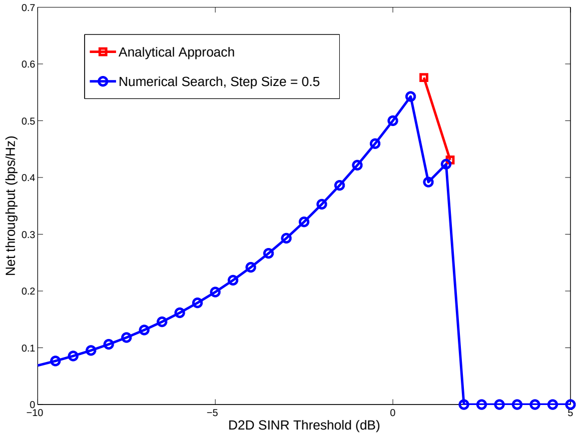



Figure: Fixed power scheme; Illustration of the numerical search approach and the analytical approach in the *uplink inband* D2D model.

# Fixed Power Scheme

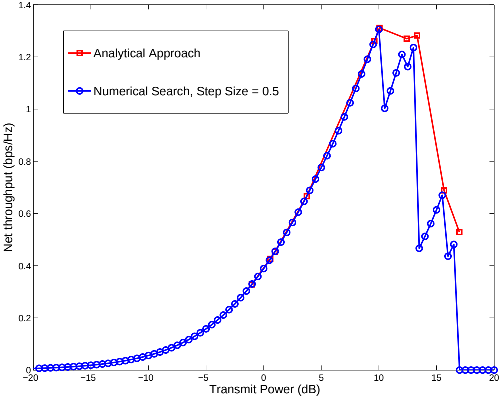



Figure: Fixed power scheme: Illustration of the numerical search approach and the analytical approach in the *uplink inband* D2D model.

THANKS!!!