Interference Model and Analysis on Device-to-Device Cellular Coexist Networks

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Outline

1. Background
2. Introduction
   - Communication modes
   - Motivations
3. Single D2D Pair Scenario
   - System Model
   - Stable Throughput Region
4. Multiple D2D Pairs Scenario
   - System Model
   - Stable Throughput Region (Upper Bound)
5. Simulations
6. Conclusions and Future Work

Background

Device-to-device (D2D) communication is proposed as a vital technique to enhance system capacity in cellular networks, which allows direct transmissions between users.

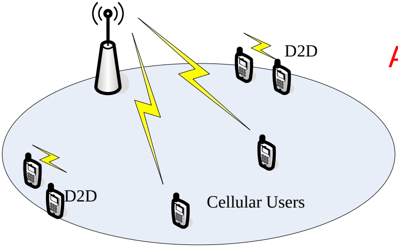


Figure: D2D communications underlaying cellular networks.

Advantages:

- Enhance spectral efficiency
- Reduce transmission powers
- Achieve high data rates
- Obtain lower delay

Communication modes

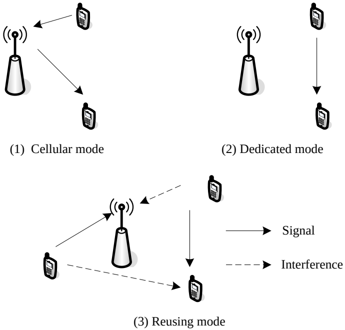


Figure: Communications modes

- Cellular Mode
- Dedicated Mode
- Reusing Mode

Research Focus: resource allocation and power control for D2D and cellular existing networks in reusing mode, to achieve maximum data rates.

Motivations

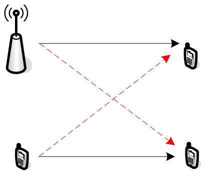


Figure: Full buffer assumption

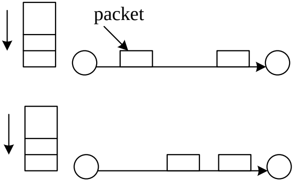


Figure: Non-Full buffer model

Full buffer assumptions fail to capture the diversity of different applications. The results serve as lower bounds of the system capacity.

Our paper are focused on non-full buffer model, capturing the real interfering scenarios, deriving the stable throughput region.

System Model

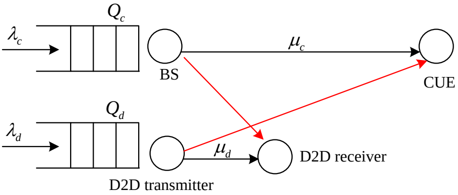


Figure: Single D2D pair scenario

Assumptions:

- One D2D pair reuse the resource of one cellular link
- "c": cellular link, "d": D2D link
- λ_c, λ_d: packet arrival rates
- Q_c, Q_d: transmission queues
- μ_c, μ_d: packet service rates

Stable throughput region is defined as the set of all arrival rate vectors (in packets/slot) to the sources such that all queues in the network remain bounded. According to Loynes' Theorem, we have

$$\mathcal{R} = \{(\lambda_c, \lambda_d) | \quad \lambda_c < \mu_c \quad \& \quad \lambda_d < \mu_d\}. \tag{1}$$

Stable Throughput Region (1/2)

The service rate of each link is equal to the probability that one packet is successfully decoded at the receiver, given as

$$\begin{aligned}\mu_c &= \Pr\{Q_d = 0\}(1-\rho_c) + \Pr\{Q_d > 0\}(1-\rho_c^{(I)}) \\ &\overset{(a)}{=} \left(1-\frac{\lambda_d}{\mu_d}\right)(1-\rho_c) + \frac{\lambda_d}{\mu_d}(1-\rho_c^{(I)})\end{aligned} \quad (2)$$

and

$$\begin{aligned}\mu_d &= \Pr\{Q_c = 0\}(1-\rho_d) + \Pr\{Q_c > 0\}(1-\rho_d^{(I)}) \\ &\overset{(a)}{=} \left(1-\frac{\lambda_c}{\mu_c}\right)(1-\rho_d) + \frac{\lambda_c}{\mu_c}(1-\rho_d^{(I)}),\end{aligned} \quad (3)$$

$\rho_c, \rho_c^{(I)}, \rho_d, \rho_d^{(I)}$ are the outage probabilities.

- 1st term of each equation: Non-interference scenario
- 2nd term of each equation: Interfering scenario

Stable Throughput Region (2/2)

Theorem 1

The stable throughput region $\mathcal{R} = \{(\lambda_c, \lambda_d) | \lambda_c < \mu_c \ \& \ \lambda_d < \mu_d\}$, *where one D2D pair with packet arrival rate* λ_d *shares the same resources with one cellular link with* λ_c, *is characterized by* $\mathcal{R} = \{(\lambda_c, \lambda_d) | (\lambda_c, \lambda_d) \in \mathcal{R}_1 \bigcup \mathcal{R}_2\}$ *where*

$$\mathcal{R}_1 = \left\{ \lambda_c < \min \left\{ (1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1-\rho_d^{(I)}}, \frac{(1-\rho_d-\lambda_d)(1-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d} \right\} \right\}, \quad (4)$$

$$\mathcal{R}_2 = \left\{ \lambda_c < \min \left\{ \frac{(1-\rho_c)(1-\rho_d) - \lambda_d(\rho_c^{(I)} - \rho_c)}{2 - \rho_d - \rho_d^{(I)}}, \frac{(1-\rho_d)(1-\rho_c)}{\rho_d^{(I)} - \rho_d} - \frac{\lambda_d(2-\rho_c-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d}, \frac{\left(\sqrt{\lambda_d(\rho_c^{(I)} - \rho_c)} - \sqrt{(1-\rho_c)(1-\rho_d)}\right)^2}{\rho_d^{(I)} - \rho_d} \right\} \right\}, \quad (5)$$

Remark:

$$\rho_c = \Pr\left\{B\log\left(1+\frac{P_cG_{cc}}{N_0}\right) < R_c\right\} = 1 - e^{-\frac{N_0\eta_c}{P_c\sigma_c^2}}, \quad (6)$$

$$\rho_d = \Pr\left\{B\log\left(1+\frac{P_dG_{dd}}{N_0}\right) < R_d\right\} = 1 - e^{-\frac{N_0\eta_d}{P_d\sigma_d^2}}, \quad (7)$$

$$\rho_c^{(I)} = \Pr\left\{B\log\left(1+\frac{P_cG_{cc}}{P_dG_{dc}+N_0}\right) < R_c\right\} = 1 - \frac{P_c\sigma_c^2 e^{-\frac{N_0\eta_c}{P_c\sigma_c^2}}}{P_c\sigma_c^2+\eta_cP_d\sigma_{dc}^2}, \quad (8)$$

and

$$\rho_d^{(I)} = \Pr\left\{B\log\left(1+\frac{P_dG_{dd}}{P_cG_{cd}+N_0}\right) < R_d\right\} = 1 - \frac{P_d\sigma_d^2 e^{-\frac{N_0\eta_d}{P_d\sigma_d^2}}}{P_d\sigma_d^2+\eta_dP_c\sigma_{cd}^2}, \quad (9)$$

B the bandwidth, P_c, P_d transmission powers, G_{ij} channel gain from node i to j, R_c, R_d targeted rates. $\eta_c = 2^{\frac{R_c}{B}} - 1$ and $\eta_d = 2^{\frac{R_d}{B}} - 1$.

Multiple D2D Pairs Model

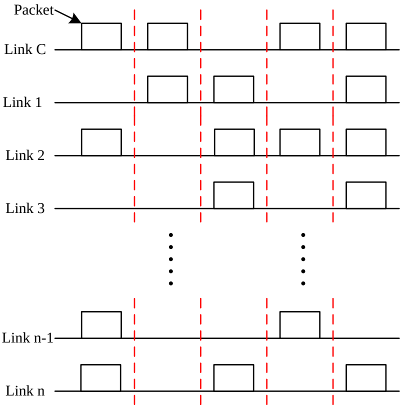


Figure: Multiple D2D pairs scenario

Assumptions:

- N D2D pairs reuse the resource of one cellular link
- "c": cellular link, "n": D2D link $n, n = 1, \cdots, N$
- λ_c, λ_n: packet arrival rates
- μ_c, μ_n: packet service rates
- P_c, P_n: transmission powers
- G_{ij}: channel gain

Stable Throughput Region (Upper Bound) (1/3)

- According to queueing theory, it is next to impossible to obtain the exact characterization of the stability region with multiple interacting queues.

Upper bound

Ignore the interference among D2D pairs

- The service rate of D2D link n:

$$\mu_n = \left(1 - \frac{\lambda_c}{\mu_c}\right)(1 - \rho_n) + \frac{\lambda_c}{\mu_c}(1 - \rho_n^{(I)}). \tag{10}$$

The stable constraint $\mu_n > \lambda_n$ results in $\mu_c > \frac{\lambda_c(\rho_n^{(I)} - \rho_n)}{1 - \rho_n - \lambda_n}$

Stable Throughput Region (Upper Bound) (2/3)

For cellular link, it has 2^N interference scenario $\{\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_{2^N}\}$, where $\mathbf{v}_k = (v_{k,1}, v_{k,2}, \cdots, v_{k,N})$ and

- $v_{k,n} = 1$: D2D pair n is transmitting
- $v_{k,n} = 0$: D2D pair n keeps silence

Hence, the service rate of the cellular link is calculated by

$$\mu_c = \sum_{k=1}^{2^N} \Pr\{\mathbf{v}_k\}(1 - \rho_{\mathbf{v}_k}), \tag{11}$$

where $\Pr\{\mathbf{v}_k\}$ is the probability of scenario k and $\rho_{\mathbf{v}_k}$ is the corresponding outage probability. Since $\Pr\{Q_n > 0\} = \frac{\lambda_n}{\mu_n}$, we have

$$\Pr\{\mathbf{v}_k\} = \prod_{n=1}^{N} \left|1 - v_{k,n} - \frac{\lambda_n}{\mu_n}\right|. \tag{12}$$

- The derivations on $\rho_{\mathbf{v}_k}$ are omitted here.

Stable Throughput Region (Upper Bound) (3/3)

- Finally, μ_c is the root of $f(\mu_c) - \mu_c = 0$, where $f(\mu_c) = \sum_{k=1}^{2^N} \Pr\{\mathbf{v}_k\}(1 - \rho_{\mathbf{v}_k})$.

Theorem 2

The upper bound of the stable throughput region $\mathcal{R}_{\text{upper}}$, when one cellular link (λ_c) and N D2D pairs ($\{\lambda_1, \lambda_2, \cdots, \lambda_N\}$ ($N \geq 1$)) share the same resources, is given as

$$\mathcal{R}_{\text{upper}} = \left\{ (\lambda_c, \lambda_1, \cdots, \lambda_N) \middle| \mu_c > \max\left\{ \lambda_c, \frac{\lambda_c(\rho_1^{(I)} - \rho_1)}{1 - \rho_1 - \lambda_1}, \frac{\lambda_c(\rho_2^{(I)} - \rho_2)}{1 - \rho_2 - \lambda_2}, \cdots, \frac{\lambda_c(\rho_N^{(I)} - \rho_N)}{1 - \rho_N - \lambda_N} \right\} \right\}, \tag{13}$$

where μ_c is the root of $f(\mu_c) - \mu_c = 0$.

- The lower bound: interference always exists among D2D pairs.

Set-up

Table: Simulation parameters

Parameters	Value
Carrier	2GHz
Bandwidth	180KHz
Path-loss Exponent	4
Small Scale Fading	Rayleigh fading
CUE Power Constraint	23dBm
D2D Power Constraint	17dBm
Noise Power	-174 dBm/Hz
Packets/Second	1000
Bits/Packet	1024
Distance between D2D Pair	20m

Single D2D pair scenario

- The stable throughput regions of single D2D pair scenarios. "L" stands for the distance between the D2D link and the cellular link.

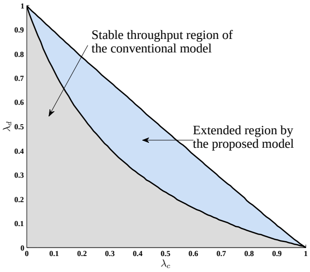


Figure: $L \approx 80m$

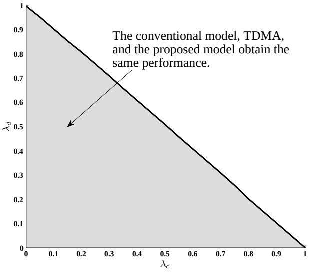


Figure: $L \approx 100m$

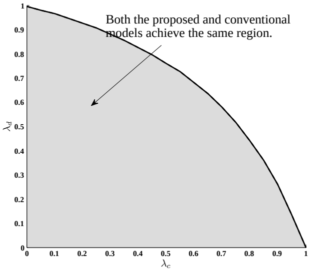
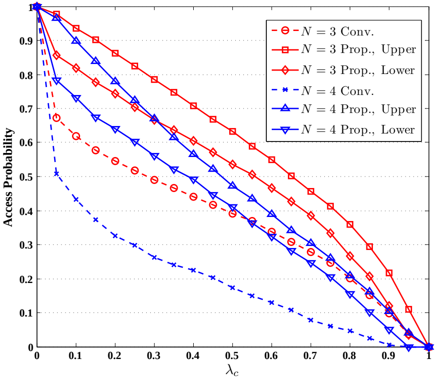


Figure: $L \approx 120m$

Multiple D2D pairs scenario

- Admission behaviors of multiple D2D pairs scenarios. $L_c = 100m$.



"Access Probability" is the probability of all the packet arrival rates obeying the stable throughput region in Monte Carlo simulations. "Prop." stands for the proposed model and "Conv." is the conventional one.

Conclusions and Future Work

Conclusions:

- A new cross-layer non-full buffer model is established to characterize the actual inter-user interference scenarios between cellular connection and D2D links when they share the same resources.
- The stable throughput regions are deduced to demonstrate the behaviors of D2D and cellular transmissions among multiple interactional links.

Future work:

- Explore a new method to accurately characterize the stable throughput region in multiple D2D pairs scenarios.
- Strengthen the analysis through adjusting transmission powers, packets length and propose the resource allocation and power control strategy.

Thank You!
Q&A