Connectivity analysis of device-to-device cellular network using stochastic geometry

Gulomov Saidkhuja
14M54020

Department of Mathematical and Computing Sciences
Tokyo Institute Of Technology

February 2, 2017

Abstract

- Device-to-device (D2D) enables direct communication between nearby mobiles;
- D2D improves spectrum utilization, energy efficiency, coverage and overall throughput;
- Thesis considers D2D cellular network in comparison with the traditional cellular network;
- Model consists of independent homogeneous Poisson point processes with contact distance probability and noise-limited environment;
- Analytical way of calculating peroformance is developed;
- Using analytical results, numerical experiments are carried out and results are displayed.

Table of contents

1. Introduction
2. Problem
3. Results
4. Numerical experiments
5. Conclusion

Device-to-device communication

- Growing demands of network capacity has led to evolution of networks from 1G to 5G;
- Device-to-device (D2D) communication becomes an effective facilitator of the upcoming high data rate;

Evolution: Four Mobile Generation
Core Services & Network Speed

Mobile Generation	Core Services & Applications	Network Speed
1G 1980s	Voice only (analog)	NA
2G 1990s	SMS / data (digital)	0.01-0.1M
3G 2000s	Internet / Multimedia	0.4-42M
4G 2010s	Cloud Computing	100M-1G

Overview of the existing studies on device-to-device communication

Device-to-device communication is classified into 2 major groups:

1. D2D sharing cellular spectrum, *a.k.a* **inband**;
    - spectrum utilization;
    - power efficiency;
    - cellular coverage
    - interference.
2. D2D exploits unlicensed spectrum, *a.k.a* **outband**;
    - video transmission;
    - average file transfer delay.

System model

- 2 stationery independent homogeneous PPPs of base stations and mobile users (Φ_b, Φ_u);
- Given parameters $(\lambda_b, P_b, N_b, \beta_b, \Theta_b), (\lambda_u, P_u, N_u, \beta_u, \Theta_u)$;
- Rayleigh fading with mean 1;
- Noise-limited environment;
- Receiver at the origin of $\mathbb{R}^2$, nearest BS at B_{nst};
- Distance to the nearest BS as d_b, to the nearest D2D node - d_u

Performance evaluation

The key performance characteristics that the paper considers is Signal-to-Noise ratio (SNR).

$$SNR_{nf} = \frac{S}{N} = \frac{Pd^{-\beta}}{N},$$

for channel without fading; and

$$SNR_{f} = \frac{Phd^{-\beta}}{N},$$

for channel with fading where h - random variable that follows an exponential distribution with mean $1/\mu$ which we denote as $h \sim \exp(\mu)$.

Performance evaluation

The purpose of the thesis is to consider the following probabilities:

$$p_{nf} = \mathbb{P}\Big[SNR_{nf} \geq \Theta\Big] = \mathbb{P}\Big[d \leq \big(\frac{P}{N\Theta}\big)^{1/\beta}\Big], \tag{1}$$

and:

$$p_f = \mathbb{P}\Big[SNR_f \geq \Theta\Big] = \mathbb{P}\Big[h \geq \frac{Nd^{\beta}\Theta}{p}\Big]. \tag{2}$$

Considering (1) for BS and D2D node, we get:

$$\mathbb{P}\Big[d_b \leq R_1\Big], \text{ where } R_1 = \Big(\frac{P_b}{N_b\Theta_b}\Big)^{1/\beta_b}$$

$$\mathbb{P}\Big[d_u \leq R_2\Big], \text{ where } R_2 = \Big(\frac{P_u}{N_u\Theta_u}\Big)^{1/\beta_u}$$

Scenarios under consideration:

1. $d_b \leq R_1$–direct cellular connection;
2. $R_1 < d_b \leq R_1 + R_2$–single D2D relay connection.

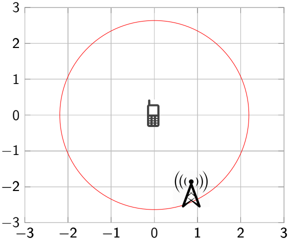
Direct cellular connection

Cellular connection with non-fading channel

$$p_{nf}^{cel} = 1 - \exp(-\lambda_b \pi R_1^2)$$

Idea: Using (1) and R_1 we get:

$$\mathbb{P}[d_b \leq R_1] = 1 - \mathbb{P}[\Phi_b(b(o, R_1)) = 0]$$



Single D2D relay link connection

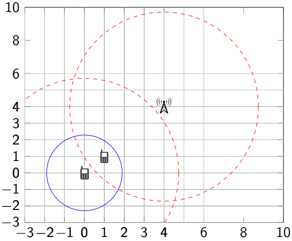
Single D2D relay connection with non-fading channel

$$p_{nf}^{s-hop} = 2\lambda_b \pi \int_{R_1}^{R_1+R_2} r \exp(-\lambda_b \pi r^2)(1 - \exp(-\lambda_u |D(r)|))dr,$$

where $|D(r)| = R_2^2 \cos^{-1}\left(\frac{r^2+R_2^2-R_1^2}{2rR_2}\right) + R_1^2 \cos^{-1}\left(\frac{r^2+R_1^2-R_2^2}{2rR_1}\right) - \frac{1}{2}\sqrt{(R_2+R_1-r)(r+R_2-R_1)(r-R_2+R_1)(r+R_1+R_2)}.$

Single D2D relay link connection

Idea: We consider the event $C = \Big[\Phi_u\big(b(o,R_2) \cap b(B_{nst},R_1)\big) \geq 1, d_b \in (R_1; R_1+R_2)\Big]$. We then derive a PDF of (1) for case of a mobile user $f_{d_b}(r) = \frac{d}{dr}(\mathbb{P}(d_b \leq r)) = 2\lambda_b \pi r e^{-\lambda_b \pi r^2}$. We use the conditioning on the nearest BS to be at distance r, $d_b = r$ and compute the integral:



$$\int_{R_1}^{R_1+R_2} f_{d_u}(r)\mathbb{P}\Big(\Phi_u\big(b(o,R_2)\cap b(B_{nst},R_1)\big) \geq 1\Big)\Big| d_b = r\Big)$$

Cellular connection with fading effect.

Cellular connection with fading in the channel

$$p_f^{cel} = 2\lambda_b\pi \int_{r>0} \exp\Big(- \frac{\mu\Theta_b N_b r^{\beta_b}}{P_b}\Big) r \exp(-\lambda_b\pi r^2) dr$$

Idea: We condition on the nearest BS to be at distance r, and using (2) we consider the following probability:

$$\mathbb{P}\Big[h \geq \frac{N_b d^{\beta_b}\Theta_b}{P_b}\Big| d_b = r\Big]$$

We then use the PDF of d_b – $f_{d_b}(r)$ and compute the integral:

$$\int_{r>0} f_{d_b}(r)\mathbb{P}\Big[h \geq \frac{N_b r^{\beta_b}\Theta_b}{P_b}\Big]$$

Testing environment

Simulations were conducted for cases:

1. direct cellular connection (without fading);
2. direct cellular connection (with fading);
3. direct cellular connection or single D2D relay link (without fading);

The value of the precision used during the numerical integration is 10^{-3}.

Initial testing parameters

The following data was used as a baseline sample for experiments:

Symbol	Simulation value
P_u	23 dBm
P_b	46 dBm+14 dBi
λ_u	5×10^{-5}
λ_b	10^{-6}
N_u	-105 dBm
N_b	-99 dBm
Θ_u	10 dB
Θ_b	5 dB
β_u	3.68
β_b	3.52

Testing scenarios.

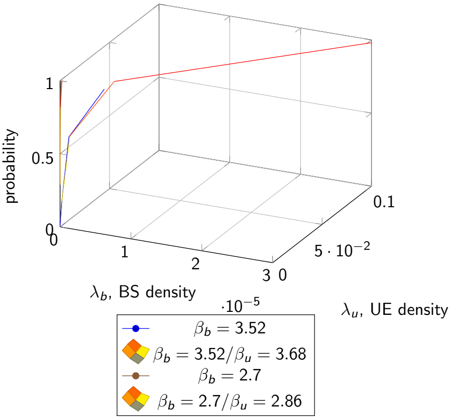
Parameters left to be constant:

- transmission power;
- thermal noise;
- service threshold.

Parameters being tested:

- density;
- propagation exponents.

Direct cellular connection or single D2D relay link without fading



Figure

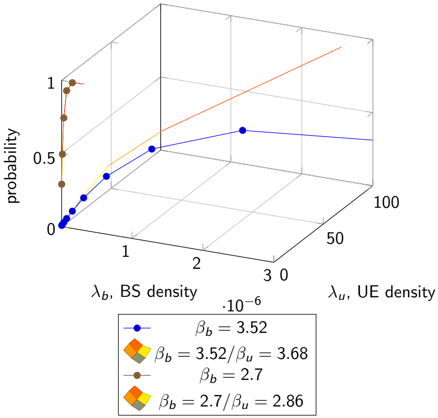
$\beta_b = 3.52/\beta_u = 3.68$:

λ_b	λ_u	$\mathbb{P}$
0.00000001	0.000001	0.008
0.00000005	0.000010	0.039
0.00000025	0.000100	0.178
0.00000125	0.001000	0.626
0.00000625	0.010000	0.993
0.00003125	0.100000	1.000

$\beta_b = 2.7/\beta_u = 2.86$:

λ_b	λ_u	$\mathbb{P}$
0.00000001	0.000001	0.290
0.00000005	0.000010	0.819
0.00000025	0.000100	1.000

Direct cellular connection or single D2D relay link without fading



Figure

$\beta_b = 3.52/\beta_u = 3.68$:

λ_b	λ_u	$\mathbb{P}$
0.00000001	0.000001	0.008
0.00000002	0.000010	0.016
0.00000004	0.000100	0.031
0.00000008	0.001000	0.061
0.00000016	0.010000	0.119
0.00000032	0.100000	0.239
0.00000064	1.000000	0.457
0.00000128	10.000000	0.705
0.00000256	100.000000	0.913

$\beta_b = 2.7/\beta_u = 2.86$:

λ_b	λ_u	$\mathbb{P}$
0.00000001	0.000001	0.290
0.00000002	0.000010	0.496
0.00000004	0.000100	0.746
0.00000008	0.001000	0.936
0.00000016	0.010000	0.996
0.00000032	0.100000	1.000

General results.

- Derivation of analytical formulas for performance evaluation;
- Numerical experiments are carried out;
- D2D enabled cellular network becomes useful when the signal propagation is seriously obstructed;
- D2D enabled cellular network yields better performance when the ratio of the number of base stations to the number of mobile users is around $1/100$.

Future work

- Consideraion of n–D2D relay links in both non-fading channel and channel with fading;
- Interference modelling;
- Additional relaying layer can be added into the model and performance evaluation is also possible (like in project 'OneWeb').

Acknowledgements

Student Gulomov Saidkhuja would like to express his deep gratitude to prof. Naoto Miyoshi for his extensive support and help during the preparation of the work.