D2D Relay Management in Multi-cell Networks

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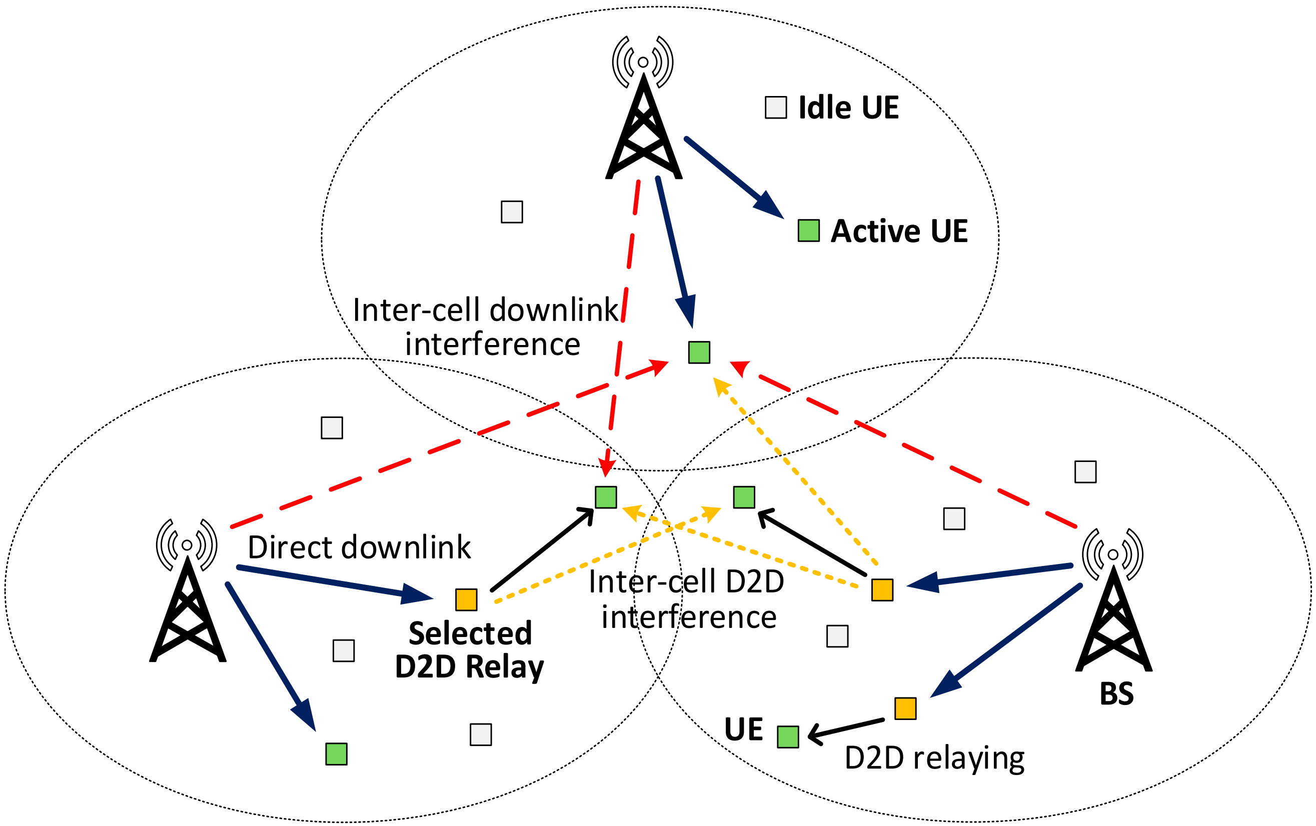
Relaying based on device-to-device (D2D) communications in cellular networks

- Different names in literature
  - D2D relaying
  - UE relaying
  - Mobile relaying
  - UE-to-network/network-to-UE relaying (3GPP)
  - V2V relaying
- Applications of D2D relaying
  - Consistent user experience in 5G
  - Cell coverage extension
  - Anti-blockage for mmWave cellular network

D2D relaying in multi-cell networks

- **Single-cell model** Study the performance of D2D relaying in one cell, no interaction between neighbor cells is assumed.
- **Multi-cell model** Consider the interference interaction among neighbor cells, relaying operations in one cell would affect the neighbor cells.



D2D relaying in multi-cell networks

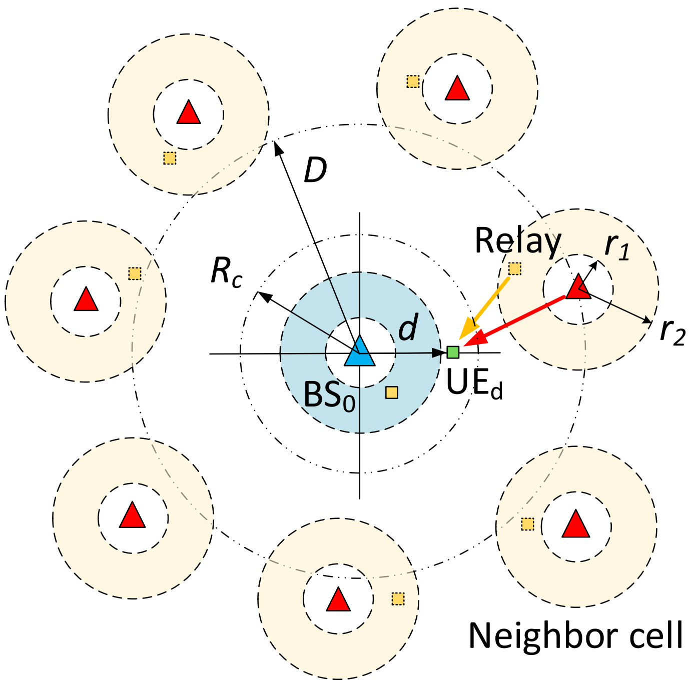
- Challenges
  - Modeling of inter-cell interference with D2D relaying
  - Relay selection and resource allocation for D2D relaying
  - Network management for multi-cell network with D2D relaying
- Research consideration
  - Network abstractions are indispensable for capturing the main effects brought by D2D relaying for the practical multi-cell networks

Multi-cell network abstraction

- Characterize the multi-cell network using a few parameters

Minimum inter-site distance	D
Cell radius	R_c
BS density	ρ_{bs}
Relaying distance threshold	R_r
Distribution of selected relays	r_1, r_2
Relaying probability	p_r

- Pathloss is modeled by two gain functions, $l_b(x) = K_b x^{-\eta}$ for BS-to-UE links and $l_d(x) = K_d x^{-\eta_d}$ for D2D links. Both are monotonically decreasing functions of distance x, with different pathloss exponents η and η_d for downlink and D2D link.



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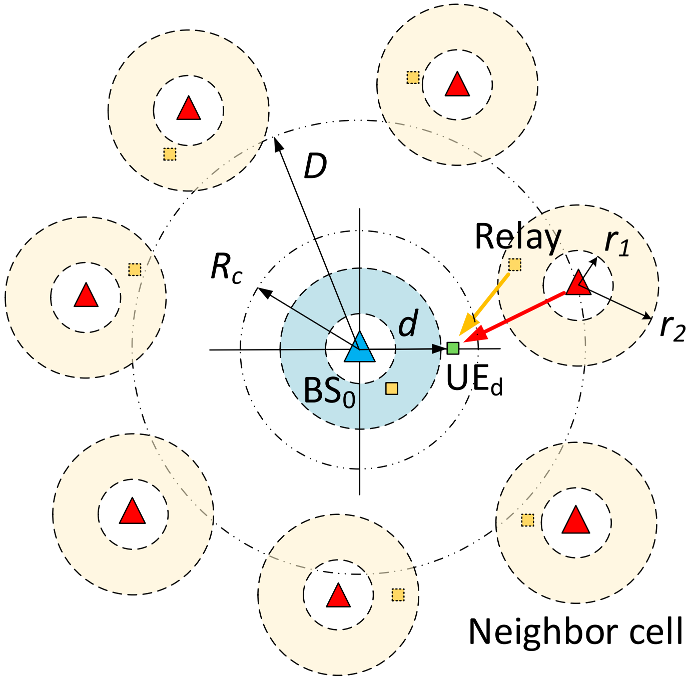
Inter-cell interference characterization

- **Fluid Model**: As in **Campbell's theorem**, the fluid model transforms an expectation of a random sum over the discrete point process (**PP**) to an integral involving the PP intensity $\boldsymbol{\rho}$ in the distribution area.
- In the fluid model, each area element ***dA*** contains ***ρdA*** interferers which contribute to the aggregate interference.

➢ **Average aggregate inter-cell DL interference from other BSs**

$$I_{dl}(d) = \frac{2\pi \rho_{bs} P_b K_b}{\eta - 2}(D-d)^{2-\eta}$$

Distribution of inter-cell DL interference from other BSs is concentrated and predictable.



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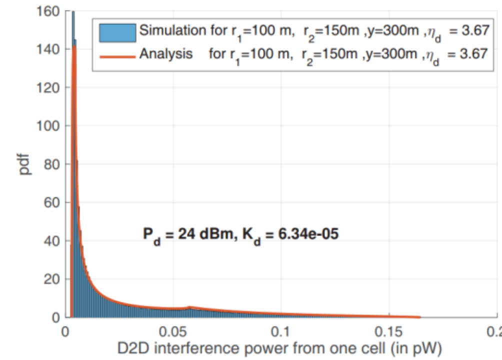
Inter-cell interference characterization

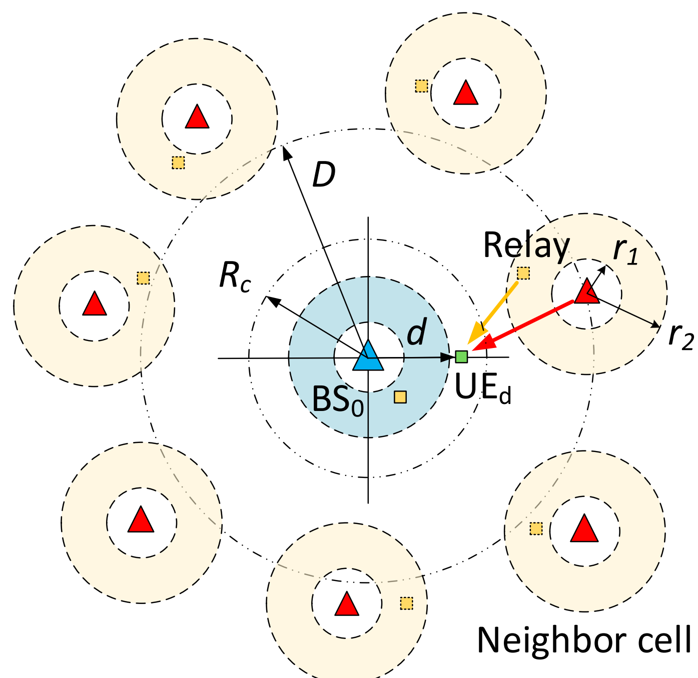
➢ **Average inter-cell D2D interference from other cells**

$$I_{d2d}(d) = \frac{M_d (D-d)^{2-\eta_d}\left(\phi(r_2) - \phi(r_1)\right)}{(r_2^2 - r_1^2)(\eta_d - 2)}$$

$$\phi(r) = r^2 \, {}_2F_1\left(\frac{\eta_d - 2}{2}, \frac{\eta_d + 1}{2}; 2; \frac{r^2}{(D-d)^2}\right)$$

Distribution of inter-cell D2D interference casued by D2D relaying is long-tailed and very random.





Inter-cell interference characterization

- Aggregate inter-cell DL&D2D interference

$$\mathbb{E}[I(d)] \approx (1-p_r) I_{dl}(d) + p_r \frac{M_d (D-d)^{2-\eta_d} (\phi(r_2) - \phi(r_1))}{(r_2^2 - r_1^2)(\eta_d - 2)}$$

Probability that one BS is transmitting on a specific RB

Aggregate DL interference

Probability that one relay is transmitting on a specific RB

Aggregate D2D interference

- ➢ When there is no D2D relaying (with $p_r = 0$), the interference is $I_{dl}(d)$.
- ➢ When D2D relaying is employed, some transmit power is offloaded from BS to D2D relays which are distributed around the BS. The offloaded power will cause random interference to UE receivers in neighbor cells.

Interference-aware D2D Relay Selection and resource allocation

- For UE_d with a UE-to-BS distance d
  - There is an estimated DL rate C_{dl}
  - There is an optimal relay position d_{opt}
  - There is an estimated relaying rate C_{e2e} using the optimal relay

$$C_{dl}(d) = \log_2\left(1 + \frac{P_b K_b d^{-\eta}}{\underline{I(d)} + \sigma^2}\right)$$

$$C_{d2d}(d, d_r) = \log_2\left(1 + \frac{P_d K_d (d - d_r)^{-\eta_d}}{\underline{I(d)} + \sigma^2}\right)$$

$$C_{e2e}(d, d_r) = \beta C_{dl}(d_r)$$

$$\beta = \frac{C_{d2d}(d, d_r)}{C_{dl}(d_r) + C_{d2d}(d, d_r)}$$

$$d_{opt}(d) = \underset{0 < d_r < d}{\arg\max}\, C_{e2e}(d, d_r) \simeq \frac{2\eta_d - \ln(K)}{2\eta + 2\eta_d} d$$

$$K = \frac{P_d K_d D^{-\eta_d}}{P_b K_b D^{-\eta}}$$

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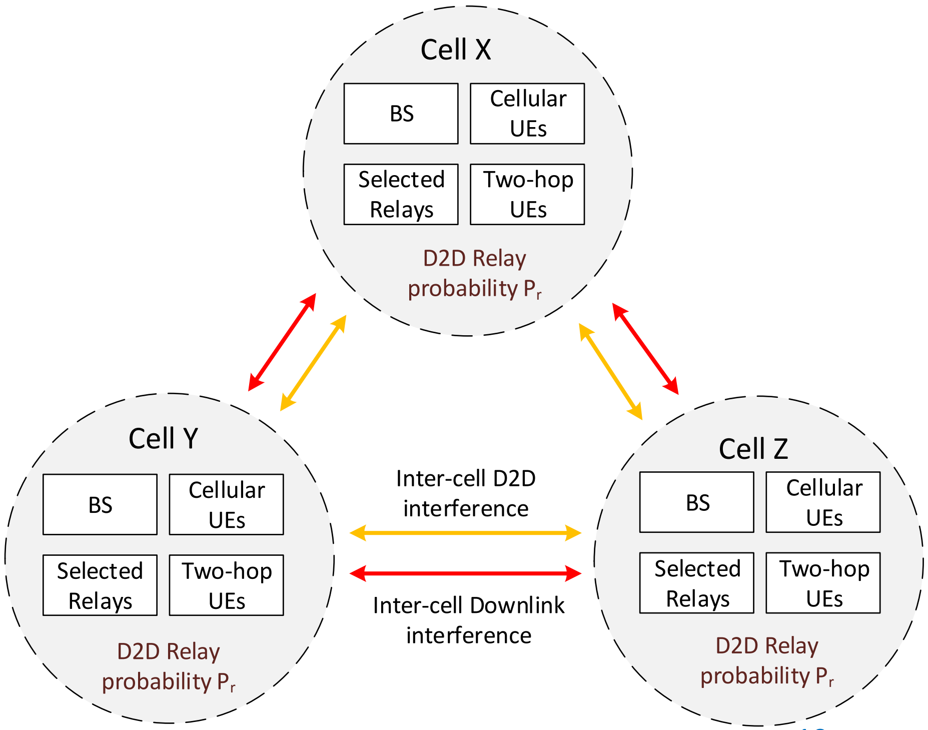
Iterative interference interaction among neighbor cells

- Assmuming a interference-limited scenario.
- D2D relay decision in one cell is made based on the observed interference on UEs and relays.
- D2D relaying in one cell would change the interference caused to other cells, other cell would change their relaying decisions and hence the observed interference for own cell.

A feedback loop exists among multiple cells as a result of the inter-cell interaction caused by D2D relaying.



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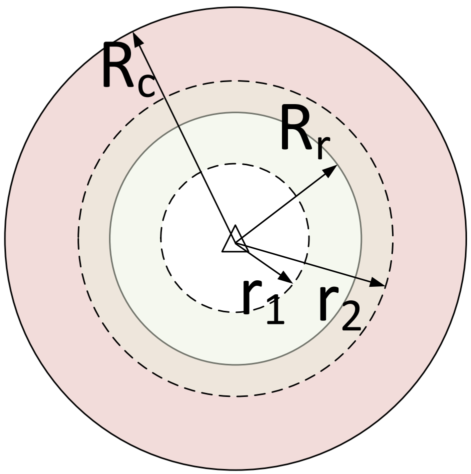
Control of relaying distance threshold R_r

- UEs have a distance larger than R_r can use D2D relaying service.
- R_r determines r_1 and r_2 which characterize the D2D interference.
- As R_r decreases, relaying probability p_r increases, and average inter-cell interference decreases (if BS tx power is much larger than UE's). As inter-cell interference decreases, the population of UEs that can benefit from D2D relaying changes.

➢ For a homogeneous network, in equilibrium of the network state, we should have:

$$C_{dl}(R_r) = C_{e2e}\big(R_r, d_{opt}(R_r)\big)$$



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Simulation parameters

Parameter	Symbol	Setting
System bandwidth	W	40 MHz
Minimum distance between BSs	D	500 m
Cell radius	R_c	250 m
BS density of triangular lattice	ρ_{bs}^h	$(\frac{\sqrt{3}}{2}D^2)^{-1}$
BS density of square lattice	ρ_{bs}^s	$(D^2)^{-1}$
Active UEs in each cell	N_u	10
Potential relays in each cell	N_r	100
PL model of cellular link	$\ell_b(x)$	$8.18 \times 10^{-5} x^{-3.67}$
PL model of D2D link	$\ell_d(x)$	$6.34 \times 10^{-5} x^{-3.67}$
TX power of BS	P_b	30 dBm
TX power of UE	P_d	24 dBm
Thermal noise power density	N_0	-174 dBm/Hz
Noise figure	N_f	8 dB

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Simulation result – search for the relay decision with optimal R_r

$$C_{dl}(R_r) = C_{e2e}\big(R_r, d_{opt}(R_r)\big)$$

Algorithm 1 Searching for R_r and p_r in equilibrium state

Initialization of R_r and p_r, using $R_r = R_c$ and $p_r = 0$

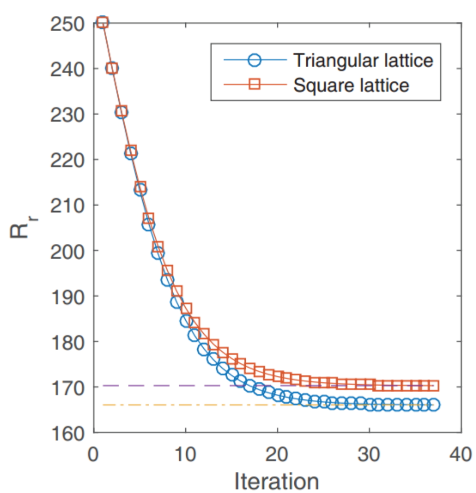
Calculate $C_\varepsilon = C_{dl}(R_r) - C_{e2e}(R_r, d_{opt}(R_r))$

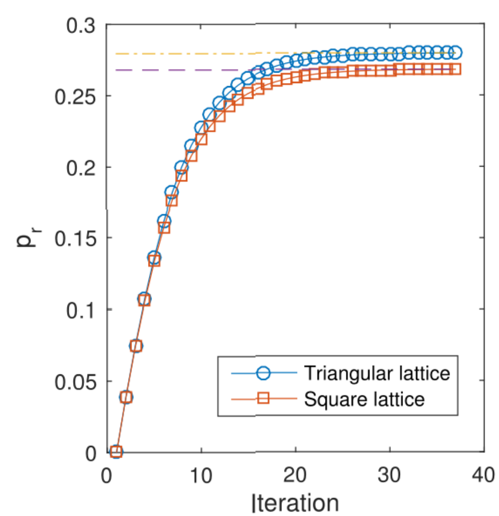
while $|C_\varepsilon| > \epsilon$ **do**

  $R_r \leftarrow R_r + C_\varepsilon \Delta,\ p_r \leftarrow \frac{R_c^2 - R_r^2}{2R_c^2}$.

  Calculate $C_\varepsilon = C_{dl}(R_r) - C_{e2e}(d, d_{opt}(R_r))$.

end while





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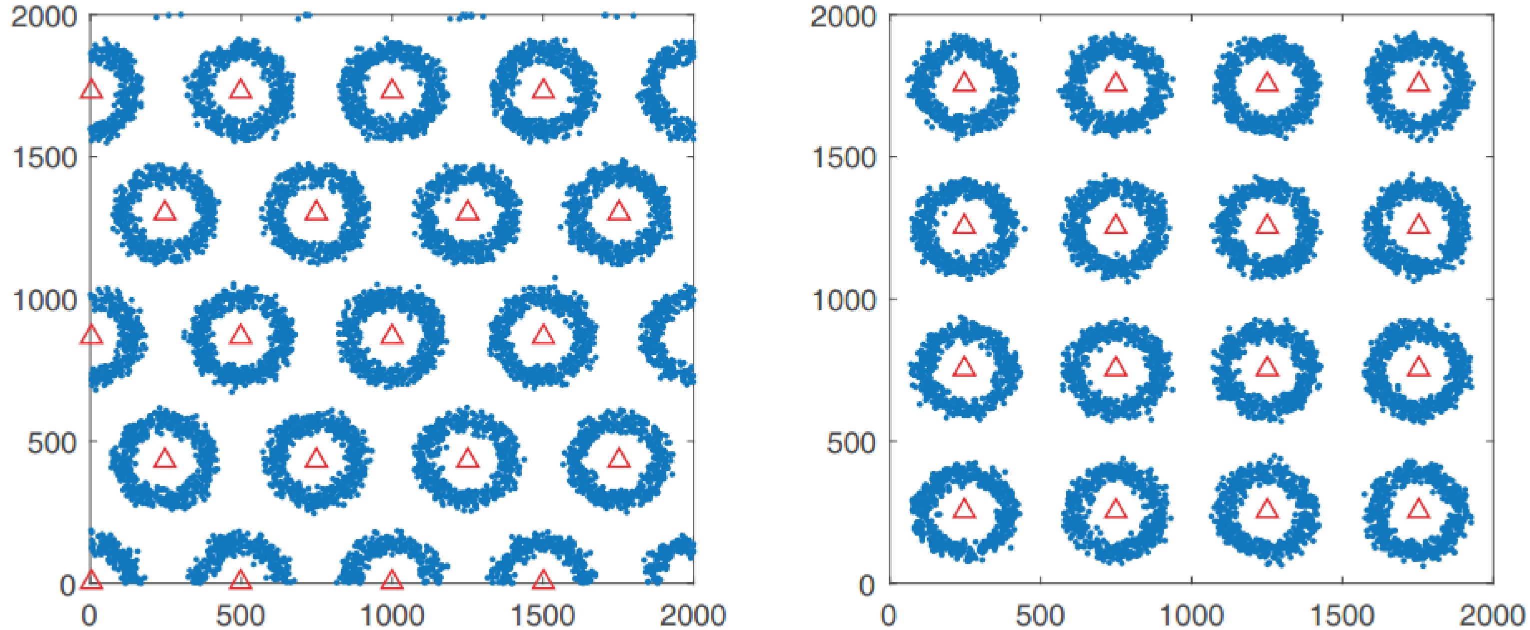
Simulation result – distribution of selected D2D relays



(a) Triangular lattice

(b) Square lattice

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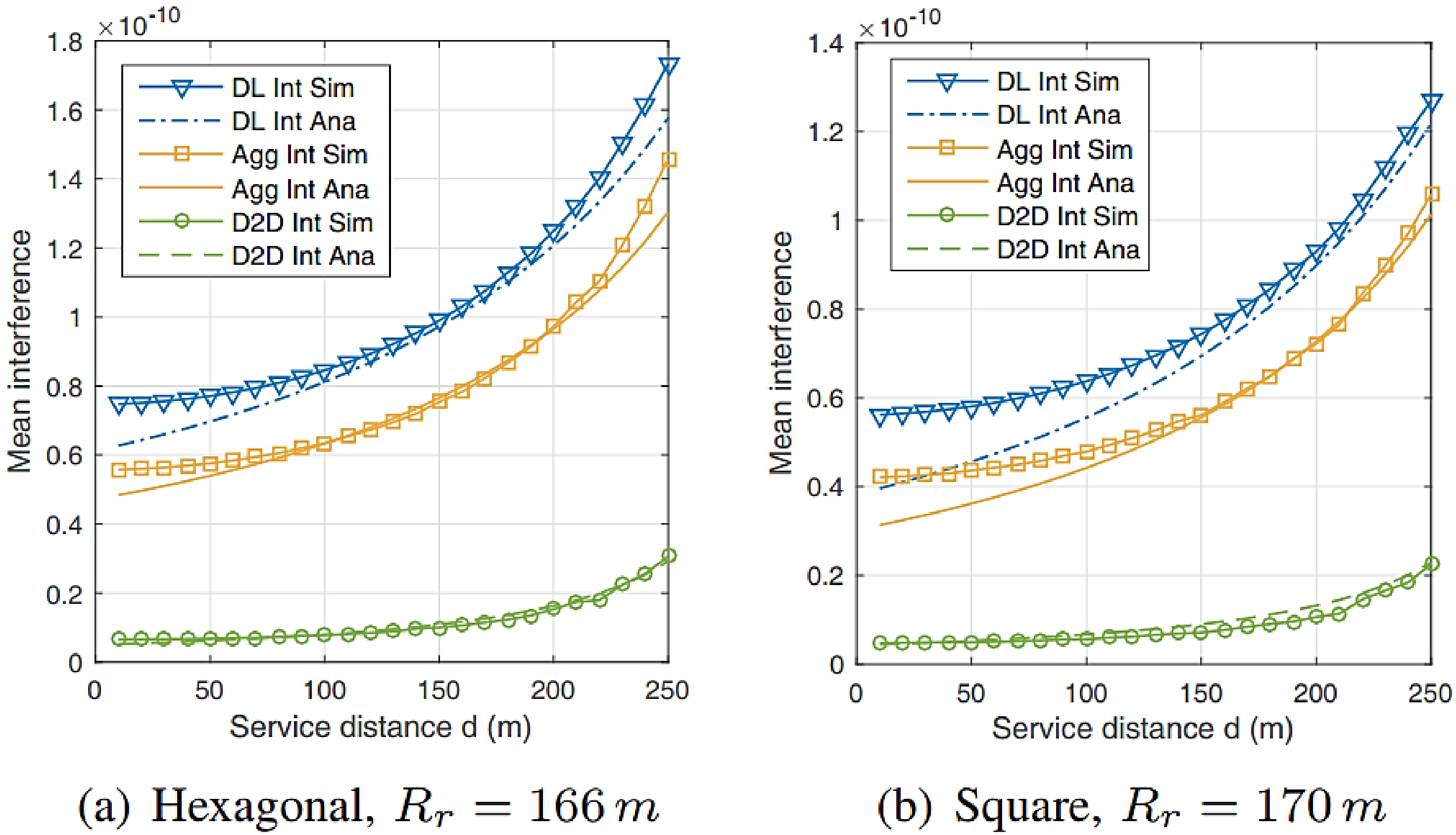
Simulation result – average inter-cell interference



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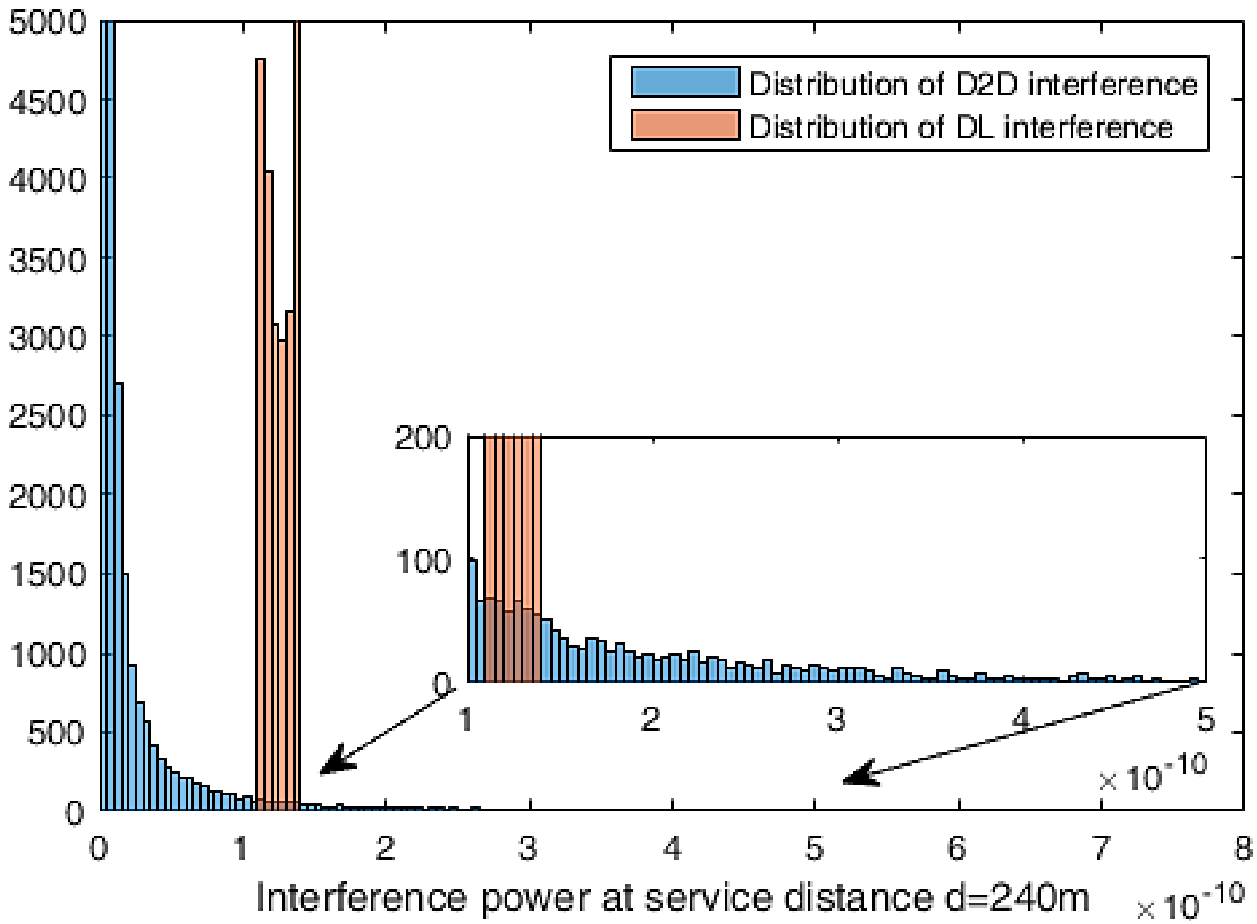
Simulation result – distribution of inter-cell interference



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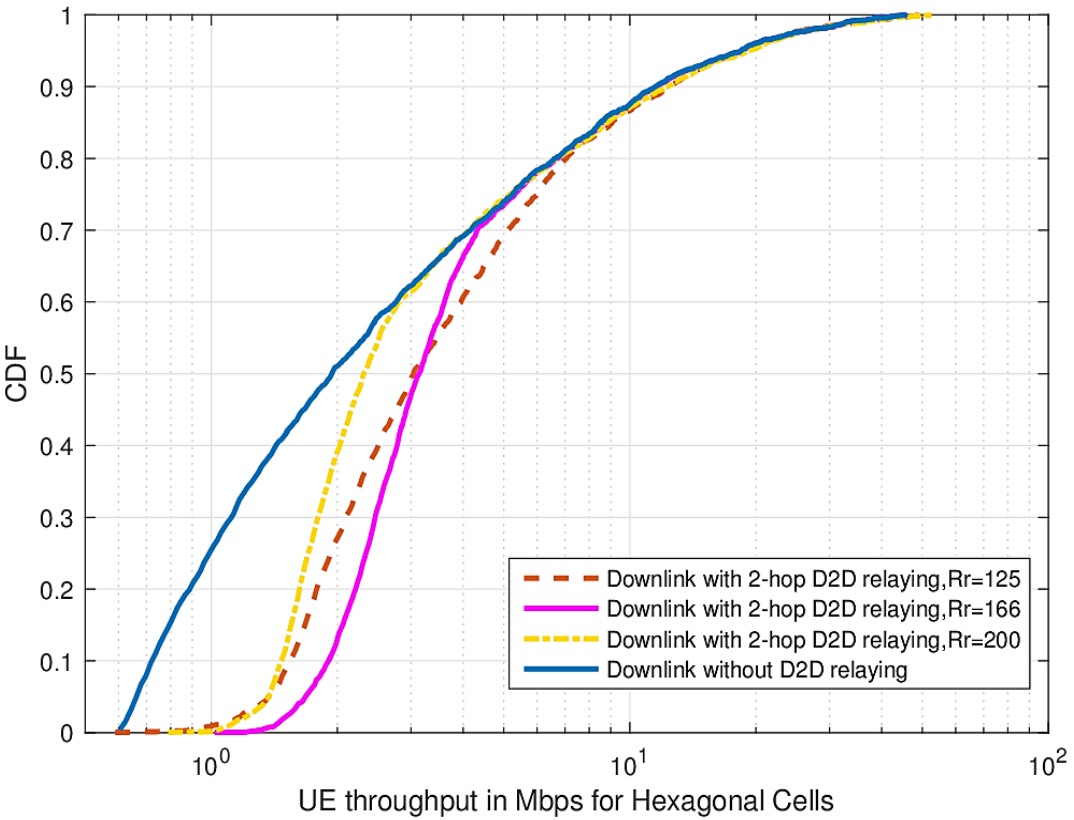
Simulation result – performance of user throughput



- D2D relaying increases cell-edge performance significantly.
- Relaying strategy using the derived value of R_r achieves the best performance among all possible values for R_r .

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Summary

- Modeling of the aggregate co-channel interference considering D2D relaying is applied in the networks based on a fluid network model.
- Several simplified parameters, including a minimum relaying distance and a relaying probability, are proposed to captured inter-cell interaction driven by interference.
- D2D relaying management using the derived parameter achieves good performance, especially for cell edge users.

Thank you!

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