D2D Relay Management in Multi-cell Networks

Junquan Deng *, Olav Tirkkonen *, Tao Chen †

*Department of Communications and Networking, Aalto University
† VTT Technical Research Centre of Finland
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum inter-site distance</td>
<td>$D$</td>
</tr>
<tr>
<td>Cell radius</td>
<td>$R_c$</td>
</tr>
<tr>
<td>BS density</td>
<td>$\rho_{bs}$</td>
</tr>
<tr>
<td>Relaying distance threshold</td>
<td>$R_r$</td>
</tr>
<tr>
<td>Distribution of selected relays</td>
<td>$r_1, r_2$</td>
</tr>
<tr>
<td>Relaying probability</td>
<td>$p_r$</td>
</tr>
</tbody>
</table>

- 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 $\eta$ and $\eta_d$ for downlink and D2D link.
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 $\rho$ in the distribution area.

- In the fluid model, each area element $dA$ contains $\rho dA$ 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.
Inter-cell interference characterization

- Average inter-cell D2D interference from other cells

\[ I_{d2d}(d) = \frac{M_d (D - d)^2 - \eta_d (\phi(r_2) - \phi(r_1))}{(r_2^2 - r_1^2)(\eta_d - 2)} \]

\[ \phi(r) = r^2 F_1 \left( \frac{\eta_d - 1}{2}, \frac{\eta_d + 1}{2}; 2; \frac{r^2}{(D - d)^2} \right) \]

Distribution of inter-cell D2D interference caused 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

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

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

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

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

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

\[
K = \frac{P_d K_d D^{-\eta_d}}{P_b K_b D^{-\eta}}
\]
Iterative interference interaction among neighbor cells

- Assuming an 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.
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:

$$C_{dl}(R_r) = C_{e2e}(R_r, d_{opt}(R_r))$$
# Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>$W$</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Minimum distance between BSs</td>
<td>$D$</td>
<td>500 m</td>
</tr>
<tr>
<td>Cell radius</td>
<td>$R_c$</td>
<td>250 m</td>
</tr>
<tr>
<td>BS density of triangular lattice</td>
<td>$\rho_{b,s}^h$</td>
<td>$(\frac{\sqrt{3}}{2} D^2)^{-1}$</td>
</tr>
<tr>
<td>BS density of square lattice</td>
<td>$\rho_{b,s}^s$</td>
<td>$(D^2)^{-1}$</td>
</tr>
<tr>
<td>Active UEs in each cell</td>
<td>$N_u$</td>
<td>10</td>
</tr>
<tr>
<td>Potential relays in each cell</td>
<td>$N_r$</td>
<td>100</td>
</tr>
<tr>
<td>PL model of cellular link</td>
<td>$\ell_b(x)$</td>
<td>$8.18 \times 10^{-5} x^{-3.67}$</td>
</tr>
<tr>
<td>PL model of D2D link</td>
<td>$\ell_d(x)$</td>
<td>$6.34 \times 10^{-5} x^{-3.67}$</td>
</tr>
<tr>
<td>TX power of BS</td>
<td>$P_b$</td>
<td>30 dBm</td>
</tr>
<tr>
<td>TX power of UE</td>
<td>$P_d$</td>
<td>24 dBm</td>
</tr>
<tr>
<td>Thermal noise power density</td>
<td>$N_0$</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Noise figure</td>
<td>$N_f$</td>
<td>8 dB</td>
</tr>
</tbody>
</table>
Simulation result – search for the relay decision with optimal $R_r$

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

**Algorithm 1** Searching for $R_r$ and $p_r$ in equilibrium state

1. Initialization of $R_r$ and $p_r$, using $R_r = R_c$ and $p_r = 0$
2. Calculate $C_\varepsilon = C_{dl}(R_r) - C_{e2e}(R_r, d_{opt}(R_r))$
3. while $|C_\varepsilon| > \varepsilon$ do
   - $R_r \leftarrow R_r + C_\varepsilon \Delta$, $p_r \leftarrow \frac{R_c^2 - R_r^2}{2R_c^2}$.
   - Calculate $C_\varepsilon = C_{dl}(R_r) - C_{e2e}(d, d_{opt}(R_r))$.
4. end while
Simulation result – distribution of selected D2D relays

(a) Triangular lattice  (b) Square lattice
Simulation result – average inter-cell interference

(a) Hexagonal, $R_r = 166 \, \text{m}$

(b) Square, $R_r = 170 \, \text{m}$
Simulation result – distribution of inter-cell interference
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 $R_r$. 
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!