Optimal Routing, Power Allocation and Link Activation for Multi-Hop D2D Communication

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Introduction

What does D2D mean?

Direct communication between devices without traversing the cellular network

Major challenges in D2D communication

- Interference avoidance/cancellation
- Device discovery
- Resource management
- Mode selection

Our Work

Motivation

- Direct path is not always feasible!
- D2D network may have other high rate data links which are feasible!!

Aim

Maximize throughput between a source-destination pair using a multi-hop path under an interference constraint imposed by the cellular network

Method

Maximization of throughput in two stages

- Optimal route discovery
- Link activation

System Model

- M D2D users and N base stations (BSs)
- Locations of D2D users are known, locations of cellular users are unknown
- Path loss model and Rayleigh fading are considered

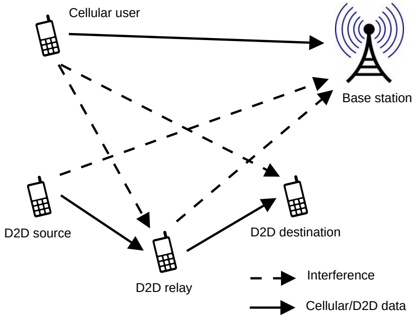

Figure: Uplink-inband D2D with $M = 3$ D2D users and $N = 1$ BS

The Two Schemes

- **Fixed rate scheme:** transmit power is allotted so that all D2D links achieve the same target rate
- **Fixed outage scheme:** each D2D link provides its maximum possible rate at a given outage probability

Fixed Rate Scheme: Overview

Given:
From cellular network,

- Interference threshold at the BS, γ_{bs}
- Interference outage probability, p_b: $\Pr\{P_b^{int} \geq \gamma_{bs}\} \leq p_b$

From D2D network,

- SINR threshold at D2D Rx, γ_{th}
- Data outage probability, p_{d2d}: $\Pr\{SINR_{tr} \leq \gamma_{th}\} \leq p_{d2d}$

1. Determine the feasible links according to the constraints above
2. Get the rate matrix and apply routing algorithm
3. For the throughput-optimal route, apply sequential link activation (SLA) scheme for data transmission

Link Feasibility

1. At D2D Rx d_r, measure P_r^{int} using a power or energy meter
2. At D2D Tx d_t, calculate $\forall\, s \in \{1, \ldots, N\}$

$$P_t^{\max} = \arg\max_{P_t} \left[\Pr\left\{P_t - 10\eta \log\left(D_{tb_s}\right) + 10 \log\left(g_{tb_s}\right) \geq \gamma_{bs}\right\} \leq p_b\right] \tag{1}$$

For Rayleigh fading channels considering the nearest BS, we get,

$$P_t^{\max} = 10 \log \left(- \frac{10^{\frac{\gamma_{bs}}{10}} \left(D_{tb_n}\right)^{\eta}}{2\sigma^2 \ln(p_b)} \right) \tag{2}$$

3. For each possible D2D Tx and D2D Rx, calculate

$$P_{tr}^{\min} = \arg\min_{P_{tr}} \left[\Pr\left\{P_{tr} - 10\eta \log\left(D_{tr}\right) + 10 \log\left(g_{tr}\right) - P_r^{\text{int}} \leq \gamma_{th}\right\} \leq p_{d2d}\right] \tag{3}$$

For Rayleigh fading channels,

$$P_{tr}^{\min} = 10 \log \left(- \frac{10^{\frac{\gamma_{th} + P_r^{\text{int}}}{10}} \left(D_{tr}\right)^{\eta}}{2\sigma^2 \ln(1 - p_{d2d})} \right) \tag{4}$$

4. $P_{tr}^{\min} \leq P_t^{\max} \Rightarrow d_t \longrightarrow d_r$ feasible

Routing

Algorithm

1. Construct rate matrix $\mathbf{R}_{M\times M}$ with $\mathbf{R}_{ij} = (1 - p_{ij}^{\text{out}})\log_2(1+\gamma_{th})$.
   Here, $\mathbf{R}_{ii} = 0 \;\forall i$ and $\mathbf{R}_{ij} = 0$ when $d_i \longrightarrow d_j$ is infeasible
   $p_{ij}^{\text{out}} = 1 - \exp(-\frac{10^{0.1(P_j^{\text{int}} + 10\eta\log(D_{ij}) + \gamma_{th} - P_i^{\text{max}})}}{2\sigma^2})$
2. Use Dijkstra's algorithm from d_S to d_D with link weights between nodes as $\frac{1}{\mathbf{R}_{ij}}$
3. Find route which minimizes $\sum \frac{1}{\mathbf{R}_{ij}}$

End-to-end throughput

$$R_{\text{eff}} = \left(\sum \frac{1}{\mathbf{R}_{ij}}\right)^{-1} \tag{5}$$

Slot-based Link Feasibility

Notation:

- Link in the throughput-optimal route is $\mathcal{L}_{l,l+1}$, where $l \in \{0, 1, \ldots, K\}$, 0^{th} node is source and $(K+1)^{\text{th}}$ node is destination
- Channel gain vector in time slot m, $\mathcal{G} = [g_{S1}(m), g_{12}(m), \ldots, g_{K-1,K}(m), g_{KD}(m)]$

Link feasibility is determined in every time slot for different channel instantiations.

1. Calculate aggregate interference and noise power, P_j^{int}
2. D2D nodes transmit at $P_i^{\max}$. For each Tx and Rx pair, find the required power to meet the target SINR at destination j

$$P_{ij}^{\text{req}}(m) = P_j^{\text{int}} + \gamma_{th} + 10\eta \log(D_{ij}) - 10 \log(g_{ij}(m)) \qquad (6)$$

3. Declare the link $d_i \longrightarrow d_j$ feasible if $P_i^{\max} \geq P_{ij}^{\text{req}}(m)$

Sequential Link Activation (SLA)

1. All the links in the route are initially assumed to be available, *i.e.*, can be activated
2. In the first time slot ($m = 1$), select the first link $\mathcal{L}_{S1}$
3. Check if the selected link is feasible
   - If the link is feasible, activate it and select the next link in the route for the next time slot
   - Otherwise, wait for the next time slot and select the same link
4. Repeat step 3 until the source has no more packets to send

Note: Source is assumed to transmit a fresh packet only after the destination receives the previous packet

Analysis

Delay across each link

$$w_{ij}^{\mathrm{SLA}} = (1 - p_{ij}^{\mathrm{out,FR}}) + 2p_{ij}^{\mathrm{out,FR}}(1 - p_{ij}^{\mathrm{out,FR}}) + 3(p_{ij}^{\mathrm{out,FR}})^2(1 - p_{ij}^{\mathrm{out,FR}}) + \cdots \tag{7}$$

$$w_{ij}^{\mathrm{SLA}} = \frac{1}{1 - p_{ij}^{\mathrm{out,FR}}} \tag{8}$$

Throughput across each link

$$\tau_{ij}^{\mathrm{SLA}} = 1 - p_{ij}^{\mathrm{out,FR}} \tag{9}$$

Total delay is sum of individual delays across all the $K + 1$ links.

$$W^{\mathrm{SLA}} = \sum_{i,j} \frac{1}{1 - p_{ij}^{\mathrm{out,FR}}} \tag{10}$$

System throughput

$$\mathcal{T}^{\mathrm{SLA}} = \frac{\mathrm{HM}(\tau_{S1}^{\mathrm{SLA}}, \tau_{12}^{\mathrm{SLA}}, \cdots, \tau_{KD}^{\mathrm{SLA}})}{K + 1} \tag{11}$$

Opportunistic Link Activation (OLA)

- Calculate slot based link feasibility using data outage constraint
- Apply buffer outage conditions corresponding to the feasible links obtained above
- Choose one of the feasible (according to data and buffer outages)links uniformly randomly at each time slot

1

I_{min}	I_{max}	*Condition*	*Action*
$\geq I_{th}$			Retain $\mathcal{L}_{k,k+1} = 1, \forall I_k = I_{max}$
	$\leq I_{th}$		Retain $\mathcal{L}_{k-1,k} = 1, \forall I_k = I_{min}$
$\leq I_{th}$	$\geq I_{th}$	$\mid I_{max} - I_{th} \mid > \mid I_{min} - I_{th} \mid$	Retain $\mathcal{L}_{k,k+1} = 1, \forall I_k = I_{max}$
$\leq I_{th}$	$\geq I_{th}$	$\mid I_{max} - I_{th} \mid < \mid I_{min} - I_{th} \mid$	Retain $\mathcal{L}_{k-1,k} = 1, \forall I_k = I_{min}$
$\leq I_{th}$	$\geq I_{th}$	$\mid I_{max} - I_{th} \mid = \mid I_{min} - I_{th} \mid$	Retain $\mathcal{L}_{k-1,k} = 1, \forall I_k = I_{min}$ $\mathcal{L}_{k,k+1} = 1, \forall I_k = I_{max}$

Table: Decision table for Step 4(c), set all other $\mathcal{L}_{ij} = 0$

Opportunistic Link Activation (OLA)

1. Set buffers of all the relay nodes to be empty, *i.e.*, $l_k = 0, \forall k = 1, 2, \ldots, K$
2. In each time slot, initially all the links are assumed to be feasible. $\mathcal{L} = [1, 1, \ldots, 1, 1]$
3. Find feasible links according to the data outage constraint
   (a) Do slot based link feasibility analysis and set $\mathcal{L}_{ij} = 0$ when the link is in outage
   (b) For $1 \le k \le K$,
      - if $l_k = L$, set $\mathcal{L}_{k-1,k} = 0$
      - if $l_k = 0$, set $\mathcal{L}_{k,k+1} = 0$
4. Set $l_{th} = \frac{L}{2}, \forall k$. Considering only the feasible links obtained from above, do the following:
   (a) Find $l_{min} = \min\{l_k\}$
   (b) Find $l_{max} = \max\{l_k\}$
   (c) Follow the actions given in Table 1 to obtain an updated $\mathcal{L}$
5. Choose one of the available links, *i.e.*, with $\mathcal{L}_{ij} = 1$, in a uniform random manner
6. Repeat the process from Step 2 until the source has no more packets to send

Analysis

1. Calculate transition probabilities for the buffer states
2. Obtain the state transition matrix and stationary probability vector
3. Arrive at outage probabilities of the links
4. Calculate delay and throughput using Little's law

Tuple of buffer lengths can be the states of a DTMC

$$s_n \triangleq (l_1, l_2, \ldots, l_k), \qquad 1 \leq n \leq (L+1)^K \tag{12}$$

State transition matrix $\mathbf{A} \in \mathbb{R}^{(L+1)^K \times (L+1)^K}$

Only one step transitions are allowed as only one link can be active in a time slot

Φ_n - set of all links that can be activated when DTMC is in state s_n

α_n - set of feasible links when DTMC is in state s_n

$$\begin{aligned} \mathbf{A}_{mn} &= \sum_{\alpha_n \subseteq \Phi_n} \Pr\{\alpha_n\} \Pr\{s_n \to s_m \mid \alpha_n\} \\ \mathbf{A}_{nn} &= \prod_{\mathcal{L}_{ij} \in \Phi_n} p_{out,ij} \end{aligned} \tag{13}$$

$$\boldsymbol{\pi} = (\mathbf{I} - \mathbf{A} + \mathbf{B})^{-1}\mathbf{b} \tag{14}$$

where $\boldsymbol{\pi}$ is the stationary probability vector $\boldsymbol{\pi} \in (L+1)^K \times 1$,
$\mathbf{b} = [1, 1, \ldots, 1]^T$ and $\mathbf{b} \in (L+1)^K \times 1$,
$\mathbf{I}$ is the identity matrix and $\mathbf{I} \in (L+1)^K \times (L+1)^K$,
$\mathbf{B}_{mn} = 1$, $\forall m, n$, such that $1 \leq m, n \leq (L+1)^K$.

System outage probability

$$p_{out}^{\text{OLA}} = \sum_{n=1}^{(L+1)^K} \mathbf{A}_{nn}\pi_n = \text{diag}(\mathbf{A})^T\boldsymbol{\pi} \tag{15}$$

Average queuing length at d_S, $\mathbb{E}[q_S] = 1 - p_{S\to1}$

$$p_{S\to1} = p_{1\to2} = \ldots = p_{i\to j} = \ldots = p_{K-1\to K} = p_{K\to D} \qquad (16)$$

where p_{ij} is the probability that the link $\mathcal{L}_{ij}$ is selected for data transmission.

$$\begin{aligned} p_{out}^{\text{OLA}} + p_{S\to1} + p_{1\to2} + \ldots + p_{K\to D} &= 1 \\ \Rightarrow \qquad p_{out}^{\text{OLA}} + (K+1)p_{send} &= 1 \\ p_{send} &= \frac{1 - p_{out}^{\text{OLA}}}{K+1} \end{aligned} \qquad (17)$$

Average queueing length at source node, d_S

$$\begin{aligned}\mathbb{E}[q_S] &= 1 - p_{send} \\ &= \frac{K + p_{out}^{\text{OLA}}}{K+1}\end{aligned} \tag{18}$$

Throughput for link $\mathcal{L}_{S1}$ is:

$$\begin{aligned}\tau_S &= p_{S\rightarrow 1} \\ &= p_{send} \\ &= \frac{1 - p_{out}^{\text{OLA}}}{K+1}\end{aligned} \tag{19}$$

Therefore, we can obtain the average delay at the source node as:

$$\begin{aligned}w_S^{\text{OLA}} &= \frac{\mathbb{E}[q_S]}{\tau_S} \\ &= \frac{K + p_{out}^{\text{OLA}}}{1 - p_{out}^{\text{OLA}}}\end{aligned} \tag{20}$$

Expected queue length at the relay node d_k

$$\mathbb{E}[q_k] = \sum_{n=1}^{(L+1)^K} \pi_n l_k^{(s_n)} \tag{21}$$

Throughput of the link from d_k to d_{k+1}

$$\begin{aligned} \tau_k &= p_{k \to k+1} \\ &= p_{send} \\ &= \frac{1 - p_{out}^{\mathrm{OLA}}}{K+1} \end{aligned} \tag{22}$$

Delay at each relay node d_k using Little's Law

$$\begin{aligned} w_k^{\mathrm{OLA}} &= \frac{\mathbb{E}[q_k]}{t_k} \\ &= \frac{K+1}{1 - p_{out}^{\mathrm{OLA}}} \sum_{n=1}^{(L+1)^K} \pi_n l_k^{(s_n)} \end{aligned} \tag{23}$$

Total delay

$$
\begin{aligned}
W^{\text{OLA}} &= w_S^{\text{OLA}} + \sum_{k=1}^{K} w_k^{\text{OLA}} \\
&= \frac{K + p_{out}^{\text{OLA}}}{1 - p_{out}^{\text{OLA}}} + \frac{K+1}{1 - p_{out}^{\text{OLA}}} \sum_{k=1}^{K} \sum_{n=1}^{(L+1)^K} \pi_n l_k^{(s_n)}
\end{aligned}
\tag{24}
$$

System throughput

$$
\begin{aligned}
\mathcal{T}^{\text{OLA}} &= \frac{\tau_i}{K+1} \\
&= \frac{1 - p_{out}^{\text{OLA}}}{(K+1)}
\end{aligned}
\tag{25}
$$

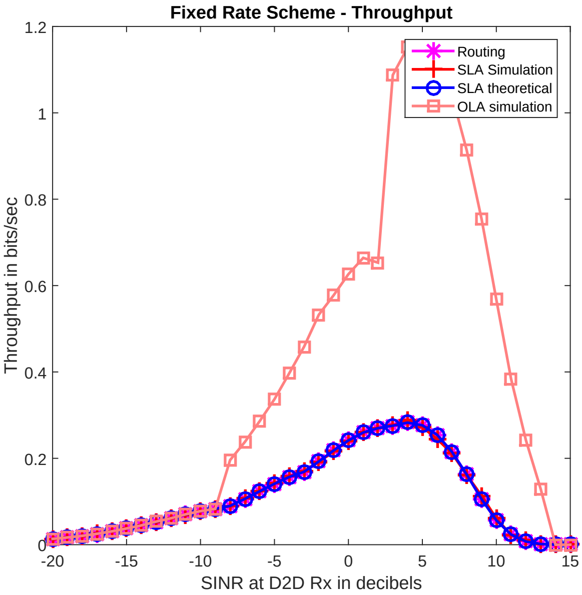

Figure: Simulation for fixed rate scheme routing and data transmission

Fixed Outage Scheme: Overview

Given:
From cellular network,

- Interference threshold at the BS, γ_{bs}
- Interference outage probability, p_b: $\Pr\{P_b^{int} \geq \gamma_{bs}\} \leq p_b$

From D2D network,

- Data outage probability, p_{d2d}: $\Pr\{\log_2(1 + SINR_{tr}) \leq R_{tr}\} \leq p_{d2d}$

1. Calculate the highest possible link rates for the data outage probability, p_{d2d}
2. Apply routing algorithm on the rate matrix
3. For the throughput-optimal route, apply modified sequential link activation (M-SLA) scheme for data transmission

Rate matrix calculation

1. At D2D Rx d_r, measure P_r^{int} (from power or energy meter) and for all Tx-Rx pairs, calculate $SINR_{tr}$
2. At D2D Tx d_t, calculate $\forall\ s \in \{1, \ldots, N\}$

$$P_t^{\max} = \arg\max_{P_t} \left[\Pr\left\{P_t - 10\eta \log\left(D_{tb_s}\right) + 10 \log\left(g_{tb_s}\right) < \gamma_{bs}\right\} \geq (1 - p_b)\right] \tag{26}$$

For Rayleigh fading channel considering the nearest BS, we get,

$$P_t^{\max} = 10 \log\left(-\frac{10^{\frac{\gamma_{bs}}{10}} \left(D_{tb_n}\right)^{\eta}}{2\sigma^2 \ln(p_b)}\right) \tag{27}$$

3. For each possible Tx and Rx pair, calculate

$$R_{tr}^{\max} = \arg\max_{R_{tr}} \left[\Pr\left\{\log_2\left(1 + SINR_{tr}\right) \geq R_{tr}\right\} \geq (1 - p_{d2d})\right] \tag{28}$$

For Rayleigh fading channel,

$$R_{tr}^{\max} = \log_2\left(1 - \frac{2\sigma^2 \ln(1 - p_{d2d})}{10^{\frac{P_r^{\text{int}} - P_t^{\max}}{10}} \left(D_{tr}\right)^{\eta}}\right) \tag{29}$$

Routing

Algorithm

1. Construct rate matrix $\mathbf{R}_{M \times M}$ with $R_{ij}^{\max}$. Here, $\mathbf{R}_{ii} = 0 \ \forall i$
2. Use Dijkstra's algorithm from d_S to d_D with link weights between nodes as $\frac{1}{\mathbf{R}_{ij}}$
3. Find route which minimizes $\sum \frac{1}{\mathbf{R}_{ij}}$

End-to-end throughput

$$R_{\text{eff}} = \left(\sum \frac{1}{\mathbf{R}_{ij}} \right)^{-1} \tag{30}$$

Modified Sequential Link Activation (M-SLA)

Similar to SLA except:

- If the selected link is feasible, activate it
  - If the link $\mathcal{L}_{S1}$ has been activated for $\frac{1}{R_{S1}}$ times, select the next link in the route
  - Otherwise, select the same link for the next time slot too
- If the link is infeasible (outage), then wait for the next time slot and select the same link

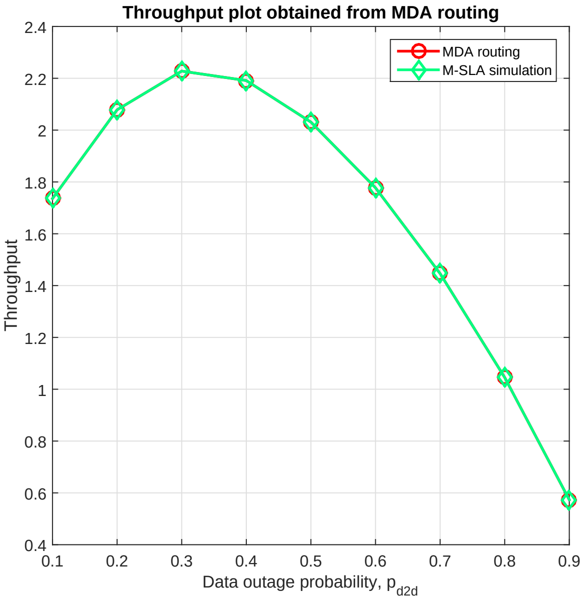

Figure: Simulation for fixed outage scheme-data transmission throughput

Conclusion

- Proposed two schemes for D2D communication system design
- Opportunistic link activation scheme which improves the end-to-end throughput
- Closed form expressions for throughput and delay

Future Work

- Incorporate chase combining at the D2D Rx
- Improve OLA by sorting the buffer lengths at the relay nodes
- Routing when D2D nodes are moving at a high speed