Optimal Routing and Data Transmission for Multi-Hop D2D Communications Under Stochastic Interference Constraints

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Outline

- Introduction
- Problem Statement
- System Model
- Throughput Optimal Routing
- Sequential and Opportunistic Link Activation Schemes
- Delay-aware Throughput Optimal Routing
- Summary
- Future Work

Introduction

Device-to-Device (D2D) communication is the direct link communication between the proximal devices without going through the infrastructure

Advantages

- Reduced out-of-cell interference
- Increased spectral efficiency

Applications

- Emergency services
- High data rate transmission
- Situational awareness

Problem Statement

- To find the D2D route that maximizes the end-to-end throughput between a given D2D source-destination pair under
  - (a) stochastic interference constraint imposed by the cellular network
  - (b) target SINR threshold or target data outage probability for D2D receiver

    delay constraint on the packet in addition to target rate constraint
- To design a link activation scheme to achieve throughput gains in buffer-aided multi-hop D2D communications

Prior Work

- P. Ren, Q. Du, and L. Sun, "Interference-aware routing for hop-count minimization in wireless D2D networks," in Proc. IEEE Int. Workshop on Internet of Things, Aug. 2013, pp. 65–70.
  –Solved under a target rate constraint using Dijkstra's algorithm

- V. Bhardwaj and C. R. Murthy, "On optimal routing and power allocation for D2D communications," in Proc. ICASSP, Apr. 2015, pp. 3063–3067.
  –Path-loss based route design for fixed rate and fixed power schemes

- Y. Liu, A. M. A. E. Bashar, F. Li, Y. Wang, and K. Liu, "Multi-copy data dissemination with probabilistic delay constraint in mobile opportunistic Device-to-Device networks," in WoWMoM, Jun. 2016, pp. 1–9.
  –Centralized and distributed routing algorithms for throughput maximization

Our Contributions

- Used channel statistics to design the throughput-optimal route under stochastic interference constraints to the cellular network, and an additional delay constraint
- Obtained analytical expressions for throughput, system idle probability and average delay for two data transmission schemes
    1. Sequential Link Activation (SLA)
    2. Opportunistic Link Activation (OLA)

Publications

1. S. Madabhushi, G.R. Gopal, and C. R. Murthy, "Optimal Routing and Data Transmission for Multi-Hop D2D Communications Under Stochastic Interference Constraints," *Proc. NCC*, Mar. 2017, pp. 394-399.
2. S. Madabhushi and C.R. Murthy, "Delay-Aware Routing and Data Transmission for Multi-Hop D2D Communications Under Stochastic Interference Constraints," *Proc. Asilomar*, Oct. 2017.
3. S. Madabhushi, G.R. Gopal, and C.R. Murthy, "Optimal Routing and Data Transmission for Buffer-Aided Multi-Hop D2D Communications Under Stochastic Interference Constraints," *to be submitted to TCOM*.

System Model

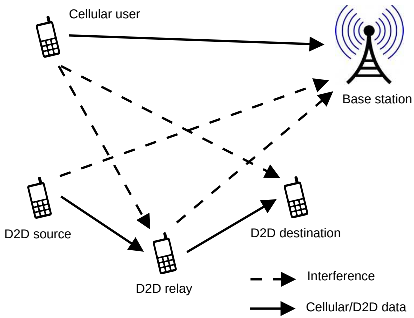


Figure: System model with $N = 1$ BS and $M = 3$ D2D users

- N BSs and M D2D users
- Positions of D2D users known and that of cellular users unknown
- SINR calculations based on the path loss model and Rayleigh fading in the wireless channels
- Fixed-rate/fixed-outage models
- d_S wishes to send data to d_D in uplink-inband D2D

In uplink-inband D2D, two types of interference arise:

(a) Interference from the D2D transmitter to the BS

(b) Interference from the cellular transmitter to the D2D receiver

Correspondingly, we have two constraints.

From the cellular network:

Interference at the BS exceeds a threshold, γ_{bs} dB, with sufficiently low probability, p_b

From the D2D network:

- **Fixed-rate model:**

  All the D2D links achieve the same target rate $\log_2(1+\gamma_{\text{th}})$, where γ_{th} is the target SINR threshold at the D2D receiver

- **Fixed-outage model:**

  All the D2D links have the same data outage probability, p_{d2d}

Proposed Routing Algorithm

Two steps to find the optimal route at a target

- SINR threshold, γ_{th} for fixed-rate
- data outage probability, p_{d2d} for fixed-outage

- Determine the following:
  - D2D transmit powers
  - D2D link outage probabilities for fixed-rate
    achievable rates for fixed-outage

- Apply Dijkstra's algorithm on the appropriate cost matrix

One dimensional search gives the optimal γ_{th} or p_{d2d}

Fixed-rate model: Transmit Power and Outage Probability

- Find the maximum allowed transmit power for a node d_t

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

- Find the aggregate interference and noise power P_r^{int} at every D2D receiver d_r using a power meter

- Find the minimum transmit power at d_t to meet the target SINR at d_r

$$P_{tr}^{\min} = \arg\min_{P_{tr}}\{P_{tr} - 10\eta\log D_{tr} + 20\log(|h_{tr}|) - P_r^{\text{int}} \geq 10\log\gamma_{\text{th}}\}$$

- Find outage probability of the link $d_t \longrightarrow d_r$

  Link outage condition: $P_{tr}^{\min} > P_t^{\max}$

$$p_{tr}^{\text{out}} = 1 - \exp\left(-\frac{10^{\frac{P_r^{int} + 10\eta\,\log D_{tr} + 10\,\log\gamma_{th} - P_t^{\max}}{10}}}{2\sigma^2}\right)$$

Fixed-outage model: Transmit Power and Achievable Rates

- Find the maximum allowed transmit power for a node d_t and the aggregate interference and noise power P_r^{int} at every D2D receiver d_r as explained for fixed-rate model
- Find the maximum rate, $R_{tr}^{\max}$, when d_t transmits at $P_t^{\max}$ to d_r, for a given data outage probability p_{d2d}

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

- Find the minimum transmit power,$P_{tr}^{\min}$, required to meet this target rate

$$P_{tr}^{\min} = \frac{P_r^{\text{int}} D_{tr}^{\eta} (2^{R_{tr}^{\max}} - 1)}{|h_{tr}(m)|^2}$$

Throughput-Optimal Routing

- Find effective rate of the link $d_t \longrightarrow d_r$

$$R_{tr} = \begin{cases} (1 - p_{tr}^{\text{out}}) \log_2(1 + \gamma_{\text{th}}) & \text{for fixed-rate} \\ (1 - p_{\text{d2d}}) R_{tr}^{\max} & \text{for fixed-outage} \end{cases}$$

- Find the inverse rate matrix, $\mathbf{C} \in \mathbb{R}^{M \times M}$
  For $M = 3$,

$$\mathbf{C} = \begin{bmatrix} 0 & R_{12}^{-1} & R_{13}^{-1} \\ R_{21}^{-1} & 0 & R_{23}^{-1} \\ R_{31}^{-1} & R_{32}^{-1} & 0 \end{bmatrix}$$

- End-to-end throughput is the scaled harmonic mean of the individual effective link rates.
  Apply Dijkstra's algorithm on **C** to find the route that gives maximum throughput.

Sequential Link Activation (SLA) Based Data Transmission

- Each of the links in the throughput-optimal route selected in a round-robin fashion
- Only one link activated per slot
- Successful reception at the D2D receiver of the link $d_t \longrightarrow d_r$ when
  - interference from d_t at the BS is less than γ_{bs}
  - fixed-rate: SINR at d_r is at least γ_{th}
    fixed-outage: achieved rate is at least $R_{tr}^{\max}$

$$\boxed{P_{tr}^{\min} \leq P_t^{\max}}$$

- 1-bit ACK from the destination, d_D, to the source, d_S, once a packet is successfully received

Throughput

Throughput is defined as the number of packets successfully delivered at the receiver per channel use.

Proposition 1

The end-to-end throughput between a given D2D source-destination pair which operates under SLA scheme for fixed-rate and fixed-outage models, resp., is given by

$$
\begin{aligned}
T_{fr}^{SLA} &= \frac{1}{w^{SLA}} \log_2(1+\gamma_{th}) \\
T_{fo}^{SLA} &= \frac{1-p_{d2d}}{K+1} R_{KD}^{max}
\end{aligned}
\tag{1}
$$

System idle probability

System idle probability is the probability with which no packet is transmitted to its destination as all the links in the system are in outage.

Lemma 1

System idle probability for fixed-rate and fixed-outage models, respectively, is given by

$$
\begin{aligned}
p_{out}^{SLA} &= \frac{1}{w^{SLA}} \sum_{\substack{t \in \{0,1,\dots,K\} \\ r=t+1}} \frac{p_{tr}^{out}}{1-p_{tr}^{out}} \\
p_{out}^{SLA} &= p_{d2d}
\end{aligned}
\tag{2}
$$

Opportunistic Link Activation (OLA) Based Data Transmission

- Each of the relay nodes has a finite buffer
- Links are activated based on the buffer states of the relay nodes and the feasibility criterion
- Further, buffers close to the half full state ensure throughput optimality [1]

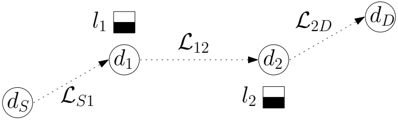


Figure: System model for data transmission with $K = 2$ relay nodes and $L = 2$ buffer size

[1] R. Srivastava and C. E. Koksal, "Basic Performance Limits and Tradeoffs in Energy Harvesting Sensor Nodes with Finite Data and Energy Storage," Networking and Internet Architecture, Sept. 2012.

Lemma 2

System idle probability under OLA scheme is given by

$$p_{out}^{OLA} = \sum_{n=1}^{(L+1)^K} \mathbf{A}_{nn}\pi_n = diag(\mathbf{A})\boldsymbol{\pi}, \quad (3)$$

where, $\mathbf{A}$ *and* $\boldsymbol{\pi}$ *are the t.p.m. and stationary distribution of the DTMC, respectively.*

Proposition 2

The end-to-end throughput of the throughput-optimal route between a given D2D source-destination pair for fixed-rate and fixed-outage models, respectively, is as follows:

$$\begin{aligned} T_{fr}^{OLA} &= \frac{1 - p_{out}^{OLA}}{K+1}\log_2(1+\gamma_{th}) \\ T_{fo}^{OLA} &= \frac{1 - p_{out}^{OLA}}{K+1} R_{KD}^{max} \end{aligned} \quad (4)$$

Proposition 3

Average delay of the packet in the system is given by

$$W^{OLA} = \frac{K + p_{out}^{OLA}}{1 - p_{out}^{OLA}} + \frac{K+1}{1 - p_{out}^{OLA}} \sum_{k=1}^{K} \sum_{n=1}^{(L+1)^K} \pi_n l_{kn}$$

where l_{kn}, *denotes the length of the data buffer at the D2D relay node,* d_k, *in state* s_n.

Simulation Results

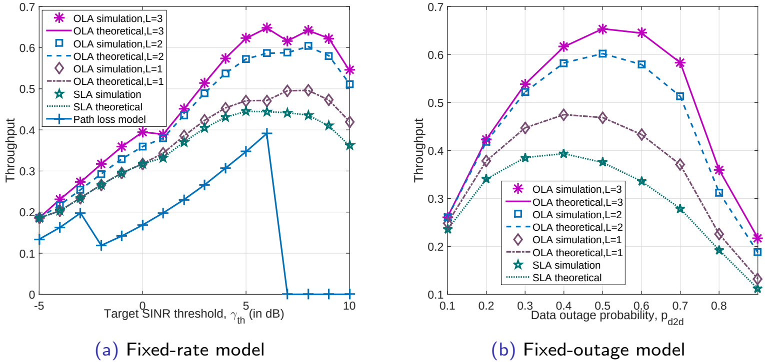


Figure: Achievable end-to-end throughput under SLA and OLA schemes $\gamma_{bs} = 3$ dB and $p_b = 0.4$. Performance of proposed algorithm compared against path loss based route design in[2] for fixed-rate model.

[2] V. Bhardwaj and C. R. Murthy, "On optimal routing and power allocation for D2D communications," in Proc. ICASSP, Apr. 2015, pp. 3063–3067.

Delay Constrained Routing and SLA Based Data Transmission

From the cellular network:

Interference at the BS exceeds a threshold, γ_{bs} dB, with sufficiently low probability, p_b

From the D2D network:

- Each D2D link achieves the target rate $\log_2(1+\gamma_{\text{th}})$, where γ_{th} is the target SINR threshold at the D2D receiver
- Maximum number of transmission attempts per packet on a link is θ

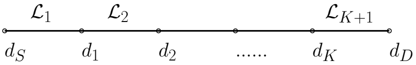


Figure: Multi-hop route between source and destination nodes.

Transmit power allocation and link outage probability calculation is same as mentioned earlier.

Theoretical Expressions

Average end-to-end delay:

$$W = \sum_{k=1}^{K+1} \left(\prod_{m=1}^{k-1} (1 - p_m^{\theta}) \right) \frac{(1 - p_k^{\theta})}{1 - p_k}. \tag{5}$$

End-to-end throughput:

$$T = \frac{\prod_{k=1}^{K+1} (1 - p_k^{\theta})}{W} \log_2(1 + \gamma_{\text{th}}). \tag{6}$$

Maximize the end-to-end throughput by solving the optimization problem:

$$\min \left\{ \sum_{k=1}^{K+1} \frac{1}{1 - p_k} \left(\prod_{m=k+1}^{K+1} \frac{1}{1 - p_m^{\theta}} \right) \right\} \tag{7}$$

Remark:

The algorithm for delay unconstrained routing is a special case of delay constrained routing algorithm when $\theta = \infty$

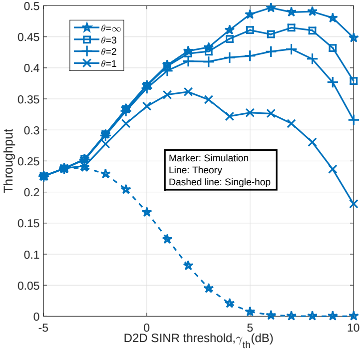
Delay-Aware Throughput-Optimal Routing

Algorithm 1 Delay-aware routing algorithm

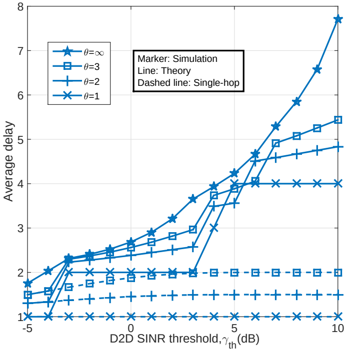
```
function FINDROUTE(ℙ, θ, S)
    Initialize: dist(1:M) = ∞; dist(S) = 0;
                            ▷ dist: shortest distance from the parent of a node
    parent(1:M) = 0; i = 1;
    ℒ = {1, 2, ... M};                              ▷ Index set of D2D nodes
    while i ≤ M − 1 do
        u = index of the node in ℒ with min value of dist;
        Remove u from ℒ;
        for v = 1 to M do
            if ( 1/(1−ℙ(u,v)) + dist(u)/(1−ℙ(u,v)^θ) < dist(v) ) then
                dist(v) = 1/(1−ℙ(u,v)) + dist(u)/(1−ℙ(u,v)^θ);
                parent(v) = u;
            end if
        end for
            i = i + 1;
        end while
    end function
```

Simulation Results

- $N = 2,\ M = 10,\ \gamma_{\text{bs}} = 3\ \text{dB},\ p_b = 0.4,\ \eta = 4$



(a) Throughput for different θ.



(b) End-to-end average delay for different θ.

Summary

- Proposed an easy-to-implement routing algorithm under stochastic interference constraint imposed by the cellular network, and an additional per hop delay constraint
- Considered channel statistics in the route design and obtained approx. 50% gain compared to the path loss based design
- Opportunistic activation of links resulted in a further 30% gain in the throughput
- Derived and validated the theoretical expressions for throughput, delay and system idle probability under SLA and OLA schemes
- Illustrated that multi-hop D2D communication offers higher end-to-end data rates compared to the direct link communication

Future Work

Mode selection in the context of massive Machine Type Communications (MTC)

1. Genetic algorithm
2. Deep learning based decentralized approach

Challenges:

- Subset discovery for simultaneous link activation
- Power control
- Clock synchronization
- Generation of labeled data set

Thank you