Quality-Aware Millimeter-Wave Device-to-Device Multi-Hop Routing for 5G Cellular Networks

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Introduction

• Millimeter (Mm-Wave) transmission has been actively studied for 5G cellular systems
  • Objective: Increasing capacity based on ultra-wide channel bandwidth
  • Thus, next generation phones will be equipped with mm-wave RF.

• Question
  If device-to-device (D2D) video streaming is performed over the mm-wave enabled phones, What kinds of algorithms are required?
  • Multi-hop routing mechanisms are required due to its propagation characteristics.

• Therefore,
  • A Quality-Aware Millimeter-Wave Multi-Hop Routing Algorithm is investigated.
Why Multi-Hop Routing is required for Mm-Wave D2D Communications?

**Multi-Hop Routing** is required in Mm-Wave D2D to combat non-line-of-sight (NLOS) situations.

*Multi-Hop Routing* is required in Mm-Wave D2D to enable long-distance transmission.
Objective Function

Maximize the sum of the qualities of all given flows

\[ \sum_{s_k \in V_s} q_k(f_{s_k \rightarrow v}) \]

Summation of the Qualities of All Flows

Summation of the Qualities of All Flows

Two Types of Quality Functions

Linear Form

Nonlinear (Concave) Form
Quality-Aware Mm-Wave D2D Multi-Hop Routing

Constraint #1: Device Constraints

\[ L_{v_i \rightarrow v_j} = \begin{cases} 1, & \text{if } v_i \text{ sends data to } v_j \\ 0, & \text{otherwise} \end{cases} \]

Each source \( s_k \) should send data to the one of the other nodes:

\[ \sum_{s_k \neq v} L_{s_k \rightarrow v} = 1, \forall s_k \]

In intermediate nodes, if it receives data, it should transmit the data, and visa versa, i.e.,

\[ \sum_{v_l \neq v_j} L_{v_l \rightarrow v_j} = \sum_{v_j \neq v_l} L_{v_j \rightarrow v_l} \]

Each destination \( d_k \) should receive data from the one of the other nodes:

\[ \sum_{v \neq d_k} L_{v \rightarrow d_k} = 1, \forall d_k \]
Quality-Aware Mm-Wave D2D Multi-Hop Routing

Constraint #2: Relay Constraints

The number of incoming flows is limited by the number of receiver RF $N_{RF}^{Rx}$ chains:

$$\sum_{v \neq r_k} L_{v \rightarrow r_k} \leq N_{RF}^{Rx}$$

The number of outgoing flows is limited by the number of transmitter RF $N_{RF}^{Tx}$ chains:

$$\sum_{r_k \neq v} L_{r_k \rightarrow v} \leq N_{RF}^{Tx}$$
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Constraint #3: Flow Constraints

The amounts of incoming traffic and outgoing traffic should be same:

In each device $v_k$,  \[ \sum_{v_i \neq v_j} f_{v_i \rightarrow v_j}^{s_k} = \sum_{v_j \neq v_l} f_{v_j \rightarrow v_l}^{s_k}, \forall s_k \]

In each relay $r_j$,  \[ \sum_{v_i \neq r_j} f_{v_i \rightarrow r_j}^{s_k} = \sum_{r_j \neq v_l} f_{r_j \rightarrow v_l}^{s_k}, \forall s_k \]
Limited by Link Capacity:

\[ C(v_i, v_j) = B \cdot \log_2(1 + SNR) \]

\[ \begin{align*}
P_{signal, dB} &= EIRP + G_{Rx} + L(d) \\
&= 47 \text{ dBm in 38GHz} \\
&= 25 \text{ dBm in relays, 13.3 dBm in phones} \\
&= \text{path loss model which is formulated as} \\
L(d) &= 20 \log_{10} \left( \frac{4\pi d_0}{\lambda} \right) + 10n \log_{10} \left( \frac{d}{d_0} \right) + X_\sigma \\
\text{where } d_0 &= 5 \text{m (unit distance), } \lambda \text{ is wavelength, } n \text{ is path-loss coefficient, } X_\sigma \text{ is a shadowing (Gaussian) random variables.}
\end{align*} \]

\[ P_{noise, dB} = 10 \log_{10} (k_B T_e \cdot B) + F_N \]

- \( k_B T_e \): noise power spectral density (-174dBm/Hz)
- \( F_N \): Rx noise figure (set to 6 dB)
Maximize: \[ \sum_{s_k \in V_s} q_k \left( f_{s_k \rightarrow v} \right) \]

Subject to

\[ \sum_{s_k \neq v} L_{s_k \rightarrow v} = 1, \forall s_k \quad \sum_{v \neq d_k} L_{v \rightarrow d_k} = 1, \forall d_k \]

\[ \sum_{v_j \neq v} L_{v_j \rightarrow v} = \sum_{v_j \neq v_l} L_{v_j \rightarrow v_l} \]

\[ \sum_{v \neq r_k} L_{v \rightarrow r_k} \leq N_{RF}^{Rx} \quad \sum_{r_k \neq v} L_{r_k \rightarrow v} \leq N_{RF}^{Tx} \]

\[ \sum_{v_j \neq v} f_{v_j \rightarrow v} = \sum_{v_j \neq v_l} f_{v_j \rightarrow v_l}, \forall s_k \]

\[ \sum_{v_j \neq r_j} f_{v_j \rightarrow r_j} = \sum_{r_j \neq v_l} f_{r_j \rightarrow v_l}, \forall s_k \]

\[ f_{v_i \rightarrow v_j} \leq C(v_i, v_j) \]

Even though max-min multi-hop flow routing is widely used for quality-aware applications, it cannot consider the differentiated quality functions of the given individual flows.

This formulation is mixed integer disciplined convex programming where the given integers are 0-1 binary (i.e., \( L_{v_i \rightarrow v_j} = \{0,1\} \)), i.e., branch-and-bound is widely used in literatures to obtain optimal solutions.
Parameters and Settings

- **Parameters**
  - Carrier frequency: 38 GHz
  - In 25 dBi Rx antenna (for relays),
    - $n$ is 2.20 in LOS and 3.88 in NLOS
    - $\sigma$ is 10.3 in LOS and 14.6 in NLOS
  - In 13.3 dBi Rx antenna (for phones),
    - $n$ is 2.21 in LOS and 3.18 in NLOS
    - $\sigma$ is 9.40 in LOS and 11.0 in NLOS

- **Settings**
  - 20 number of phones; 5 number of relays
  - Each relay has 4 Tx RF and 4 Rx RF
  - 4 sessions with various quality functions

DQC presents 33% better average throughput compared to max-min flow routing.

Performance Evaluation

- The proposed algorithm (*differentiated quality consideration (DQC)*) is compared with max-min scheme routing (*MmF*).
- Average throughput of DQC & MmF, i.e., $E[T_{DQC} | p_k]$ & $E[T_{MmF} | p_k]$ depending on link failure probability $p_k$. 
Conclusions and Future Work

- We propose a millimeter-wave multi-hop routing protocol for 5G cellular systems:
  - Assisted by multi-antenna relays
  - Quality-Awareness is introduced
  - Differentiated quality metrics for individual flows are taken account (better performance than max-min routing)
  - 33% performance improvement compared to max-min flow routing

- Future research direction
  - Conducting further research for the other 5G frequency, i.e., 28 GHz, as well.
• For more questions, please email to joongheon.kim@usc.edu, molisch@usc.edu