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.

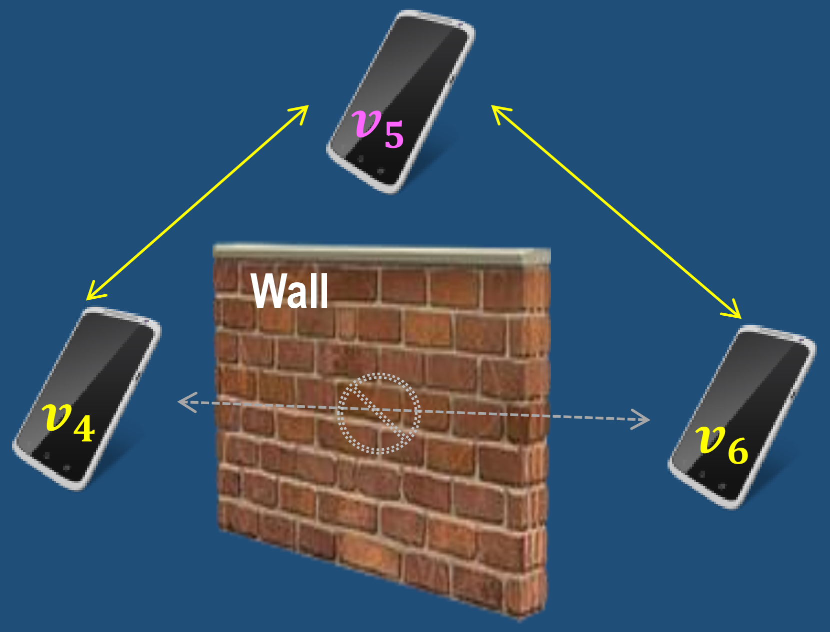
- **Question**
  If device-to-device (D2D) video streaming is performed over the mm-wave enabled phones,
  What kinds of algorithms are required?
  - Multi-hop routing mechanisms are required due to its propagation characteristics.

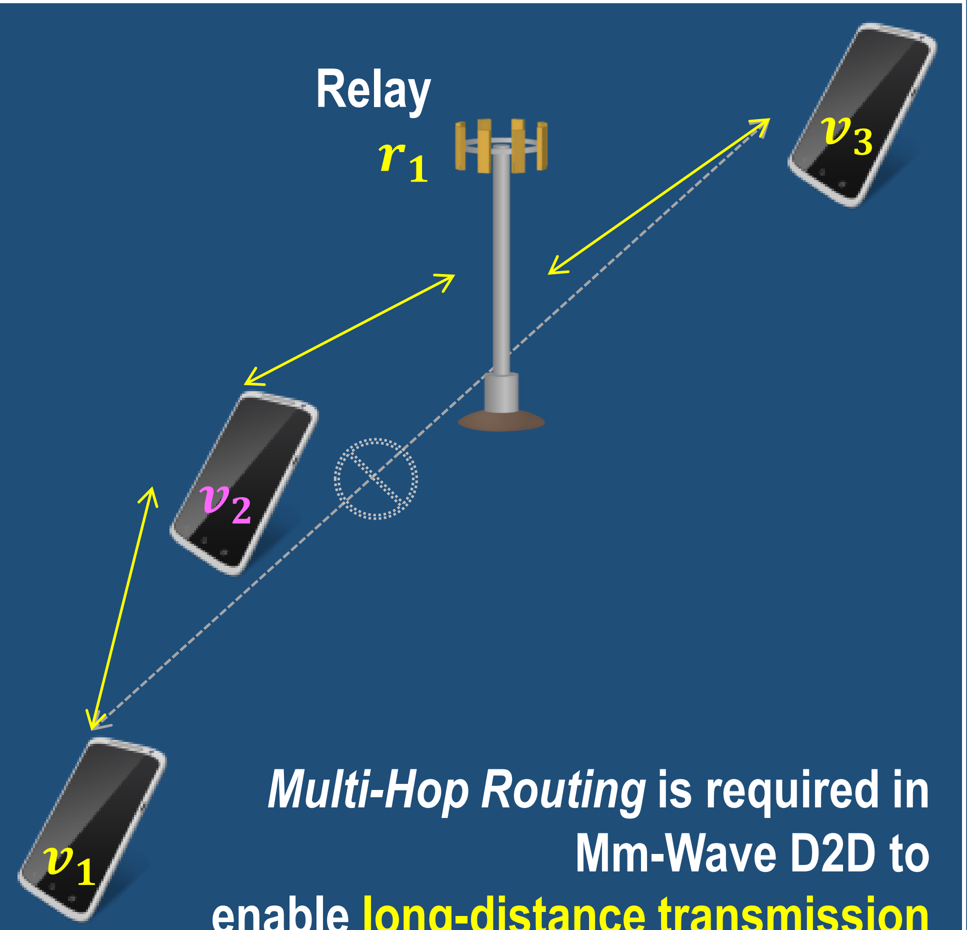
- Therefore,
  - A Quality-Aware Millimeter-Wave Multi-Hop Routing Algorithm is investigated.

A Reference Network Model

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

Quality-Aware Mm-Wave D2D Multi-Hop Routing

Mathematical Modeling

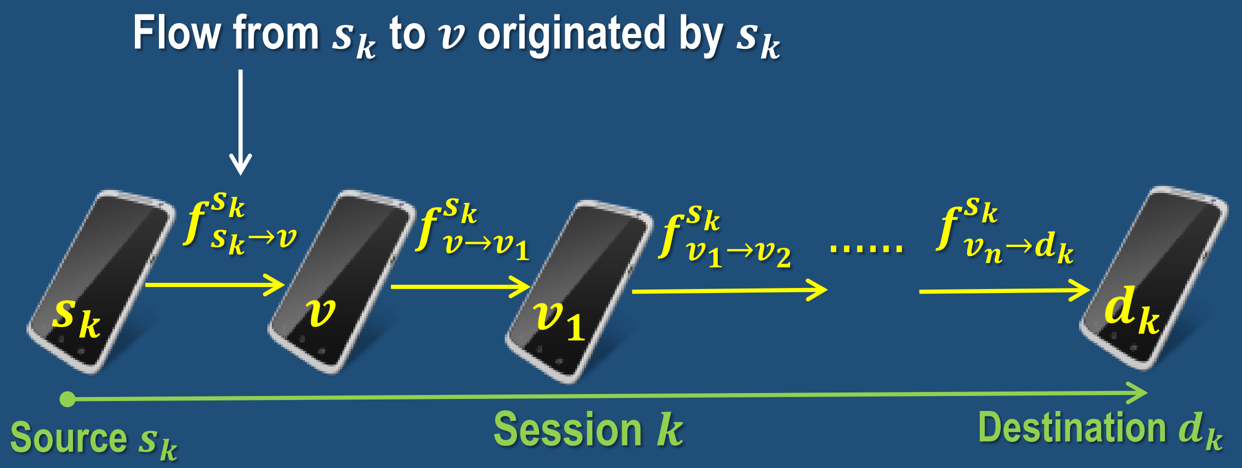
Objective Function

Maximize the sum of the qualities of all give flows

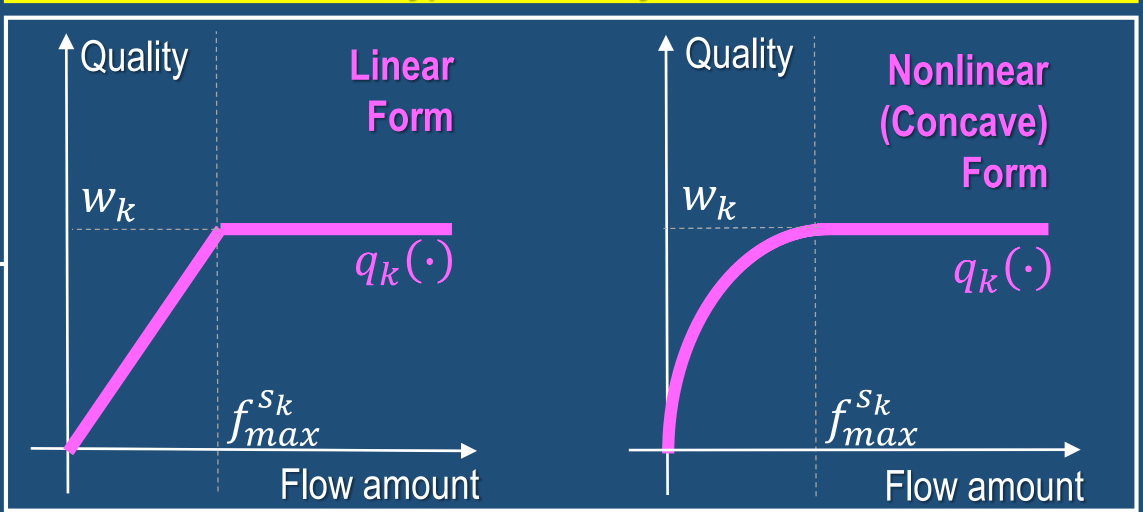
Maximize: $\sum_{s_k \in V_s} q_k\left(f^{s_k}_{s_k \to v}\right)$

Summation of the Qualities of All Flows (V_s is a set of sources)

The Quality Function of the Flow Originated by s_k



Two Types of Quality Functions



Quality-Aware Mm-Wave D2D Multi-Hop Routing

Constraint #1: Device Constraints

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

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

$$\sum_{s_k \neq v} L_{s_k \to v} = 1, \forall s_k$$

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

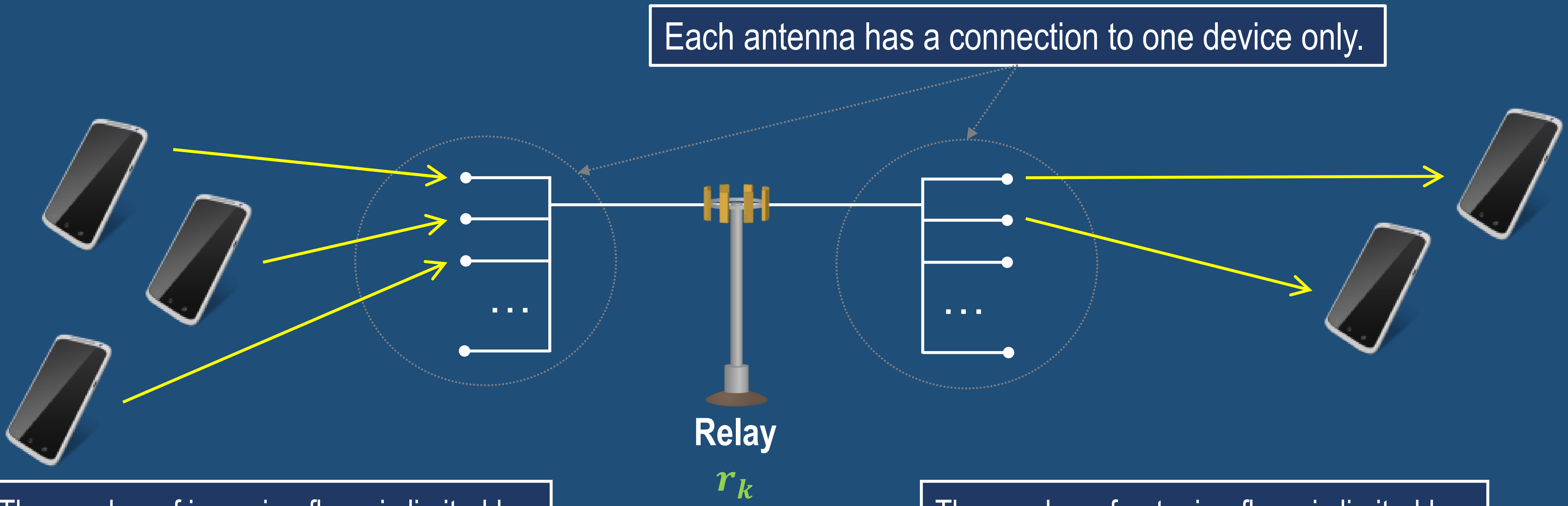
$$\sum_{v_i \neq v_j} L_{v_i \to v_j} = \sum_{v_j \neq v_l} L_{v_j \to v_l}$$

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

$$\sum_{v \neq d_k} L_{v \to d_k} = 1, \forall d_k$$

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:

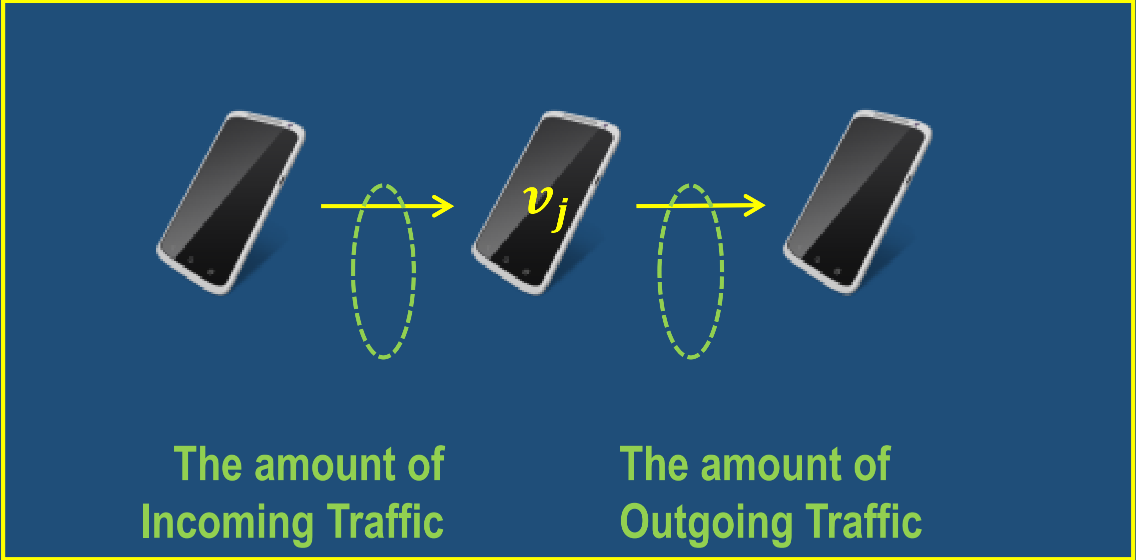
$$\sum_{v \neq r_k} L_{v \to r_k} \leq N_{RF}^{Rx}$$

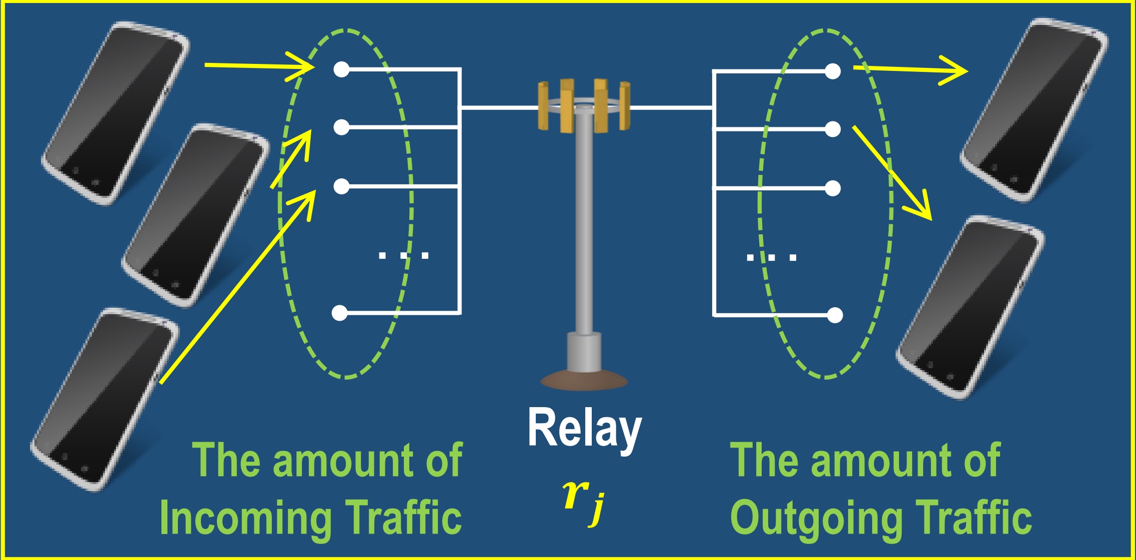
The number of outgoing flows is limited by the number of transmitter RF N_{RF}^{Tx} chains:

$$\sum_{r_k \neq v} L_{r_k \to v} \leq N_{RF}^{Tx}$$

Quality-Aware Mm-Wave D2D Multi-Hop Routing

Constraint #3: Flow Constraints





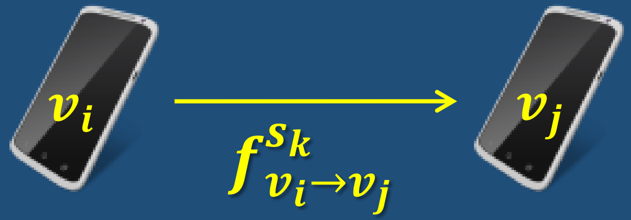
The amounts of incoming traffic and outgoing traffic should be same:

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

In each relay r_k, $\sum_{v_i \neq r_j} f_{v_i \to r_j}^{s_k} = \sum_{r_j \neq v_l} f_{r_j \to v_l}^{s_k}, \forall s_k$

Quality-Aware Mm-Wave D2D Multi-Hop Routing

Constraint #3: Flow Constraints (Continued), Capacity Calculation



Limited by Link Capacity: $C_{(v_i,v_j)} = B \cdot \log_2(1 + SNR)$

$SNR = P_{signal,dB} - P_{noise,dB}$

$$P_{signal,dB} = EIRP + G_{Rx} + L(d)$$

- $EIRP$: 47 dBm in 38GHz
- G_{Rx}: Rx antenna gain (25 dBm in relays, 13.3 dBm in phones)
- $L(d)$: path loss model which is formulated as

$$L(d) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

where $d_0 = 5$m (unit distance), λ is wavelength, n is path-loss coefficient, X_σ is a shadowing (Gaussian) random variables.

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

- $k_B T_e$: noise power spectral density (-174dBm/Hz)
- F_N: Rx noise figure (set to 6 dB)

Quality-Aware Mm-Wave D2D Multi-Hop Routing

Mathematical Optimization Formulation

Quality-Aware Mm-Wave D2D Multi-Hop Routing

Maximize: $\sum_{s_k \in V_s} q_k\left(f_{s_k \to v}^{s_k}\right)$

Subject to

$$\sum_{s_k \neq v} L_{s_k \to v} = 1, \forall s_k \quad \sum_{v \neq d_k} L_{v \to d_k} = 1, \forall d_k$$

$$\sum_{v_i \neq v_j} L_{v_i \to v_j} = \sum_{v_j \neq v_l} L_{v_j \to v_l}$$

$$\sum_{v \neq r_k} L_{v \to r_k} \leq N_{RF}^{Rx} \quad \sum_{r_k \neq v} L_{r_k \to v} \leq N_{RF}^{Tx}$$

$$\sum_{v_i \neq v_j} f_{v_i \to v_j}^{s_k} = \sum_{v_j \neq v_l} f_{v_j \to v_l}^{s_k}, \forall s_k$$

$$\sum_{v_i \neq r_j} f_{v_i \to r_j}^{s_k} = \sum_{r_j \neq v_l} f_{r_j \to v_l}^{s_k}, \forall s_k$$

$$\boldsymbol{f_{v_i \to v_j}^{s_k} \leq C_{(v_i, v_j)}}$$

Max-Min Multi-Hop Flow Routing

Maximize: Q

where $\boldsymbol{Q \leq f_{v_i \to v_j}^{s_k}}$

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., $L_{v_i \to v_j} = \{0,1\}$), i.e., **branch-and-bound** is widely used in literatures to obtain optimal solutions.

Performance Evaluation

Parameters, Settings, and Results

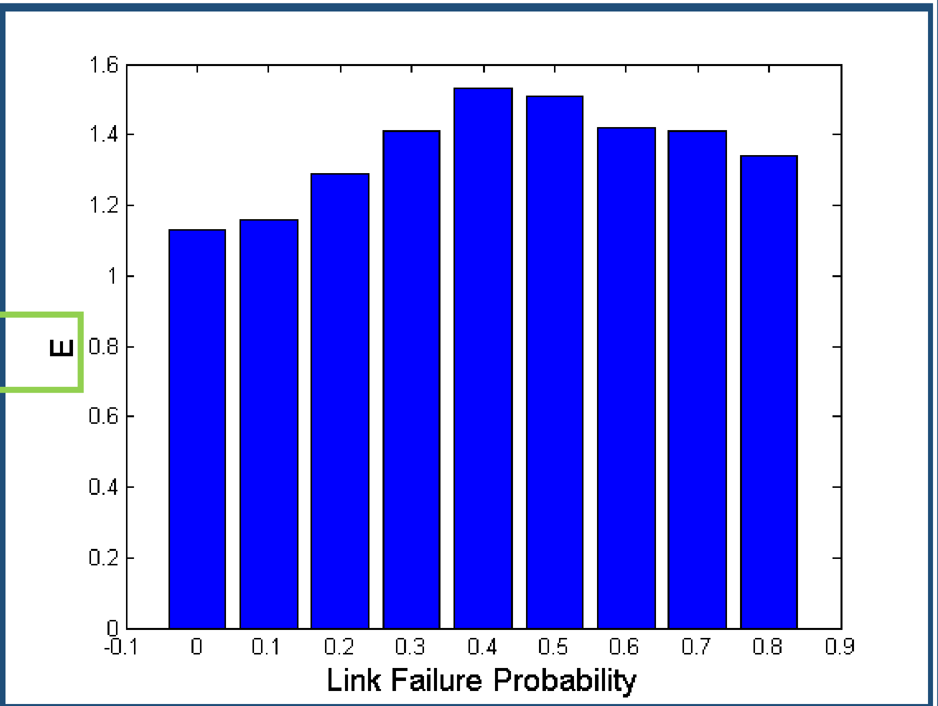
Parameters and Settings

- Parameters
  - Carrier frequency: 38 GHz
  - In 25 dBi Rx antenna (for relays),
    - n is 2.20 in LOS and 3.88 in NLOS
    - σ 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
    - σ 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

$$\frac{E[\,T_{\mathrm{DQC}}|p_k]}{E[\,T_{\mathrm{MmF}}|p_k]}$$



- 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.

Q&A

- For more questions,
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