PhD Final Examination

Analysis of Millimeter Wave Wireless Relay Networks

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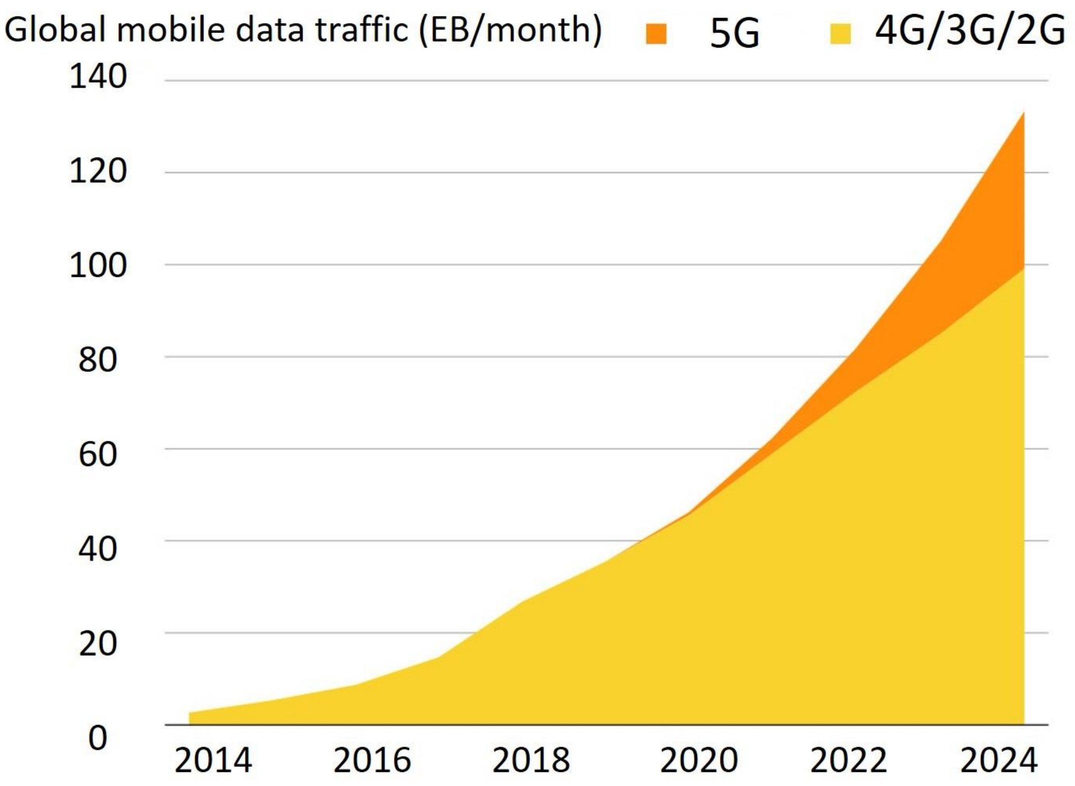
Outline

- Background and Motivation
- Major Contributions of the Thesis
  - Decode-and-forward (DF) relaying
  - Multi-hop relaying
  - Two-way relaying
  - Non-orthogonal multiple access DF relaying
- Conclusion and Future Research

Background

- ❑Rocketing Mobile Data Growth
  - ❑400% increase in 6 years! (2018-2024)



[1] Ericsson Mobility Report, November 2018

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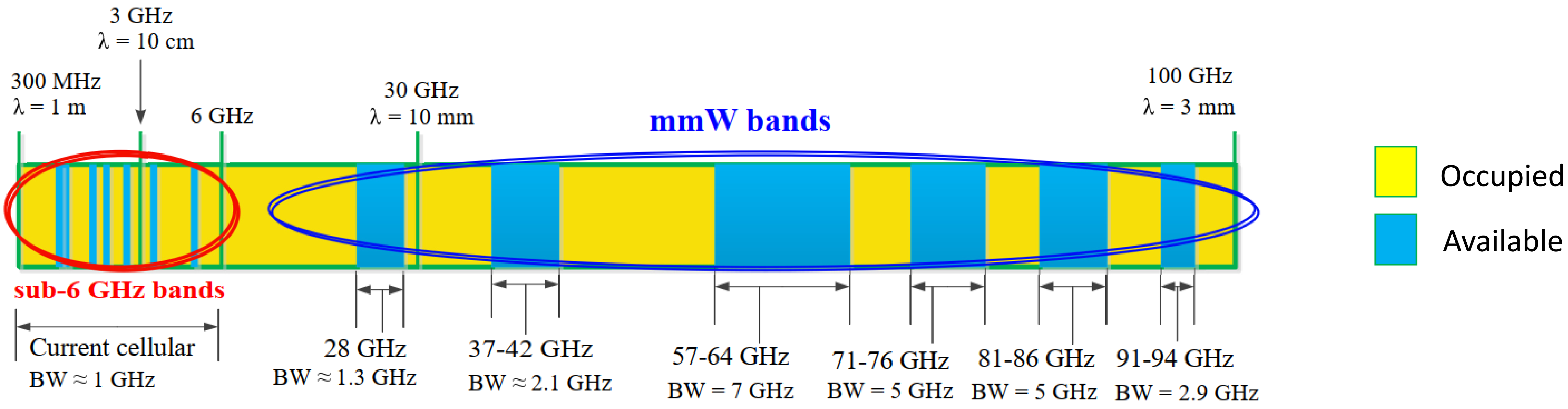
High Data Rates via Millimeter Wave (mmW) Bands



Potential: Huge bandwidth opportunities! → Gbps data rates

Major issues: Path loss and blockage! → limit coverage distance

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Blockage Mitigation via Relays

Relaying can mitigate blockage and improve performance of mmW networks [1, 2, 3].

Major Contributions of the Thesis

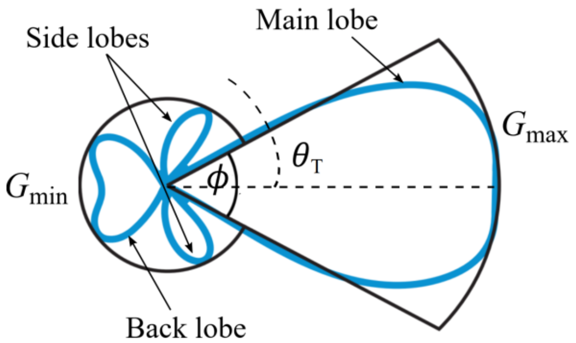
Performance gains due to mmW relays in:

1. Decode-and-forward (DF) networks
2. Multi-hop networks
3. Two-way amplify-and-forward networks
4. Non-orthogonal multiple access DF networks

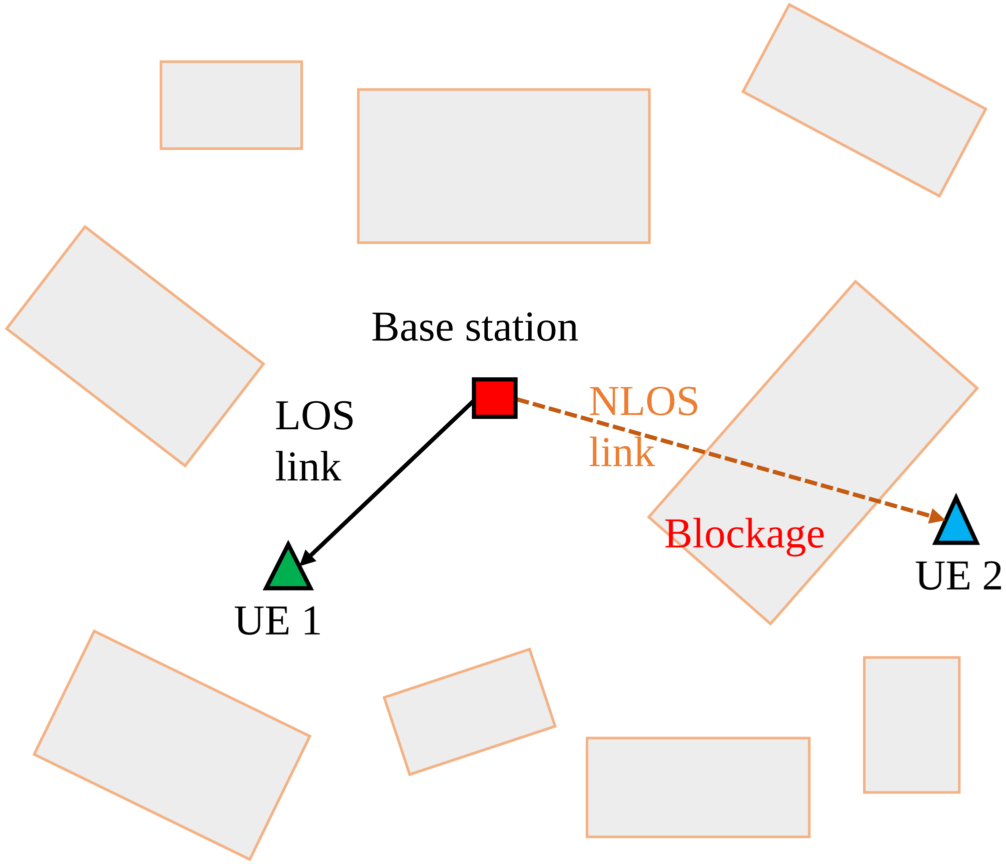
[1] S. Rangan et al., "Millimeter-wave cellular wireless networks: Potential and challenges" *Proc. of the IEEE*, Mar. 2014.
[2] S. Biswas et al.,, "On the performance of relay aided millimeter wave networks," *IEEE J. Sel. Topics Signal Process.*, Apr. 2016.
[3] A. Chelli et al., "On bit error probability and power optimization in multihop millimeter wave relay systems," *IEEE Access*, Jan. 2018.

Key mmW Concepts

- Beamforming



- Blockage
  - Line of Sight (LOS)
  - Non Line of Sight (NLOS)



Research Problem 1:

Decode and Forward Relaying in mmW Networks [1]

[1] K.Belbase et al., “Coverage Analysis of Decode and Forward Networks with Best Relay Selection”, *IEEE Access*, June 2018

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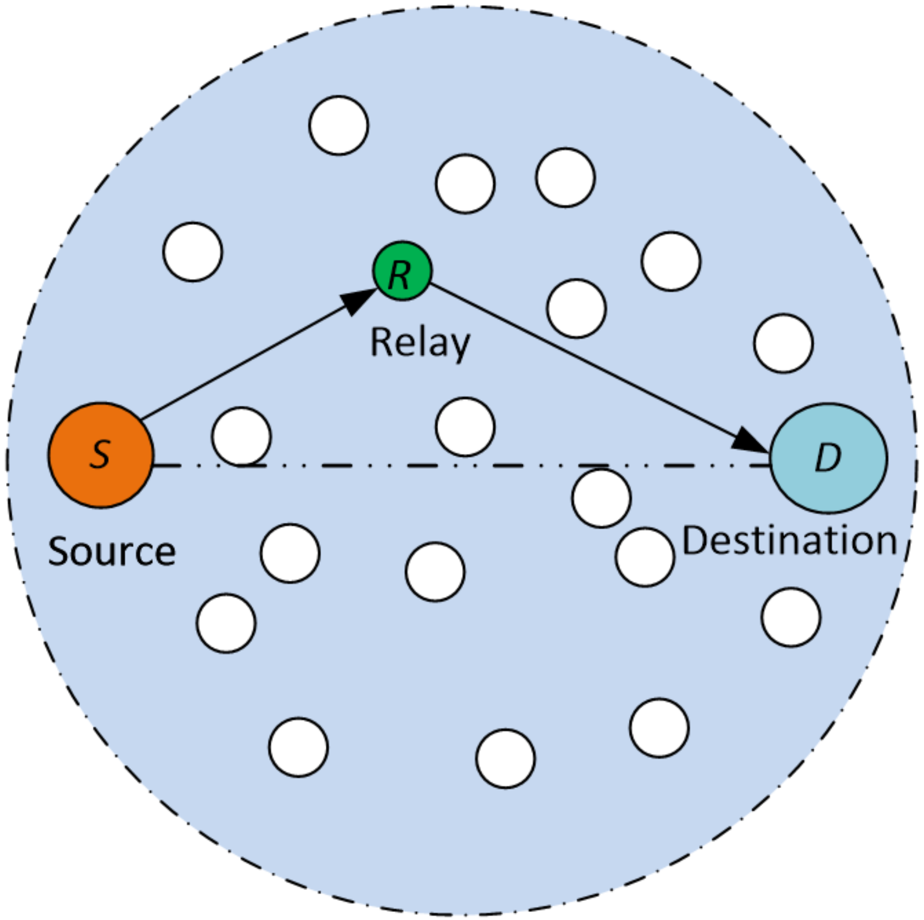
Problem Statement

What is:

- coverage without relay?
- coverage due to random relay selection?
- coverage gain due to best relay selection?



Significance of the problem and contribution

- Past Works:
  - AF relaying [1], no small-scale fading
  - D2D relaying [2], no small-scale fading, no NLOS

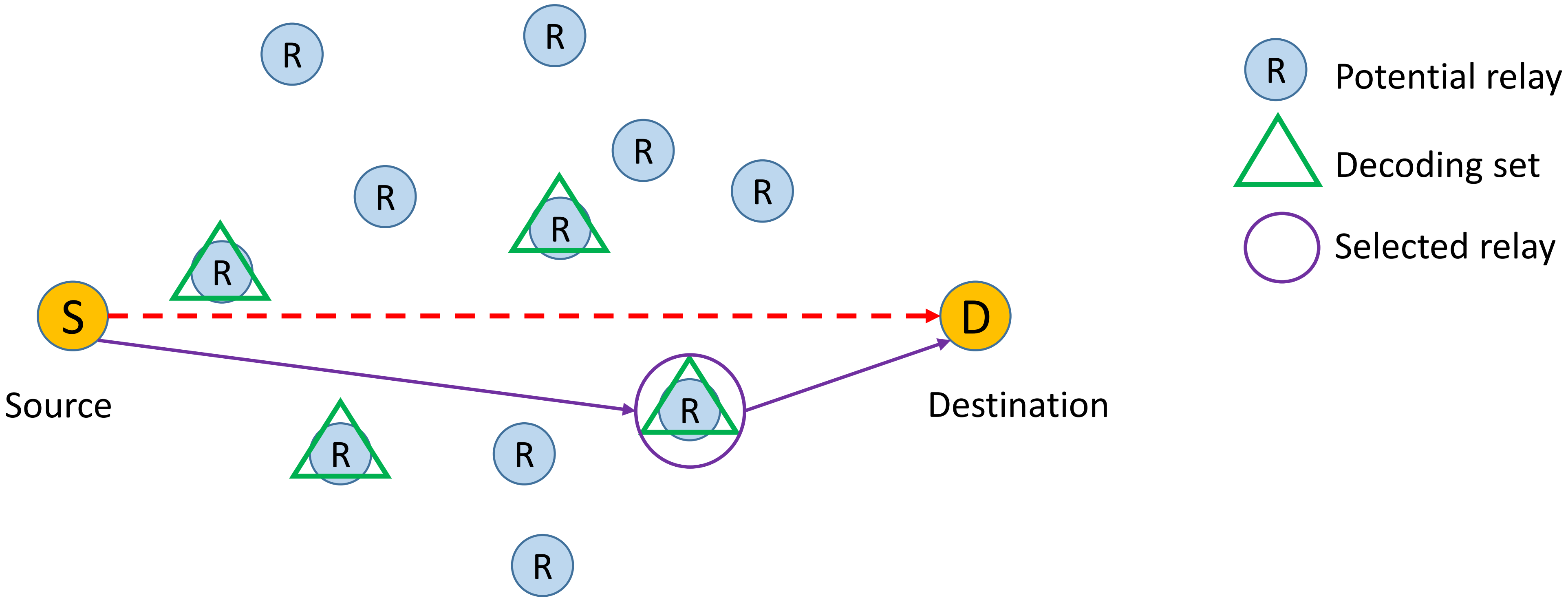
This Work:

- DF networks
- best relay selection
- spatial randomness
- small-scale fading
- NLOS paths
- blockage

[1] S. Biswas et al., “On the performance of relay aided millimeter wave networks,” *IEEE J. Sel. Topics Signal Process.*, Apr. 2016.

[2] S. Wu et al., “Improving the coverage and spectral efficiency of millimeter-wave cellular networks using device-to-device relays," *IEEE Trans. Commun.*, 2017

Best Relay Selection



Coverage Probability with Best Relay Selection

$$P_{\text{cov,SRD}} = A_L P_{R,L}(\gamma_{\text{th}}) + A_N P_{R,N}(\gamma_{\text{th}}),$$

where, A_L – probability of selecting a LOS relay
A_N – probability of selecting a NLOS relay

$P_{R,l}(\gamma_{\text{th}}), l \in \{L, N\}$ are given by

$$P_{R,L}(\gamma_{\text{th}}) \approx \sum_{k=1}^{m_L} (-1)^{k+1} \binom{m_L}{k} \int_{\theta=0}^{2\pi} \int_{z=0}^{\infty} e^{-k b_L z^{\alpha_L}} g_{r_L}(z) z dz d\theta,$$

and

$$P_{R,N}(\gamma_{\text{th}}) \approx \sum_{k=1}^{m_N} (-1)^{k+1} \binom{m_N}{k} \int_{\theta=0}^{2\pi} \int_{z=0}^{\infty} e^{-k b_N z^{\alpha_N}} g_{r_N}(z) z dz d\theta,$$

where $b_L = \frac{\eta_L \gamma_{\text{th}} N_0}{P_R \Psi}$, and $b_N = \frac{\eta_N \gamma_{\text{th}} N_0}{P_{\text{R}} \Psi}$.

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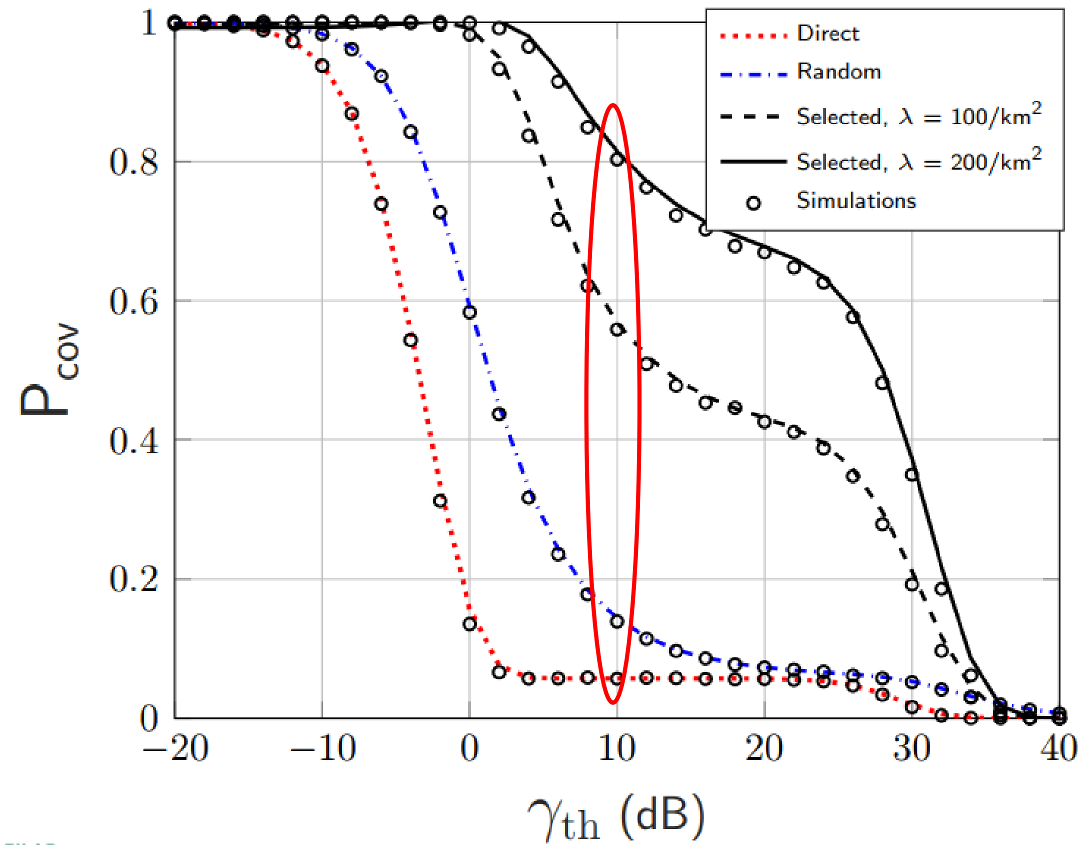
Numerical Results

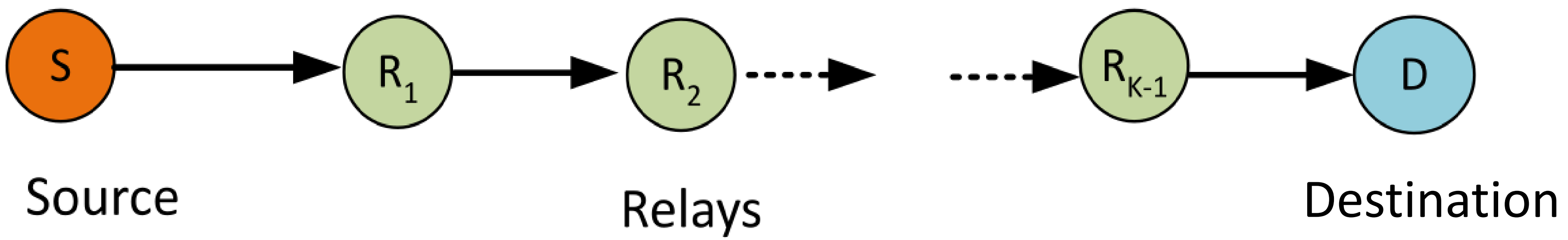


- Small gain due to random relay
- Significant gain due to relay selection
- Increasing relay density increases coverage

Research Problem 2:

Multi-hop DF Relaying in mmW Networks

Problem Statement



Major goals:

1. What will be the coverage, capacity, and symbol error rates?
2. What will be the effect of co-channel interference at relays and destination?

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Significance of the problem and contribution

- Past Works:
  - Multiple works on MAC and Network layers [1,2]
  - In PHY, BEP and power optimization of multi-hop AF [3],
    - ignores blockage
    - ignores NLOS
    - ignores sparse deployments

This Work:

- Multi-hop DF
- small-scale fading
- NLOS paths
- Blockage
- Sparse + dense scenario
- Coverage, Capacity, and SER

[1] J. García-Rois et al., “On the analysis of scheduling in dynamic duplex multihop mmwave cellular systems,” *IEEE Trans. Wireless Commun.*, Nov. 2015.
[2] X. Lin et al., “Connectivity of millimeter wave networks with multi-hop relaying,” *IEEE Wireless Commun. Lett.*, Apr. 2015.
[3] A. Chelli et al., “On bit error probability and power optimization in multihop millimeter wave relay systems,” *IEEE Access*, Jan. 2018.

Sparse Deployment (Noise Limited Case)

PDF of destination SNR

$$f_{\gamma_{\text{eq}}}(x) = \sum_{\mathbf{s}} p^{w(\mathbf{s})} q^{K-w(\mathbf{s})} \left(\frac{1}{\bar{\gamma}}\right) \mathrm{e}^{-\frac{\Lambda_{\mathbf{s}} x}{\bar{\gamma}}} \left(\Lambda_{\mathbf{s}} \sum_{m=0}^{\hat{k}} \mu_m^{\mathbf{s}} \left(\frac{x}{\bar{\gamma}}\right)^m - \sum_{m=1}^{\hat{k}} m \mu_m^{\mathbf{s}} \left(\frac{x}{\bar{\gamma}}\right)^{m-1} \right)$$

where,

p = LOS probability of a given hop
q = NLOS probability of a given hop
K = total number of hops
$\mathbf{s}$ = total number of link states
$w(\mathbf{s})$ = weight of end-to-end link states
$\Lambda_{\mathbf{s}} = \lambda_1^{s_1} + \cdots + \lambda_K^{s_K}$
$\hat{k} = \sum_k \alpha_k - K$

Use this PDF to derive:

- Coverage Probability
- Ergodic Capacity
- Asymptotic Capacity
- Symbol Error Rate (SER)

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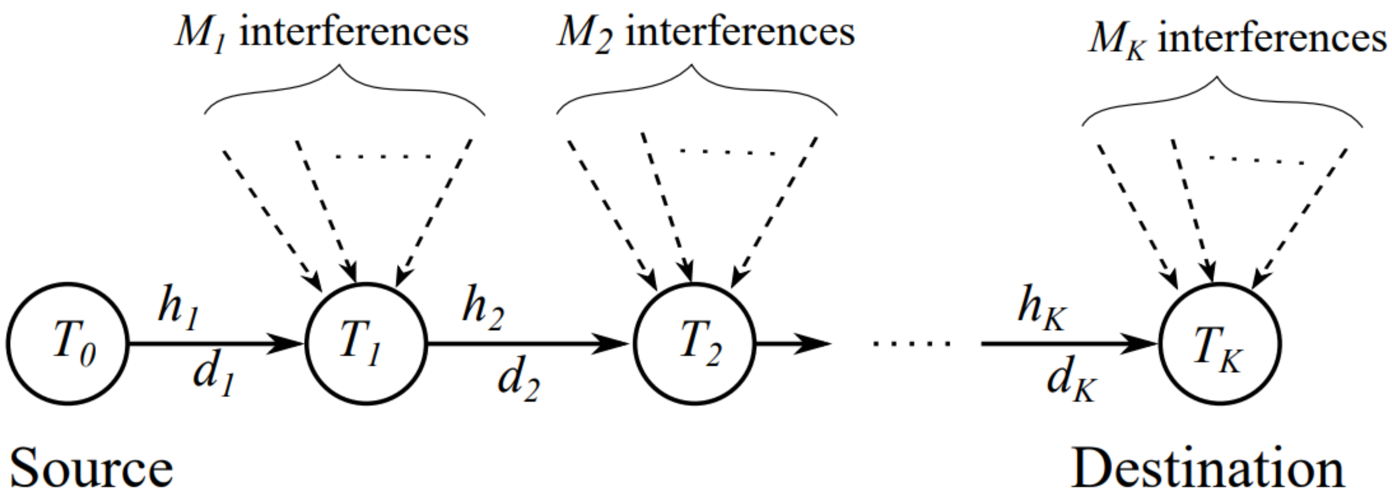
Dense Deployment (Interference Limited Case)



Two cases:

- Interferers at T_k are i.i.d.
- Interferers at T_k are i.n.i.d.

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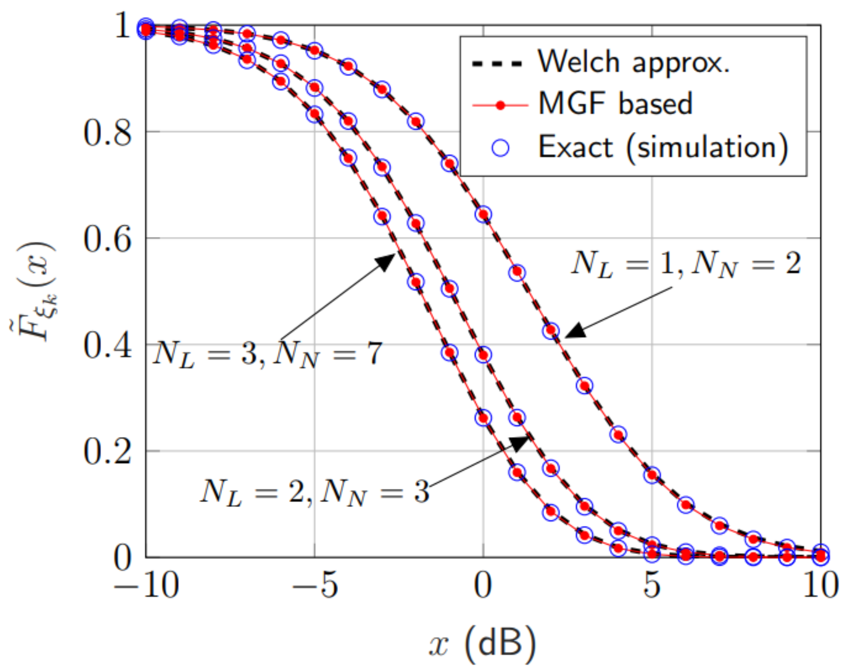
Distribution of sum of i.n.i.d. Gamma r.v.s

- MGF Based approach: for integer shape parameters

$$\tilde{F}_{\xi_k}(x) = \sum_{m=0}^{\alpha_k - 1} \frac{(-1)^m (x\lambda_k/\zeta_k)^m}{m!} \mathcal{M}_{I_k}^m (x\lambda_k/\zeta_k)$$

- *Welch-Satterthwaite Approximation*

Let $Y = X_1 + X_2 + \cdots + X_{M_k}$, with mutually independent $X_n \sim \mathcal{G}(\alpha_n, \lambda_n)$ for $n = 1, \ldots, M_k$. Then Y is approximately $\mathcal{G}(\alpha_y, \lambda_y)$, where $\alpha_y = \frac{\mu^2}{\sum_{n=1}^{M_k} \alpha_n \lambda_n^2}$, $\lambda_y = \frac{\mu}{\alpha_y}$ and $\mu = \sum_{n=1}^{M_k} \alpha_n \lambda_n$



SIR distribution → i.i.d. interference case

- Very well approximated!
- Used for Ergodic Capacity and SER evaluation

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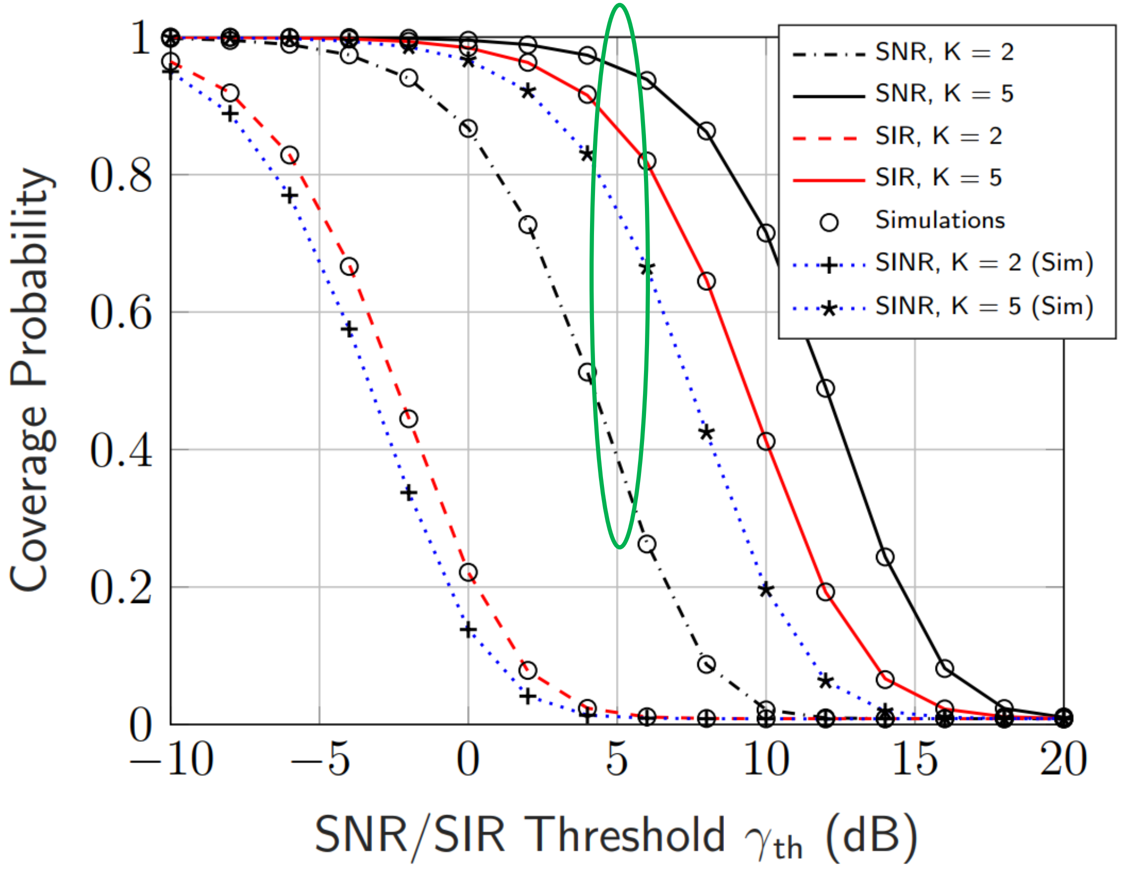
Numerical Results



- SINR results given for comparison
- Coverage improves in each case when going from K=2 to K=5
- Gain of 40% to 95% from K=2 to K =5 for 5 dB SNR threshold

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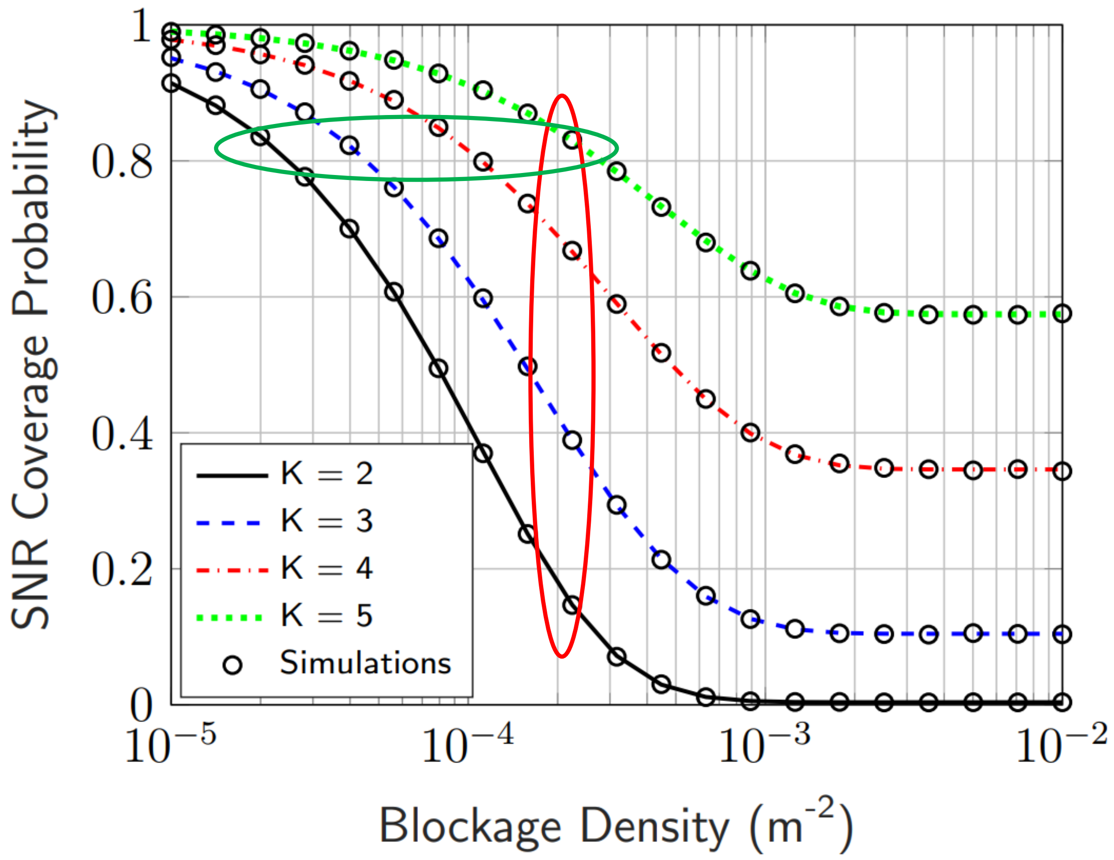
Coverage vs Blockage



Increase in K mitigates blockage

> 300% gain from K=2 to K=5!

Research Problem 3:

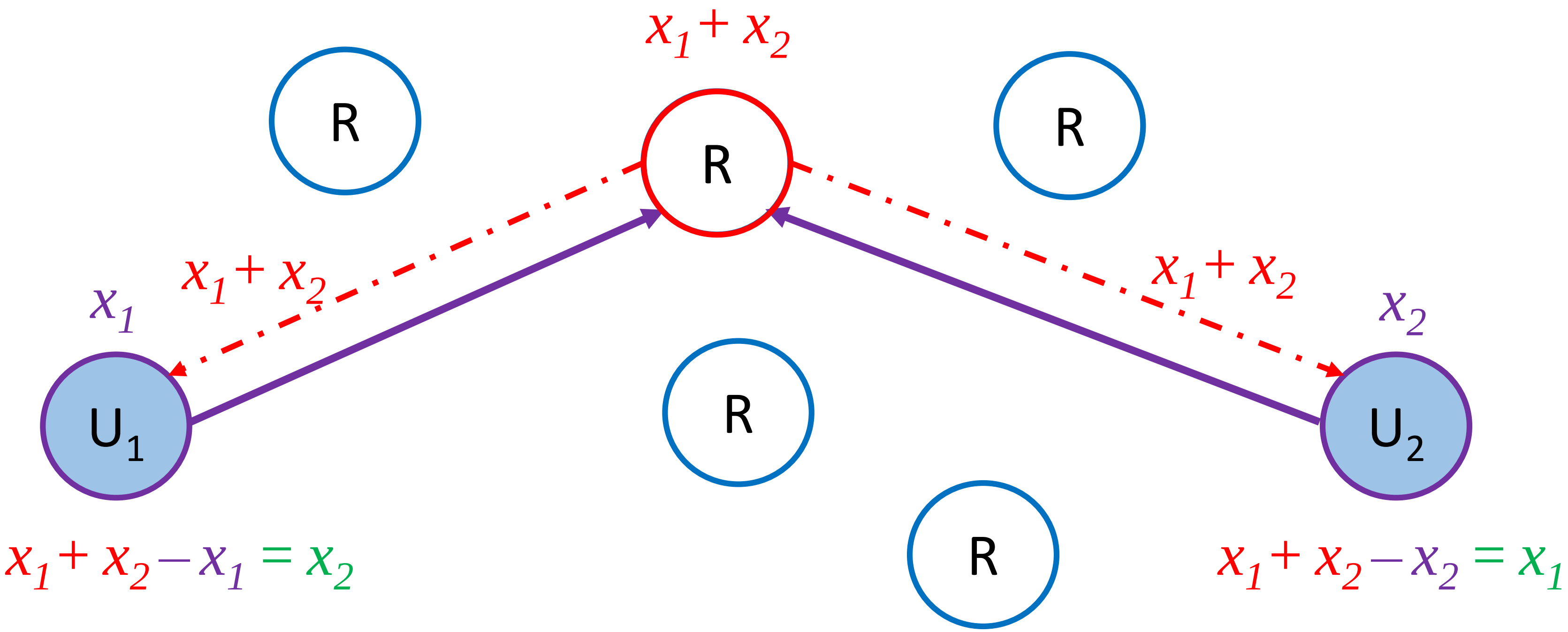
Two-way Relaying in mmW Networks [1]

[1] K. Belbase et.al "Two-way Relay Selection in Millimeter Wave Networks," IEEE Communications Letters, Jan. 2018

Two-way Relays

Problem with one way relay – 4 time-slots to exchange two user message

Two-way relay can do it in 2 time slots – doubles SE compared to one-way



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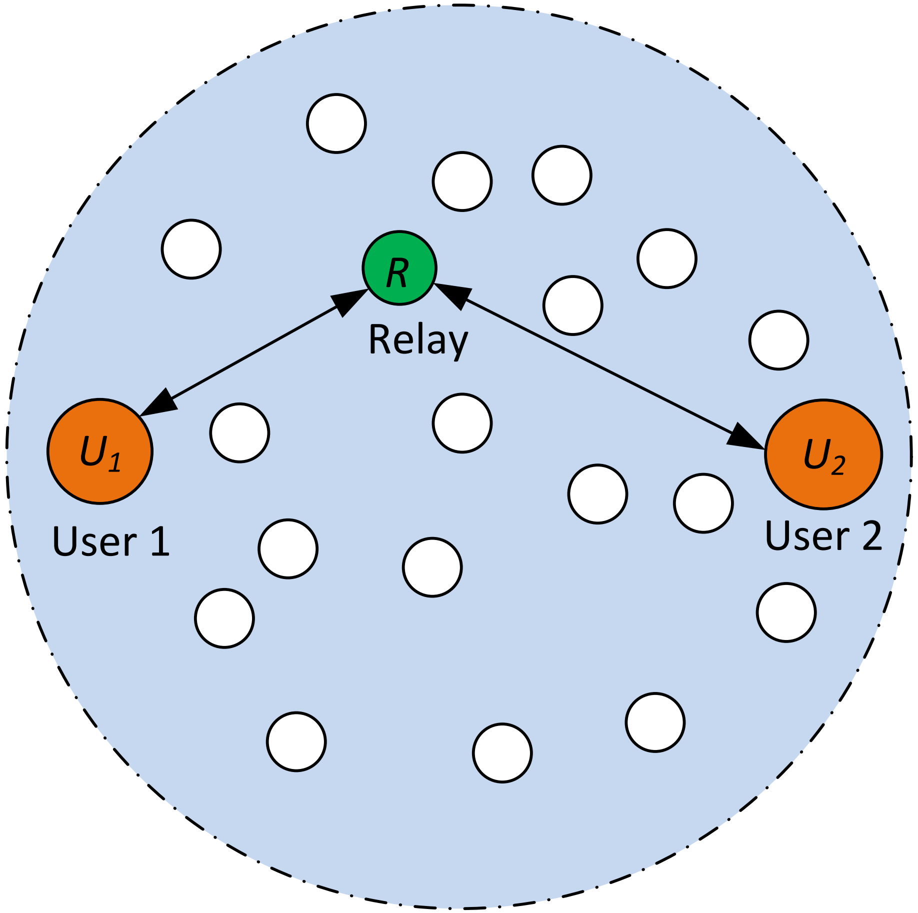
Problem Statement

Major goal:

What is coverage gain due to relay selection?



Significance of the problem and contribution

- Many existing works on sub-6 GHz – not directly applicable
- Two-way mmW relay [1] – beamforming design aspects but no relay selection, no spatial randomness

- This Work:
  - Two-way AF relays
  - Log-normal shadowing
  - Relay selection
  - Spatial randomness
  - Blockage

[1] S. Gong et al., "Millimeter-Wave Secrecy Beamforming Designs for Two-Way Amplify-and-Forward MIMO Relaying Networks," IEEE Trans. Veh. Tech., Mar. 2017

Coverage Probability

$$\mathrm{P}_{\mathrm{cov}} = 1 - e^{-\lambda|\mathcal{S}|}\left(e^{\lambda|\mathcal{S}|\nu} - 1\right)$$

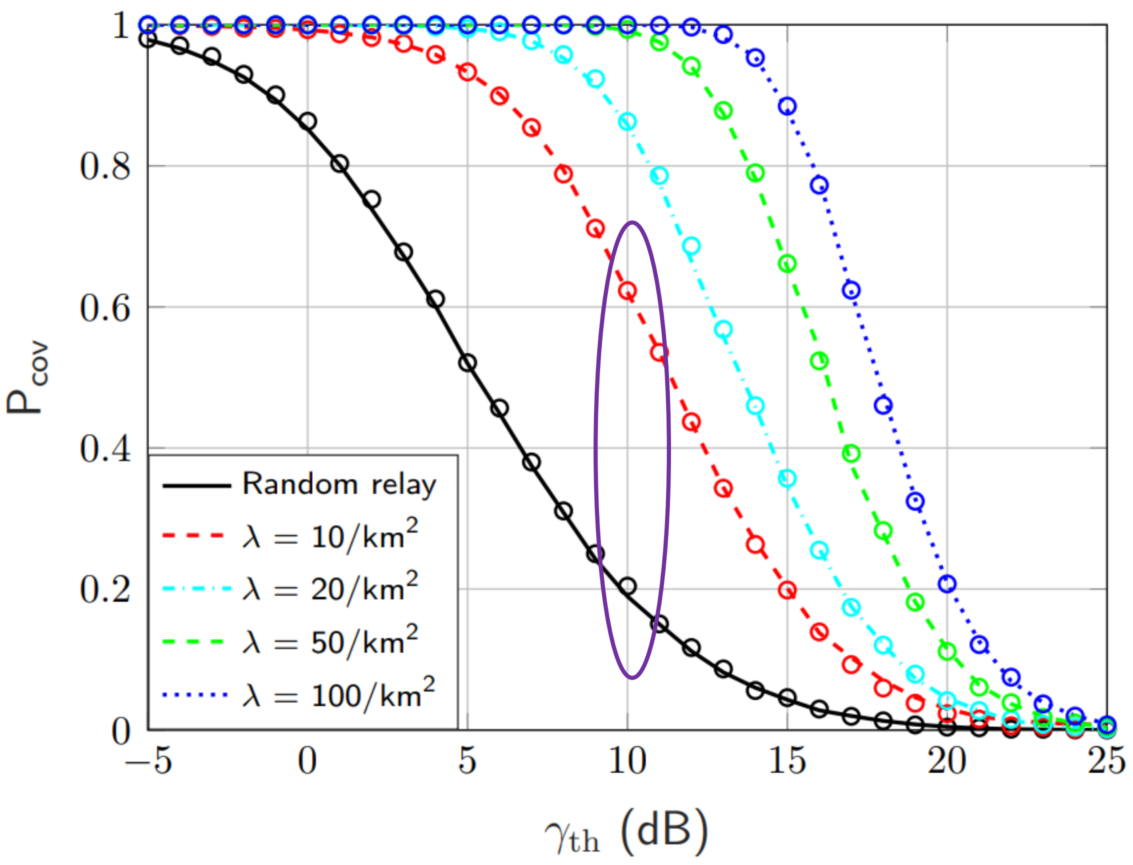
where

$$\nu = \mathbb{E}_z\left[F_{\gamma_z}(\gamma_{th})\right] = \frac{1}{|\mathcal{S}|}\int_0^{2\pi}\int_0^{r_d} F_{\gamma_z}(\gamma_{th}) r dr d\theta$$

where $F_{\gamma_z}(\gamma_{th})$ is the conditional CDF of end-to-end SNR γ_z.

Numerical Results

- 200% coverage gain with selection!
- Gain due to increasing density



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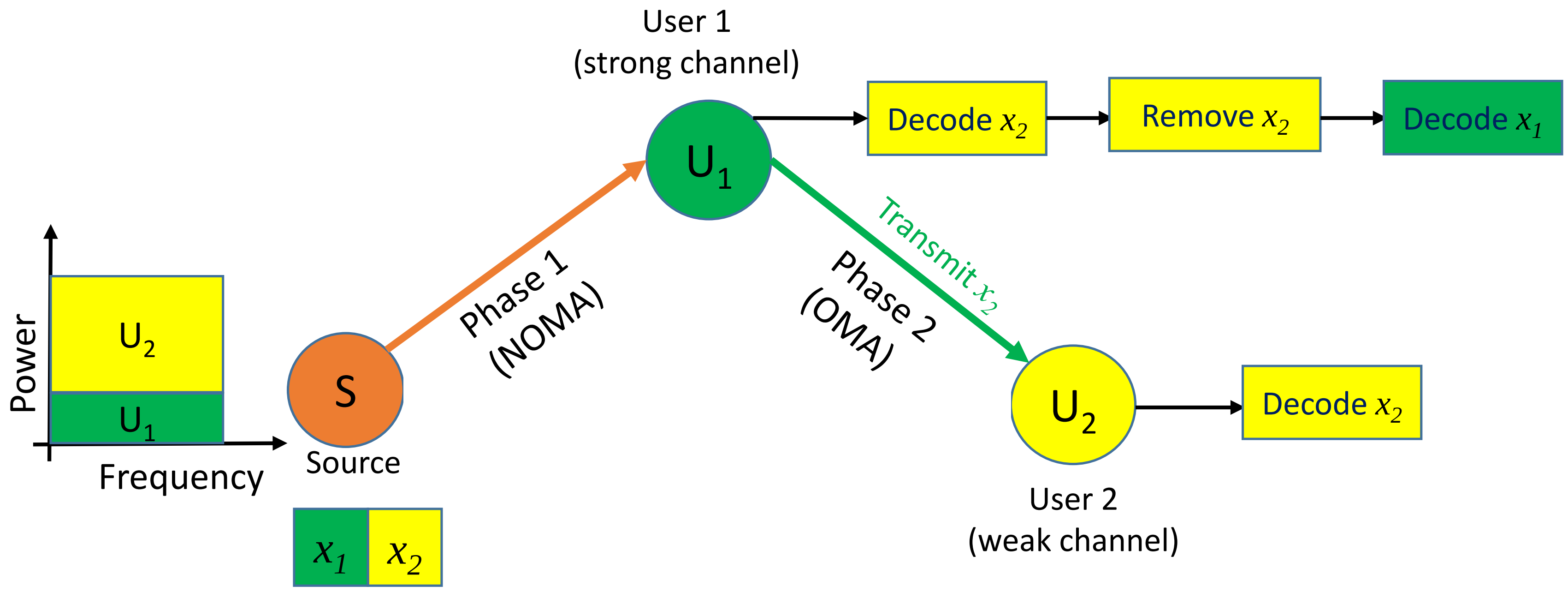
Research Problem 4:

Cooperative NOMA in mmW Networks

Cooperative NOMA Operation



- 3 time-slots in OMA vs 2 time-slots using NOMA

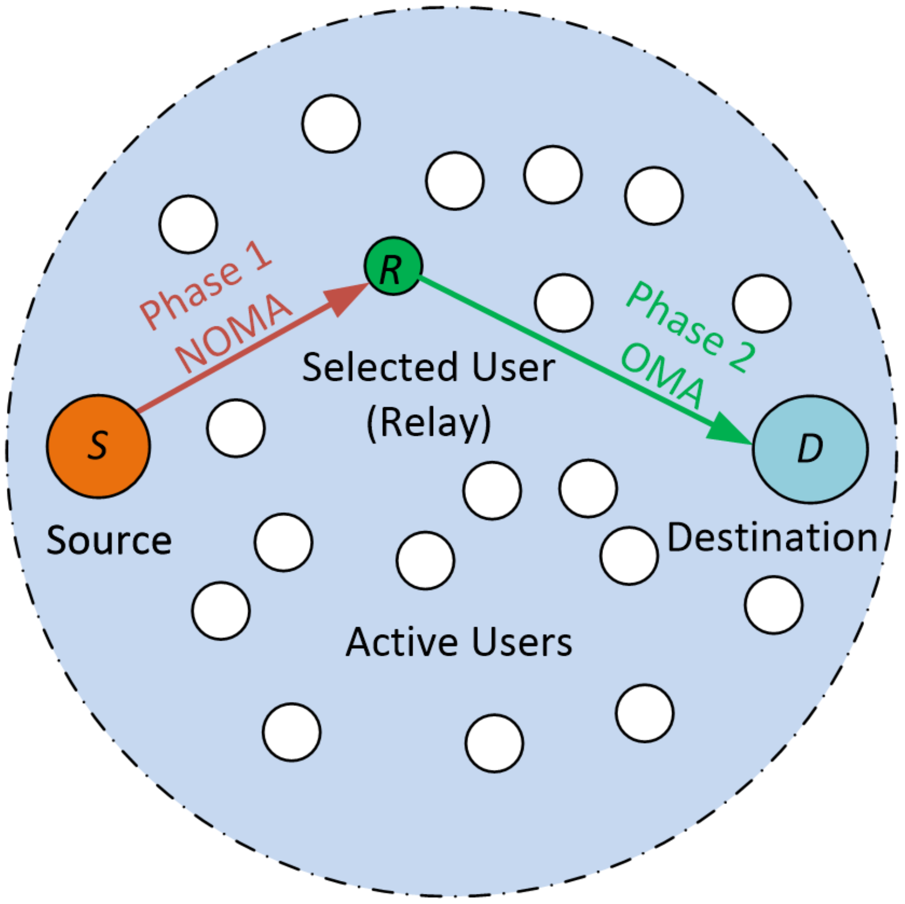
Problem Statement

3 Relay Selection Schemes

- Nearest-to-source selection (Scheme S_1)
- Nearest-to-destination selection (Scheme S_2)
- Random Selection (Scheme S_3)

Major goal:

What is the coverage due to different relay selection schemes?



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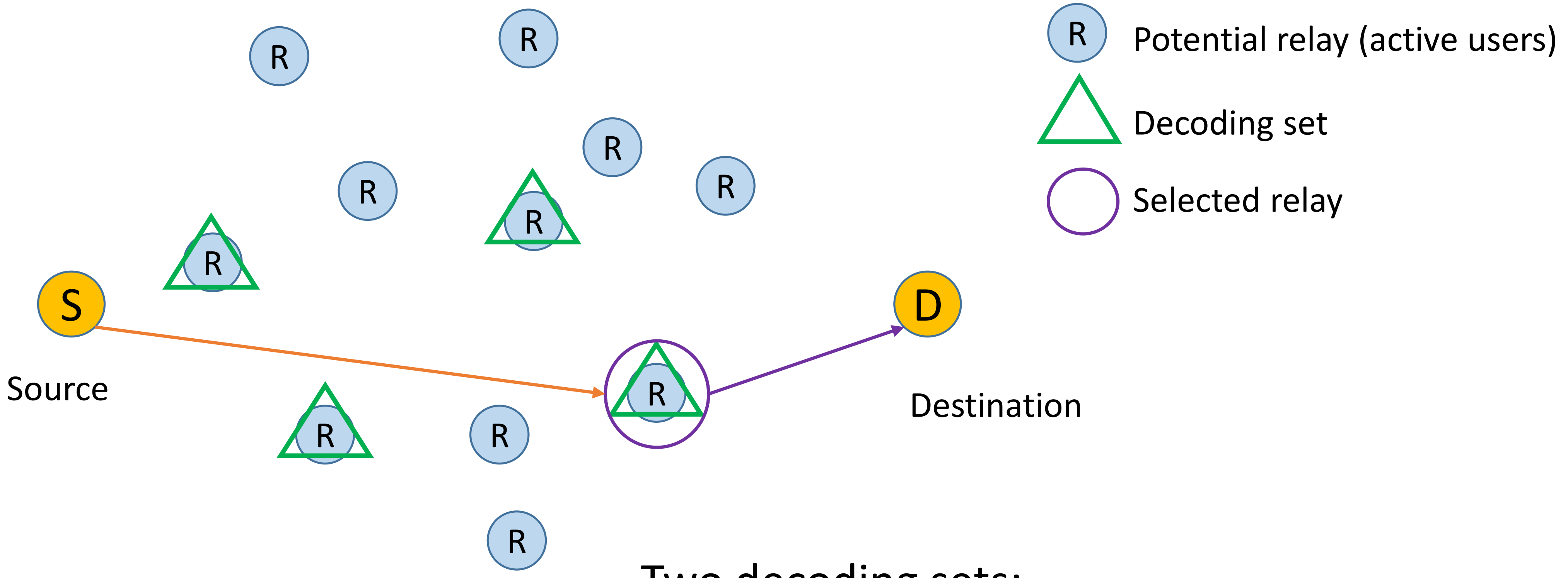
Significance of the problem and contribution

- Improved spectral efficiency with NOMA
- Use of mmW relays to mitigate blockage
  - ➢ Joint use of NOMA and relays can achieve both
- Existing works
  - Cooperative NOMA [1] – not applicable in mmW, fixed relays
  - mmW NOMA [2] – do not include relaying

- This Work:
  - Cooperative NOMA with DF relays
  - Small scale fading
  - Spatial randomness
  - Blockage
  - Different relay selection schemes

[1] Z. Ding et al., "Relay Selection for Cooperative NOMA," IEEE Wireless Commun. Lett., Aug. 2016
[2] Y. Zhou et al., "Coverage and rate analysis of millimeter wave NOMA networks with beam misalignment," IEEE Trans. Commun., Dec. 2018

Relay Selection

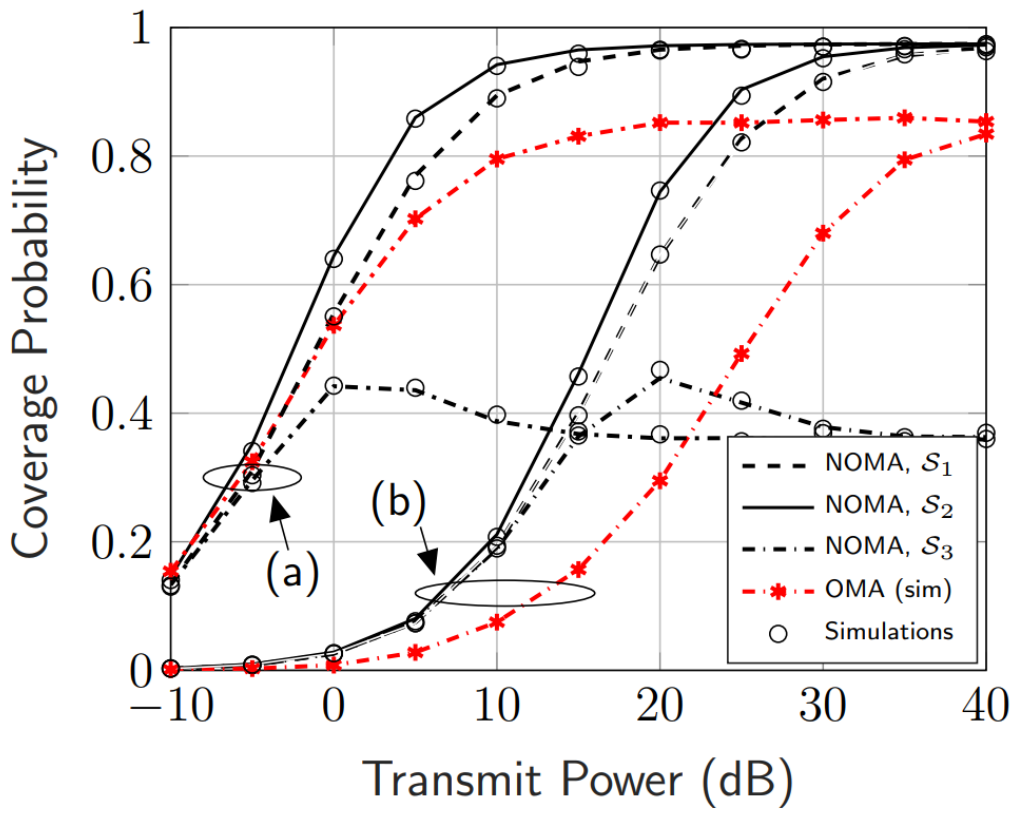


Two decoding sets:

- S_1 decoding set: achieves rate for D
- S_2 and S_3 decoding set: meets rates for R and D in first hop

Numerical Results

- Higher coverage for lower rate requirements
- S_1 and S_2 perform better than orthogonal transmission
- Random relay performs poorly than orthogonal case



(a) $R_D = 1$ and $R_R = 3$ bps/Hz, and (a) $R_D = 1.9$ and $R_R = 6$ bps/Hz

Conclusion and Future Research

Conclusion

- Coverage and rate of **a DF relay network** – minimum path loss relay
- Coverage, capacity and SER of **a multi-hop DF relay network** – noise-limited and interference-limited scenarios
- Coverage and rate of **a two-way AF relay network** – relay with best SNR at both users,
- Coverage and rate of **a cooperative NOMA network** – three relay selection schemes

Future Research

- Interference analysis of mmW DF relay network

- Stochastic geometry based interference analysis of multi-hop relay network

- SER of M-QAM modulation schemes in interference limited multi-hop network

Thank you!