Scalable Two-hop Relaying for mmWave Networks

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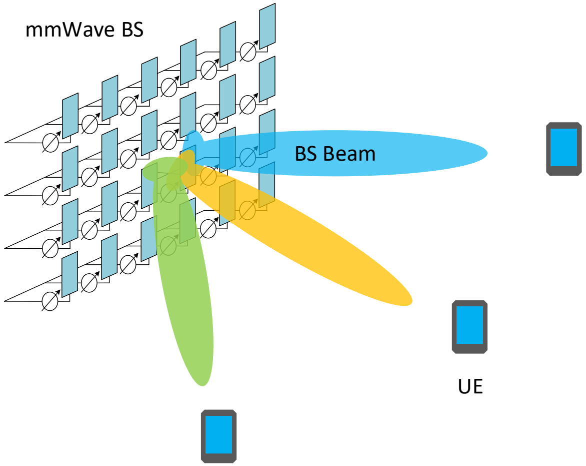
Outline

- Cellular mmWave communication and its challenges
- System model for mobile mmWave relaying
- Two-hop LOS probability
- Relay & beam discovery and selection protocol
- Relaying overhead analysis and reduction
- Performance evaluation

Cellular mmWave communication and its challenges

- **Path loss due to aperture** -> large antenna array required
- **Large antenna array** -> hybrid or analog architecture required
- **Diffraction not significant** -> sensitive to blockages
- **Huge penetration loss** -> LOS condition/strong reflection is crucial
- **Dense deployment**[1] for full coverage -> high CAPEX and OPEX

Building footprint in urban scenario[2]



mmWave directional transmission

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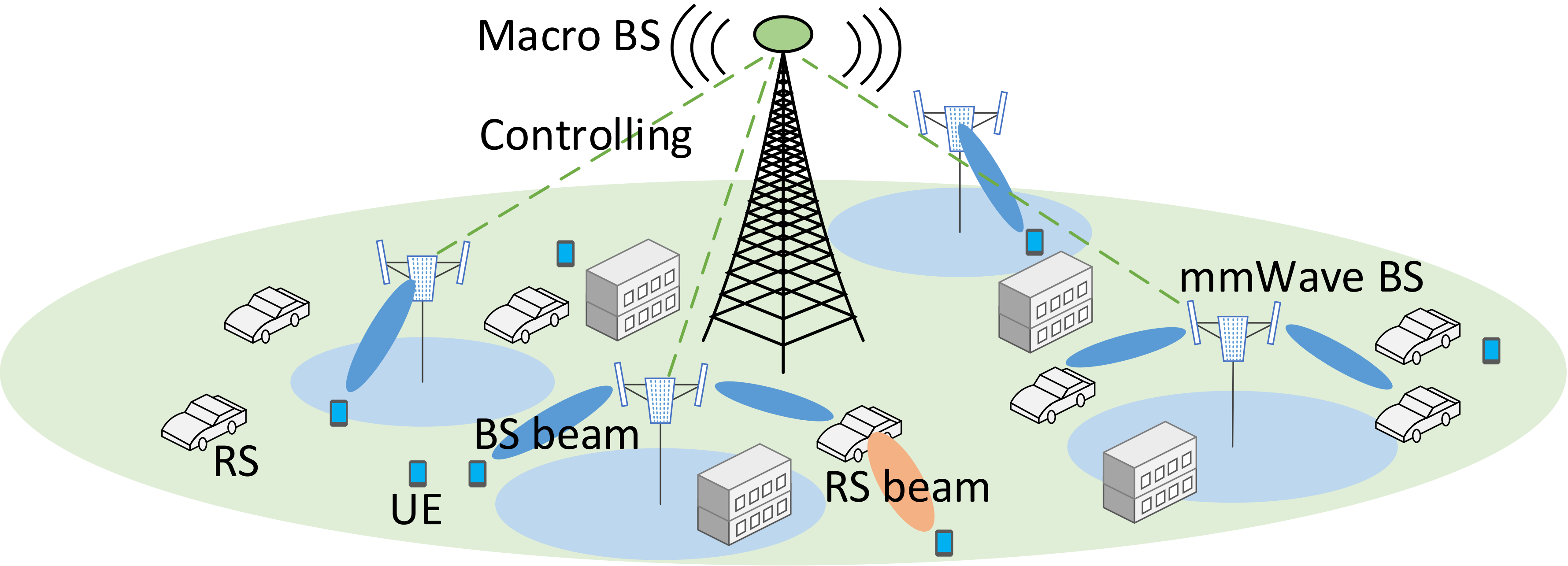
[1] T. Bai and R. W. Heath, "Coverage and Rate Analysis for Millimeter-Wave Cellular Networks," in *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, pp. 1100-1114, Feb. 2015.

[2] https://cesiumjs.org/NewYork/index.html

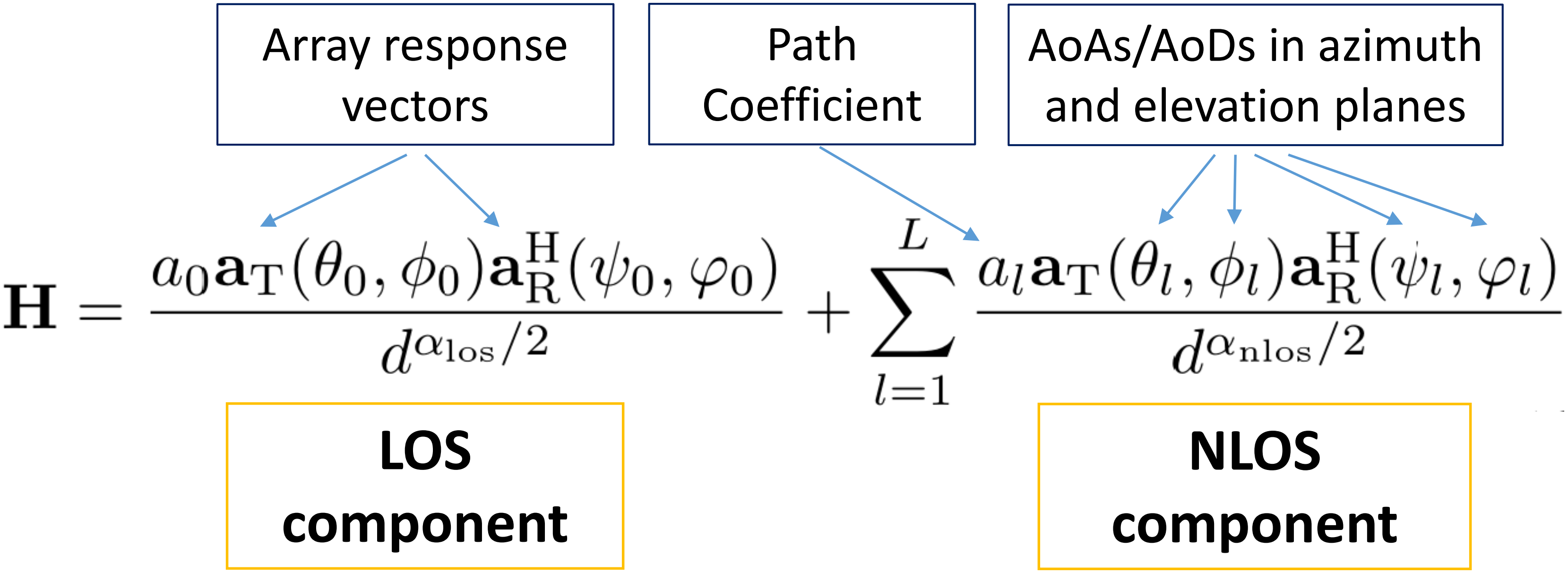
System model for mobile mmWave relaying

- mmWave BSs, mobile relay stations (RS) and UEs
- Controlled by a sub-6 GHz macro cellular network
- Downlink transmission
- BS-to-UE, BS-to-RS and RS-to-UE links



System model for mobile mmWave relaying

- BS: 3 UPA with *M* antennas
- RS: 1 UCA with *N* antennas
- UE: 1 antenna
- Channel: GSCM + LOS/NLOS/outage model



Array response vectors

Path Coefficient

AoAs/AoDs in azimuth and elevation planes

$$\mathbf{H} = \frac{a_0 \mathbf{a}_\mathrm{T}(\theta_0, \phi_0)\mathbf{a}_\mathrm{R}^\mathrm{H}(\psi_0, \varphi_0)}{d^{\alpha_\mathrm{los}/2}} + \sum_{l=1}^{L} \frac{a_l \mathbf{a}_\mathrm{T}(\theta_l, \phi_l)\mathbf{a}_\mathrm{R}^\mathrm{H}(\psi_l, \varphi_l)}{d^{\alpha_\mathrm{nlos}/2}}$$

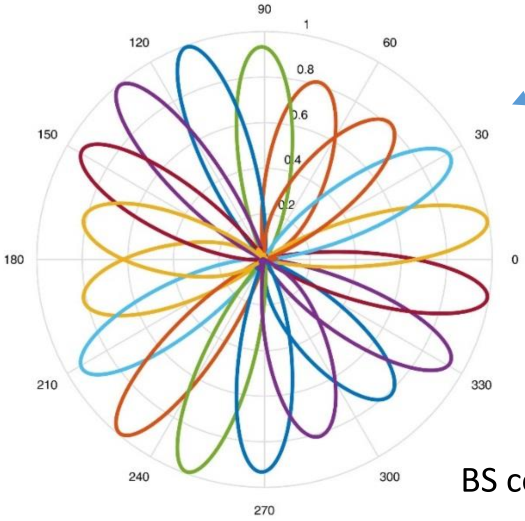
LOS component

NLOS component

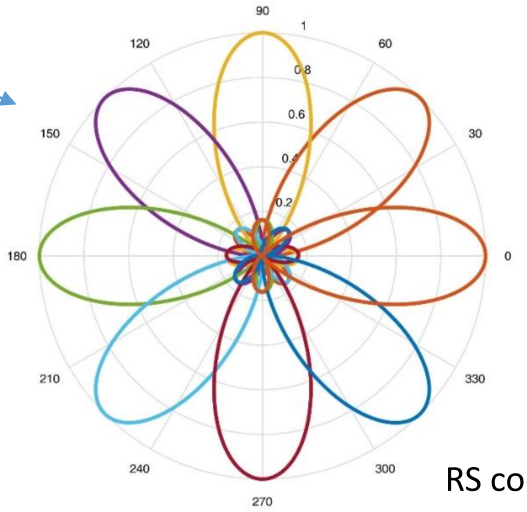
System model for mobile mmWave relaying

- ABF with fixed beams is used for training and transmission
- BS: a codebook of L_{BS} beams
- RS: a codebook of L_{RS} beams
- Received power increases as L_{BS} or L_{RS} increases
- System overhead increases as L_{BS} or L_{RS} increases

$$\boxed{P = \|\mathbf{w}_{(n)}^{\mathrm{H}} \mathbf{H}^{\mathrm{H}} \mathbf{b}_{(m)}\|^2 \|\mathbf{x}\|^2}$$



BS codebook

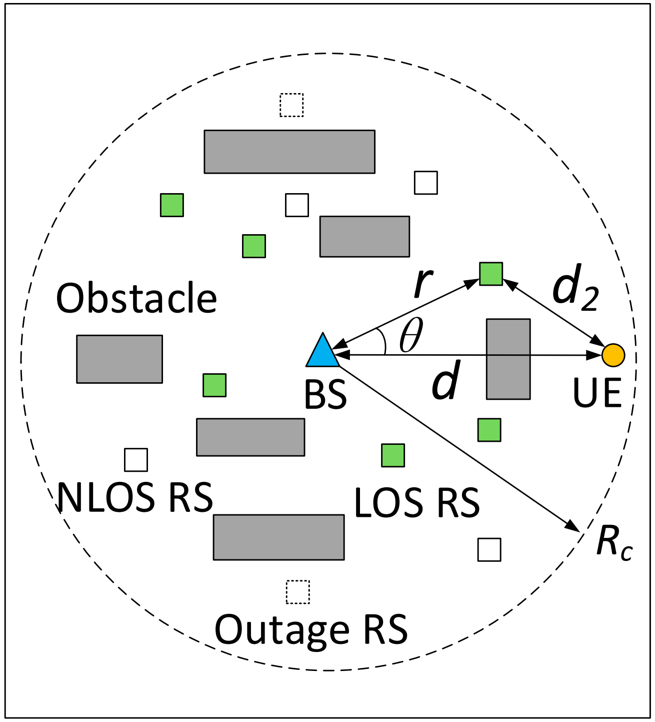


RS codebook

Two-hop LOS probability for mmWave relaying

- **One-hop LOS** probability[3]

$$\begin{aligned} p_{\text{out}}(d) &= \max(0, 1 - e^{-a_{\text{out}}d + b_{\text{out}}}) \\ p_{\text{los}}(d) &= (1 - p_{\text{out}}(d))e^{-a_{\text{los}}d} \ , \\ p_{\text{nlos}}(d) &= 1 - p_{\text{out}} - p_{\text{los}}(d). \end{aligned}$$



- **Two-hop LOS** analysis based on one-hop LOS probability. Consider a cell with radius R_c and RS set $\mathcal{R}_0$, assuming LOS condition $\xi(i, j)$ between node *i* and *j* is independent, the two-hop LOS probability is a function of the size of $\mathcal{R}_0$

$$\begin{aligned} p_{\text{2los}}(d) &= 1 - \prod_{j=1}^{|\mathcal{R}_0|} \mathbb{P}\Big(\xi(b, j) \neq 0 \text{ or } \xi(j, k) \neq 0\Big) \\ &= 1 - \left(\int_0^{2\pi} \int_0^{R_c} \frac{r}{\pi R_c^2} \left(1 - p_{\text{los}}(r) p_{\text{los}}(d_2)\right) dr d\theta \right)^{|\mathcal{R}_0|} \end{aligned}$$

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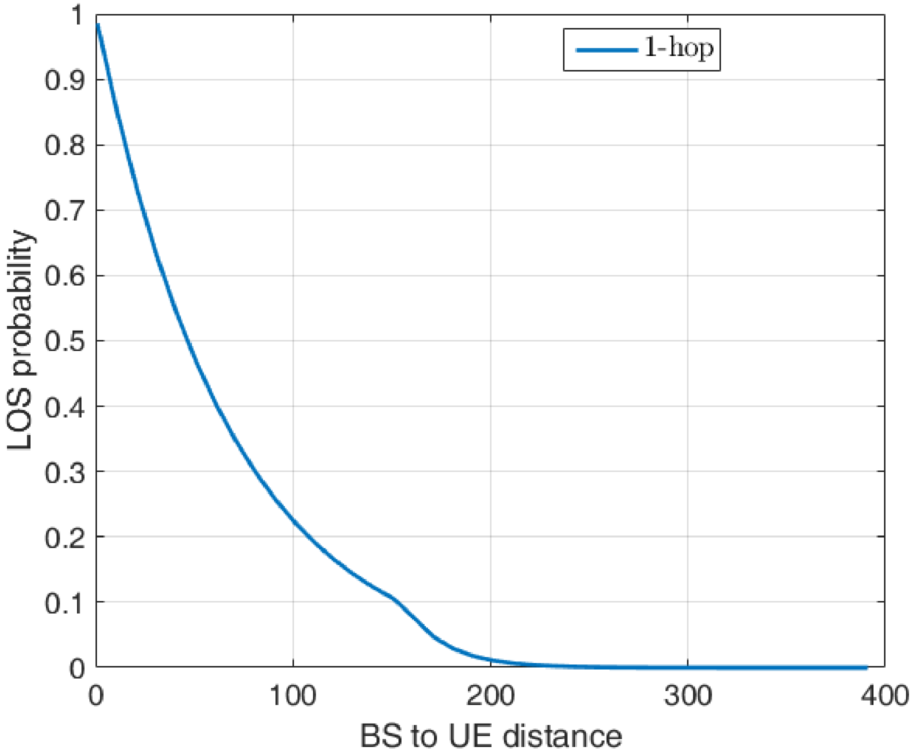
[3] M. R. Akdeniz et al., "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," IEEE J. Sel. Areas Commun. , vol. 32, no. 6, pp. 1164-1179, June 2014.

Two-hop LOS probability for mmWave relaying

- mmWave communication suffers severe **blockage effect**
- **Key idea of relaying**: create two-hop LOS connection for blocked UEs

  - ➢ Large number of cell-edge UEs can not find direct LOS connection to BS
  - ➢ Dense deployment or relays can improve the mmWave network performance



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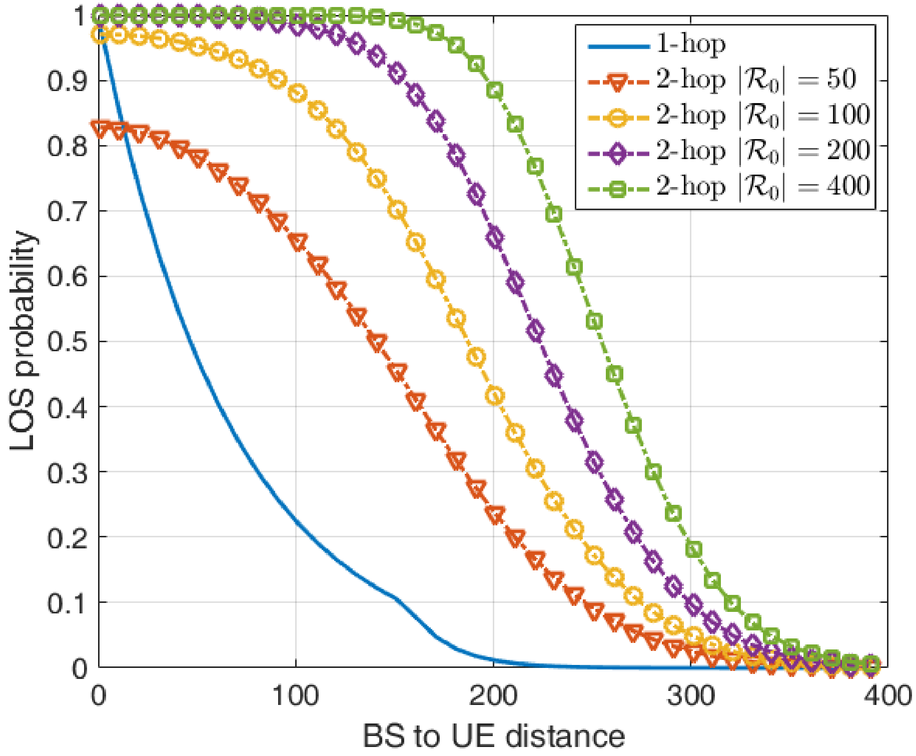
[3] M. R. Akdeniz et al., “Millimeter Wave Channel Modeling and Cellular Capacity Evaluation,” IEEE J. Sel. Areas Commun. , vol. 32, no. 6, pp. 1164-1179, June 2014.

Two-hop LOS probability for mmWave relaying

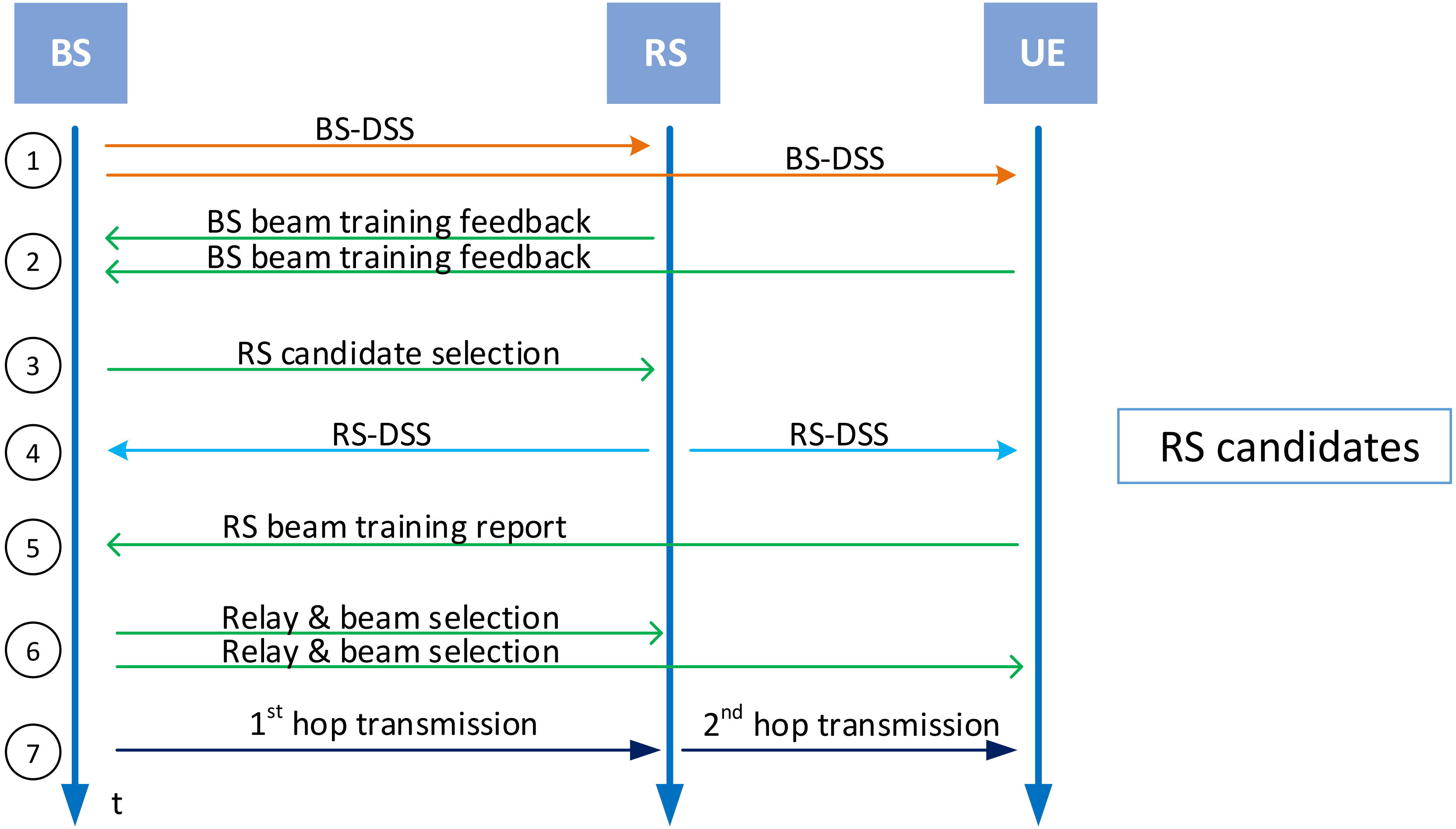
- mmWave communication suffers severe **blockage effect**
- **Key idea of relaying**: create two-hop LOS connection for blocked UEs

  - ➢ Two-hop LOS probability increases as the density of RSs increases
  - ➢ However, the relay & beam discovery and selection overhead also increases as number of RSs increases



Relay & beam discovery and selection protocol

- **BS-DSS**: BS Directional Search Signals transmitted by BSs periodically
- **RS-DSS**: RS Directional Search Signals transmitted by RS candidates periodically



Relaying overhead analysis and reduction

- **LOS coherence time** T_{los} : during which LOS condition is unchanged
- **Beam coherence time** T_{beam} : during which optimal beam is unchanged
- **Minimum signal duration** t_{min}: signal should be long enough to be detected [4]

BS-DSS with period T_b and duration t_b

RS-DSS with period T_r and duration t_r

$$\boxed{T_b\ ,\ T_r\ \ll\ \min\left(T_{\text{los}}\ ,\ T_{\text{beam}}\right)}$$

$$\boxed{t_b\ ,\ t_r\ \geq\ t_{\text{min}} \approx 10\mu s}$$

- ➢ T_{los} and T_{beam} depends on network mobility, beamwidth and blockage distribution
- ➢ T_{los} and T_{beam} in the order of 100 ms with RS/UE speed of 30 km/h
- ➢ Signaling periods T_b and T_r for BS-DSS and RS-DSS should be in the order of 10 ms

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[4] C. N. Barati et al., “Directional initial access for millimeter wave cellular systems,” Asilomar Conference on Signals, Systems and Computers, pp. 307-311, Nov. 2015.

Relaying overhead analysis and reduction

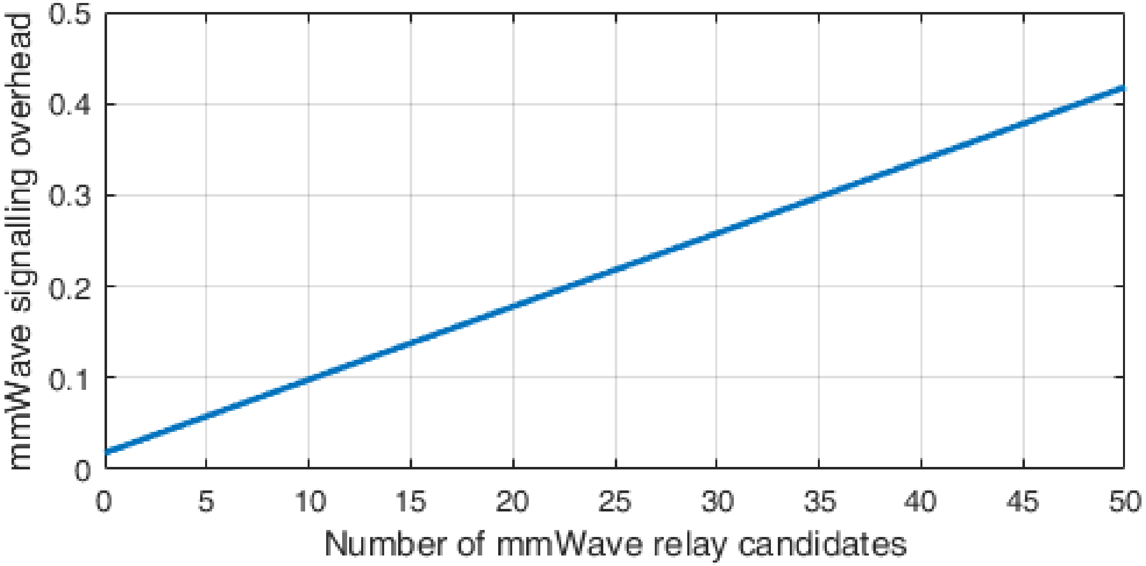
- **Signaling overhead**

Size of BS beam codebook

Size of RS beam codebook

Size of RS candidate set

$$\eta = \frac{L_{\mathrm{BS}} t_{\mathrm{b}}}{T_{\mathrm{b}}} + \frac{L_{\mathrm{RS}} N_{\mathrm{c}} t_{\mathrm{r}}}{T_{\mathrm{r}}}$$



$$t_{\mathrm{b}} = t_{\mathrm{r}} = 10\mu\mathrm{s}$$

$$T_{\mathrm{b}} = T_{\mathrm{r}} = 10\mathrm{ms}$$

Relaying overhead analysis and reduction

- **RS candidate set selection**
  - To exploit the benefit of two-hop LOS transmission for outage/NLOS UEs and to reduce discovery overhead, a set of optimal mmWave RS candidates $\mathcal{R}_{\mathrm{c}} \subseteq \mathcal{R}_0$ needs to be found.
  - We consider $\mathcal{R}_{\mathrm{c}} \subseteq \mathcal{R}_{\mathrm{los}} \subseteq \mathcal{R}_0$, i.e. the RS candidates should be in LOS to BS.
  - The size of $\mathcal{R}_{\mathrm{c}}$ is limited to be smaller than a parameter $\boldsymbol{N_{\max}}$
  - When there are more than $N_{\max}$ LOS RSs, $\mathcal{R}_{\mathrm{c}}$ is selected using a **relay utility function** for each candidate and **a dissimilarity metric** for two candidates in $\mathcal{R}_{\mathrm{c}}$, e.g.

$$u(j) \triangleq \left[L_j/\beta_{\mathrm{los}}\right]^{1/\alpha_{\mathrm{los}}}, \ \mathrm{RS}_j \in \mathcal{R}_{\mathrm{los}}$$

$$s(i,j) \triangleq \mathbb{1}\Big(b_i \neq b_j\Big) + \mathbb{1}\Big(|u(i) - u(j)| > d_{\min}\Big)$$

Relaying overhead analysis and reduction

- **RS candidate set selection**
  - To measure the quality of candidate set $\mathcal{R}_\mathrm{c}$, consider a heuristic **set utility function**

$$U(\mathcal{R}_c) = \sum_{i,j} \underbrace{\boxed{\left(\frac{s(i,j)}{2}+1\right)}}_{\text{dissimilarity coefficients}} \underbrace{\boxed{\frac{u(i)+u(j)}{2}}}_{\text{relay utilities}}$$

  - **RS candidate set selection algorithm**

Algorithm 1 RS candidate set selection algorithm.

```
$\mathcal{R}_\mathrm{c} \leftarrow \mathcal{R}_\mathrm{los}$, $\mathcal{R}_\mathrm{c} = \{\mathrm{RS}_{c_1}, \ldots, \mathrm{RS}_{c_N}\}$ with $N = N_\mathrm{los}$
while $N > N_\mathrm{max}$ do
    $\Delta \leftarrow [0, \ldots, 0]_{1\times N}$
    for $k \leftarrow 1$ to $N$ do
        $\Delta[k] = U(\mathcal{R}_c) - U(\mathcal{R}_c \setminus \mathrm{RS}_{c_k})$
    end for
    $[\Delta_\mathrm{min}, k^*] \leftarrow \min(\Delta)$, $\mathcal{R}_c \leftarrow \mathcal{R}_c \setminus \mathrm{RS}_{c_{k^*}}$, $N \leftarrow N-1$
end while
```

Performance evaluation

Single-stream spectral efficiency

$$\rho = \min\left(\log_2\left(1 + \gamma_{\text{eff}}\frac{P}{I + N_0}\right), \rho_{\max}\right)$$

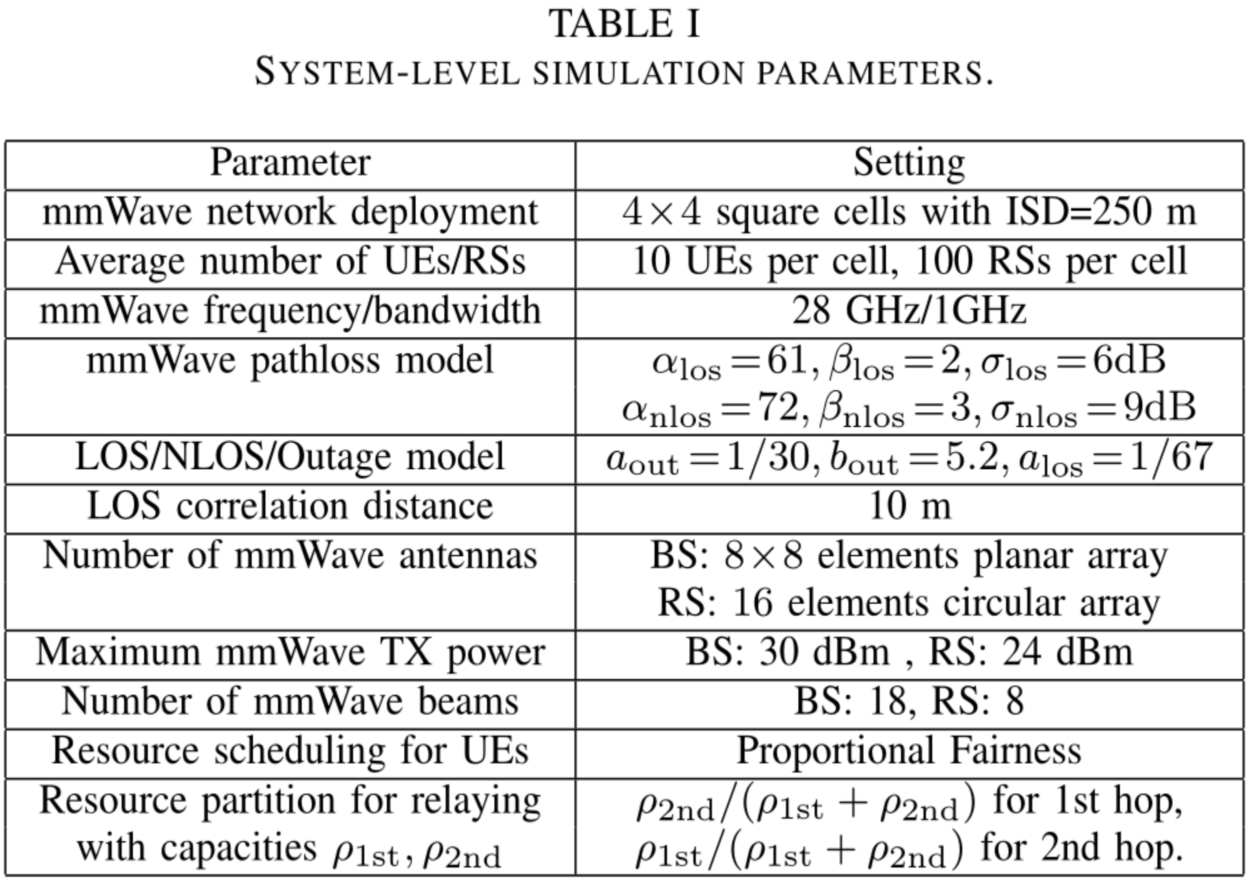
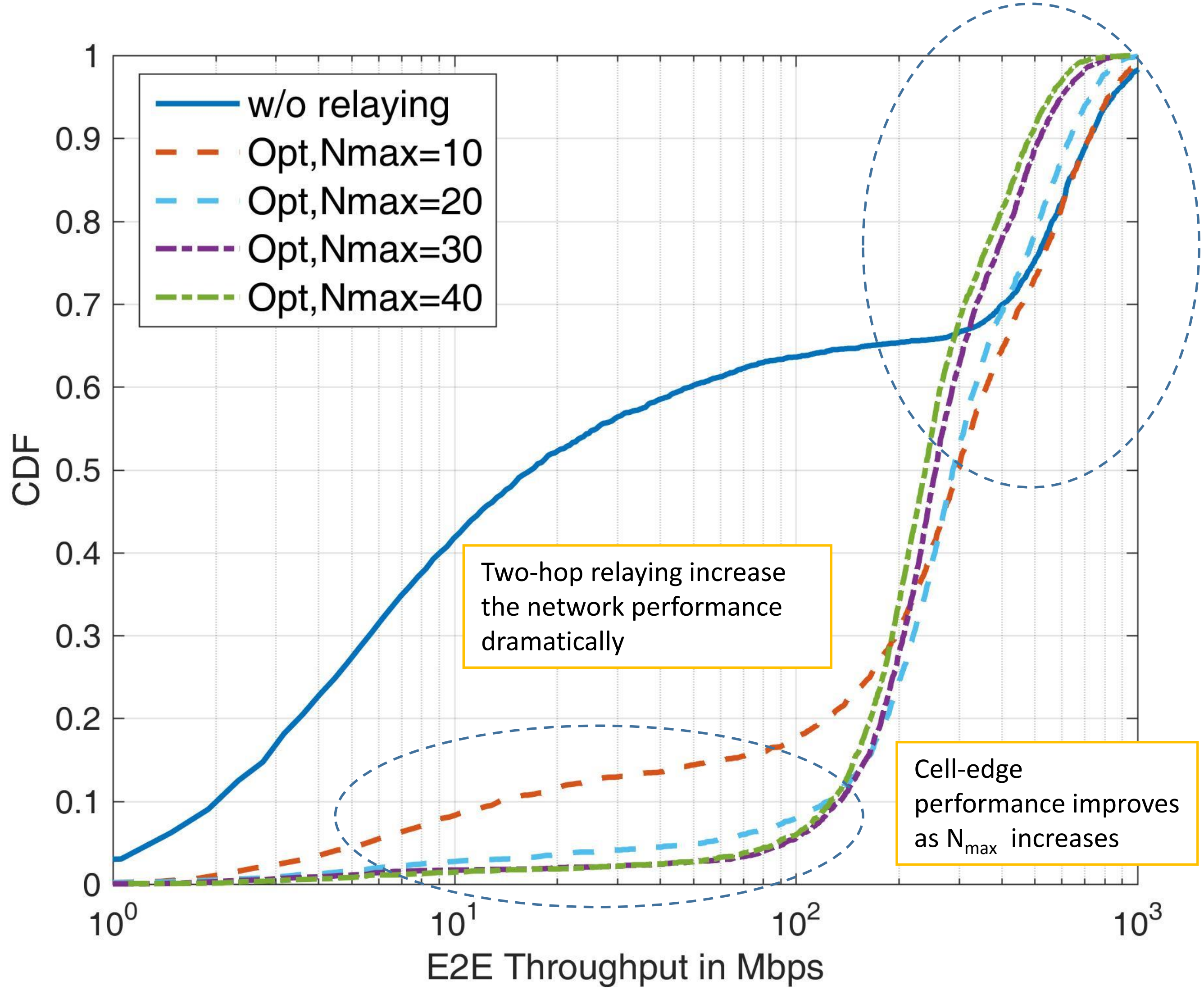


TABLE I
SYSTEM-LEVEL SIMULATION PARAMETERS.

Parameter	Setting
mmWave network deployment	4×4 square cells with ISD=250 m
Average number of UEs/RSs	10 UEs per cell, 100 RSs per cell
mmWave frequency/bandwidth	28 GHz/1GHz
mmWave pathloss model	$\alpha_{\text{los}}=61, \beta_{\text{los}}=2, \sigma_{\text{los}}=6$dB $\alpha_{\text{nlos}}=72, \beta_{\text{nlos}}=3, \sigma_{\text{nlos}}=9$dB
LOS/NLOS/Outage model	$a_{\text{out}}=1/30, b_{\text{out}}=5.2, a_{\text{los}}=1/67$
LOS correlation distance	10 m
Number of mmWave antennas	BS: 8×8 elements planar array RS: 16 elements circular array
Maximum mmWave TX power	BS: 30 dBm , RS: 24 dBm
Number of mmWave beams	BS: 18, RS: 8
Resource scheduling for UEs	Proportional Fairness
Resource partition for relaying with capacities $\rho_{\text{1st}}, \rho_{\text{2nd}}$	$\rho_{\text{2nd}}/(\rho_{\text{1st}} + \rho_{\text{2nd}})$ for 1st hop, $\rho_{\text{1st}}/(\rho_{\text{1st}} + \rho_{\text{2nd}})$ for 2nd hop.

Performance evaluation



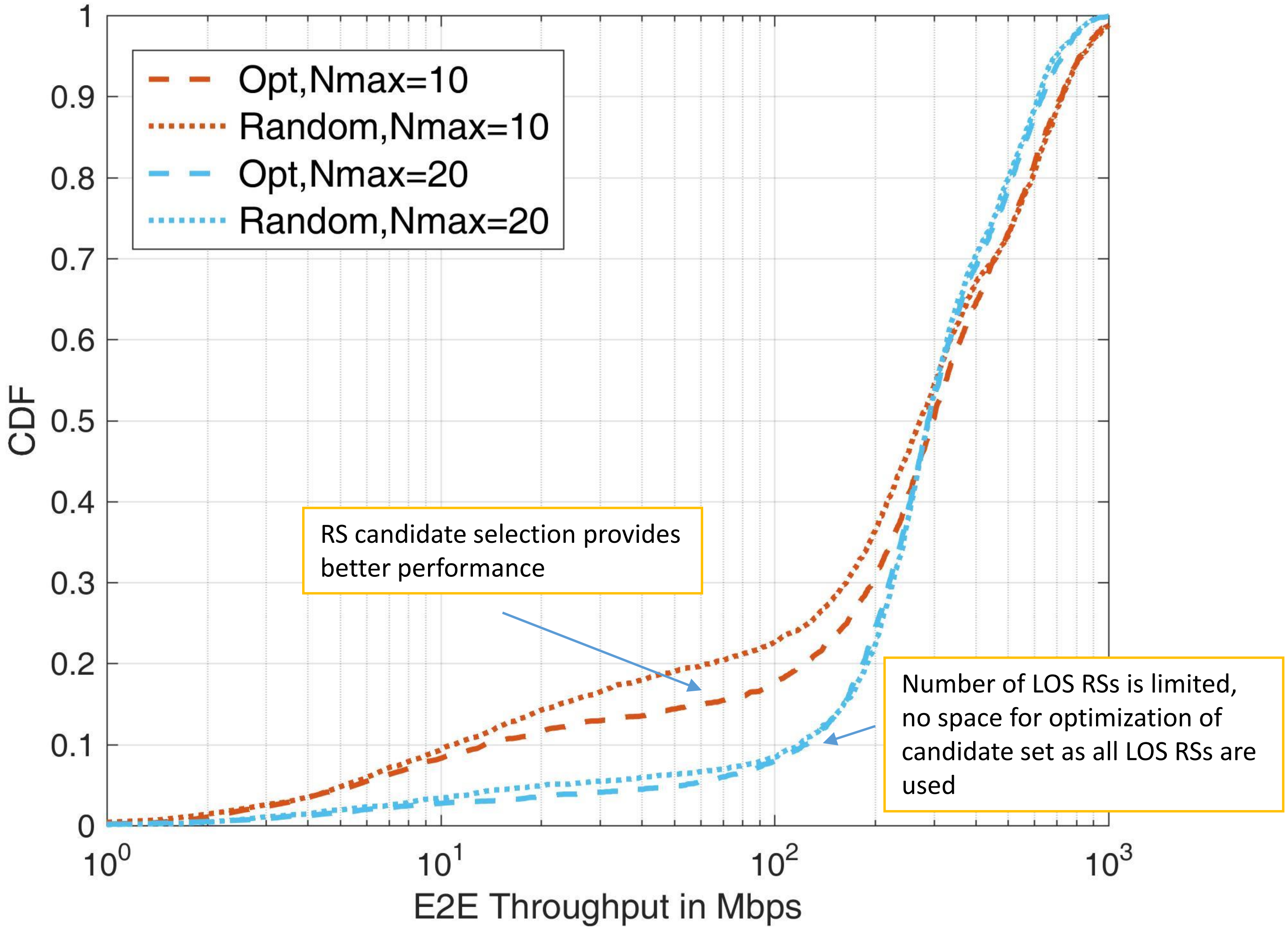
Two-hop relaying increase the network performance dramatically

Cell-edge performance improves as N_{max} increases

1/3 of UEs have one-hop LOS DL

Overhead increases as N_{max} increases

Performance evaluation



RS candidate selection provides better performance

Number of LOS RSs is limited, no space for optimization of candidate set as all LOS RSs are used

Conclusions

- Without relaying, blocked UEs suffer from low throughput
- Number of two-hop LOS UEs increases when relaying is applied
- Signal overhead is significant and must be considered
- Proposed RS candidate set selection method provides better performance than random selection
- Choosing a proper size for relay candidate set is important to achieve both high mean user performance and consistent user experience

Thank you!