University of Bristol
Communication Systems and Network Group

Millimeter-Wave Networks for Vehicular Communication: Modeling and Performance Insights

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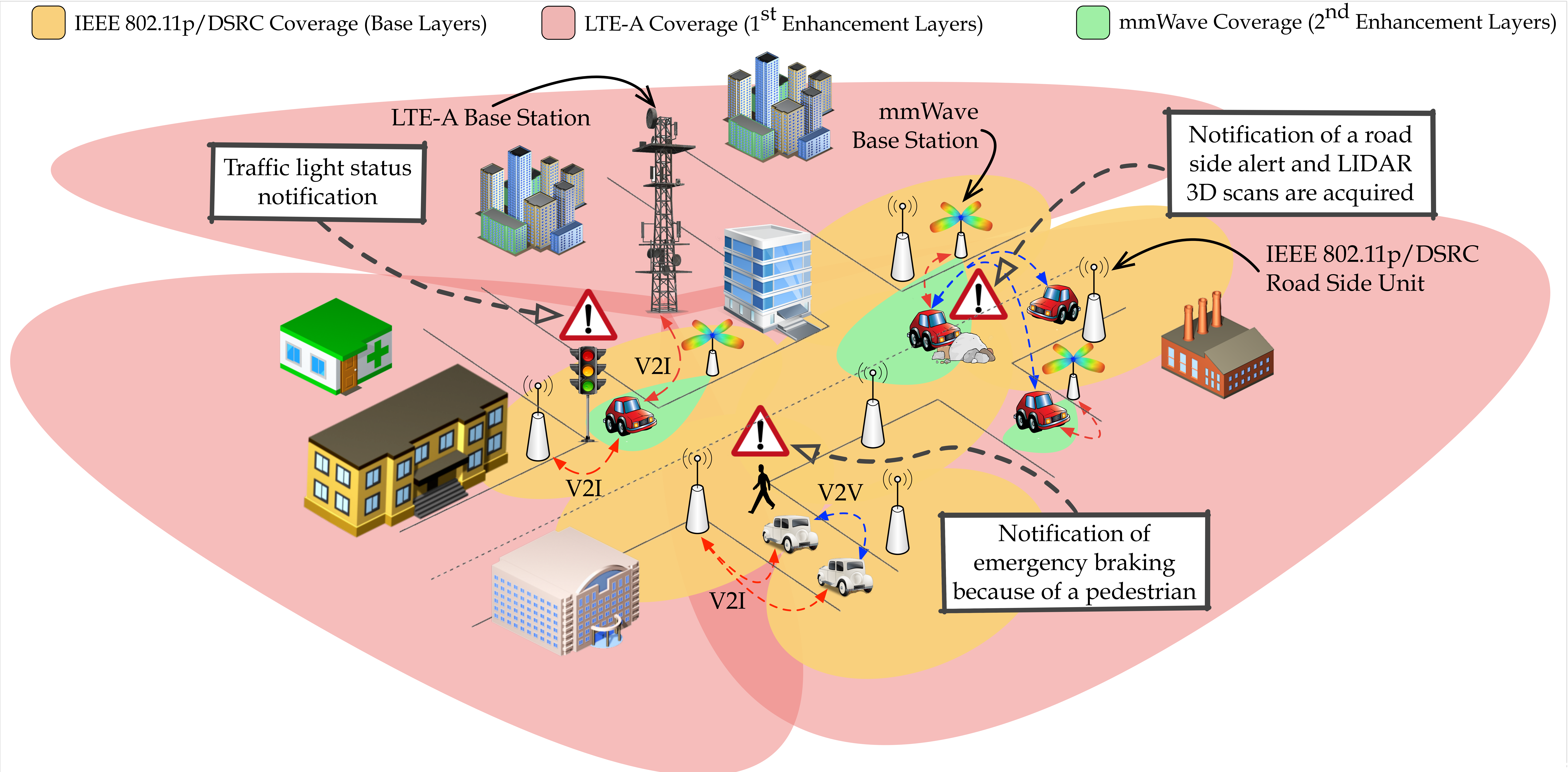
- Why Should I Put Comms Onto Self-Driving Vehicles?
- … and Why Should I go for mmWave Systems?
- Proposed mmWave V2I System Model
- Numerical Results
- Conclusions

mmWave Comms for Next Generation ITSs

- The IEEE 802.11p/DSRC can achieve at most ~27 Mbps, in practice it is hard to observe that.
- However, DSRC standards are suitable for low-rate data services (for e.g., positioning beacon, emergency stop messages, etc.).
- On the other hand, future CAVs will require solutions ensuring gigabit-per-second communication links to achieve proper ‘look-ahed’ services (involving cameras, LIDARS, etc.), etc.
- It is reasonable to design hybrid networks integrating both mmWave and DSRC technologies

mmWave Comms for Next Generation ITSs



System Model

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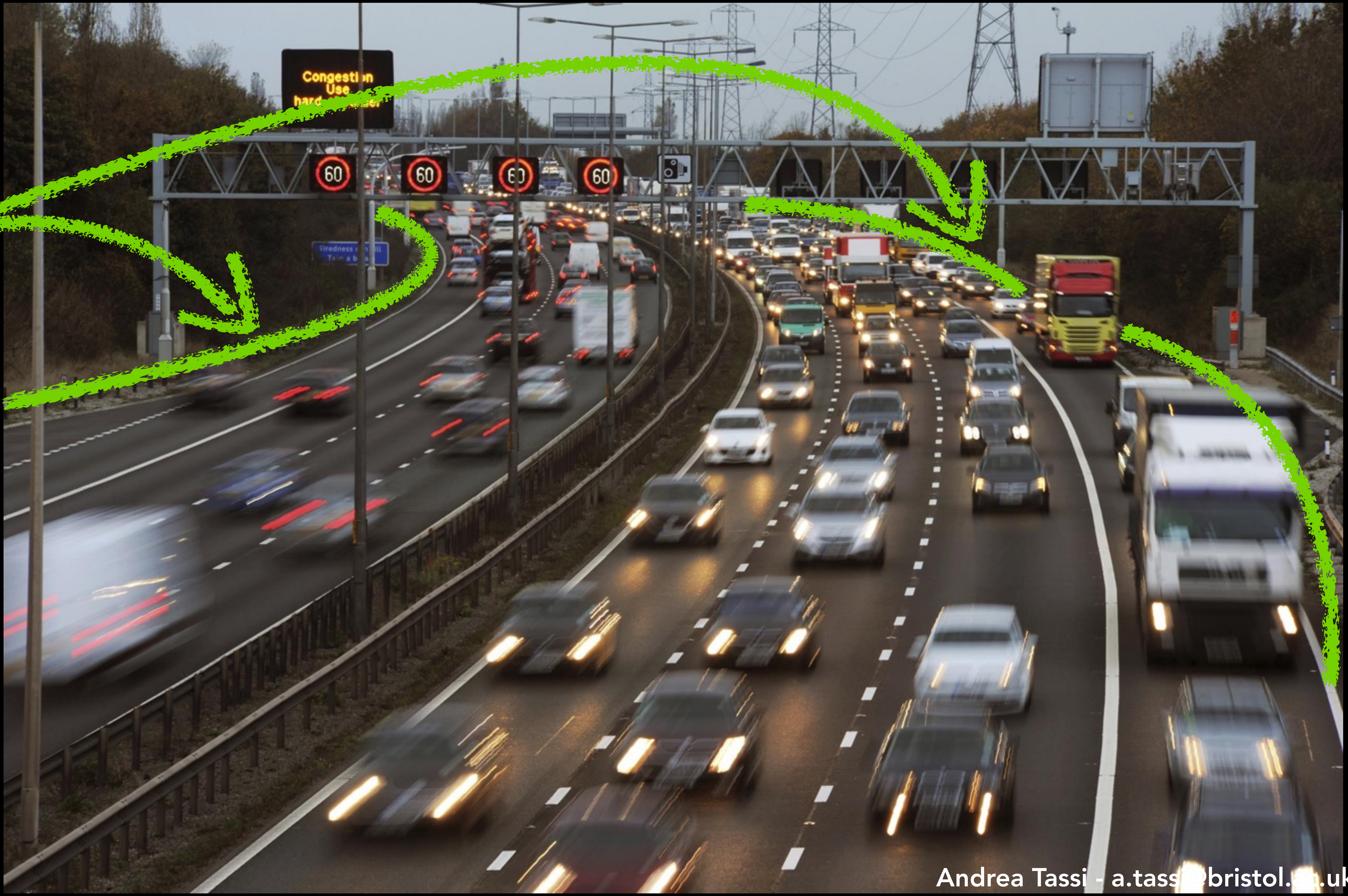
Practical Highway Scenario

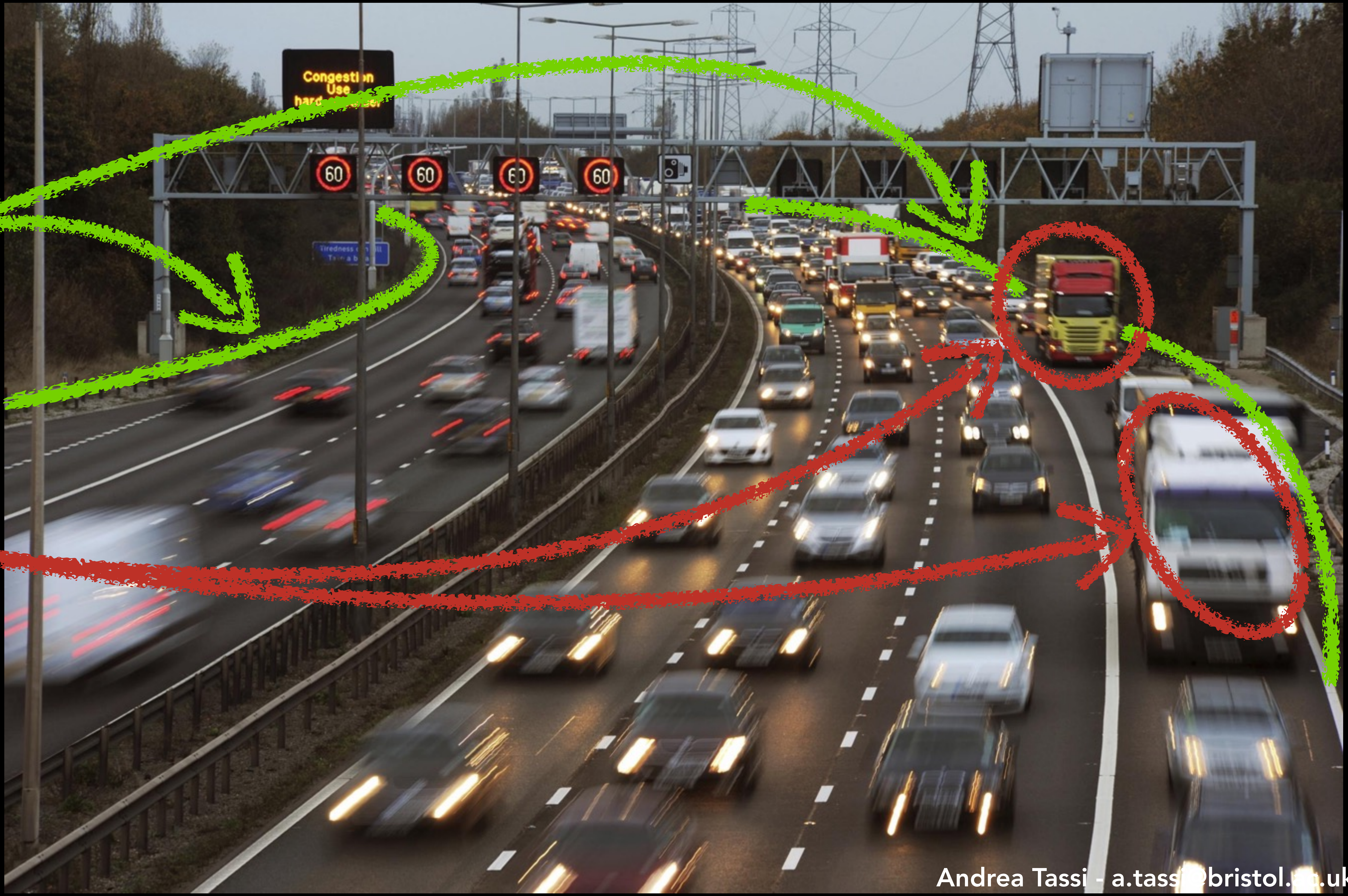
mmWave BSs placed at the side of the road



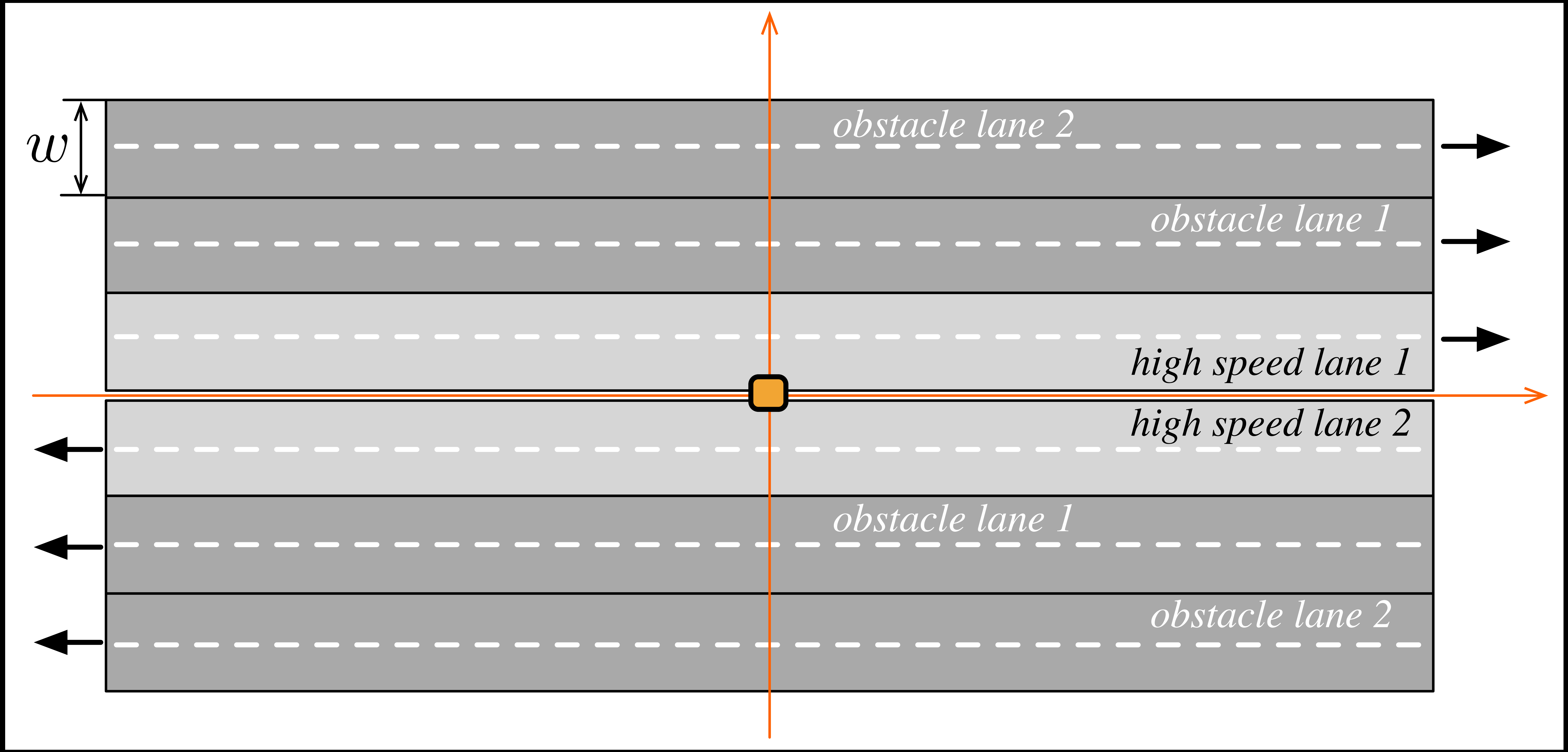
Practical Highway Scenario

mmWave BSs placed at the side of the road

Obstacles

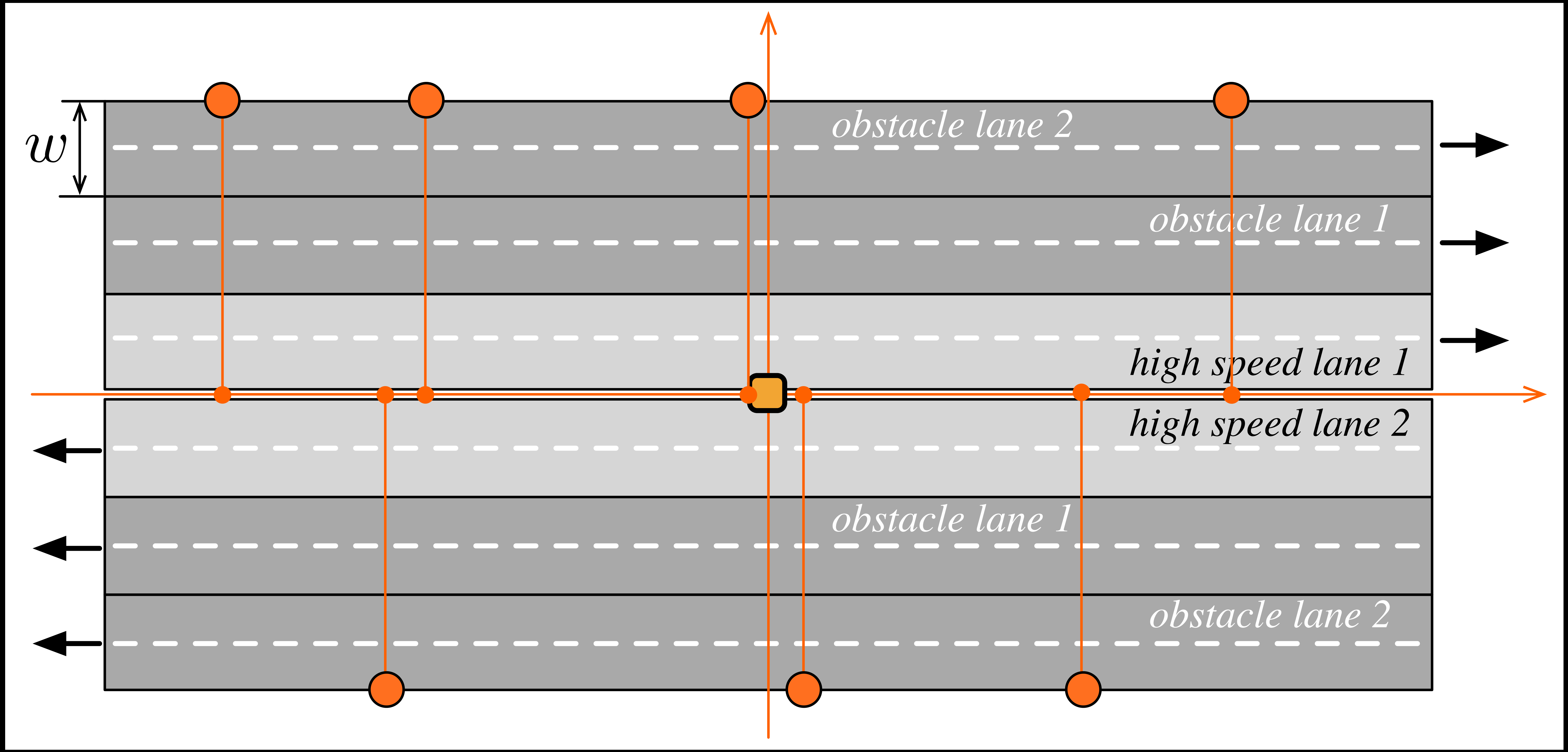


System Model (Road Layout)



- Straight and homogeneous road section
- Vehicles are required to drive on the left hand side of the road
- We characterize the performance of a standard user placed at the origin of the axis.

System Model (BS Distribution)



- x-comp. of BS positions follow a 1D PPP of density λ_{BS}
- A BS is placed on a side of the road (upper/bottom side) with probability $q = 0.5$. Hence, BSs on a side of the road define a 1D PPP of density $q\lambda_{\mathrm{BS}}$

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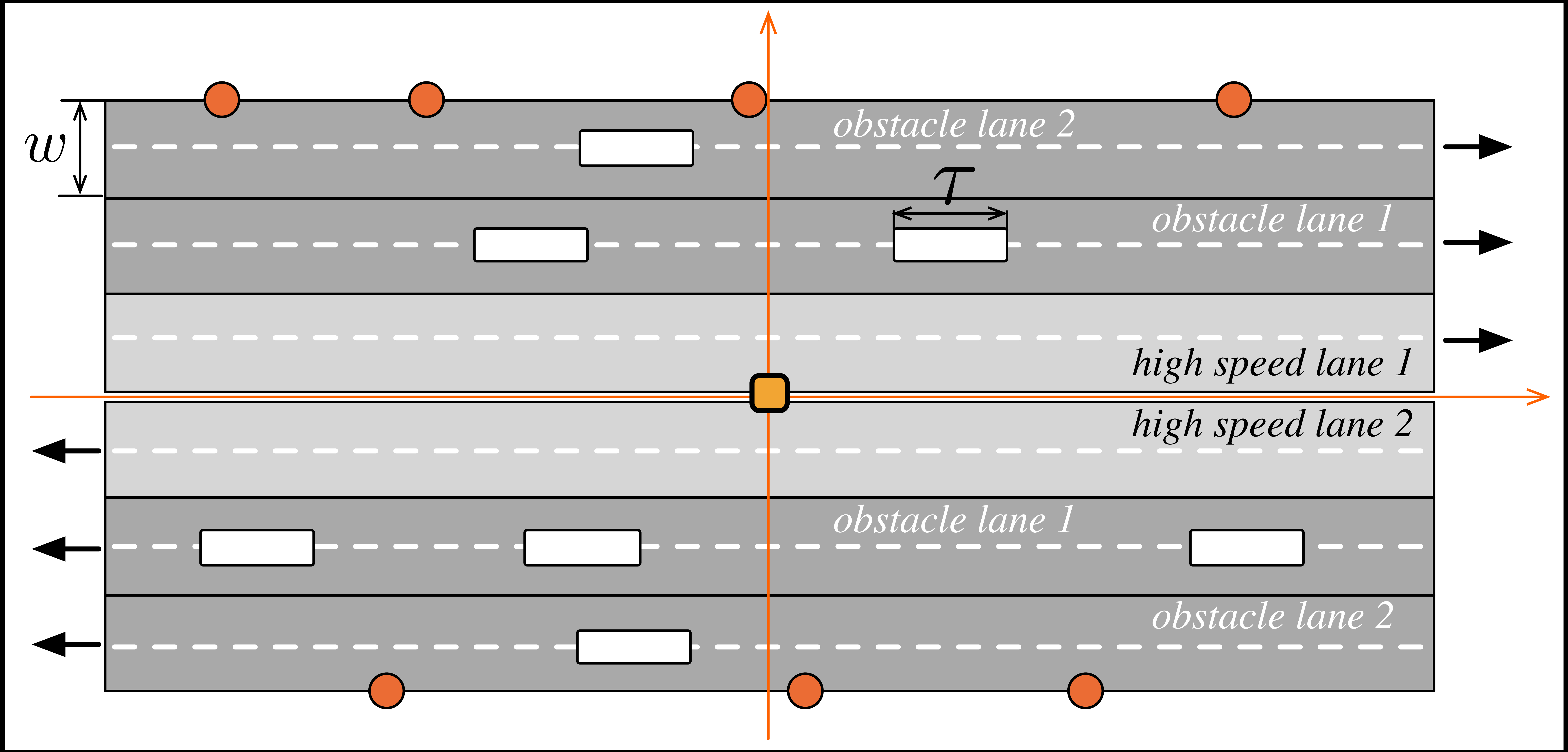
System Model (Blockage Distribution)



- Obstacles on each obstacle lane follow a 1D PPP of density $\lambda_{\mathrm{o},\ell}$
- Obstacle processes are independent but the blockage density of lane ℓ on each traffic direction is the same
- Each blockage is associated with a footprint of length $\mathcal{T}$

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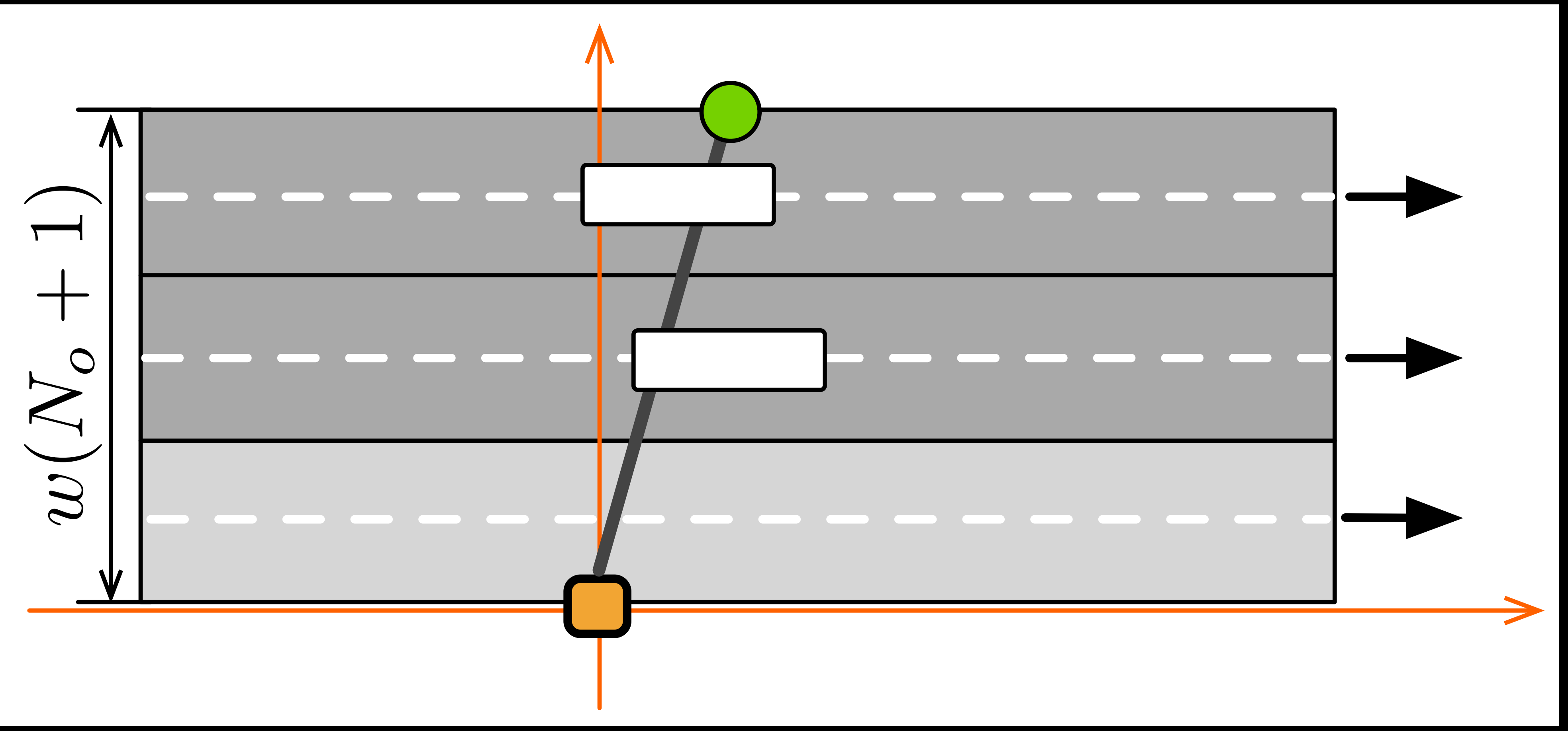
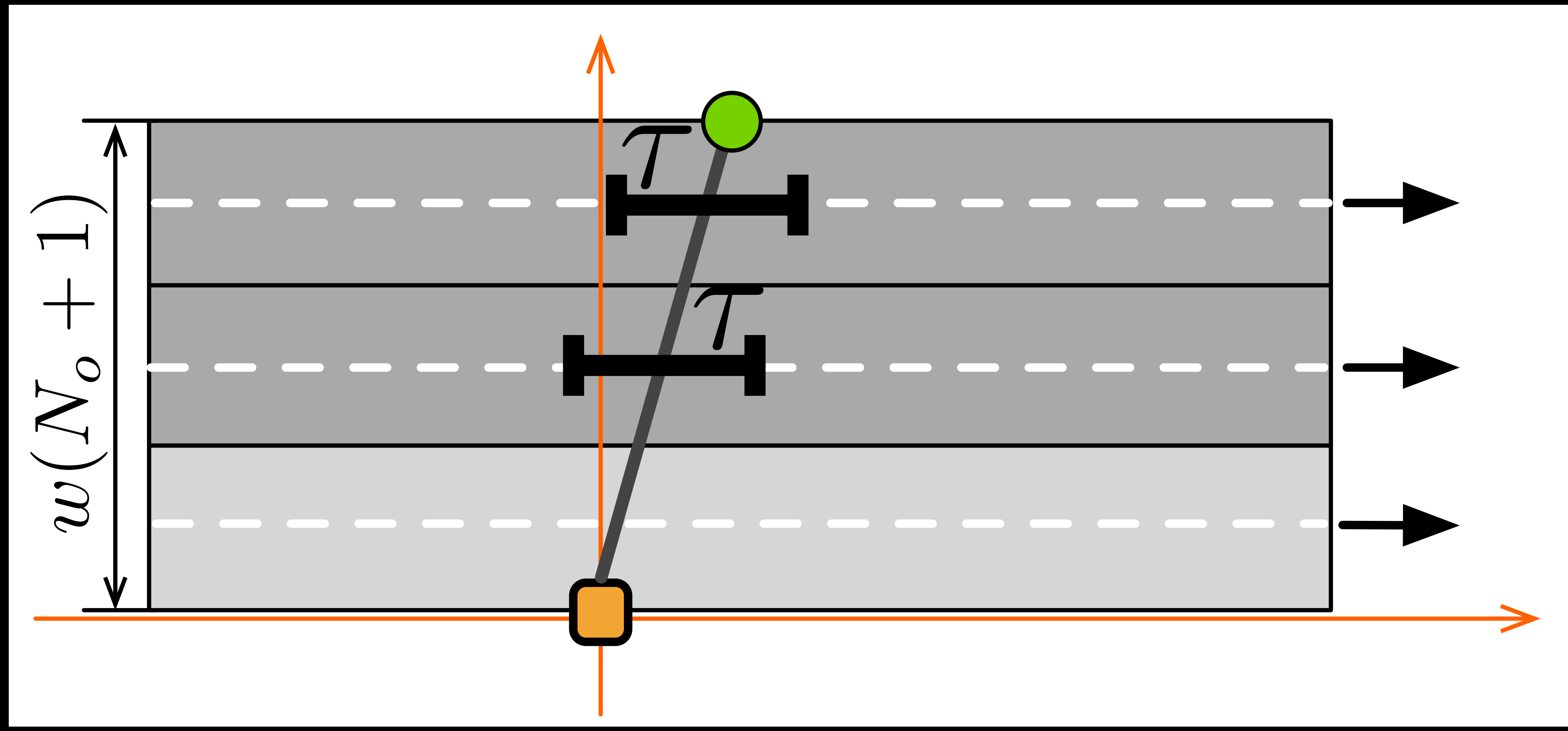
PL Model and User Association

- We approximate p_{L} with the probability that no blockages are present within a distance of $\tau/2$ on either side of the ray connecting the user to a BS. Hence, our approximation is independent on the distance of BS i to O





- The PL function associated with BS i is

$$\ell(r_i) = \mathbf{1}_{i,\mathrm{L}} C_{\mathrm{L}} r_i^{-\alpha_{\mathrm{L}}} + (1 - \mathbf{1}_{i,\mathrm{L}}) C_{\mathrm{N}} r_i^{-\alpha_{\mathrm{N}}}$$

- The standard user always connects to the BS with the minimum PL component

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PL Model and User Association

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#Obs. lane per driving direction

$$p_\mathrm{L} \cong \prod_{\ell=1}^{N_o} e^{-\lambda_{\mathrm{o},\ell}\tau}$$

1D PPP void probability

- The PL function associated with BS i is

$$\ell(r_i) = \mathbf{1}_{i,\mathrm{L}} C_\mathrm{L} r_i^{-\alpha_\mathrm{L}} + (1 - \mathbf{1}_{i,\mathrm{L}}) C_\mathrm{N} r_i^{-\alpha_\mathrm{N}}$$

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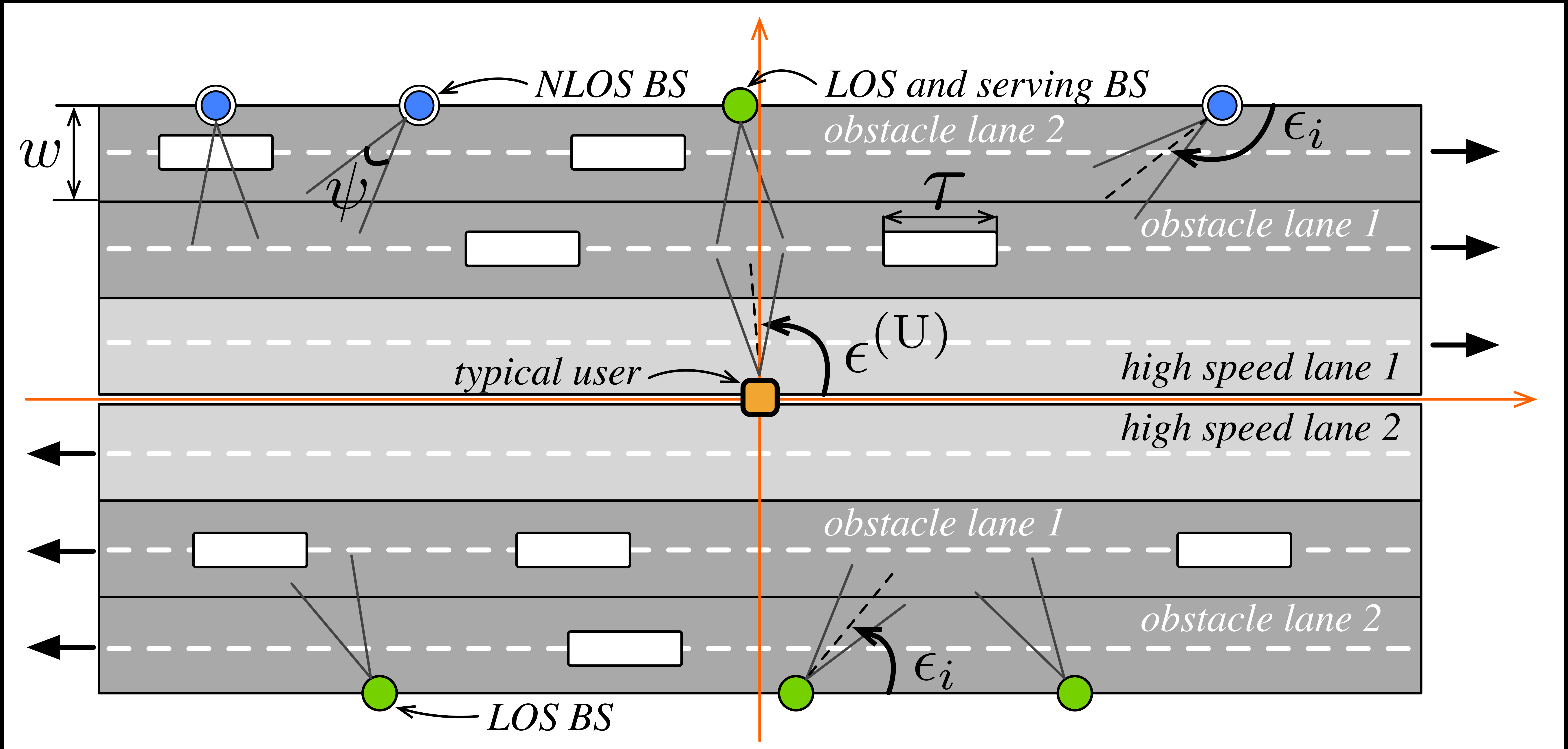
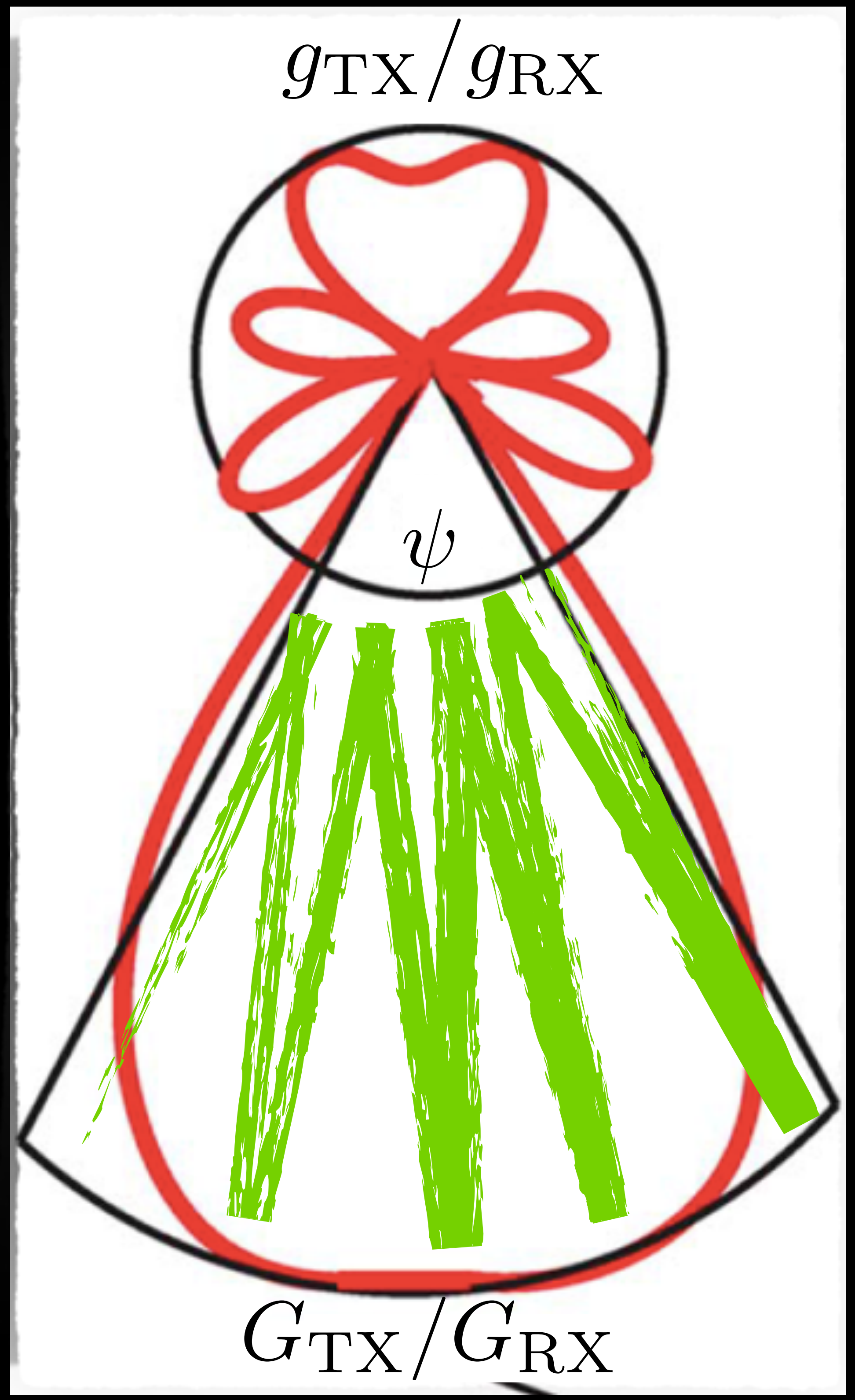
System Model (Beam Steering)





- The main lobe of each BS is always entirely directed towards the road
- The user/BS beam alignment is assumed error-free
- The beam on an interfering BS is steered uniformly within 0° and 180°

SINR Outage and Rate Coverage

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The Probability Framework

- Assume the user connects to BS 1, we define the SINR as

$$\mathrm{SINR}_O = \frac{h_1\,\Delta_1\,\ell(r_1)}{\sigma + \sum_{j=2}^{b} h_j\,\Delta_j\,\ell(r_j)}$$

antenna gains

normalized thermal noise power

hj ~ EXP(1)

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The Probability Framework

- Assume the user connects to BS 1, we define the SINR as

$$\mathrm{SINR}_O = \frac{h_1\,\Delta_1\,\ell(r_1)}{\sigma + \sum_{j=2}^{b} h_j\,\Delta_j\,\ell(r_j)}$$

antenna gains

normalized thermal noise power

$h_j \sim \mathrm{EXP}(1)$

- We characterize the following SINR outage

$$\overbrace{\mathbb{P}[\mathrm{SINR}_O < \theta]}^{\mathrm{P_T}(\theta)} = \mathrm{P_L} - \overbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in LOS}]}^{\mathrm{P_{CL}}(\theta)}$$
$$+\,\mathrm{P_N} - \underbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in NLOS}]}_{\mathrm{P_{CN}}(\theta)}$$

Probability of Being Served in LOS/NLOS

- The standard user connects to a NLOS BS with probability

$$\mathrm{P_N} = \int_{w(N_o+1)}^{\infty} f_{\mathrm{N}}(r) e^{-2\lambda_{\mathrm{L}}\sqrt{A_{\mathrm{L}}^2(r) - w^2(N_o+1)^2}} dr$$

PDF of the closest NLOS BS

PPP LOS void probability in the segment [0, $A_L(r)$]

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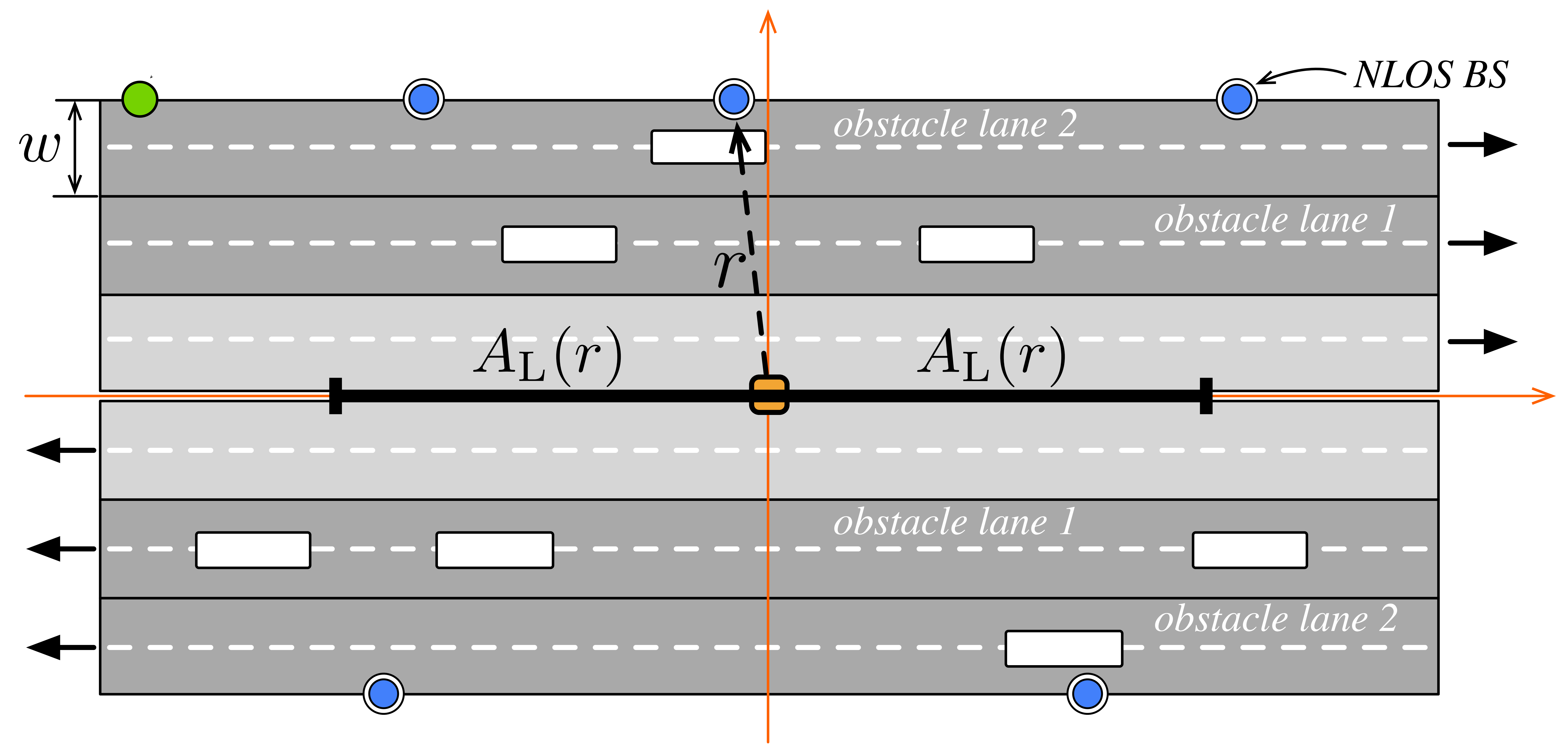

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where

$$A_{\mathrm{L}}(r) = \max\left\{ w(N_o+1), \left[\frac{C_{\mathrm{N}}}{C_{\mathrm{L}}} r^{-\alpha_{\mathrm{N}}}\right]^{-\frac{1}{\alpha_{\mathrm{L}}}} \right\}$$

from

$$C_{\mathrm{N}} r^{-\alpha_{\mathrm{N}}} = C_{\mathrm{L}} A_{\mathrm{L}}^{-\alpha_{\mathrm{L}}}$$

- While, $\mathrm{P_L} = 1 - \mathrm{P_N}$

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Coverage Probability Terms

$$\overbrace{\mathbb{P}[\mathrm{SINR}_O < \theta]}^{\mathrm{P_T}(\theta)} = \mathrm{P_L} - \overbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in LOS}]}^{\mathrm{P_{CL}}(\theta)}$$
$$+ \mathrm{P_N} - \underbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in NLOS}]}_{\mathrm{P_{CN}}(\theta)}$$

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Coverage Probability Terms

as $h_1 \sim \mathrm{EXP}(1)$

$$\mathrm{P_{CL}}(\theta) = \mathbb{P}\left[\frac{h_1\,\Delta_1\,\ell(r_1)}{\sigma + \mathrm{I}} > \theta \text{ and std. user is served in LOS}\right]$$

$$\overset{(i)}{=} \mathbb{E}_{\mathrm{I}} \int_{w(N_o+1)}^{+\infty} e^{-\frac{(\sigma+\mathrm{I})\theta}{\Delta_1 \mathrm{C_L}} r_1^{\alpha_\mathrm{L}}} f_\mathrm{L}(r_1) \mathrm{F_N}(\mathrm{A_N}(r_1))\, dr_1$$

$$\overset{(ii)}{=} \int_{w(N_o+1)}^{+\infty} e^{-\frac{\sigma\theta}{\Delta_1 \mathrm{C_L}} r_1^{\alpha_\mathrm{L}}} \mathcal{L}_{\mathrm{I,L}}\left(\frac{\theta r_1^{\alpha_\mathrm{L}}}{\Delta_1 \mathrm{C_L}}\right) f_\mathrm{L}(r_1) \mathrm{F_N}(\mathrm{A_N}(r_1))\, dr_1$$

Expectation w.r.t I

Prob. of not being served in NLOS

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Coverage Probability Terms

$$\overbrace{\mathbb{P}[\mathrm{SINR}_O < \theta]}^{\mathrm{P_T}(\theta)} = \mathrm{P_L} - \overbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in LOS}]}^{\mathrm{P_{CL}}(\theta)} + \mathrm{P_N} - \underbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in NLOS}]}_{\mathrm{P_{CN}}(\theta)}$$

- As α_{N} increases, in order to be convenient, a NLOS BS has to be quite close to *O*. Up to a point where $\mathrm{P_L}$ is (almost) 1. If so,

$$\mathrm{P_T}(\theta) \cong 1 - \int_{w(N_o+1)}^{+\infty} e^{-\frac{\theta\sigma}{\Delta_1 \mathrm{C_L}} r_1^{\alpha_{\mathrm{L}}}} \mathcal{L}_{\mathrm{I,L}}\left(\frac{\theta r_1^{\alpha_{\mathrm{L}}}}{\Delta_1 \mathrm{C_L}}\right) f_{\mathrm{L}}(r_1)\, dr_1$$

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- The rate coverage follows from the Fubini's theorem (for a bandwidth *W*)

$$\mathrm{R_C}(\kappa) = 1 - \mathrm{P_T}(2^{\kappa/W} - 1)$$

$\mathcal{L}_{\mathrm{I}}(s)$ at a glance...

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A Fundamental Result

- We proved that the Laplace transform of the interference component generated by the BSs on the upper/bottom side of the road (S = U, S = B) that are in LOS/NLOS with the user (E = L, E = N) can be approximated as

$$\mathcal{L}_{\mathrm{I}_{\mathrm{S},\mathrm{E},\mathbb{E}_1}}(s) \cong \prod_{\substack{\mathbb{S}_1 \in \{\mathrm{U},\mathrm{B}\}, \\ (a,b,\Delta) \in \mathcal{C}_{|\mathrm{x}_1|,\mathbb{S}_1,\mathbb{E}_1,\mathrm{S},\mathrm{E}}}} \sqrt{\mathcal{L}_{\mathrm{I}_{\mathrm{S},\mathrm{E},\mathbb{E}_1}}(s; a, b, \Delta)}$$

Conditioned of being served in LOS/NLOS ($\mathbb{E}_1$ = L, $\mathbb{E}_1$ = N).

- Where the fundamental Laplace transform term is…

A Fundamental Result

$$\mathcal{L}_{\mathrm{I}_{\mathrm{S,E}},\mathbb{E}_1}(s;a,b,\Delta) \quad \cong \quad \exp\left(-\left(\mathbb{E}_h[\Theta(h,\Delta)] + \mathbb{E}_h[\Lambda(h,\Delta)]\right)\right)$$

$$\mathbb{E}_h\left[\Theta(h,\Delta)\right] = 2q\lambda_{\mathrm{E}}\left[x^{-\alpha_{\mathrm{E}}^{-1}}\left(1-\frac{1}{s\Delta x+1}\right)\right]_{x=a^{-\alpha_{\mathrm{E}}}}^{b^{-\alpha_{\mathrm{E}}}}$$

$$\mathbb{E}_h\left[\Lambda(h,\Delta)\right] \quad = \quad -2q\lambda_{\mathrm{E}}(s\Delta)^{\frac{1}{\alpha_{\mathrm{E}}}}\Bigg[t(-t^{-1})^{-\frac{1}{\alpha_{\mathrm{E}}}}\Gamma\left(\frac{1}{\alpha_{\mathrm{E}}}+1\right)$$

$$\cdot {}_2\tilde{F}_1\left(\frac{1}{\alpha_{\mathrm{E}}},\frac{1}{\alpha_{\mathrm{E}}}+1;\frac{1}{\alpha_{\mathrm{E}}}+2;-t\right)\Bigg]_{t=-(s\Delta a^{-\alpha_{\mathrm{E}}}+1)^{-1}}^{-(s\Delta b^{-\alpha_{\mathrm{E}}}+1)^{-1}}$$

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A Fundamental Result

$$\mathcal{L}_{\mathrm{I}_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; a, b, \Delta) \cong \exp\Bigg(-\Big(\mathbb{E}_h[\Theta(h,\Delta)] + \mathbb{E}_h[\Lambda(h,\Delta)]\Big)\Bigg)$$

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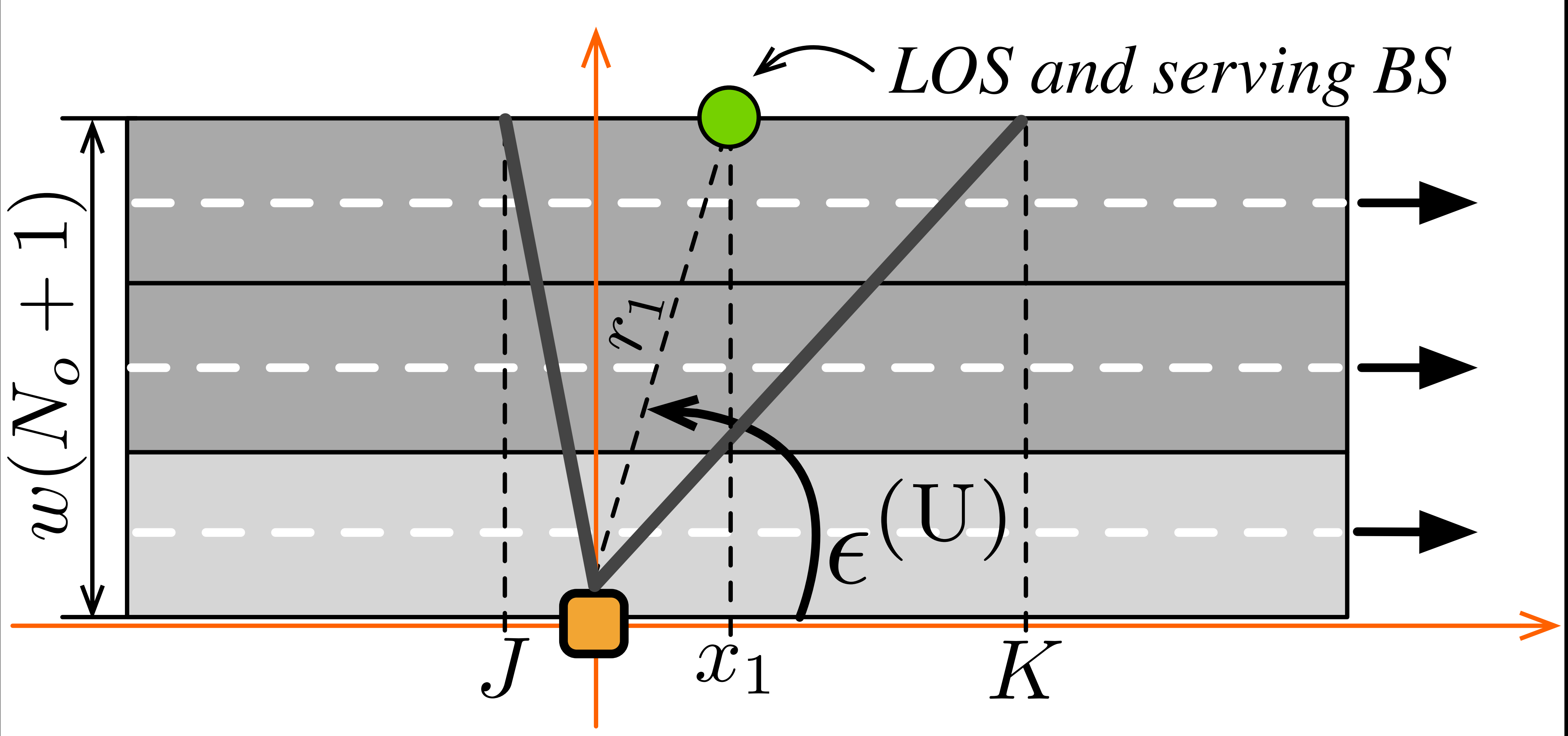
Parametrization of $\mathcal{L}_{\mathrm{I}_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}$

- For simplicity, we assume that the TX antenna gain is always equal to the minimum value.

- However, we characterize the RX antenna gain.



Parametrization of $\mathcal{L}_{\mathrm{I_{S,E}},\mathbb{E}_1}$

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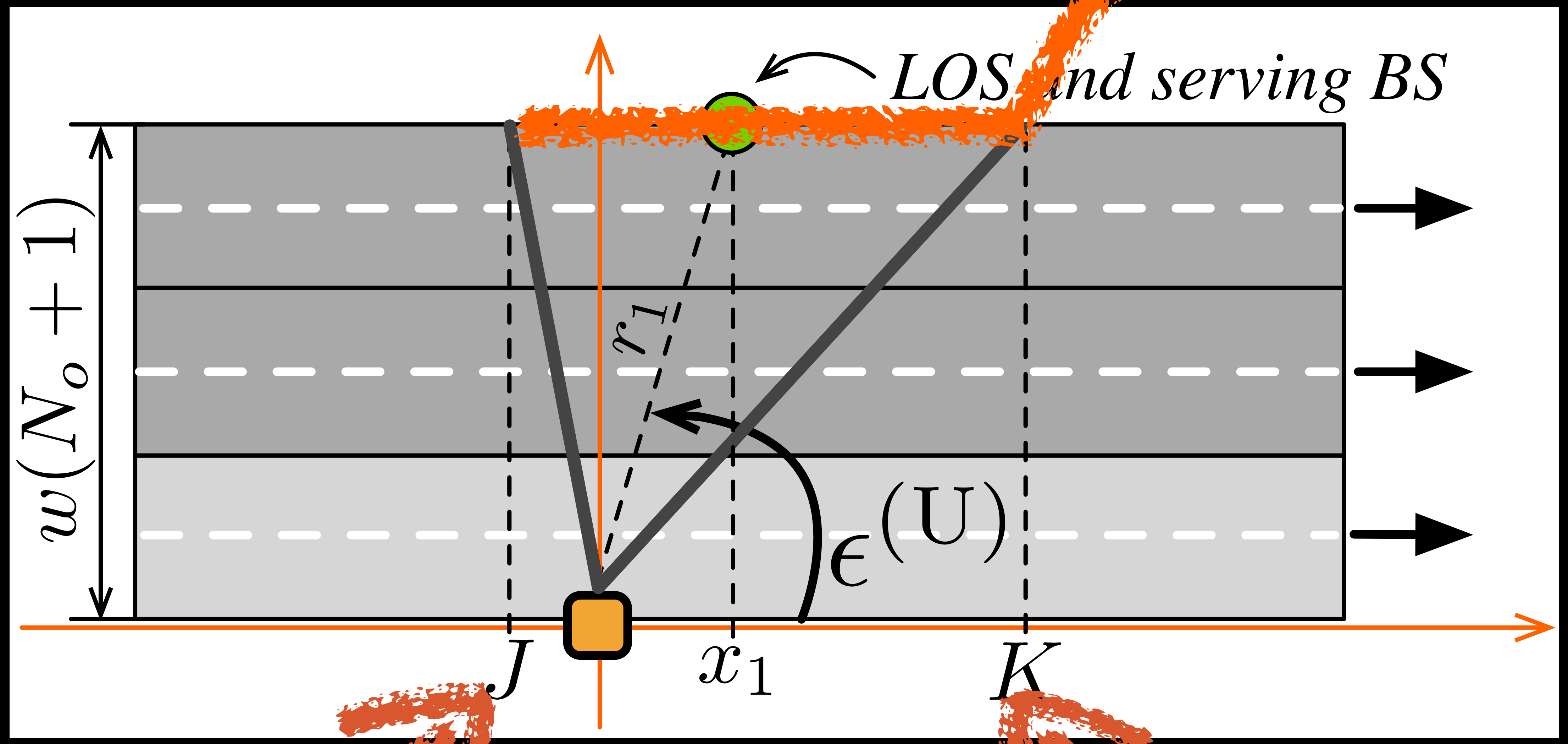


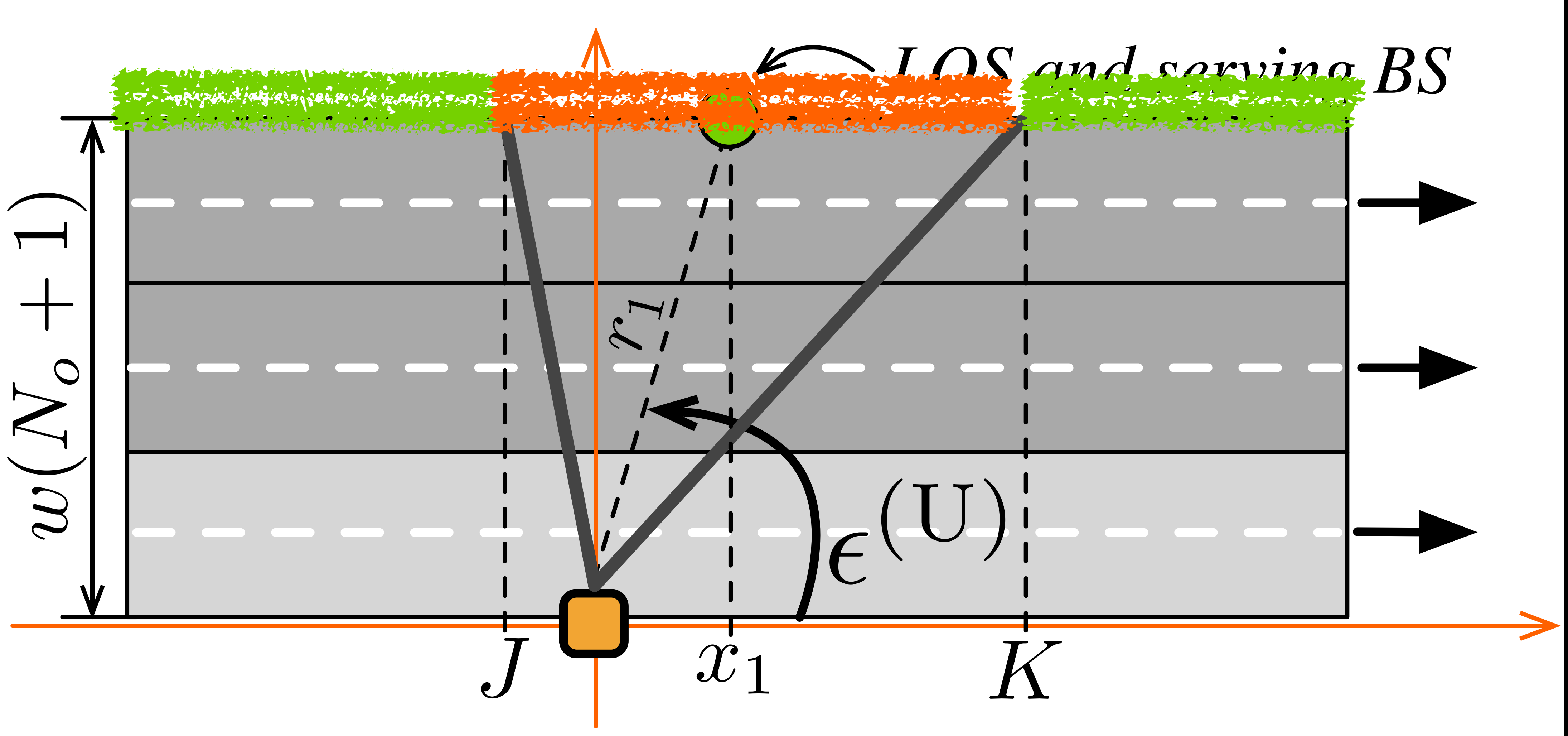
No other LOS BSs can be present in this interval

Parametrization of $\mathcal{L}_{\mathrm{I_{S,E}},\mathbb{E}_1}$

- For simplicity, we assume that the TX antenna gain is always equal to the minimum value.

- However, we characterize the RX antenna gain.

Min RX gain
Max RX gain



Parametrization of $\mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}$

$<\mathbb{S}_1,\mathbb{E}_1,\mathrm{S},\mathrm{E}>$	Conditions on $\lvert x_1 \rvert$	$(a,b,\Delta) \in \mathcal{C}_{\lvert x_1 \rvert,\mathbb{S}_1,\mathbb{E}_1,\mathrm{S},\mathrm{E}}$
$<\mathrm{U},\mathrm{L},\mathrm{U},\mathrm{L}>$	For any $\lvert x_1 \rvert$ such that $J > 0$	$(\lvert x_1 \rvert, K, g_{\mathrm{TX}} G_{\mathrm{RX}})$, $(K, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$, $(\lvert x_1 \rvert, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$
	For any $\lvert x_1 \rvert$ such that $J \leq 0$	$(\lvert x_1 \rvert, K, g_{\mathrm{TX}} G_{\mathrm{RX}})$, $(K, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$, $(\lvert x_1 \rvert, \lvert J \rvert, g_{\mathrm{TX}} G_{\mathrm{RX}})$, $(\lvert J \rvert, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$
$<\mathrm{U},\mathrm{L},\mathrm{U},\mathrm{N}>$	For any $\lvert x_1 \rvert$ such that $J > 0$	$(x_{\mathrm{N}}(r_1), J, g_{\mathrm{TX}} g_{\mathrm{RX}})$, $(x_{\mathrm{N}}(r_1), +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$, $(J, K, g_{\mathrm{TX}} G_{\mathrm{RX}})$, $(K, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$
	For any $\lvert x_1 \rvert$ such that $J \leq 0$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{U},\mathrm{L}>$ $(J \leq 0)$ and replace $\lvert x_1 \rvert$ with $x_{\mathrm{N}}(r_1)$
$<\mathrm{U},\mathrm{L},\mathrm{B},\mathrm{L}>$	For any $\lvert x_1 \rvert$	$(\lvert x_1 \rvert, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$, $(\lvert x_1 \rvert, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})$,
$<\mathrm{U},\mathrm{L},\mathrm{B},\mathrm{N}>$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{B},\mathrm{L}>$ and replace $\lvert x_1 \rvert$ with $x_{\mathrm{N}}(r_1)$	
$<\mathrm{U},\mathrm{N},\mathrm{U},\mathrm{L}>$	For any $\lvert x_1 \rvert$ such that $x_{\mathrm{L}}(r_1) > K$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{B},\mathrm{L}>$ and replace $\lvert x_1 \rvert$ with $x_{\mathrm{L}}(r_1)$
	For any $\lvert x_1 \rvert$ such that $x_{\mathrm{L}}(r_1) \leq K$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{U},\mathrm{L}>$ and replace $\lvert x_1 \rvert$ with $x_{\mathrm{L}}(r_1)$
$<\mathrm{U},\mathrm{N},\mathrm{U},\mathrm{N}>$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{U},\mathrm{L}>$	
$<\mathrm{U},\mathrm{N},\mathrm{B},\mathrm{L}>$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{B},\mathrm{L}>$ and replace x_1 with $x_{\mathrm{L}}(r_1)$	
$<\mathrm{U},\mathrm{N},\mathrm{B},\mathrm{N}>$	Refer to the case $<\mathrm{U},\mathrm{L},\mathrm{B},\mathrm{L}>$	
Cases where $\mathbb{S}_1 = \mathrm{B}$, $\mathrm{S} = \mathrm{B}$	Refer to the correspondent cases where $\mathbb{S}_1 = \mathrm{U}$ and $\mathrm{S} = \mathrm{U}$	
Cases where $\mathbb{S}_1 = \mathrm{B}$, $\mathrm{S} = \mathrm{U}$	Refer to the correspondent cases where $\mathbb{S}_1 = \mathrm{U}$ and $\mathrm{S} = \mathrm{B}$	

- Finally, we can say

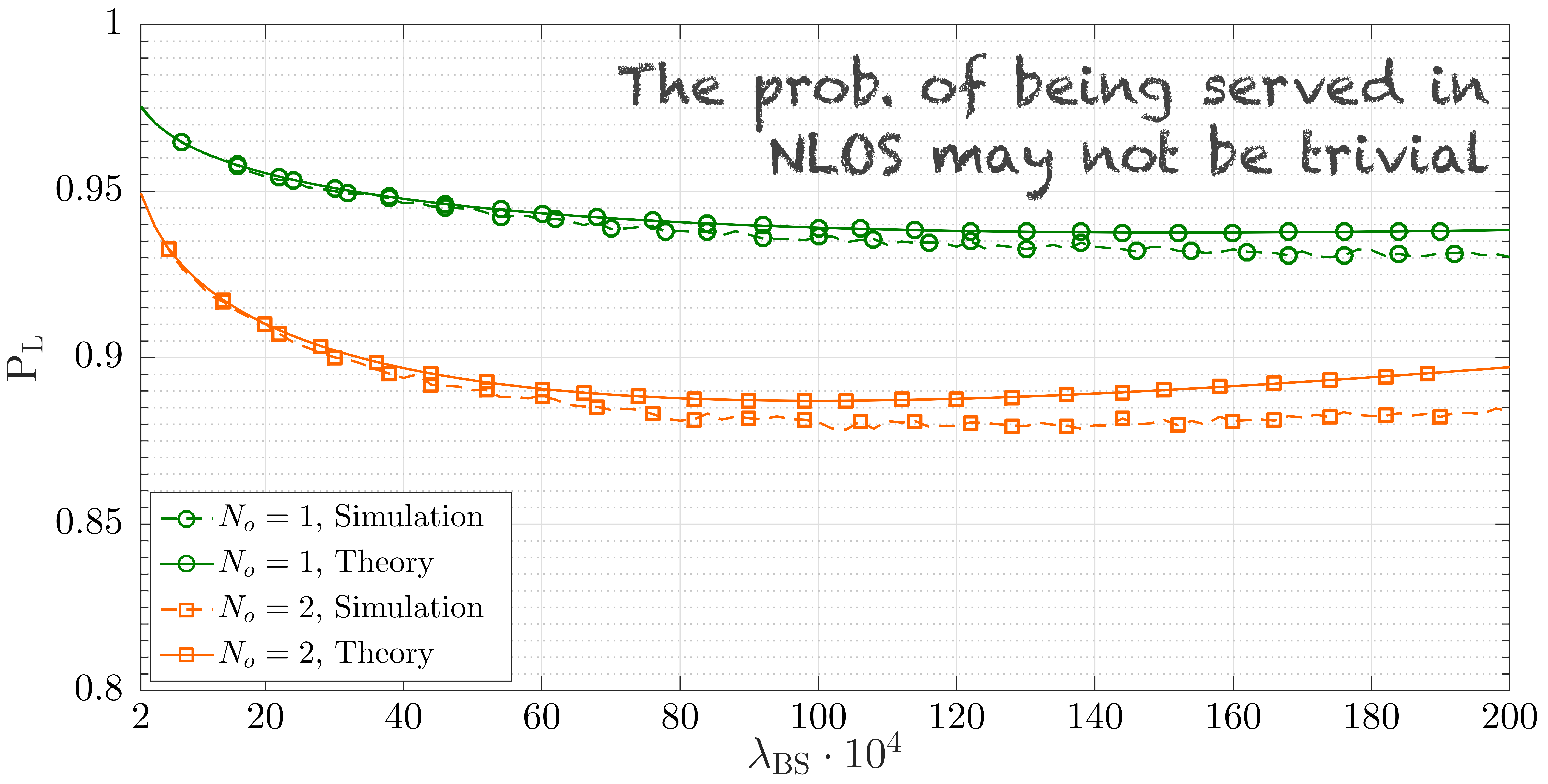
$$\mathcal{L}_{\mathrm{I},\mathbb{E}_1}(s) \cong \prod_{\mathrm{S}\in\{\mathrm{U},\mathrm{B}\},\mathrm{E}\in\{\mathrm{L},\mathrm{N}\}} \mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s)$$

- For e.g., if $\mathbb{E}_1 = \mathrm{L}$ and $J > 0$, it follows

$$\begin{aligned}\mathcal{L}_{\mathrm{I},\mathbb{E}_1}(s) \cong\ & \mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; |x_1|, K, g_{\mathrm{TX}} G_{\mathrm{RX}}) \\ & \cdot \mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; x_{\mathrm{N}}(r_1), J, g_{\mathrm{TX}} g_{\mathrm{RX}}) \\ & \cdot \mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; J, K, g_{\mathrm{TX}} G_{\mathrm{RX}}) \\ & \cdot \left(\mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; K, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})\right)^2 \\ & \cdot \left(\mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; |x_1|, +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})\right)^3 \\ & \cdot \left(\mathcal{L}_{I_{\mathrm{S},\mathrm{E}},\mathbb{E}_1}(s; x_{\mathrm{N}}(r_1), +\infty, g_{\mathrm{TX}} g_{\mathrm{RX}})\right)^3\end{aligned}$$

Numerical Results

LOS vs. NLOS



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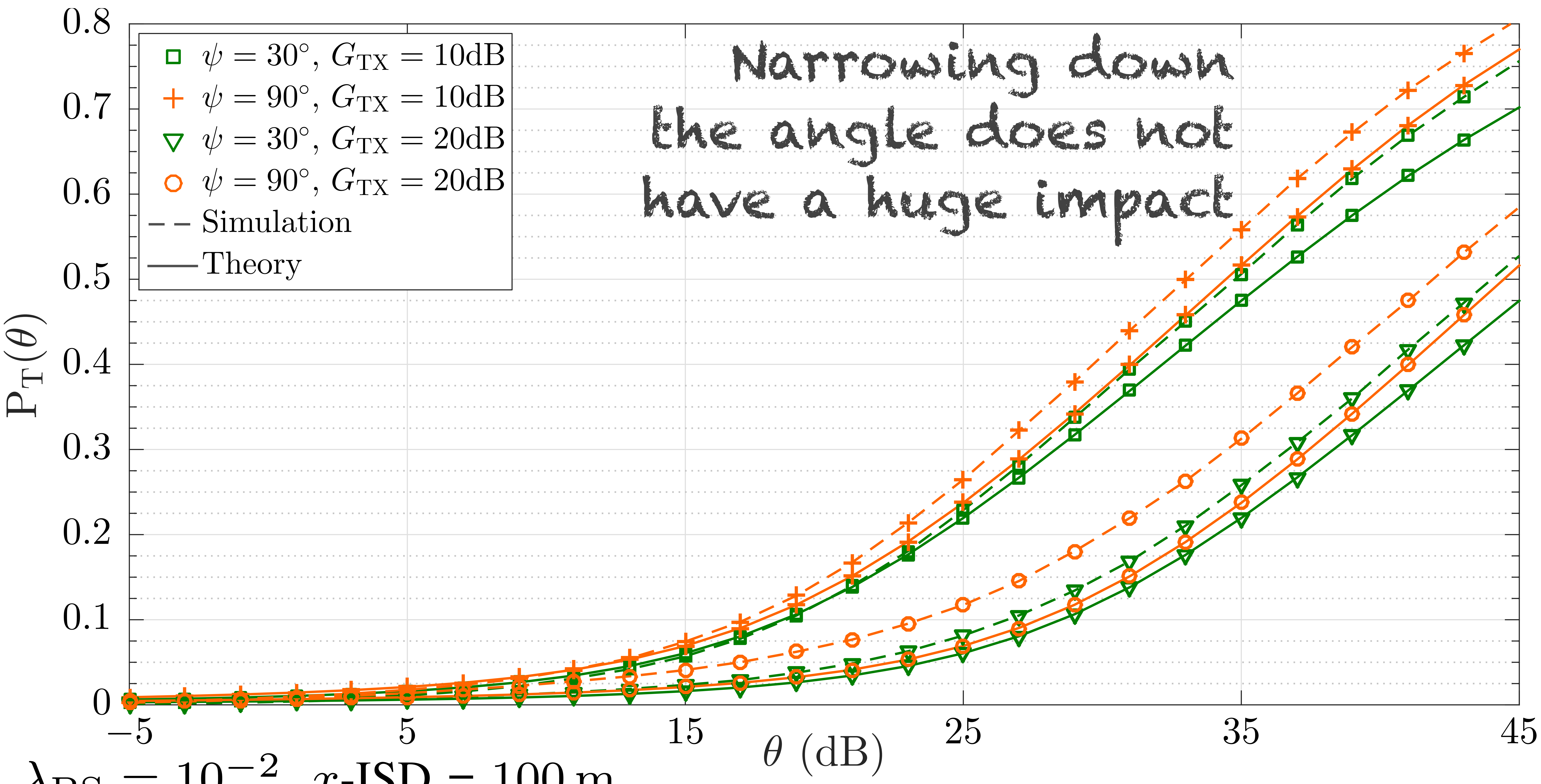
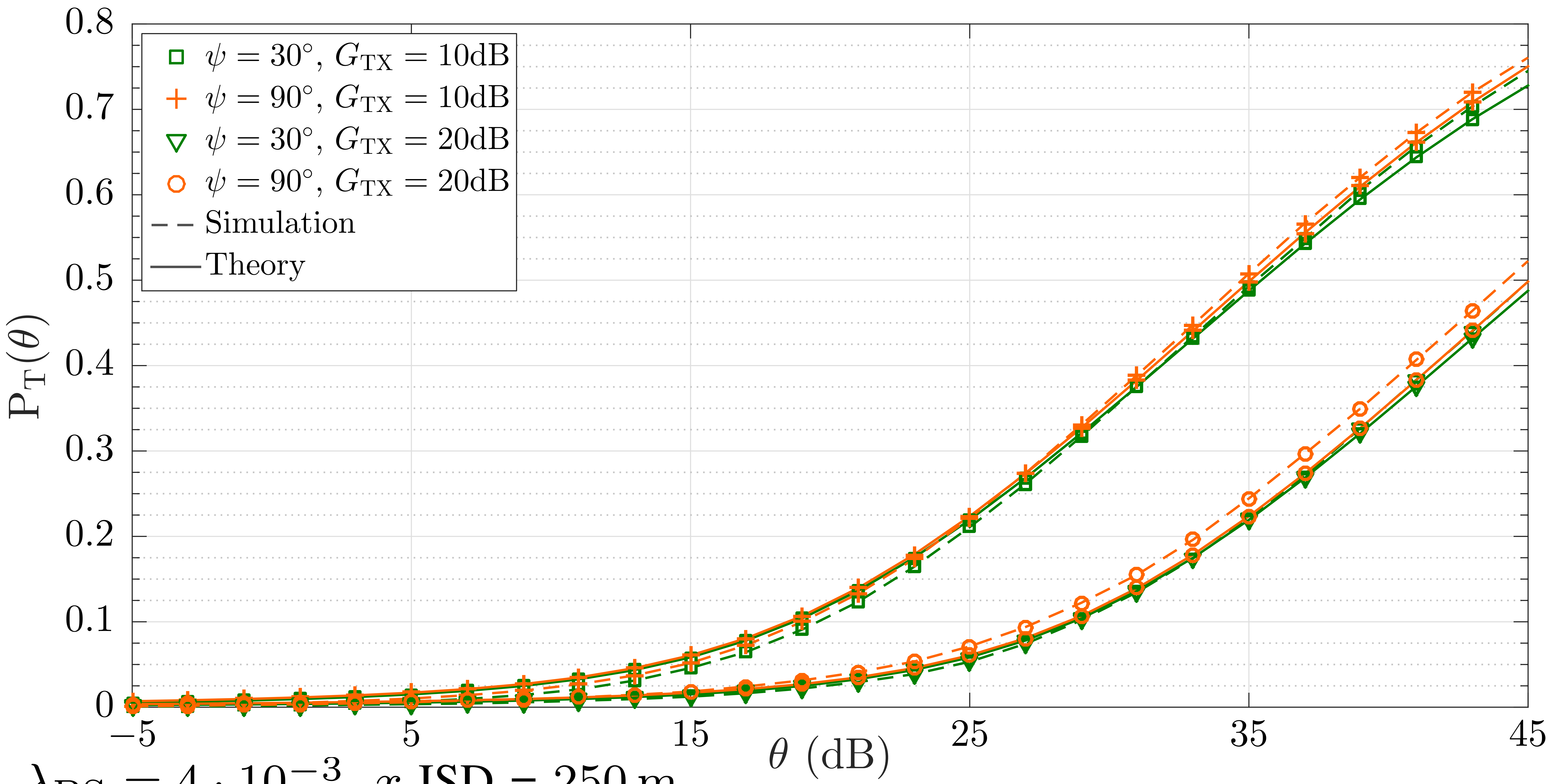
SINR Outage



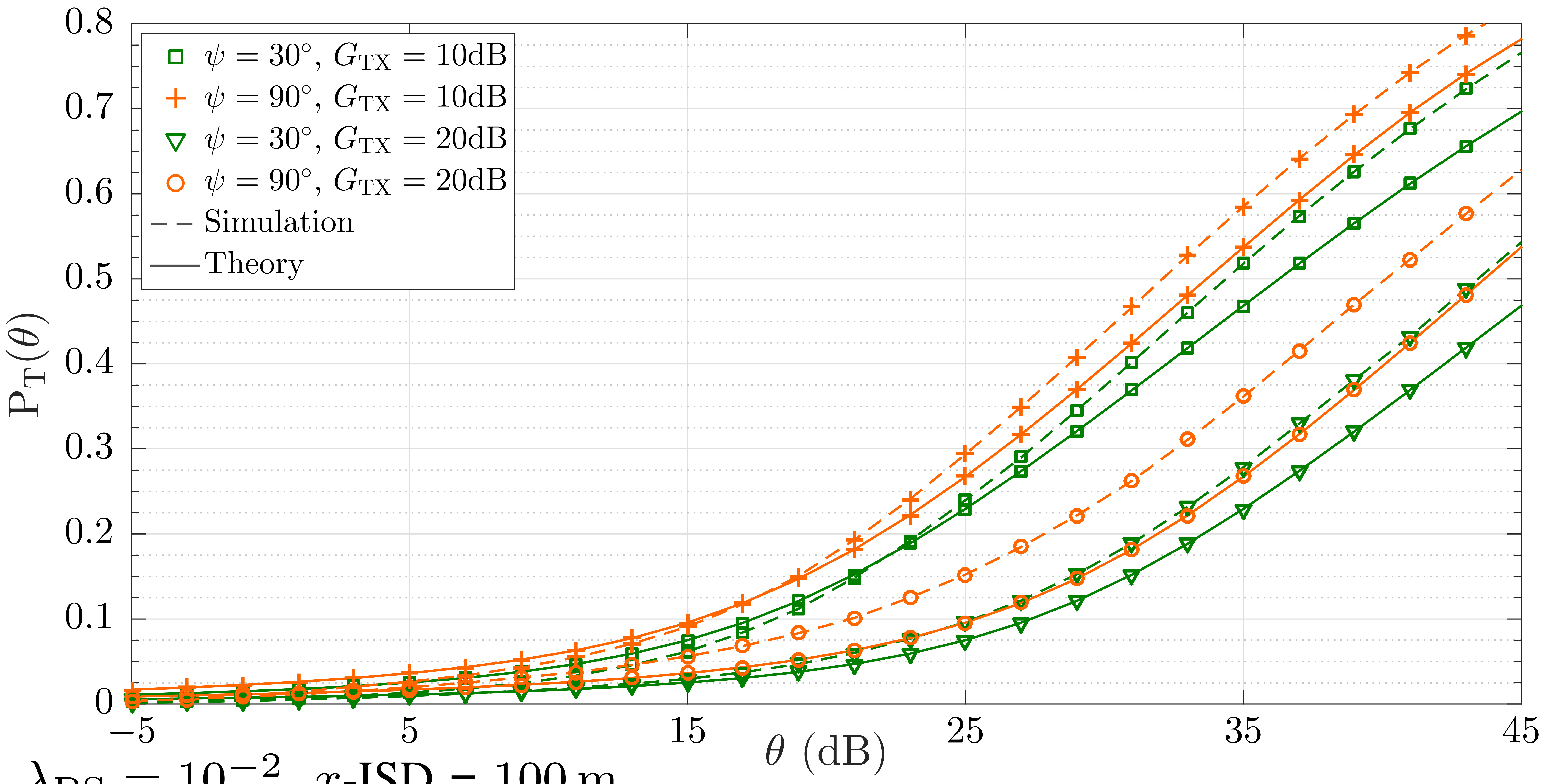
$\lambda_{BS} = 10^{-2}$, x-ISD = 100 m

SINR Outage



$\lambda_{BS} = 4 \cdot 10^{-3}$, x-ISD = 250 m

SINR Outage



$\lambda_{BS} = 10^{-2}$, x-ISD = 100 m

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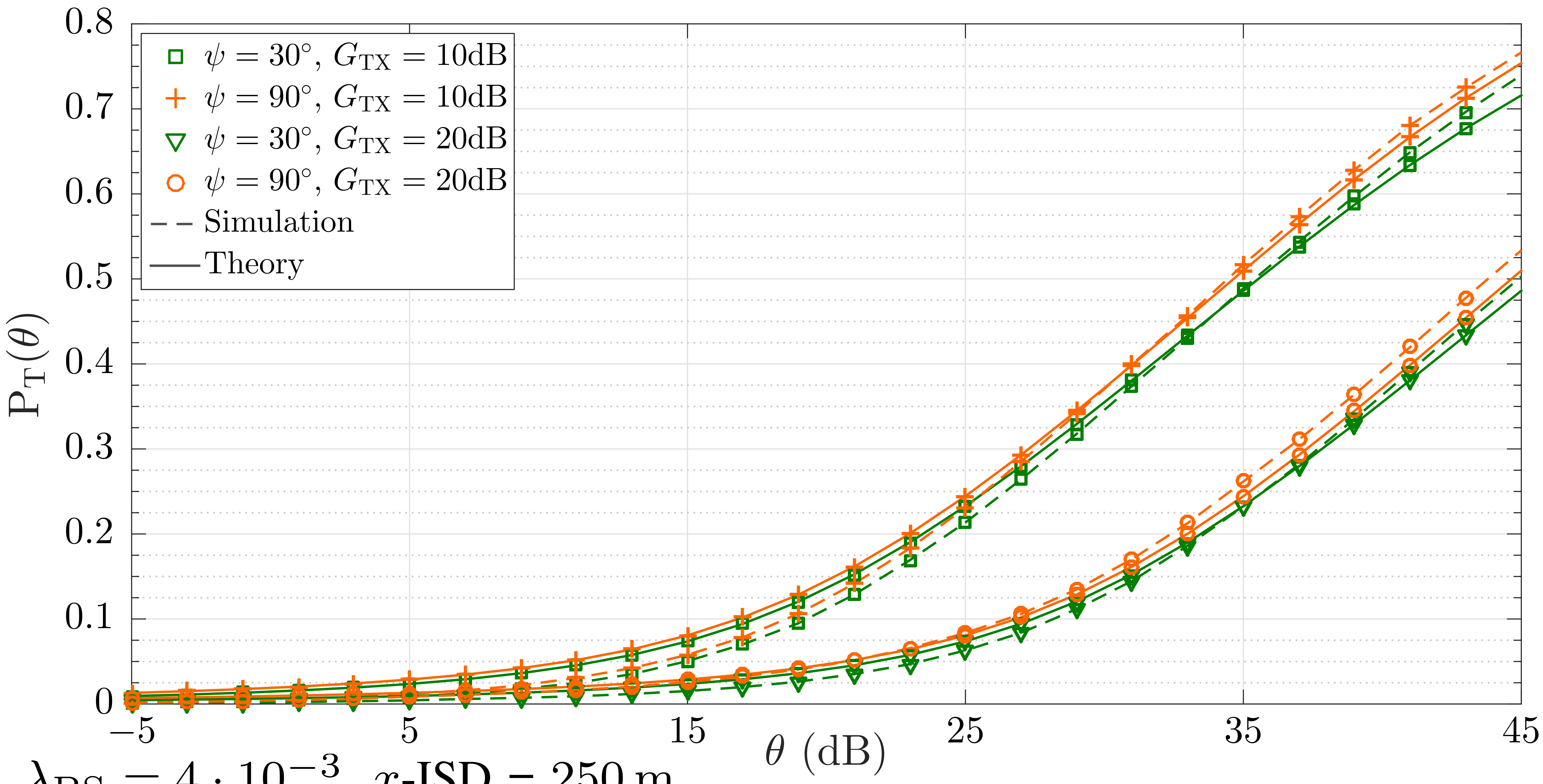
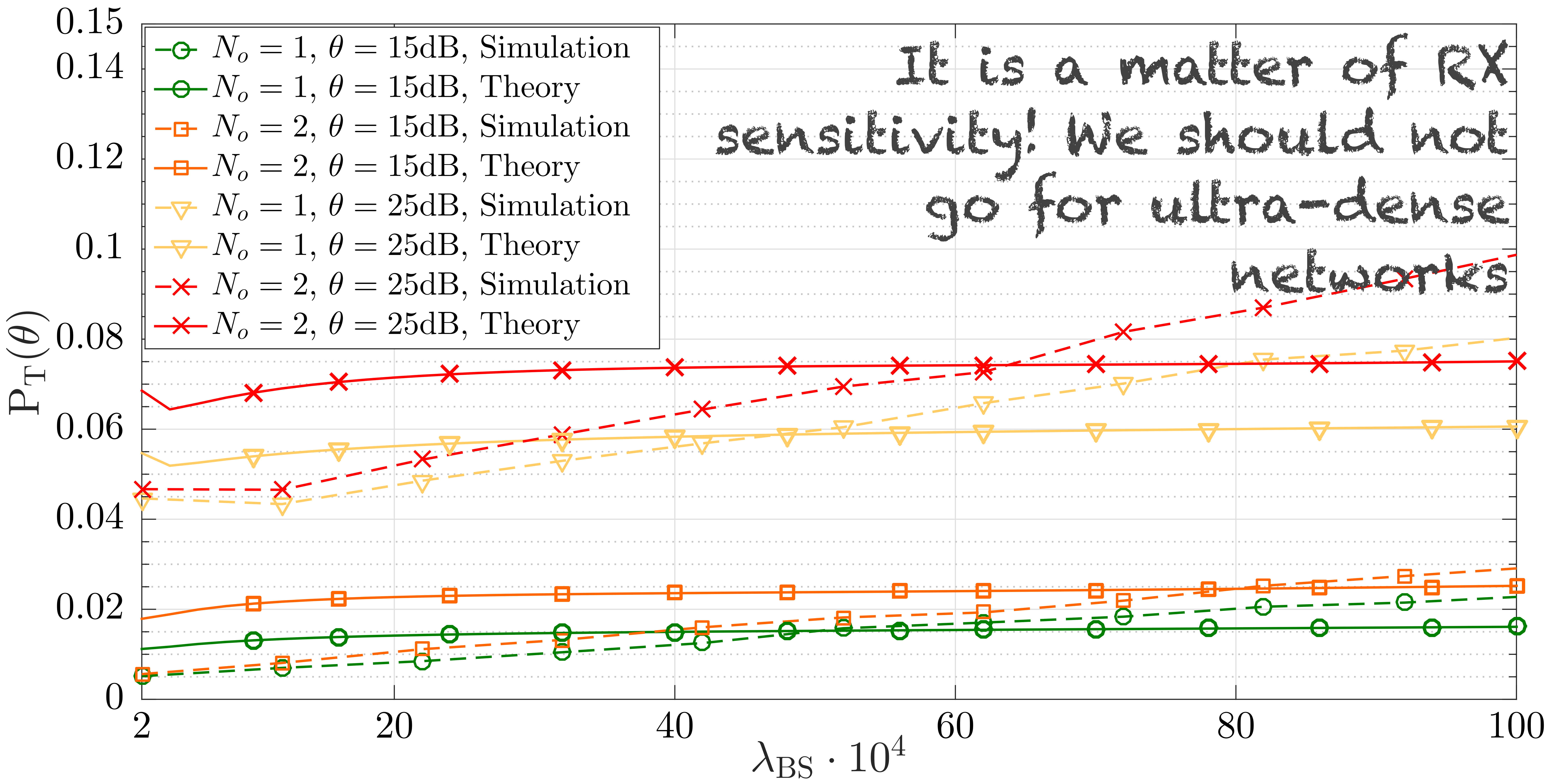
SINR Outage



$\lambda_{BS} = 4 \cdot 10^{-3}$, x-ISD = 250 m

SINR Outage



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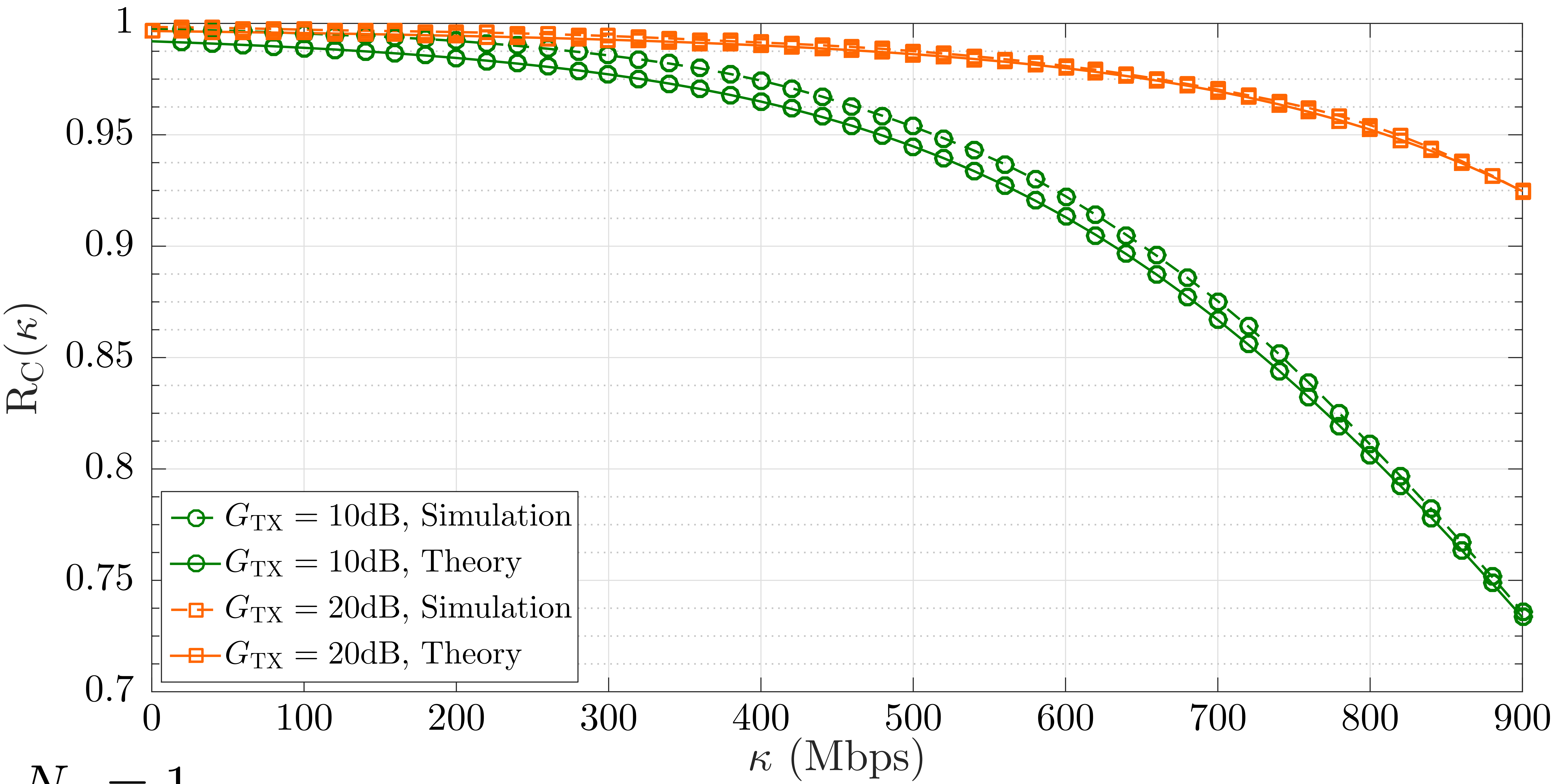
Rate Coverage



$N_o = 1$

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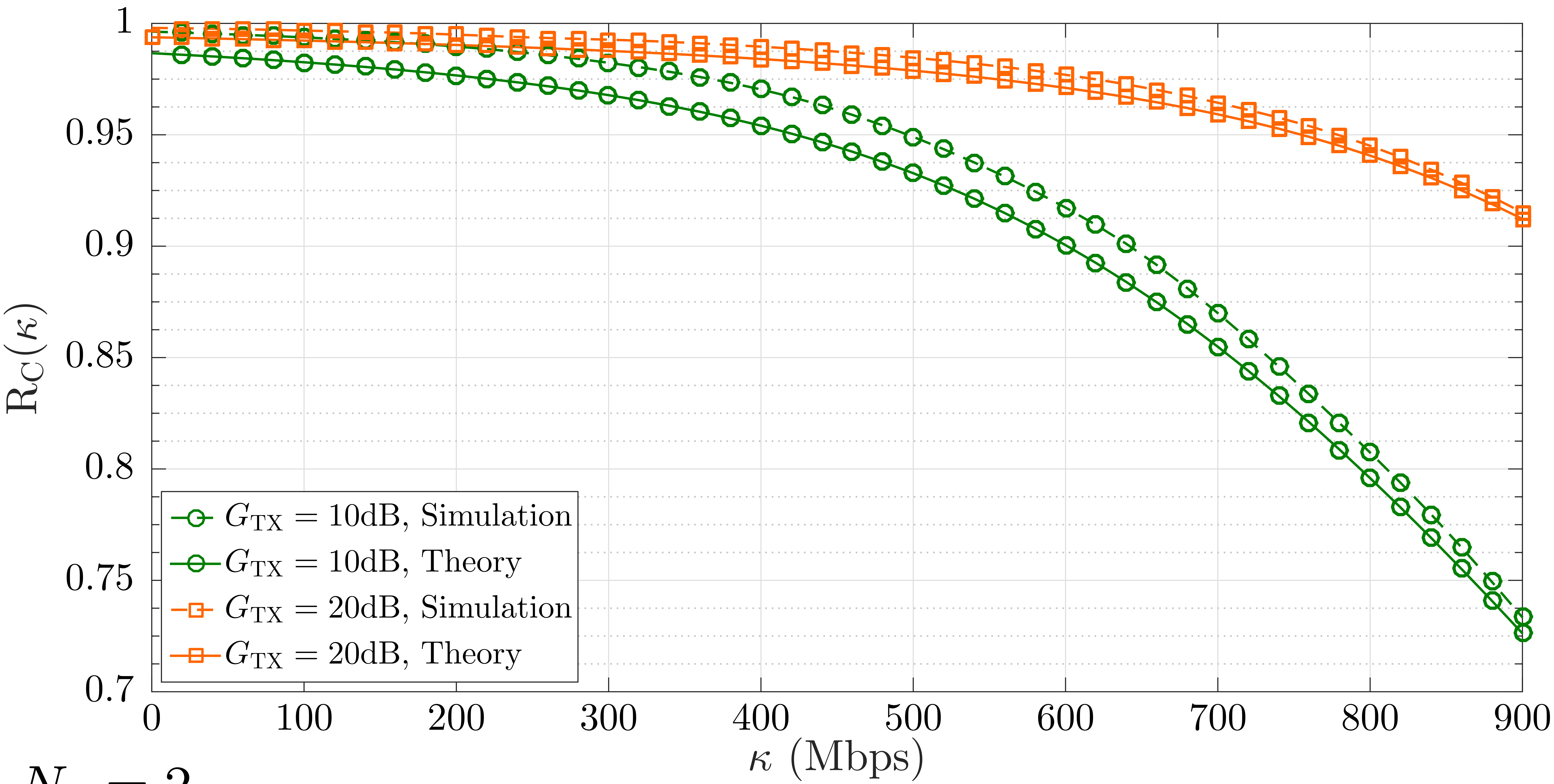
Rate Coverage



$N_o = 2$

Conclusions

What Have we seen?

- The probability of being served by a NLOS BS cannot be considered negligible.
- By reducing the antenna beamwidth form 30° to 90° does not necessarily have a disruptive impact on the the SINR outage probability, and hence, on the rate coverage probability.
- Differently to what happens in bi-dimensional mmWave cellular networks, the BSs density does not largely affect the network performance.
- Overall, for a fixed SINR threshold, the SINR outage probability tends to be minimized by density values associated to sparse network deployments.

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Thanks for your attention!

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