University of Bristol
Communication Systems and Network Group

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

Andrea Tassi - a.tassi@bristol.ac.uk
Malcolm Egan - *Université Blaise Pascal, Clermont-Ferrand, FR*

ECIT, Queen's University Belfast

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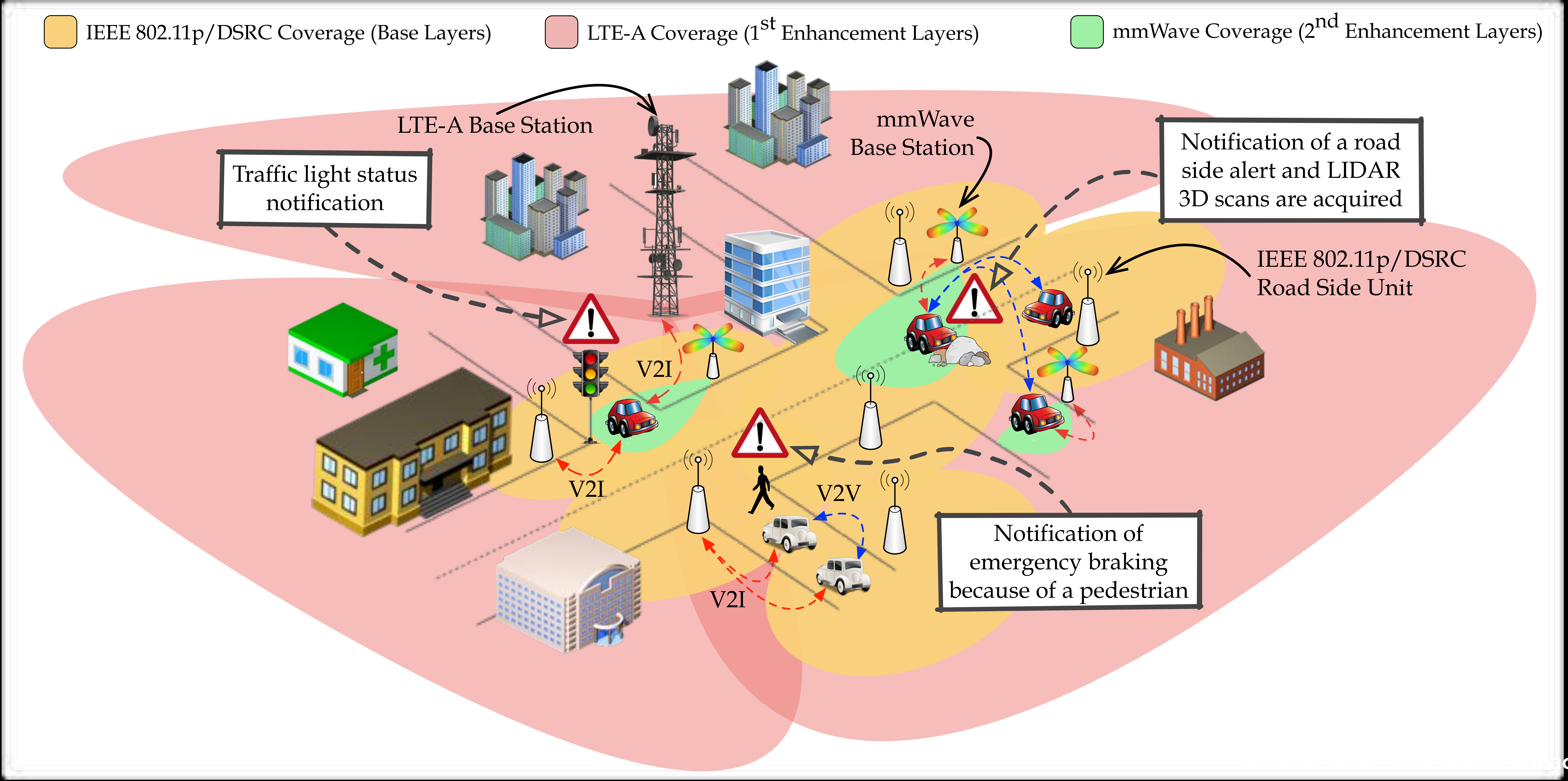
- Why Should I Put Comms Onto Self-Driving Vehicles?
- … and Why Should I go for mmWave Systems?
- Proposed mmWave V2I System Model
- Numerical Results
- Conclusions

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

Andrea Tassi - a.tassi@bristol.ac.uk

Practical Highway Scenario

mmWave BSs placed at the side of the road

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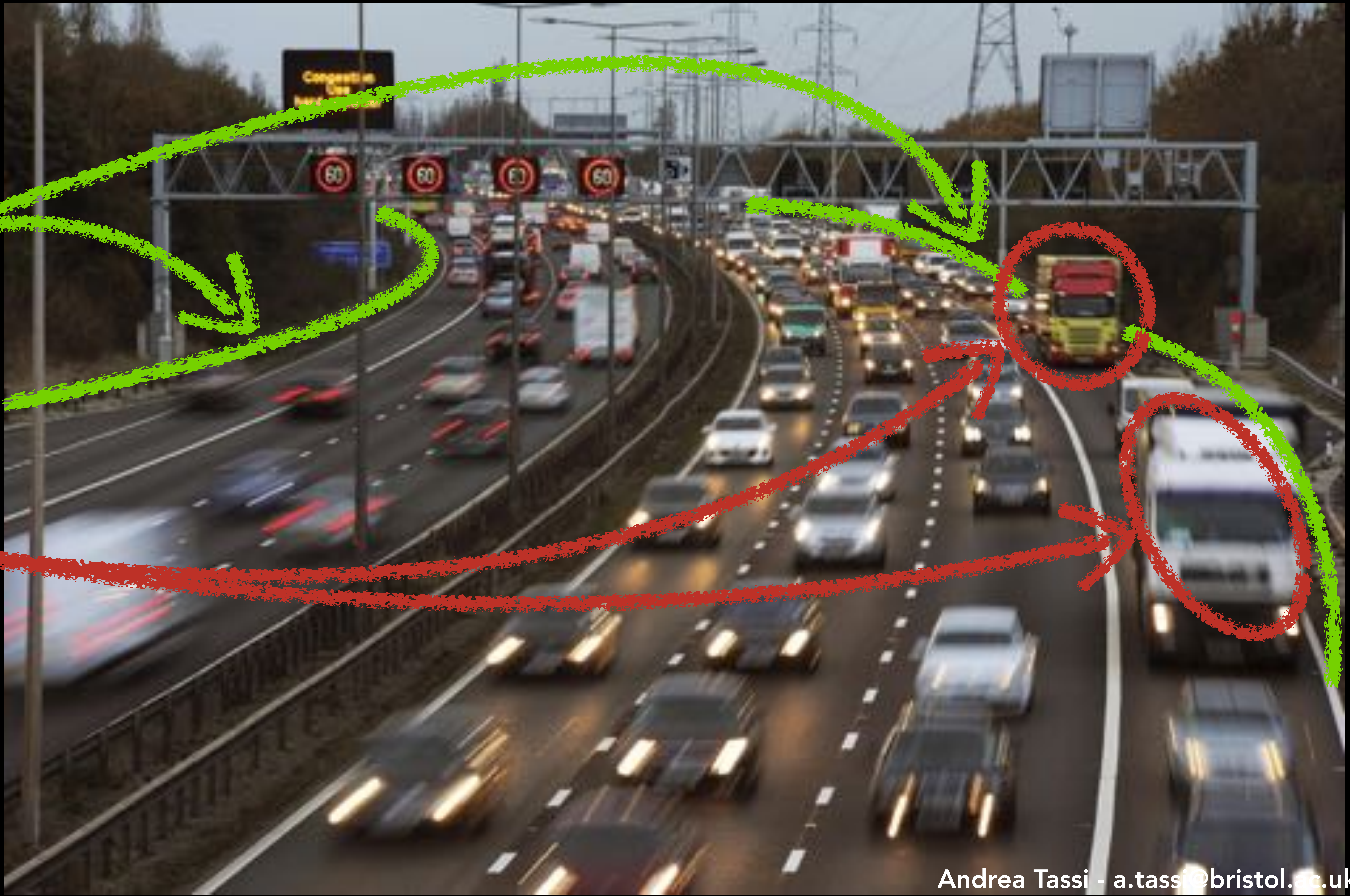
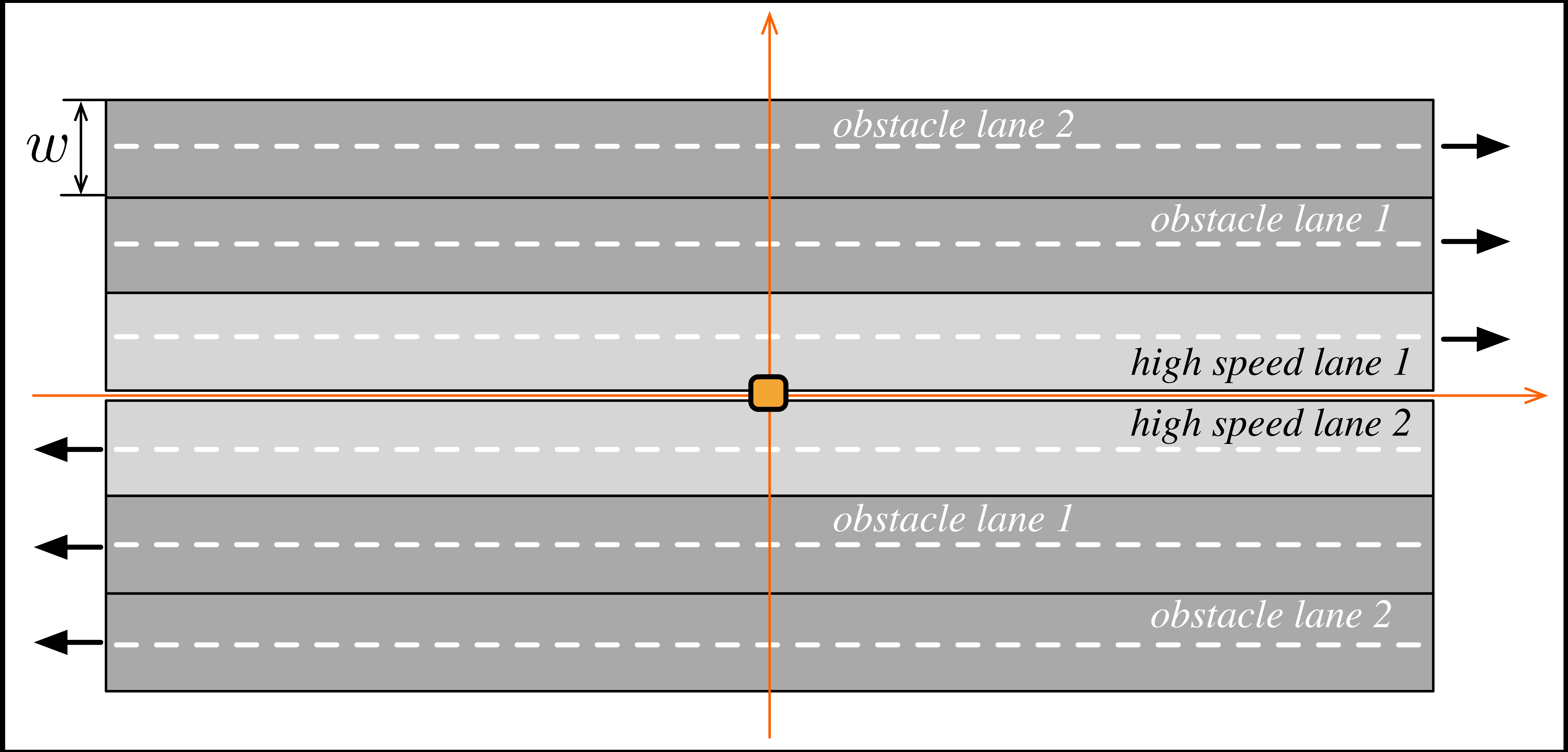
mmWave BSs placed at the side of the road

Obstacles



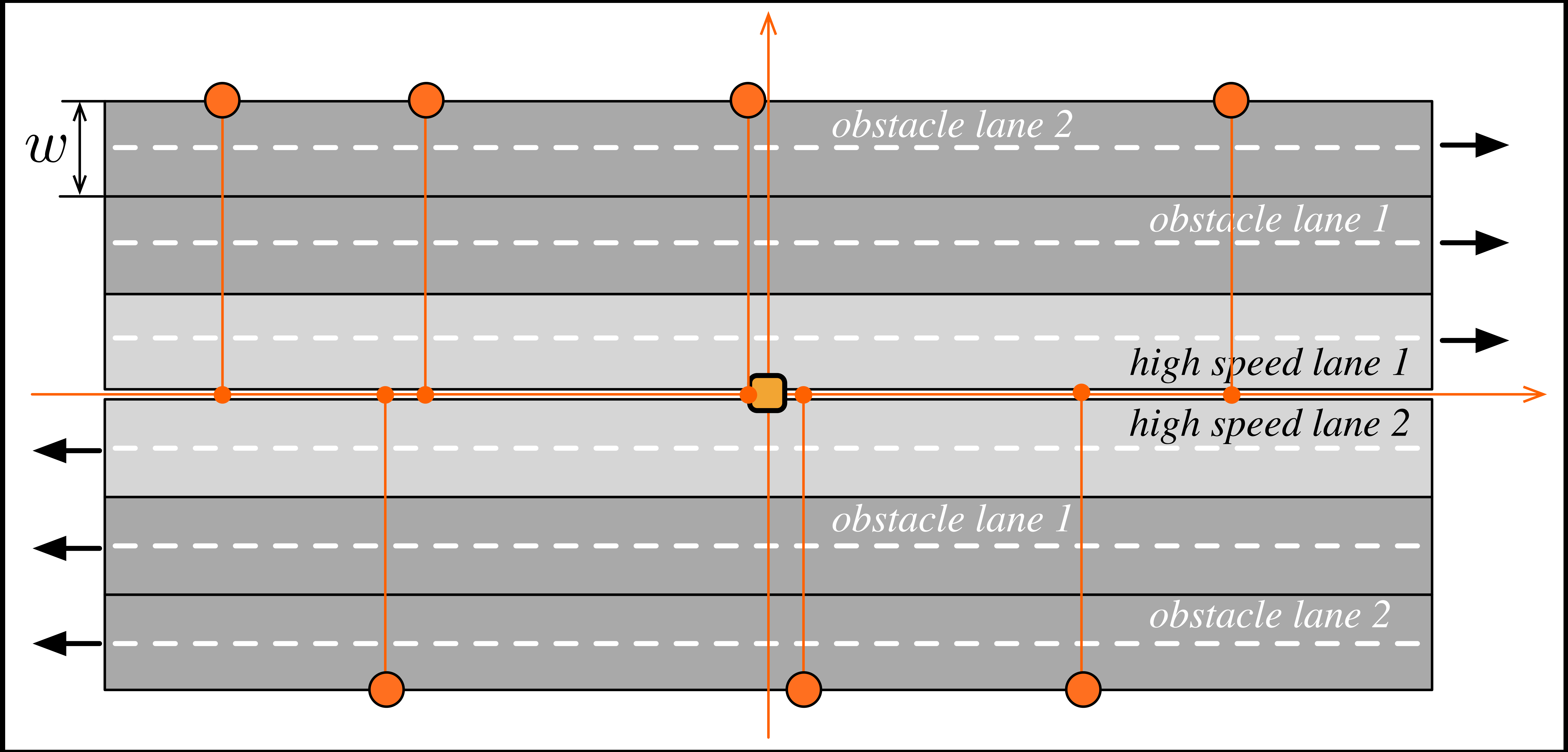
System Model (Road Layout)



- 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.

Andrea Tassi - a.tassi@bristol.ac.uk

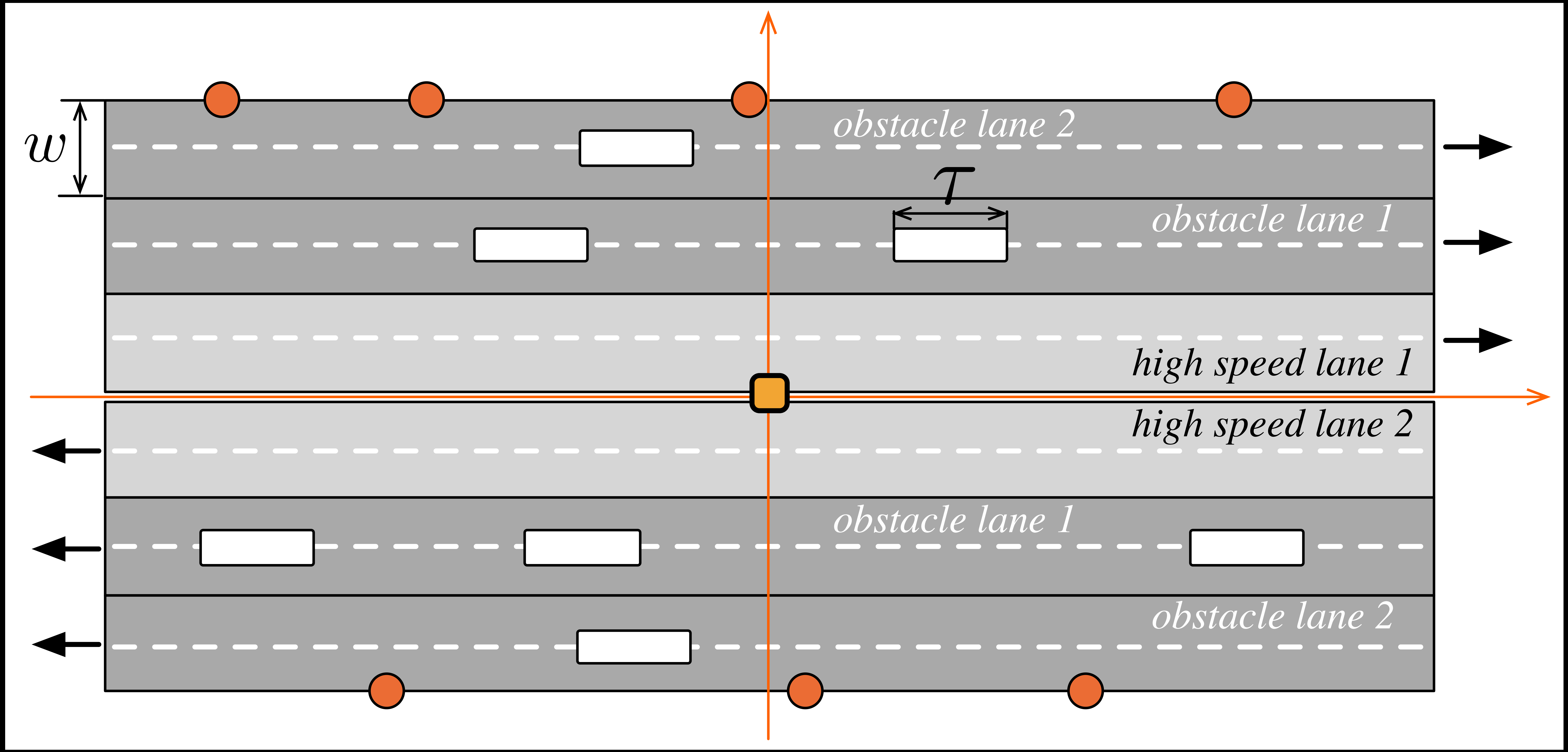
System Model (BS Distribution)



- 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 $q\lambda_{\mathrm{BS}}$

Andrea Tassi - a.tassi@bristol.ac.uk

System Model (Blockage Distribution)

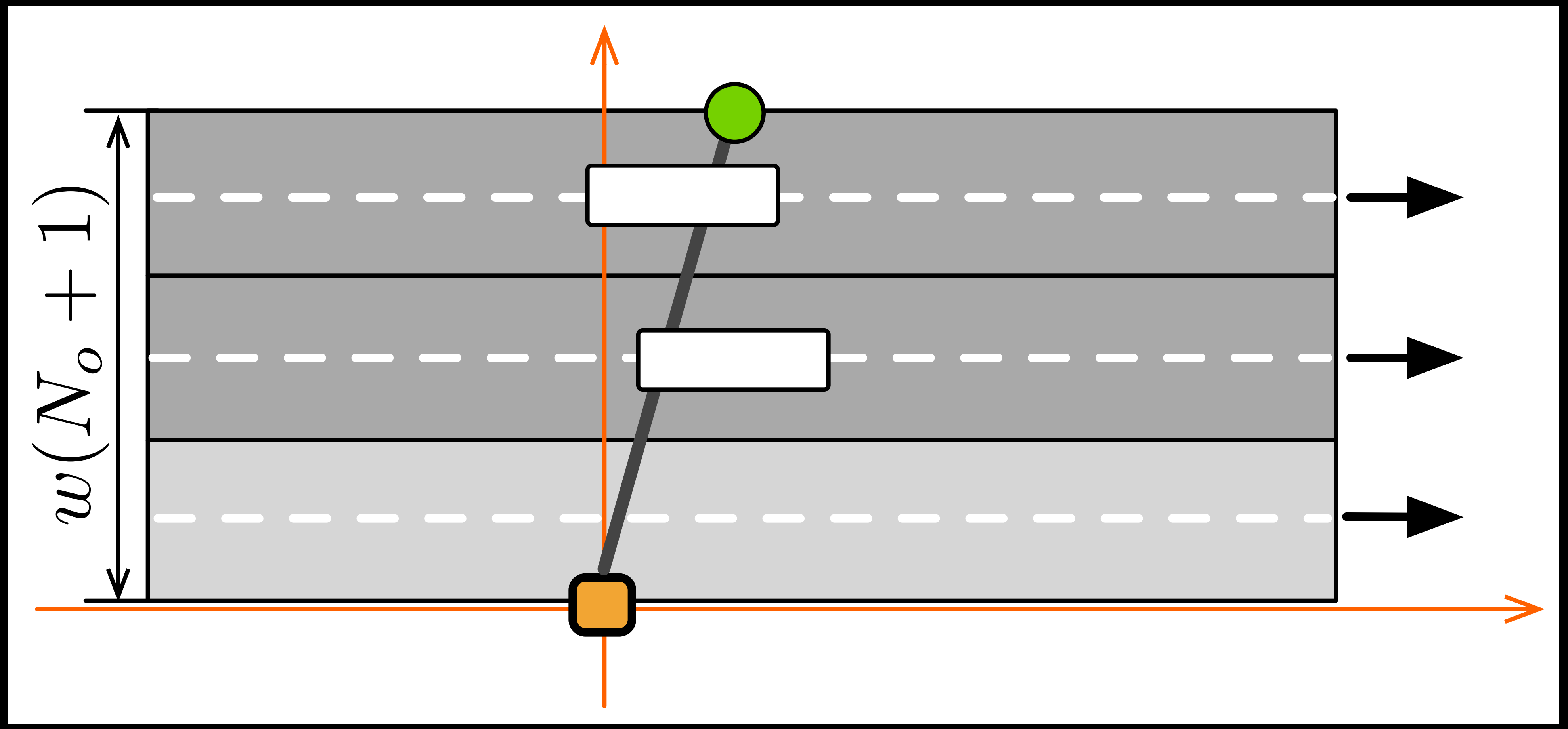


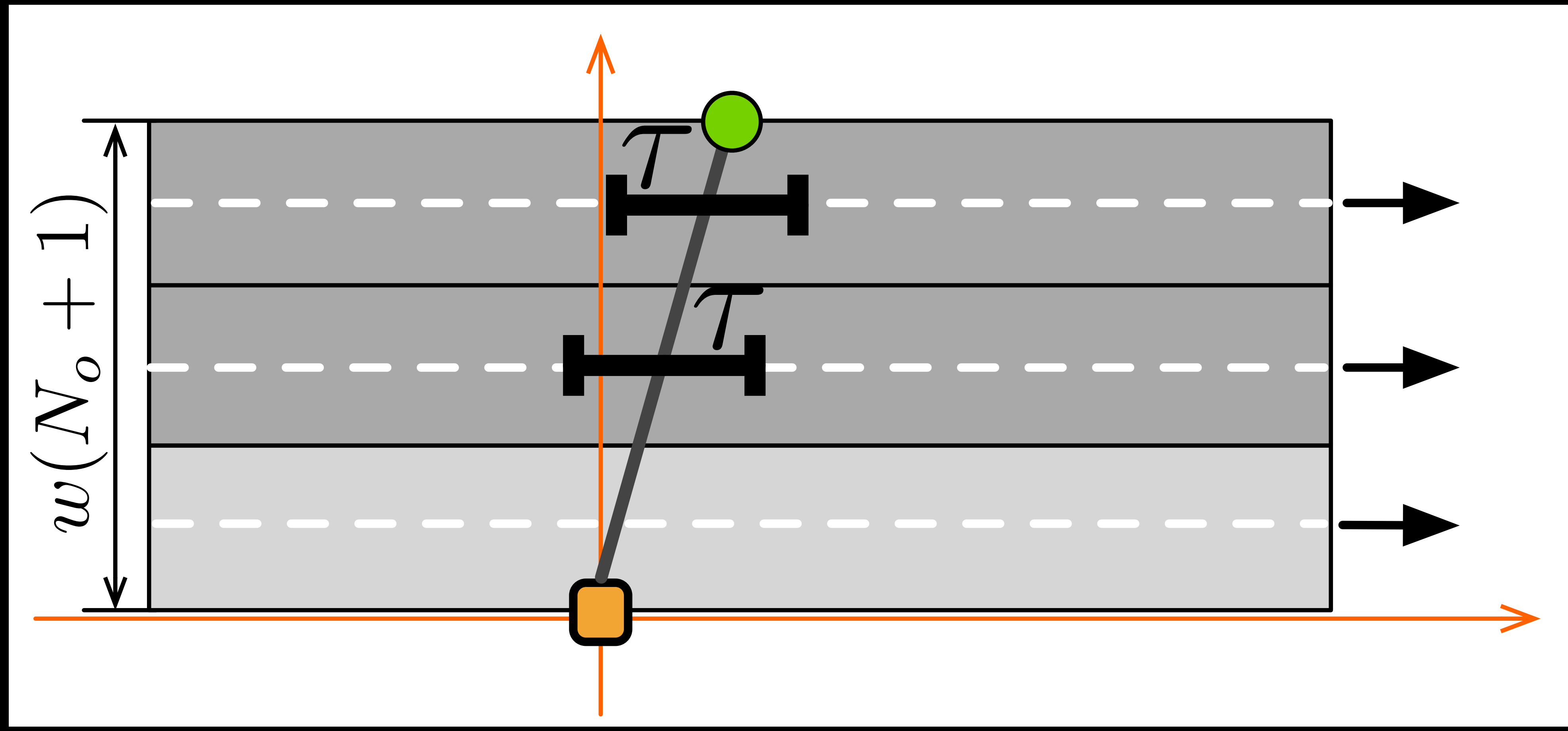
- Obstacles on each obstacle lane follow a 1D PPP of density $\lambda_{\mathrm{o},\ell}$
- Obstacle processes are independent but the blockage density of lane ℓ on each traffic direction is the same
- Each blockage is associated with a footprint of length τ

Andrea Tassi - a.tassi@bristol.ac.uk

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

Andrea Tassi - a.tassi@bristol.ac.uk

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

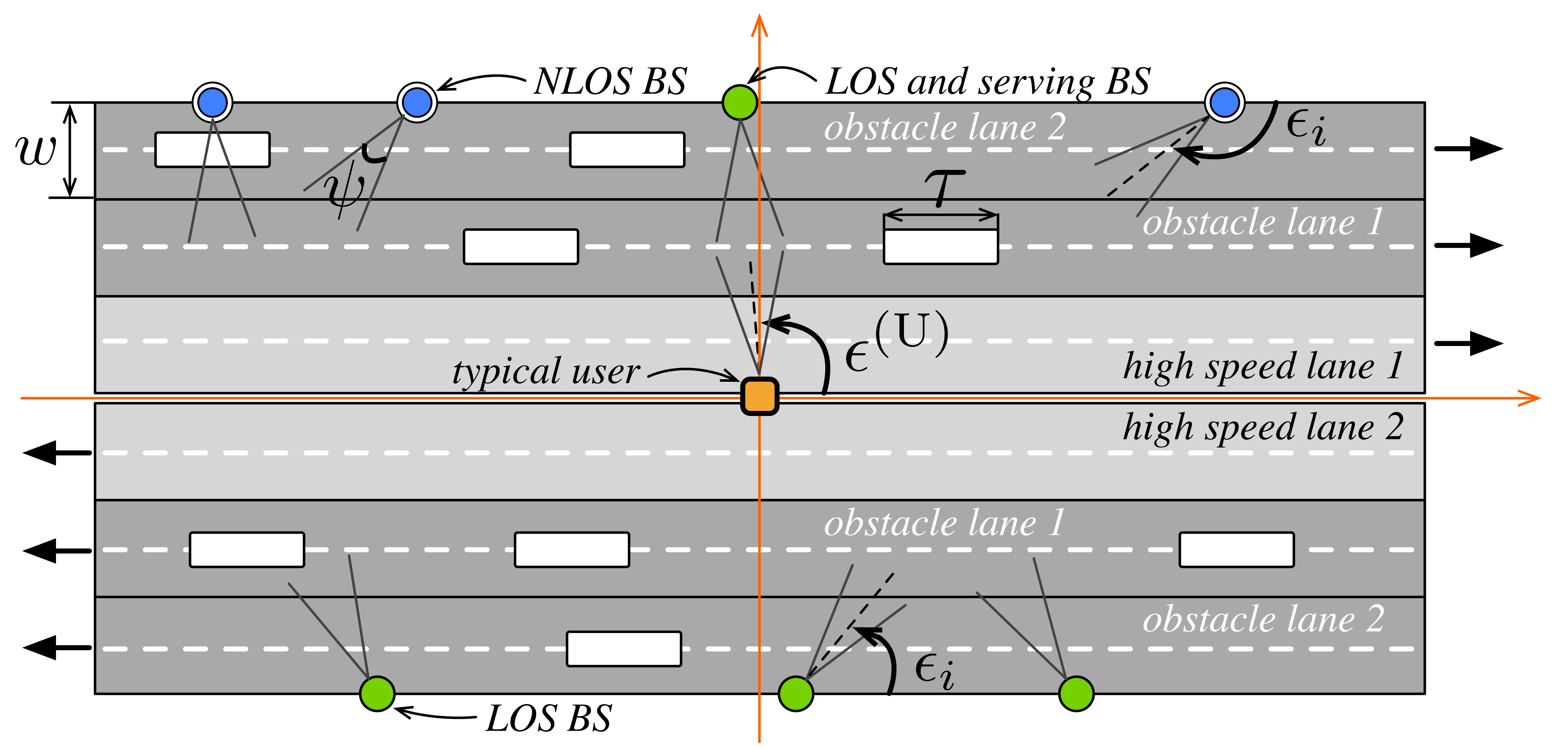
- The PL function associated with BS i is

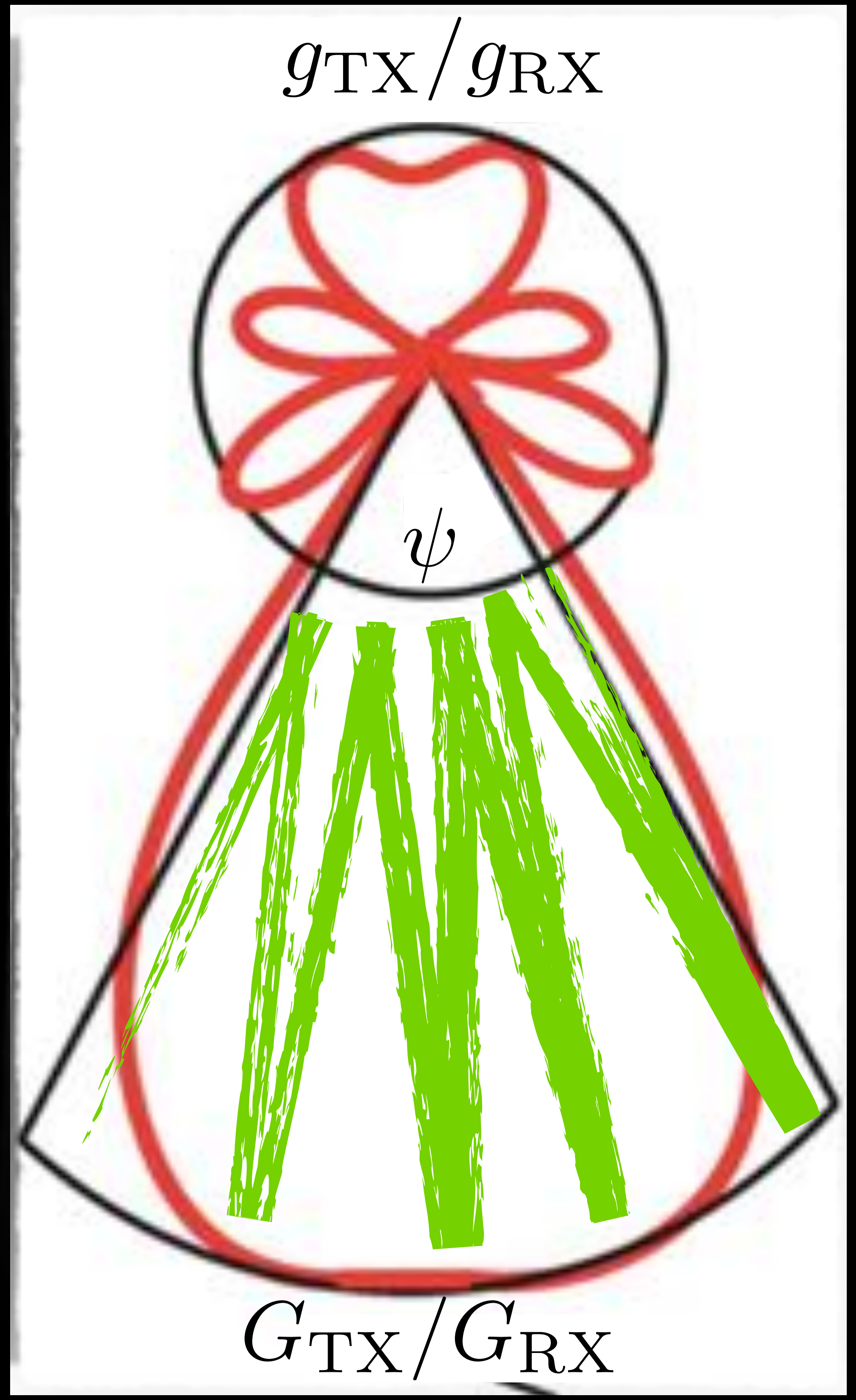
$$\ell(r_i) = \mathbf{1}_{i,\mathrm{L}} C_{\mathrm{L}} r_i^{-\alpha_{\mathrm{L}}} + (1 - \mathbf{1}_{i,\mathrm{L}}) C_{\mathrm{N}} r_i^{-\alpha_{\mathrm{N}}}$$

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

Andrea Tassi - a.tassi@bristol.ac.uk

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

Andrea Tassi - a.tassi@bristol.ac.uk

The Probability Framework

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

antenna gains

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

normalized thermal noise power

hj ~ EXP(1)

The Probability Framework

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

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, $A_L(r)$]

Probability of Being Served in LOS/NLOS

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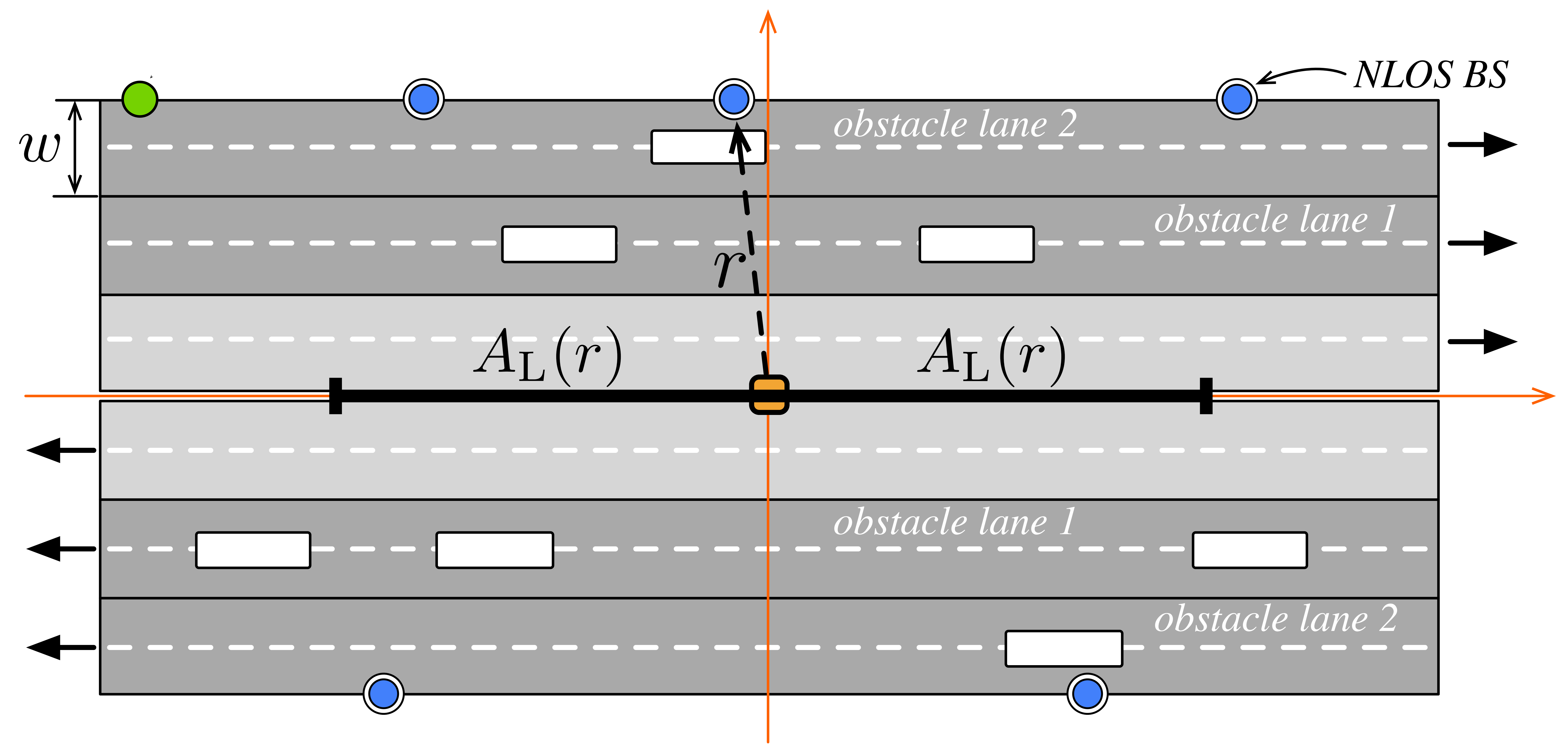

Probability of Being Served in LOS/NLOS

- The standard user connects to a NLOS BS with probability

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

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

Coverage Probability Terms

$$\overbrace{\mathbb{P}[\mathrm{SINR}_O < \theta]}^{\mathrm{P_T}(\theta)} = \mathrm{P_L} - \overbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in LOS}]}^{\mathrm{P_{CL}}(\theta)}$$
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Coverage Probability Terms

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

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

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

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

Expectation w.r.t I

Prob. of not being served in NLOS

Andrea Tassi - a.tassi@bristol.ac.uk

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,

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

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Coverage Probability Terms

$$\overbrace{\mathbb{P}[\mathrm{SINR}_O < \theta]}^{\mathrm{P_T}(\theta)} = \mathrm{P_L} - \overbrace{\mathbb{P}[\mathrm{SINR}_O > \theta \text{ and std. user served in LOS}]}^{\mathrm{P_{CL}}(\theta)}$$
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- The rate coverage follows from the Fubini's theorem (for a bandwidth *W*)

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

Andrea Tassi - a.tassi@bristol.ac.uk

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

Andrea Tassi - a.tassi@bristol.ac.uk

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

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

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

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

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

A Fundamental Result

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

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

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

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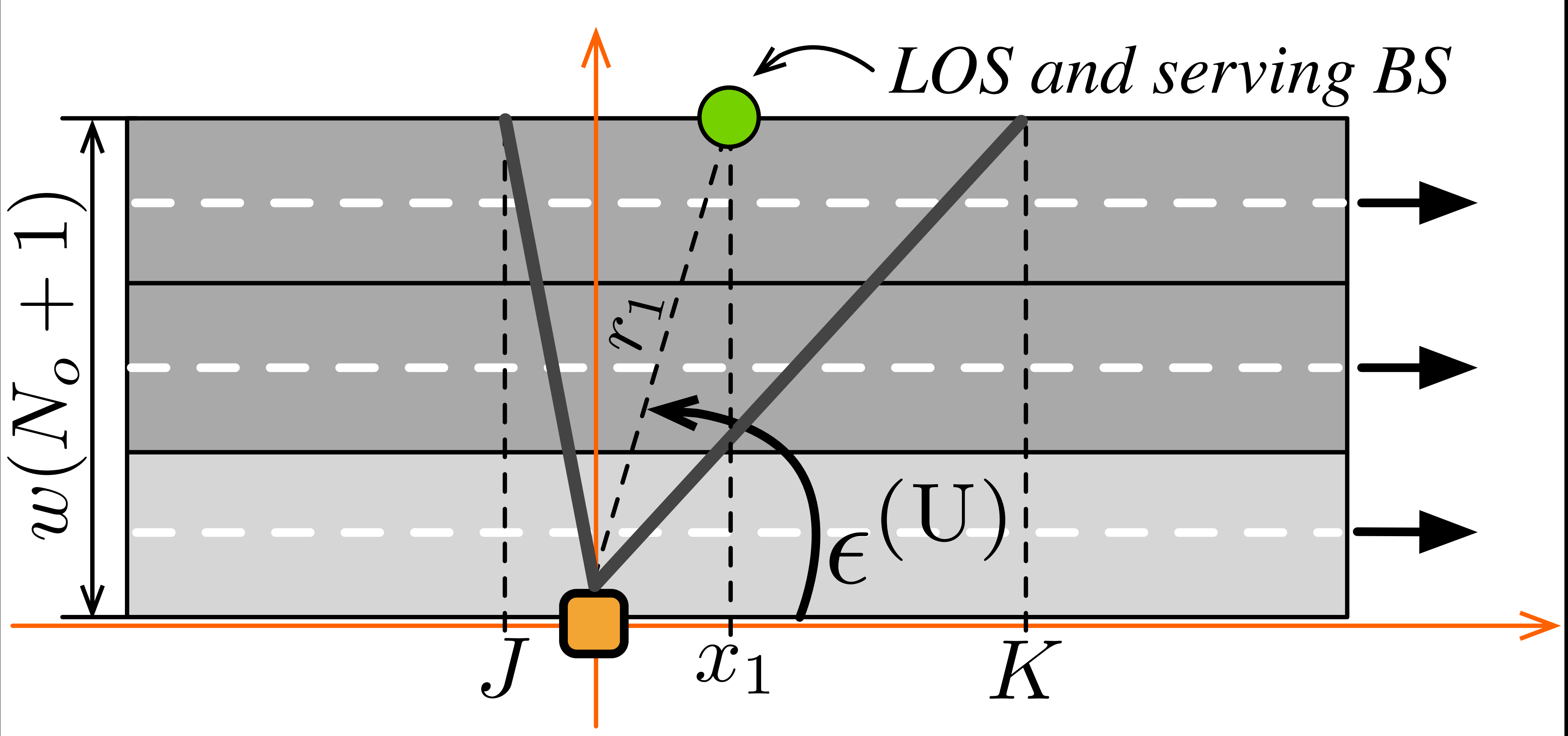
Parametrization of $\mathcal{L}_{\mathrm{I}_{\mathrm{S,E}},\mathbb{E}_1}$

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

- However, we characterize the RX antenna gain.



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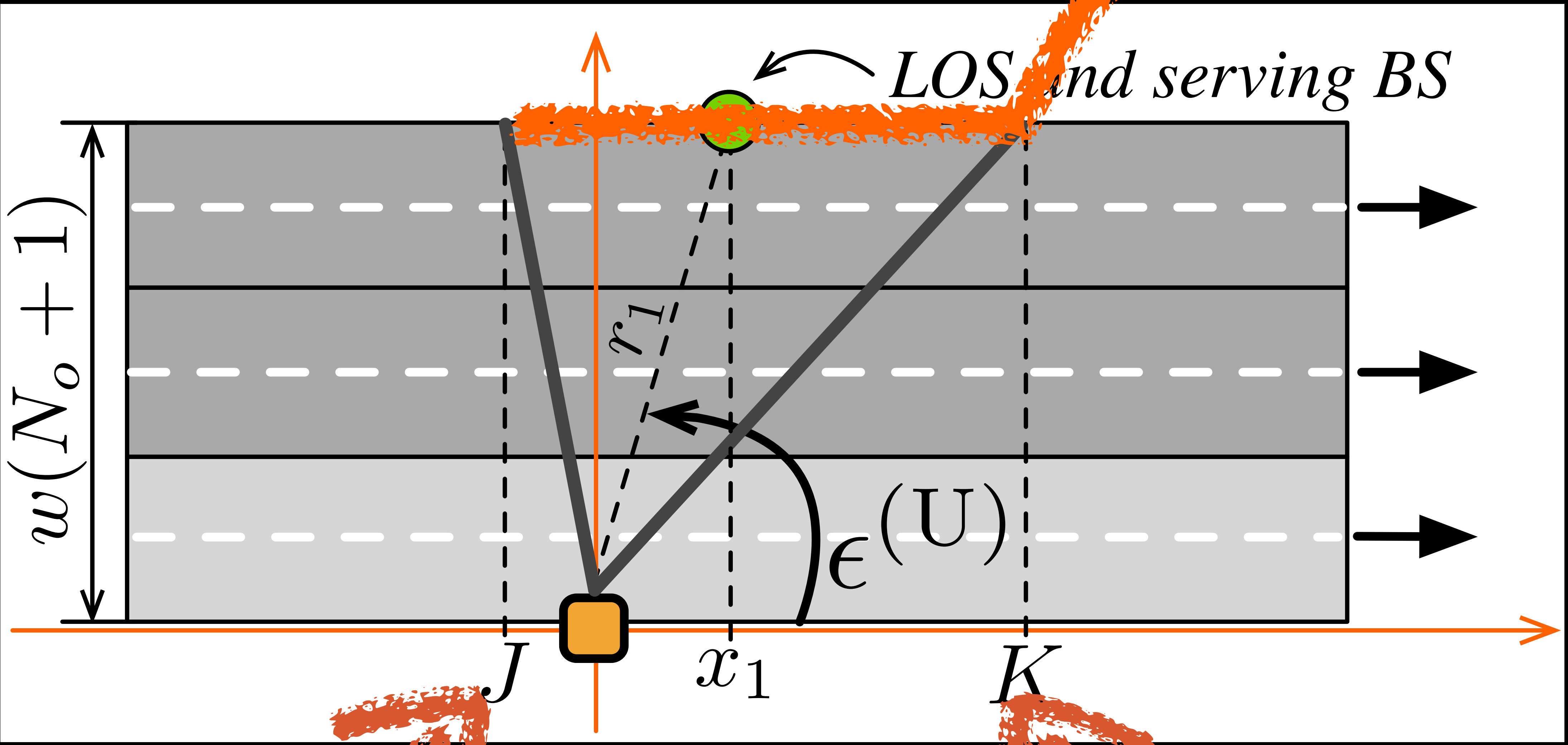

No other LOS BSs can be present in this interval

Andrea Tassi - a.tassi@bristol.ac.uk

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

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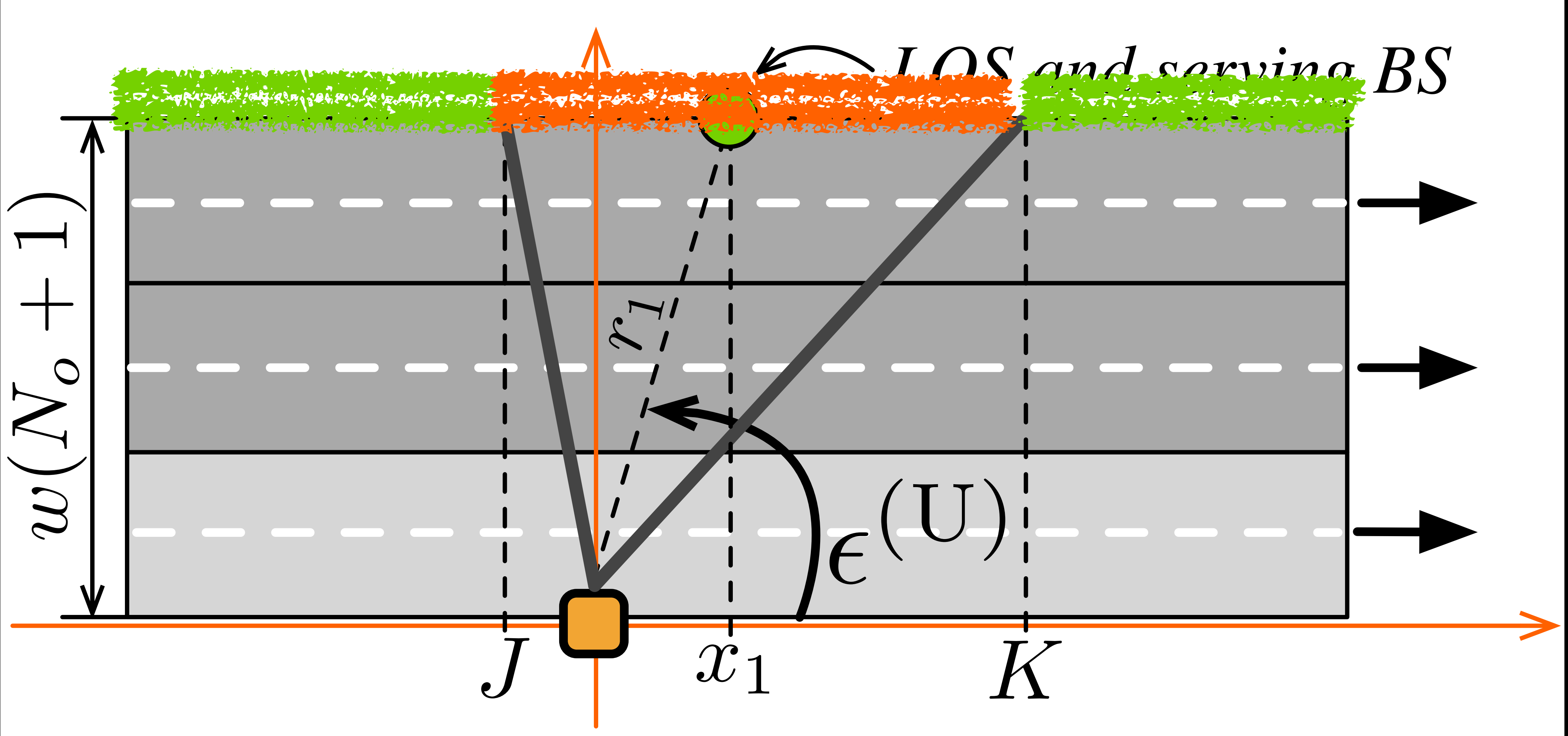
- However, we characterize the RX antenna gain.

Min RX gain
Max RX gain



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

$<\mathbb{S}_1,\mathbb{E}_1,\mathrm{S},\mathrm{E}>$	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

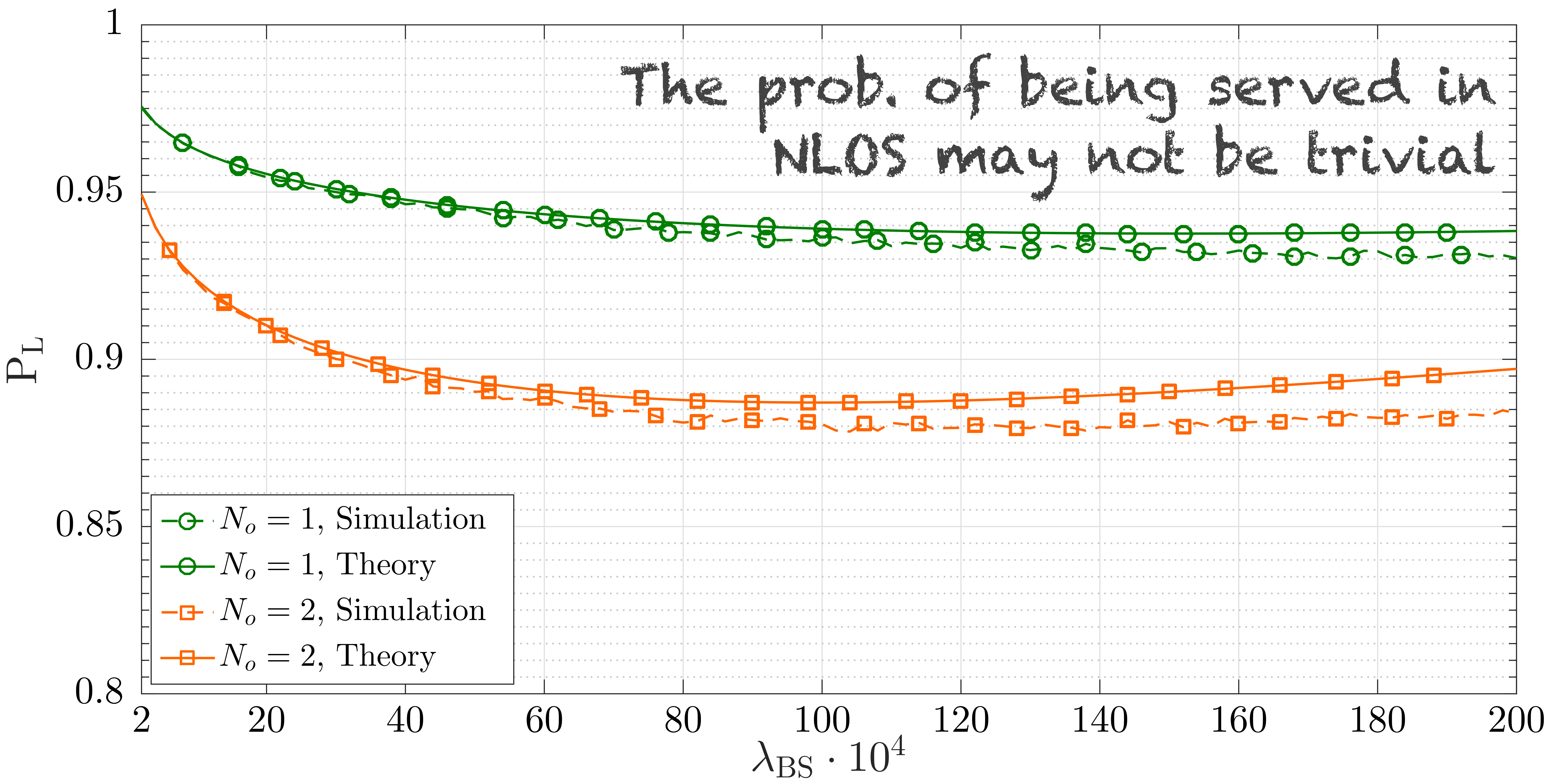
$$\mathcal{L}_{\mathrm{I},\mathbb{E}_1}(s) \cong \prod_{\mathrm{S}\in\{\mathrm{U},\mathrm{B}\},\mathrm{E}\in\{\mathrm{L},\mathrm{N}\}} \mathcal{L}_{I_{\mathrm{S,E}},\mathbb{E}_1}(s)$$

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

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

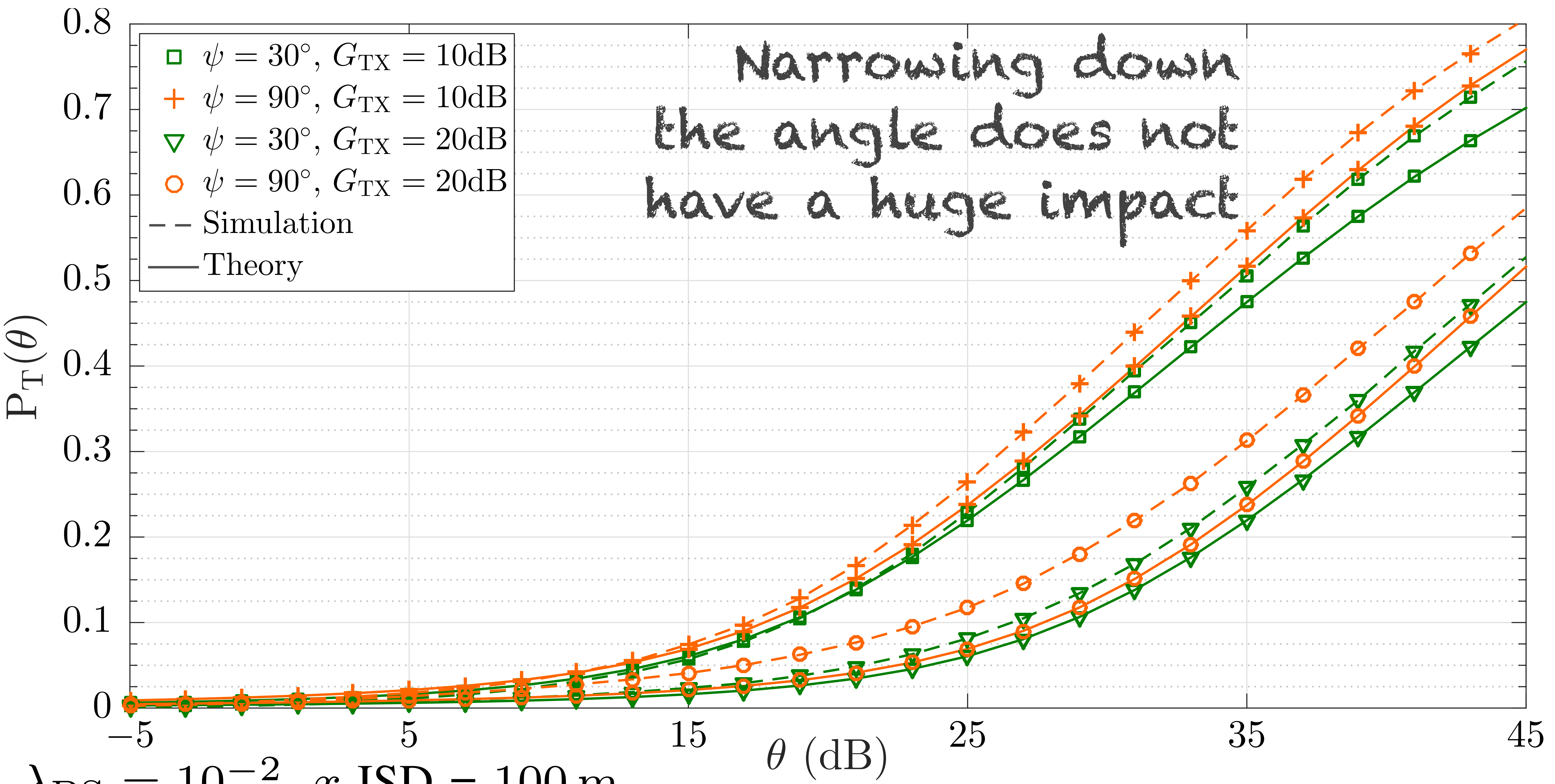
Numerical Results

LOS vs. NLOS



Andrea Tassi - a.tassi@bristol.ac.uk

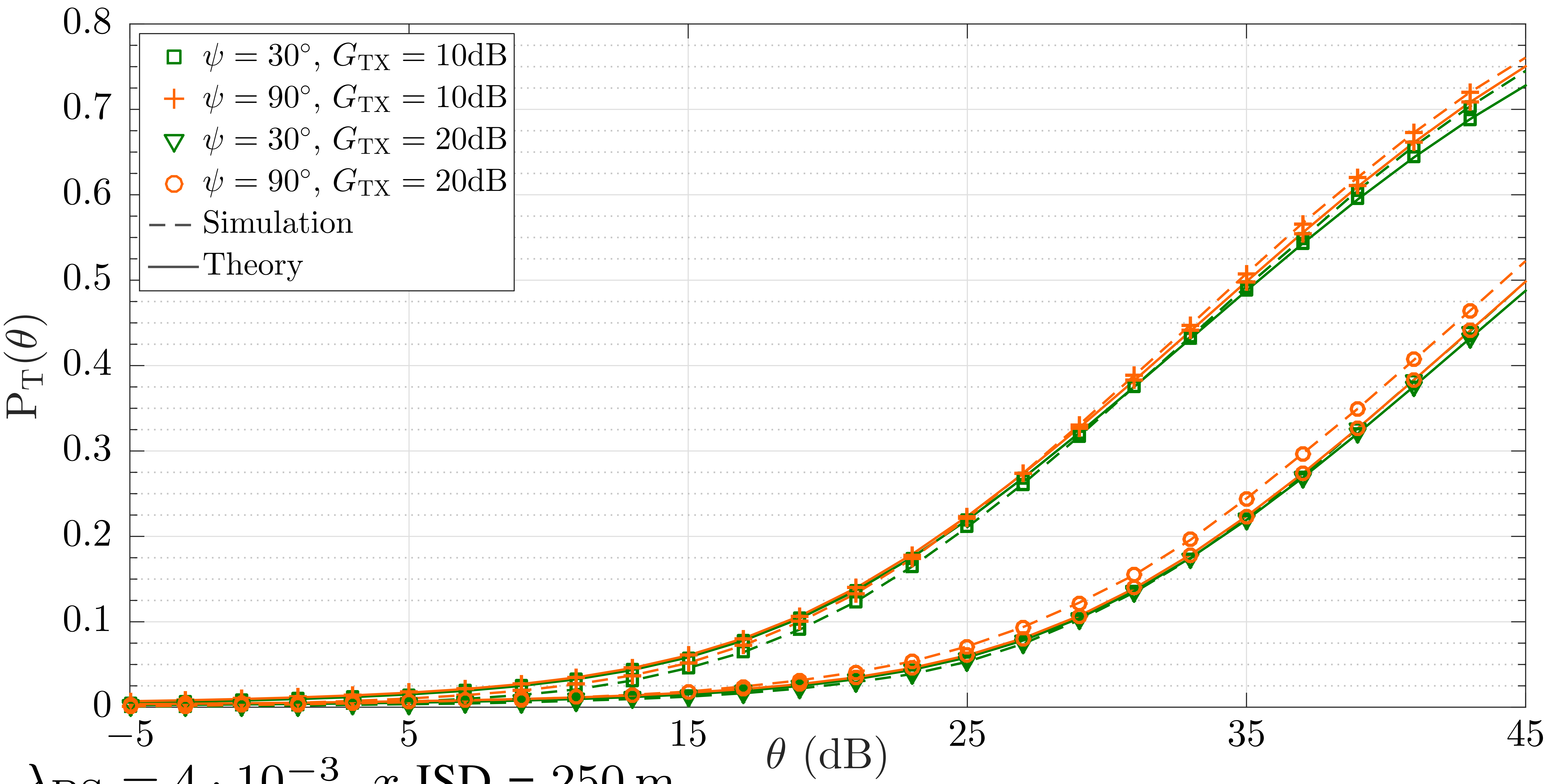
SINR Outage



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

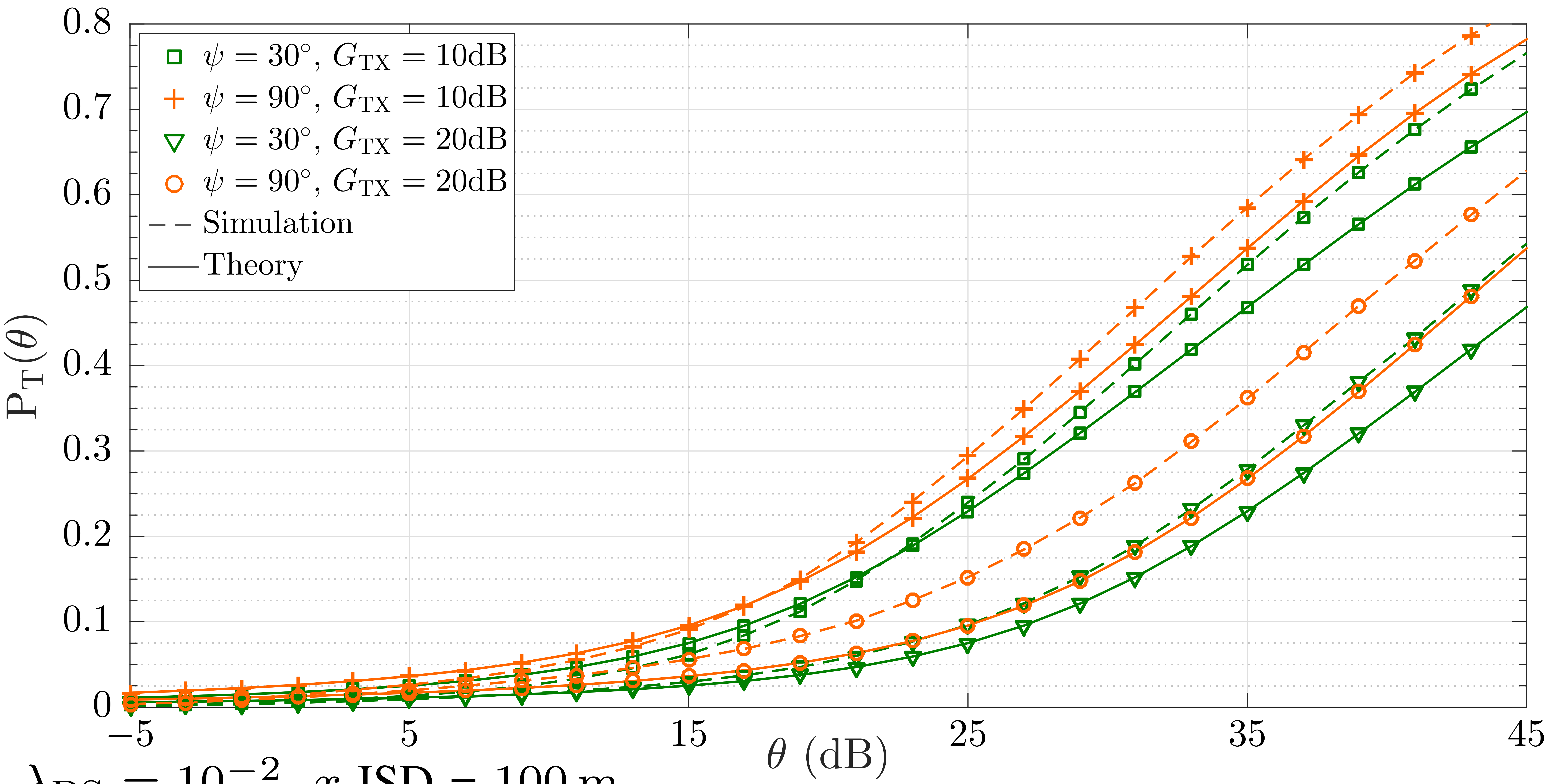
Andrea Tassi - a.tassi@bristol.ac.uk

SINR Outage



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

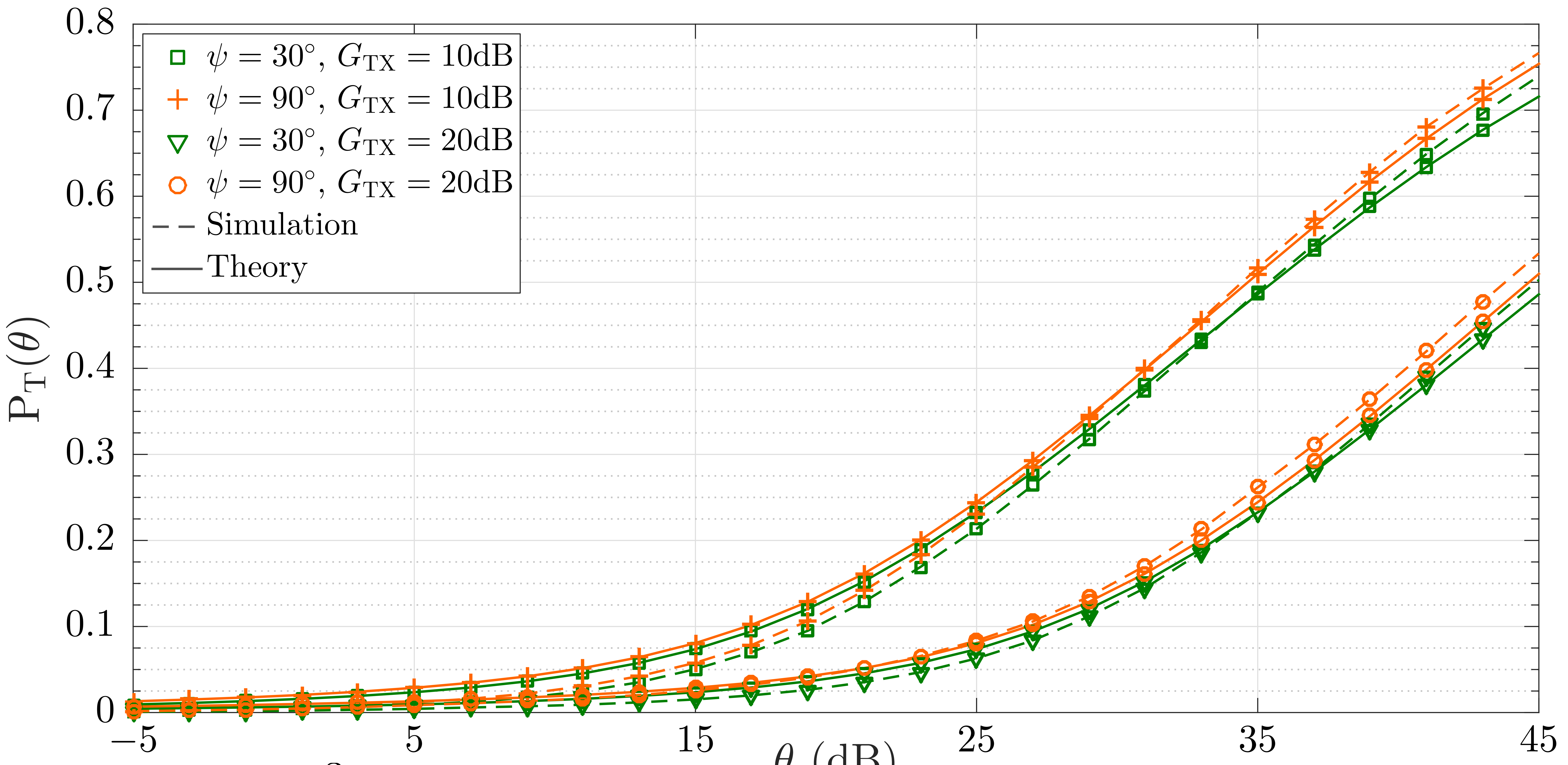
SINR Outage



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

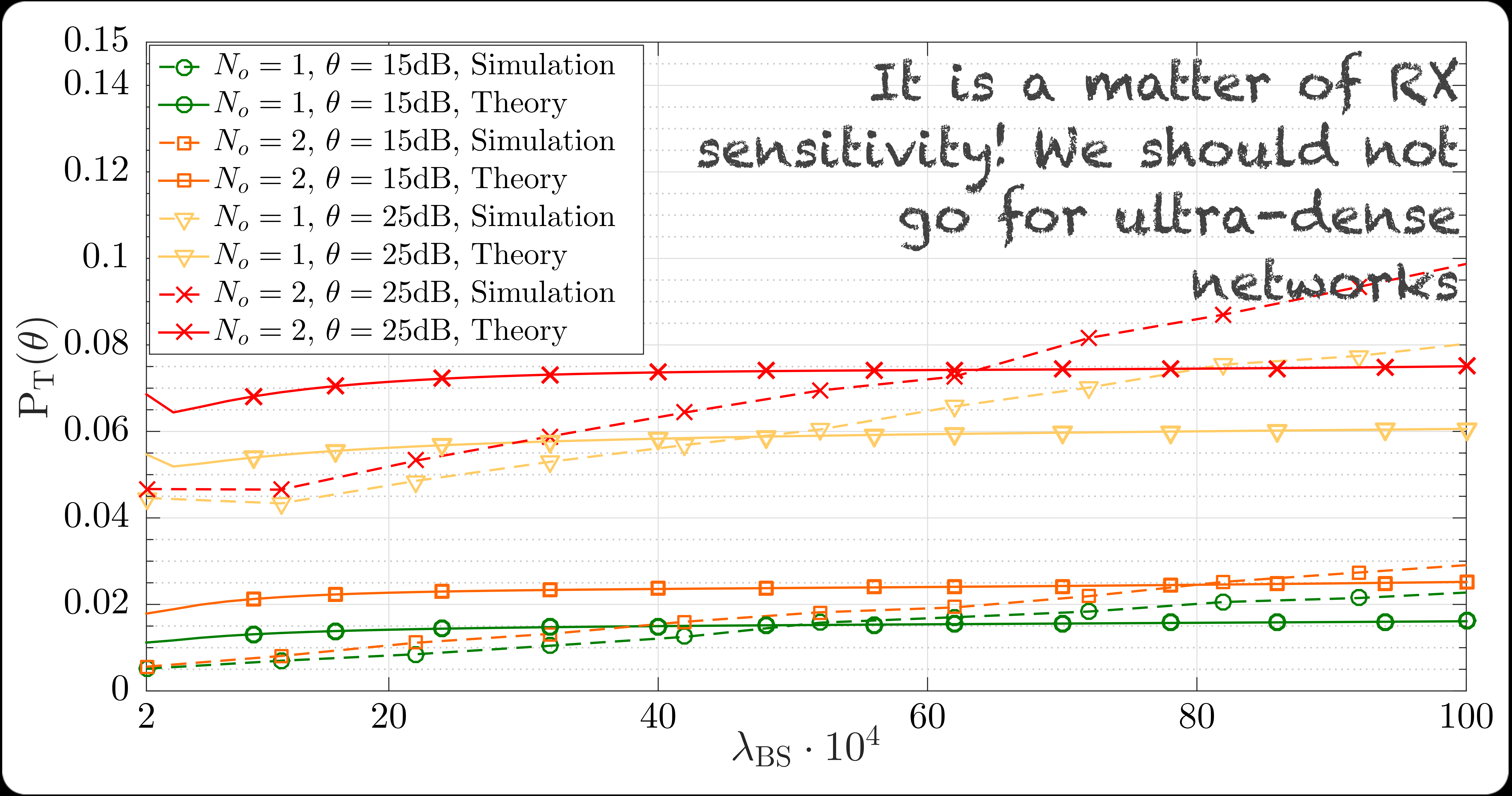
Andrea Tassi - a.tassi@bristol.ac.uk

SINR Outage



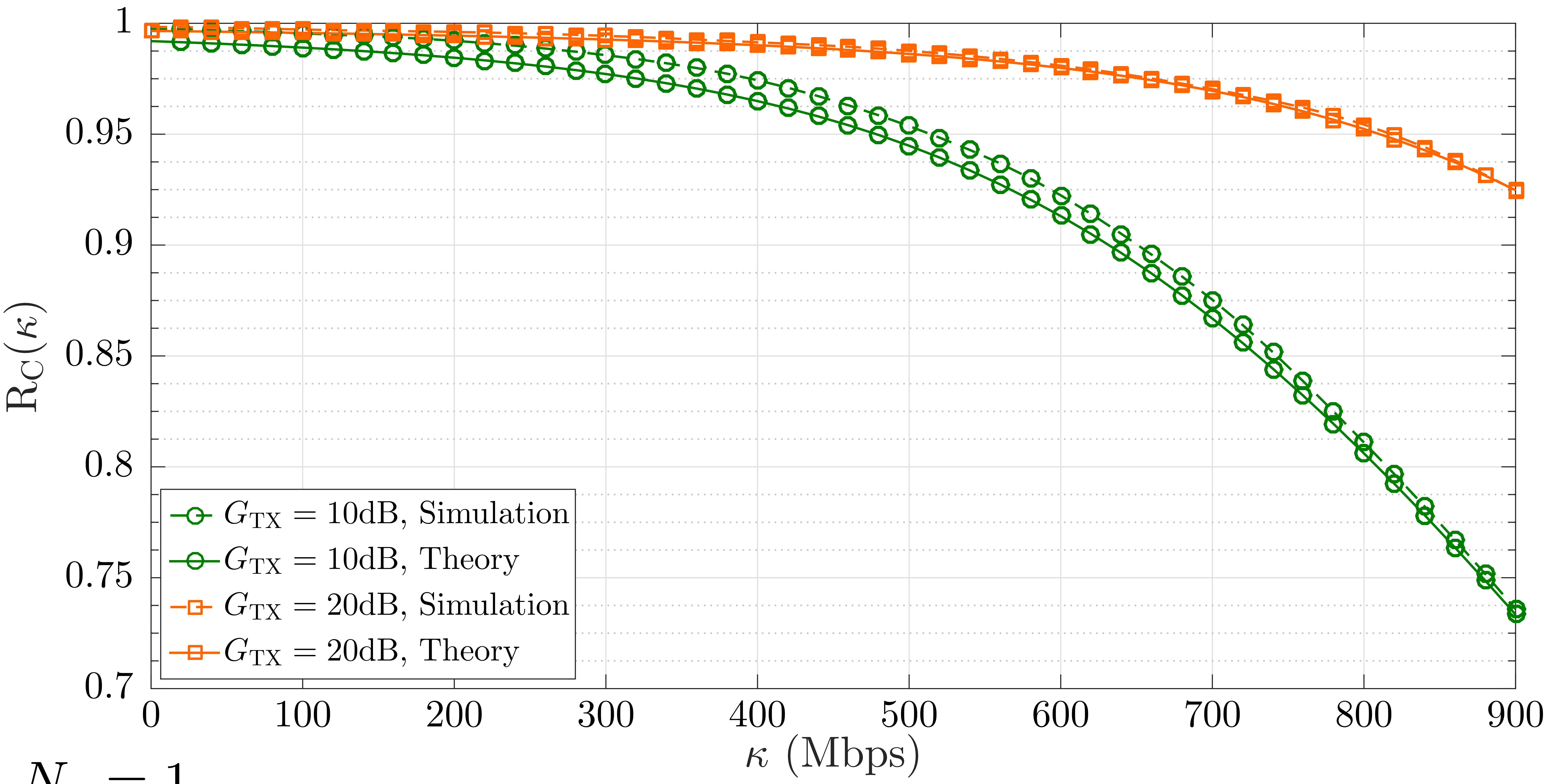
$\lambda_{BS} = 4 \cdot 10^{-3}$, x-ISD = 250 m

SINR Outage



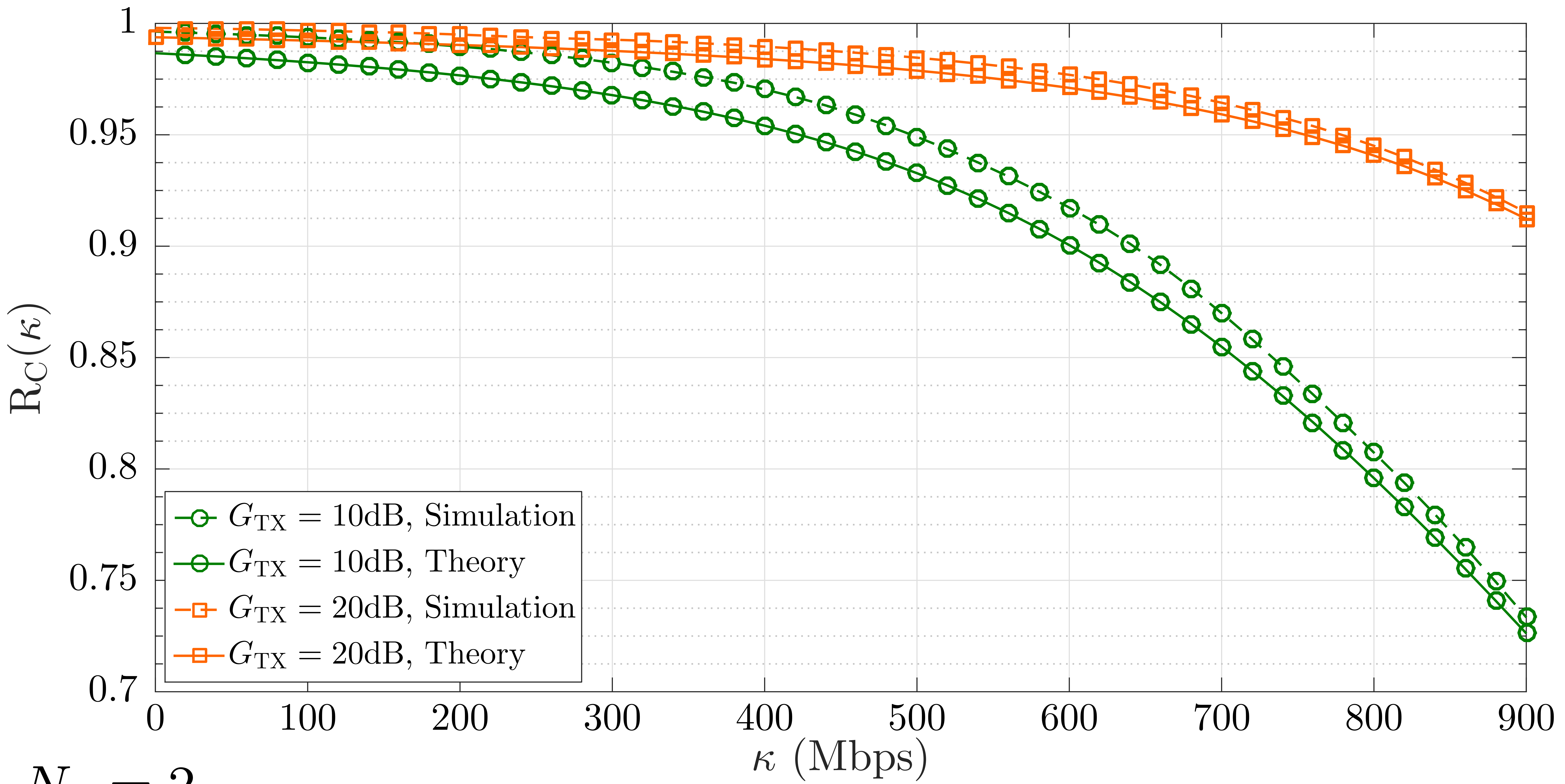
Andrea Tassi - a.tassi@bristol.ac.uk

Rate Coverage

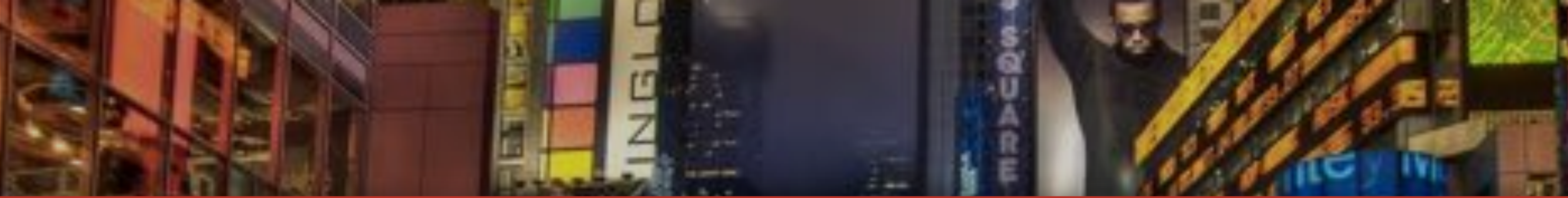


$N_o = 1$

Rate Coverage



$N_o = 2$



Conclusions

Andrea Tassi - a.tassi@bristol.ac.uk

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.

University of Bristol

Communication Systems and Network Group

Thanks for your attention!

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

Andrea Tassi - a.tassi@bristol.ac.uk

ECIT, Queen's University Belfast

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