# Near-field Liquid Crystal RIS Phase-Shift Design for Secure Wide-band Illumination

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08 December 2025

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This paper was funded in part by the DFG, German Research Foundation, within the Collaborative Research Center MAKI and in part by the LOEWE initiative (Hesse, Germany) within the emergenCITY Centre.

# Outline

1- Introduction

2- LC Model

3- Secure Wideband Illumination

4- Performance Evaluation

5- Conclusions

6- References

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# Introduction

## Motivation

- Demands:
  Higher data rates and capacity are required in modern communication systems (e.g., 5G, 6G).
- To provide higher data rates, expanding available bandwidth through increased frequency is essential.

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  Higher data rates and capacity are required in modern communication systems (e.g., 5G, 6G).
- To provide higher data rates, expanding available bandwidth through increased frequency is essential.

| Time | XG | Aim | Data rate |
|---|---|---|---|
| 1979 | 1G | Voice | 2 - 3 kbps |
| 1991 | 2G | SMS | 20 - 40 kbps |
| 1998 | 3G | Data | 0.5 - 3 Mbps |
| 2009 | 4G | Streaming | 20 – 100 Mbps |
| 2019 | 5G | Sensing | 100 – 400 Mbps |
| 2030 | 6G | Intelligence | 1 – 10 Gbps |

# Introduction

## RIS Implementation

| | Varactor | PIN Diode | MEMS Switch | MEMS Mirror | LC |
|---|---|---|---|---|---|
| Tuning time | ns | ns | $\mu$s | 100s of $\mu$s | $>$ 10 ms |
| Tunability | continuous | discrete (1 bit/diode) | discrete | discrete | continuous |
| Power consumption | medium | medium | low | low | low |
| Scalability | low (cost per diode) | low (cost per diode) | medium (encapsulation) | medium (cost per area) | high |
| Frequency range | few GHz | mm-Wave | mm-Wave | THz | $>$ 10 GHz |
| Cost | high | high | high | high | low |

Comparison of technologies used for the realization of RIS [1].

[1] Alejandro Jiménez-Sáez et al. "RISs with LC Technology: A Hardware Design and Communication Perspective". In: arXiv:2308.03065 (2023).

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# LC Model
## LC Model

$$[\boldsymbol{\omega}(f_k)]_n = \left(1 + \beta(\frac{f_k}{f_c} - 1)\right)[\boldsymbol{\omega}_c]_n, \forall n, \forall k,$$

$f_c$ : Center frequency,
$f_k$ : $k$th subcarrier,
$[\omega_c]_n$ : RIS phase shifter in $n$th element and $f_c$,
$\beta$ : A physical constant parameter.

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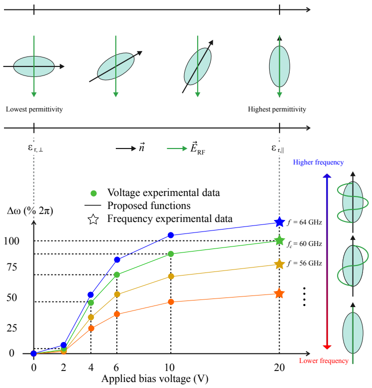



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# Secure Wideband Illumination

## System Model and Problem

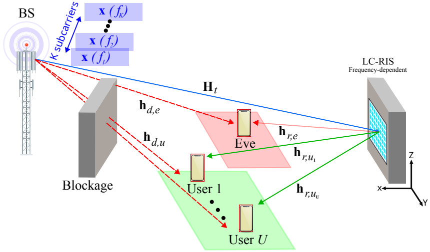


Figure: $\mathcal{P}_u$ and $\mathcal{P}_e$ are the green and red areas, respectively.

# Secure Wideband Illumination

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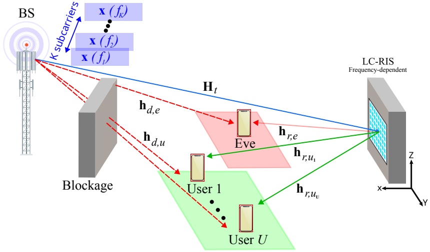


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P1:

$$\max_{\alpha,\boldsymbol{\omega}_c,\mathbf{q}} \ \alpha$$

$$\text{s.t.} \ \ \mathrm{SR}(f_k) \geq \alpha, \ \forall \mathbf{p}_u \in \mathcal{P}_u, \ \forall \mathbf{p}_e \in \mathcal{P}_e, \ \forall k,$$

$$0 \leq [\boldsymbol{\omega}_c]_n < 2\pi,$$

$$[\boldsymbol{\omega}(f_k)]_n = [\boldsymbol{\omega}_c]_n \beta_k, \forall n, \ \forall k,$$

$$\|\mathbf{q}\|_2^2 \leq P_t.$$

$$\mathrm{SR}(f_k) = [\log(1+\mathrm{SNR}_u(f_k)) - \log(1+\mathrm{SNR}_e(f_k))]^+,$$

$$\mathrm{SNR}_u(f_k) = |(\mathbf{h}_u^{\text{eff}}(f_k))^{\mathsf{H}}\mathbf{q}|^2/\sigma_n^2,$$

$$\mathrm{SNR}_e(f_k) = |(\mathbf{h}_e^{\text{eff}}(f_k))^{\mathsf{H}}\mathbf{q}|^2/\sigma_n^2,$$

# Secure Wideband Illumination

## Impact of the Number of Tx Antennas on Beam Squinting

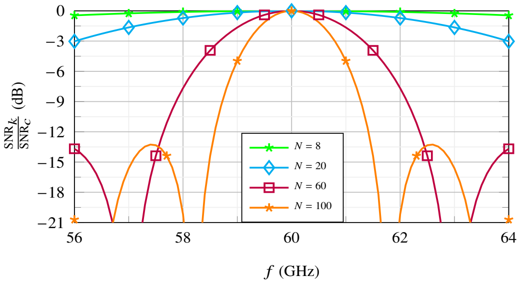


Figure: The normalized Rx power (dB) versus frequency for given $N$ values 8, 20, 60, and 100.

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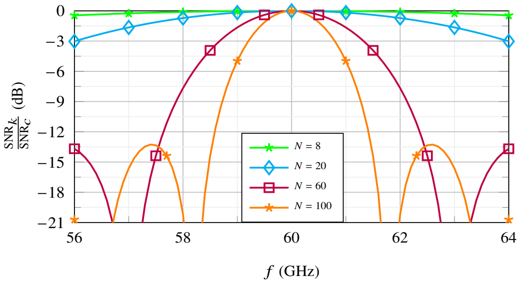


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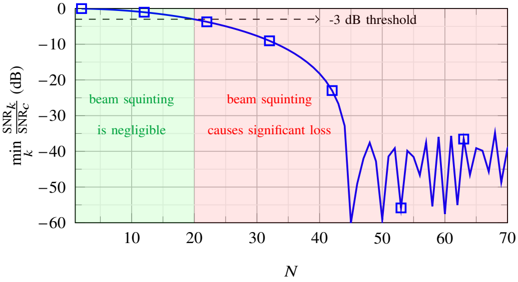


Figure: The normalized minimum Rx power (dB) across all subcarriers versus number of Tx antenna for given bandwidth 8.64 GHz, where $f_c = 60$ GHz.

# Secure Wideband Illumination
## Beamformer Design

$$\text{P2:} \quad \max_{\alpha,\mathbf{q}} \alpha$$
$$\text{s.t.} \quad \mathrm{SR}(f_k) \geq \alpha, \ \forall \mathbf{p}_u \in \mathcal{P}_u, \ \forall \mathbf{p}_e \in \mathcal{P}_e, \ \forall k,$$
$$\|\mathbf{q}\|_2^2 \leq P_t.$$

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$$\|\mathbf{q}\|_2^2 \leq P_t.$$

**Lemma**

*Assuming a dominant LOS link, fixed RIS phase shifts, and blocked direct channels for both the legitimate user and the eavesdropper, the optimal beamformer for P2 is given by* $\mathbf{q} = \sqrt{P_t}\mathbf{a}_{\mathrm{BS}}(\mathbf{p}_{\mathrm{RIS}}, f_c)$*, where* $\mathbf{a}_{\mathrm{BS}}$ *is steering vector in BS and* $\mathbf{p}_{\mathrm{RIS}}$ *is the RIS location.*

**Proof.**

The proof is provided in [3, Lemma 1]. □

[3] Mohamadreza Delbari, et al. "Temperature-aware phase-shift design of LC-RIS for secure communication". In: ICC (2025).

# Secure Wideband Illumination

## RIS Phase Shifter Design

P3:

$$\begin{aligned} \max_{\alpha,\boldsymbol{\omega}_c} \ & \alpha \\ \text{s.t.} \ & \mathrm{SR}(f_k) \geq \alpha, \ \forall(\mathbf{p}_u, \mathbf{p}_e) \in \mathcal{P}_u \times \mathcal{P}_e, \ \forall k, \\ & 0 \leq [\boldsymbol{\omega}_c]_n < 2\pi, \\ & [\boldsymbol{\omega}(f_k)]_n = [\boldsymbol{\omega}_c]_n \beta_k, \forall n, \ \forall k. \end{aligned}$$

# Secure Wideband Illumination
## RIS Phase Shifter Design

P3: $$\max_{\alpha,\boldsymbol{\omega}_c} \alpha$$
s.t. $$\mathrm{SR}(f_k) \geq \alpha,\ \forall(\mathbf{p}_u,\mathbf{p}_e)\in\mathcal{P}_u\times\mathcal{P}_e,\ \forall k,$$
$$0 \leq [\boldsymbol{\omega}_c]_n < 2\pi,$$
$$[\boldsymbol{\omega}(f_k)]_n = [\boldsymbol{\omega}_c]_n\beta_k, \forall n,\ \forall k.$$

P4: $$\max_{\gamma,\mathbf{S}_c} \gamma$$
s.t. C1: $$\mathrm{tr}(\mathbf{A}_k(\gamma)\mathbf{S}_c^{\circ\beta_k}) \geq \gamma - 1, \forall(\mathbf{p}_u,\mathbf{p}_e)\in\mathcal{P}_u\times\mathcal{P}_e,\ \forall k,$$
C2: $$\mathbf{S}_k \succeq 0,\ \forall k,$$
C3: $$\mathrm{rank}(\mathbf{S}_k) = 1,\ \forall k,$$
C4: $$\mathrm{diag}(\mathbf{S}_k) = \mathbf{1}_N,\ \forall k,$$

where $\log(\gamma) = \alpha$, $\mathbf{s}_k \triangleq [\mathrm{e}^{\mathrm{j}[\boldsymbol{\omega}(f_k)]_1}, \cdots, \mathrm{e}^{\mathrm{j}[\boldsymbol{\omega}(f_k)]_N}]^{\mathsf{T}}, \forall k$, $\mathbf{S}_c^{\circ\beta_k} \triangleq \mathbf{s}_k\mathbf{s}_k^{\mathsf{H}}, \forall k$, and

$$\mathbf{A}_k(\gamma) \triangleq \mathbf{A}_k^u(\mathbf{p}_u) - \gamma\mathbf{A}_k^e(\mathbf{p}_e),\quad \mathbf{A}_k^g = \frac{\mathrm{diag}(\mathbf{h}_{r,g}(f_k)^{\mathsf{H}})\mathbf{H}_t(f_k)\mathbf{q}\mathbf{q}^{\mathsf{H}}\mathbf{H}_t(f_k)^{\mathsf{H}}\mathrm{diag}(\mathbf{h}_{r,g}(f_k))}{\sigma_n^2}, g = \{u_1,\cdots,u_U,e\}.$$

# Secure Wideband Illumination

## RIS Phase Shifter Design

$$
\begin{aligned}
\text{P5: } & \max_{\gamma, \mathbf{S}_c} \; \gamma \\
& \text{s.t. } \; \text{C1}, \; \widehat{\text{C2}} : \mathbf{S}_c \succeq 0, \\
& \qquad \widehat{\text{C3}} : \operatorname{rank}(\mathbf{S}_c) = 1, \; \widehat{\text{C4}} : \operatorname{diag}(\mathbf{S}_c) = \mathbf{1}_N.
\end{aligned}
$$

**Proof.**

It can be proved by [4, Lemma 2]. □

[4] Mohamadreza Delbari, et al. "Near-field Liquid Crystal RIS Phase-Shift Design for Secure Wideband Illumination". In: arXiv:2508.04331 (2025).

# Secure Wideband Illumination

## RIS Phase Shifter Design

P5: $$\max_{\gamma,\mathbf{S}_c} \gamma$$
$$\text{s.t. C1}, \widehat{\text{C2}} : \mathbf{S}_c \succeq 0,$$
$$\widehat{\text{C3}} : \operatorname{rank}(\mathbf{S}_c) = 1,\ \widehat{\text{C4}} : \operatorname{diag}(\mathbf{S}_c) = \mathbf{1}_N.$$

P6: $$\max_{\gamma,\mathbf{S}_c} \gamma - \eta^{(i)} \Big( \|\mathbf{S}_c\|_* - \|\mathbf{S}_c^{(i)}\|_2 - \operatorname{tr}\big(\boldsymbol{\lambda}_{\max}(\mathbf{S}_c^{(i)}) \times \boldsymbol{\lambda}_{\max}^{\mathsf{H}}(\mathbf{S}_c^{(i)})(\mathbf{S}_c - \mathbf{S}_c^{(i)})\big)\Big)$$
$$\text{s.t. } \widehat{\text{C1}}, \widehat{\text{C2}}, \widehat{\text{C4}}.$$

**Proof.**

It can be proved by [4, Lemma 2]. □

where $\widehat{\text{C1}}$ is:

$$\operatorname{tr}\left(\mathbf{A}_k(\gamma)\left(\left(\mathbf{S}_c^{(i)}\right)^{\circ(\beta_k)} + \left(\beta_k\left(\mathbf{S}_c^{(i)}\right)^{\circ(\beta_k-1)}\right) \odot \left(\mathbf{S}_c - \mathbf{S}_c^{(i)}\right)\right)\right) \geq \gamma - 1, \forall(\mathbf{p}_u, \mathbf{p}_e) \in \mathcal{P}_u \times \mathcal{P}_e, \forall k.$$

[4] Mohamadreza Delbari, et al. “Near-field Liquid Crystal RIS Phase-Shift Design for Secure Wideband Illumination”. In: arXiv:2508.04331 (2025).



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# Secure Wideband Illumination
## Solution

Two optimization variables $\gamma$ and $\boldsymbol{S}_c$:
-> Alternative Optimization

[5] Grant, Michael. "CVX: Matlab software for disciplined convex programming, version 1.21," http://cvxr. com/cvx (2014).

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Two optimization variables $\gamma$ and $\boldsymbol{S}_c$:
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When $\gamma$ is fixed:

Problem P6 can be solved using standard convex optimization solvers, e.g., CVX [5].

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Two optimization variables $\gamma$ and $\boldsymbol{S}_c$:
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When $\mathbf{S}_c$ is fixed:

$$\gamma = \min_{\forall \mathbf{p}_u \in \mathcal{P}_u,\, \forall \mathbf{p}_e \in \mathcal{P}_e,\, \forall k} \frac{\mathrm{tr}(\mathbf{A}_k^u(\mathbf{p}_u)\mathbf{S}_k) + 1}{\mathrm{tr}(\mathbf{A}_k^e(\mathbf{p}_e)\mathbf{S}_k) + 1}.$$

[5] Grant, Michael. "CVX: Matlab software for disciplined convex programming, version 1.21," http://cvxr. com/cvx (2014).

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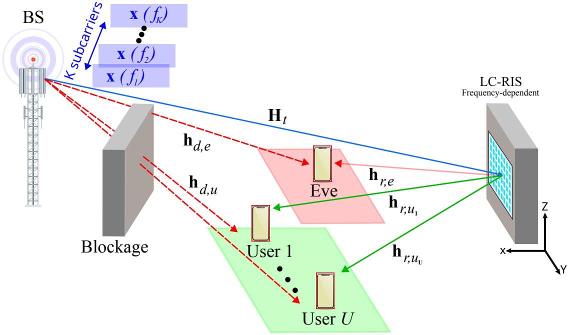
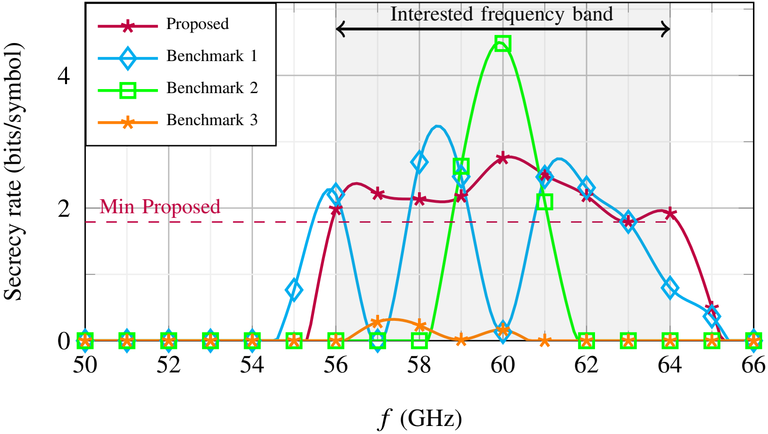
# Performance Evaluation

## Simulation Setup

| Parameter | Value |
|---|---|
| Frequency | 60 GHz |
| Bandwidth | 8.64 GHz |
| Transmission Power | 43 dBm |
| BS Antennas (x – z axes) | $16 \times 16$ |
| RIS Elements (y-axis) | 100 |
| Channel Model | Ricean |
| Path Loss Model | $(c/(4\pi f_k d))^2$ |
| Noise Level | -95 dBm |
| Direct Blockage | - 40 dB |
| $\beta$ | 2.4 |



# Performance Evaluation
## Simulation Result



# Performance Evaluation
## Simulation Result

(a) Proposed (b) Benchmark 1 (c) Benchmark 2 (d) Benchmark 3

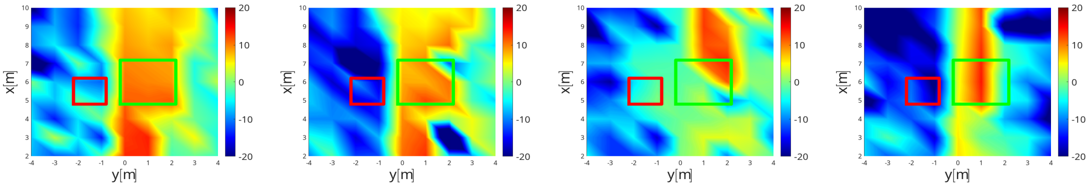
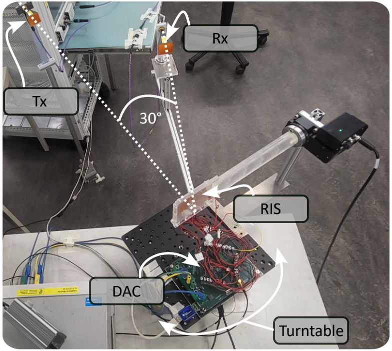
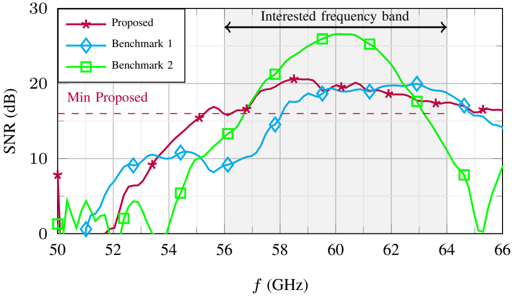



Figure: SNR (dB) using four different methods at $f_k = 57$ GHz. The green area represents the user coverage region, while the red area indicates the possible locations of the eavesdropper.

# Performance Evaluation
## Experimental Results



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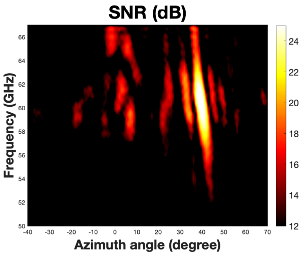
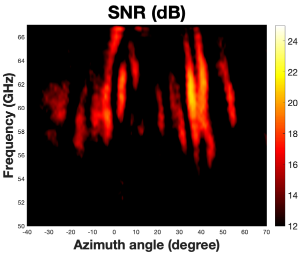
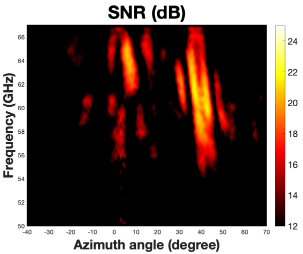



(a) Benchmark 2




(b) Benchmark 1




(c) Proposed

# Outline

# Conclusions

## Summary and takeaways

**Summary:**

- We need higher frequencies, and LCs are one potential way for implementation.
- Despite being good candidates to implement RISs, LC's RIS phase shifters are frequency-dependent.
- We derived a frequency model of the LC RIS phase shifters.
- We have optimized LC-RIS phase shifts in the secure communication scenario by considering the frequency dependency.

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- We derived a frequency model of the LC RIS phase shifters.
- We have optimized LC-RIS phase shifts in the secure communication scenario by considering the frequency dependency.

**Future research directions:**

- Developing a scalable solution since the complexity of the current algorithm is $\mathcal{O}(I_{\max}|\mathcal{P}_u||\mathcal{P}_e|N^3K)$.

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Thank you for your attention!

**Questions?**

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