# On the Performance of IRS-Assisted Relay Systems

**Diluka Loku Galappaththige, IEEE Student Member**
**Alan Devkota, IEEE Student Member**
**Gayan Amarasuriya, IEEE Senior Member**

School of Electrical, Computer, and Biomedical Engineering
Southern Illinois University, Carbondale, USA

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# Introduction

- An **intelligence reflecting surface (IRS)** having a large number of tiny passive reflectors can enable a controllable wireless propagation environment by introducing distinct delays to the reflected electromagnetic (EM) waves.
- These delays in turn result in controllable phase-shifts, which can be used to intelligently reconfigure propagation properties of EM waves through the wireless medium.
- This feature of IRSs can be utilized to improve the signal-to-noise ratio (SNR) of an end-to-end communication between a transmitter and a receiver by enabling constructive additions of EM waves at a desired destination.
- **Relay-assisted** cooperative communications have been studied for well over two decades due to their potential of enhancing the performance of wireless systems
- Relaying can effectively reduce the end-to-end path-loss in terms of shorter-hop distances and amplify-and-forward (AF) or decode-and-forward (DF) operations at intermediate relays.

# Motivation and contribution

- The fundamental performance metrics of the IRS-relay cascaded communication systems have not yet been investigated in the open literature.
- Our objective is to develop an analytical framework of an IRS-assisted relay system by deriving the performance bounds pertaining to the proposed IRS-relay cascaded system.
- First, the end-to-end optimal SNR is probabilistically characterized by tightly approximating it by a mathematically tractable counterpart by invoking the central limit theorem (CLT).
- Thereby, a tight upper bound for the cumulative distribution function (CDF) of this approximated optimal SNR is derived.
- By using this CDF, tight bounds/approximations for the average achievable rate, SNR/rate outage probability, and average SER are derived in closed-form.
- Then, the tightness of our performance bounds/approximations is validated through Monte-Carlo simulations.
- Finally, a set of insightful numerical results is presented to explore the performance gains of the proposed IRS-assisted relay system.

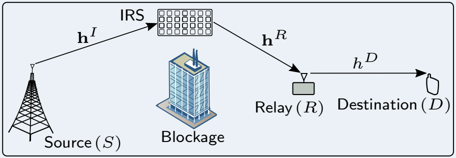
# System and channel model

- System model:
  - A single-antenna source $(S)$
  - A single-antenna destination $(D)$
  - A single-antenna relay $(R)$
  - An IRS having $N$ reflectors
- Channel model:
  - $h_n^I$: the channel between $S$ and the $n$th reflector of the IRS
  - $h_n^R$: the channel between the $n$th reflector and $R$
  - $h^D$: the channel between $R$ and $D$
- The polar-form of these channels

$$u = \beta_u e^{j\theta_u},$$

where $u \in \{h_n^I, h_n^R, h^D\}$ and $n \in \mathcal{N}$.

## IRS-aided cell-free set-up




- $\beta_u$ denotes the envelop of $u$, and $\theta_u$ is the phase of $u$.
- $\beta_u$ is assumed to be independent Rayleigh distributed as

$$f_{\beta_u}(x) = (x/\xi_u) \exp\left(-x^2/(2\xi_u)\right),$$

where $\xi_u = \zeta_u/2$ is the Rayleigh parameter, and $\zeta_u$ accounts for the large-scale fading/path-loss of the channel $u$.

# Signal model

- The signal transmitted by $S$ reaches $D$ through the IRS-$R$ cascaded channel.
- The signal received at $R$ during the first time-slot as

$$y_R = \sqrt{P}(\mathbf{h}^R)^T \boldsymbol{\Theta} \mathbf{h}^I x + w_R,$$

  - $x$: the transmit signal from $S$ satisfying $\mathbb{E}\left[|x|^2\right] = 1$
  - $P$: the transmit power at $S$
  - $w_R \sim \mathcal{CN}\left(0, \sigma_{w_R}^2\right)$:: AWGN at $R$
  - $\mathbf{h}^I = [h_1^I, \cdots, h_n^I, \cdots, h_N^I]^T \in \mathbb{C}^{N \times 1}$
  - $(\mathbf{h}^R)^T = [h_1^R, \cdots, h_n^R, \cdots, h_N^R] \in \mathbb{C}^{1 \times N}$
  - $\boldsymbol{\Theta} = \mathrm{diag}\left(\eta_1 \mathrm{e}^{j\theta_1}, \cdots, \eta_n \mathrm{e}^{j\theta_n}, \cdots, \eta_N \mathrm{e}^{j\theta_N}\right) \in \mathbb{C}^{N \times N}$: the reflective properties of the IRS, $\eta_n \mathrm{e}^{j\theta_n}$, represents the complex-valued reflection coefficient of the $n$th reflector of the IRS.
- By exploiting the properties of $\boldsymbol{\Theta}$, the rearranged received signal at $R$

$$y_R = \sqrt{P} \sum_{n \in \mathcal{N}} h_n^R \eta_n \mathrm{e}^{j\theta_n} h_n^I x + w_R.$$

# Signal model continued

- During the second time-slot, $R$ first amplifies its received signal and then forwards it towards $D$.
- the signal received at $D$ can be written as

$$y_D = Gh^D y_R + w_D = \sqrt{P} G h^D \sum_{n \in \mathcal{N}} h_n^R \eta_n \mathrm{e}^{j\theta_n} h_n^I x + G h^D w_R + w_D,$$

where $w_D \sim \mathcal{CN}\left(0, \sigma_{w_D}^2\right)$ is an AWGN at $D$.

- $G$ denotes the relay amplification factor, which is designed to constraint the instantaneous transmit power $(P_R)$ at $R$

$$G = \sqrt{P_R \Big/ \left(P \left|\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I} \mathrm{e}^{j\phi_n}\right|^2 + \sigma_{w_R}^2\right)},$$

where $\phi_n = \theta_n + \theta_{h_n^R} + \theta_{h_n^I}$.

- the received SNR at $D$ as

$$\gamma = \frac{P \left|G h^D \sum_{n \in \mathcal{N}} h_n^R \eta_n \mathrm{e}^{j\theta_n} h_n^I\right|^2}{\left|G h^D\right|^2 \sigma_{w_R}^2 + \sigma_{w_D}^2}.$$

# Signal model continued

- This SNR in terms of the channel phases

$$\gamma = \frac{P\left|G\beta_{h^D}\mathrm{e}^{j\theta_{h^D}}\sum_{n\in\mathcal{N}}\eta_n\beta_{h_n^R}\beta_{h_n^I}\mathrm{e}^{j\phi_n}\right|^2}{\left|G\beta_{h^D}\mathrm{e}^{j\theta_{h^D}}\right|^2\sigma_{w_R}^2+\sigma_{w_D}^2}.$$

- We maximize the received SNR at $D$ by smartly adjusting the phase-shifts $(\theta_n)$ at each reflector to enable constructive addition of the signal terms inside the summation.

- The optimal choice of $\theta_n$ to maximize the received SNR

$$\theta_n^* = \underset{-\pi\leq\theta_n\leq\pi}{\mathrm{argmax}}\ \gamma = -\left(\theta_{h_n^R}+\theta_{h_n^I}\right), \quad \text{for} \quad n\in\mathcal{N}.$$

- The optimal SNR at $D$

$$\gamma^* = \frac{P\left(G^*\right)^2\beta_{h^D}^2\left(\sum_{n\in\mathcal{N}}\eta_n\beta_{h_n^R}\beta_{h_n^I}\right)^2}{\left(G^*\right)^2\beta_{h^D}^2\sigma_{w_R}^2+\sigma_{w_D}^2} = \frac{\bar{\gamma}_R\bar{\gamma}_D\beta_{h^D}^2\left(\sum_{n\in\mathcal{N}}\eta_n\beta_{h_n^R}\beta_{h_n^I}\right)^2}{\bar{\gamma}_R\left(\sum_{n\in\mathcal{N}}\eta_n\beta_{h_n^R}\beta_{h_n^I}\right)^2+\bar{\gamma}_D\beta_{h^D}^2+1},$$

where $\bar{\gamma}_R = P_R/\sigma_{w_R}^2$ and $\bar{\gamma}_D = P/\sigma_{w_D}^2$.

# Preliminary analysis

- The optimal received SNR is probabilistically characterized by deriving a tight approximate to its CDF.
- First, we define $Z = \sum_{n\in\mathcal{N}} \eta_n \beta_{h_n^R}\beta_{h_n^I}$.
- By using the fact that the envelops $\beta_{h_n^R}$ and $\beta_{h_n^I}$ are independent Rayleigh distributed random variables, $Z$ is closely approximated by an one-sided Gaussian distributed random variable $(\tilde{Z})$ by invoking the CLT

$$f_Z(y) \approx f_{\tilde{Z}}(y) = \frac{\psi}{\sqrt{2\pi\sigma_Z^2}} \exp\left(\frac{-(y-\mu_Z)^2}{2\sigma_Z^2}\right), \text{ for } y \geq 0.$$

  - $\psi \triangleq 1/\mathcal{Q}\left(-\mu_Z/\sigma_Z\right)$: normalization factor, $\int_{-\infty}^{\infty} f_{\tilde{Y}}(x)dx = 1$
  - $\mu_Z = \sum_{n\in\mathcal{N}} \pi\eta_n \left(\xi_{h_n^R}\xi_{h_n^I}\right)^{1/2}/2$
  - $\sigma_Z^2 = \sum_{n\in\mathcal{N}} \eta_n^2 \xi_{h_n^R}\xi_{h_n^I}\left(16-\pi^2\right)/4$
- We define $\gamma_R$ to be

$$\gamma_R = \bar{\gamma}_R Z^2 = \bar{\gamma}_R \left(\sum_{n\in\mathcal{N}} \eta_n \beta_{h_n^R}\beta_{h_n^I}\right)^2.$$

# Preliminary analysis continued

- A tight approximation for the PDF of $\gamma_R$

$$f_{\gamma_R}(x) \approx \frac{\psi}{2\sqrt{\pi\sigma_R^2 x}} \exp\left(\frac{-(\sqrt{x}-\mu_R)^2}{2\sigma_R^2}\right), \text{ for } x \geq 0,$$

where $\mu_R = \sqrt{\bar{\gamma}_R}\mu_Z$ and $\sigma_R^2 = \bar{\gamma}_R\sigma_Z^2$.

- An approximated CDF for $\gamma_R$

$$F_{\gamma_R}(x) \approx 1 - \psi\mathcal{Q}\left((\sqrt{x}-\mu_R)/\sigma_R\right), \text{ for } x \geq 0.$$

- Next, we define $\gamma_D$ to be $\gamma_D = \bar{\gamma}_D\beta_{h^D}^2$. The CDF of $\gamma_D$

$$F_{\gamma_D}(x) = 1 - \exp\left(-x/\sigma_D^2\right), \text{ for } x \geq 0,$$

where $\sigma_D^2 = \bar{\gamma}_D\zeta_{h^D}$.

- Since the exact derivation of the CDF of $\gamma^*$ appears to be mathematically involved, we resort to an asymptotically exact upper bound

$$\gamma^* \approx \tilde{\gamma}^* = \min\left(\bar{\gamma}_R\left(\sum_{n\in\mathcal{N}}\eta_n\beta_{h_n^R}\beta_{h_n^I}\right)^2, \bar{\gamma}_D\beta_{h^D}^2\right).$$

# Preliminary analysis continued

- By noticing that $\tilde{\gamma}^* = \min(\gamma_R, \gamma_D)$, the approximated CDF of $\gamma^*$ (or the exact CDF of $\tilde{\gamma}^*$)

$$
\begin{aligned}
F_{\gamma^*}(y) &\approx F_{\tilde{\gamma}^*}(y) = 1 - (1 - F_{\gamma_R}(y))(1 - F_{\gamma_D}(y)) \\
&= 1 - \psi \mathcal{Q}\left((\sqrt{y} - \mu_R)/\sigma_R\right) \exp\left(-y/\sigma_D^2\right).
\end{aligned}
$$

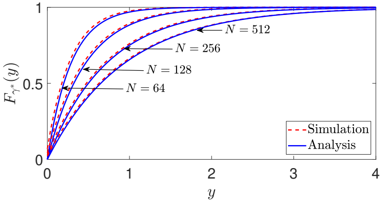



Figure: The CDF of SNR ($\gamma^*$) for $N \in \{64, 128, 256, 512\}$ and $\bar{\gamma} = 10$ dB.

Figure illustrates that our analytical CDF approximation is accurate for medium-to-large numbers of reflective elements ($N$) at the IRS. A relatively larger $N$ is practically feasible and cost effective for IRSs, and hence, our probabilistic characterization of the optimal SNR is useful in deriving performance bounds for the cascaded IRS-relay channels.

# Average Achievable Rate

- The average achievable rate of the proposed system

$$\mathcal{R} = \mathbb{E}\left[\frac{1}{2}\log_2\left(1+\gamma^*\right)\right],$$

where the pre-log factor of $1/2$ is due to the fact that half-duplex relay mode requires two time-slots for end-to-end data transmission for the proposed system model.

- The exact derivation of $\mathcal{R}$ seems mathematically intractable, and hence, a tight upper bound by invoking the Jensen's inequality

$$\mathcal{R} \leq \mathcal{R}_{ub} = \frac{1}{2}\log_2\left(1+\mathbb{E}[\gamma^*]\right) \approx \frac{1}{2}\log_2\left(1+\mathbb{E}[\tilde{\gamma}^*]\right).$$

- The closed-form expressions of $\mathcal{R}_{ub}$

$$\mathcal{R}_{ub} = \frac{1}{2}\log_2\left(1+2\psi\sigma_D^2\mathcal{Q}\left(-\mu_R/\sigma_R\right)\right).$$

# The SNR/rate outage probability

- For the proposed system, the probability that the instantaneous SNR ($\gamma$) falls below a threshold SNR ($\gamma_{th}$) is referred as the SNR outage probability.
- An approximation to this SNR outage probability

$$P_{out} = \Pr\left(\gamma^* \leq \gamma_{th}\right) \approx F_{\gamma^*}(\gamma_{th}).$$

- The rate outage probability can also be readily obtained as

$$\begin{aligned} P_{out} &= \Pr\left(\mathcal{R}' \leq \mathcal{R}_{th}\right) = \Pr\left(\gamma^* \leq 2^{2\mathcal{R}_{th}} - 1\right) \\ &\approx F_{\gamma^*}(2^{2\mathcal{R}_{th}} - 1), \end{aligned}$$

where $\mathcal{R}' = \frac{1}{2}\log_2\left(1 + \gamma^*\right)$ is the achievable rate, and $\mathcal{R}_{th}$ denotes a threshold rate.

# The average symbol error rate (SER)

- The average SER of the proposed systems is defined as the expectation of conditional error probability $(P_{e|\gamma^*})$ over the probability distribution of $\gamma^*$.
- $P_{e|\gamma^*}$ is given for a broad range of coherent modulation schemes by $P_{e|\gamma^*} = \omega \mathcal{Q}\left(\sqrt{\vartheta\gamma^*}\right)$, where the modulation scheme determines the values of fixed parameters $\omega$ and $\vartheta$.
- Thus, the average SER: $\bar{P}_e = \mathbb{E}\left[\omega \mathcal{Q}\left(\sqrt{\vartheta\gamma^*}\right)\right]$.
- A tight approximation for $\bar{P}_e$ can be given as

$$\bar{P}_e \approx \frac{\omega}{2} - \frac{\omega\sqrt{\vartheta}}{2\sqrt{2\pi}} \int_0^\infty x^{-1/2} \exp\left(-\frac{\vartheta x}{2}\right) \bar{F}_{\tilde{\gamma}^*}(x) dx,$$

  where $\bar{F}_{\tilde{\gamma}^*}(x) = 1 - F_{\tilde{\gamma}^*}(x)$ is the CCDF of $\gamma^*$.
- The closed-form solution to $\bar{P}_e$

$$\begin{aligned}\bar{P}_e \;\; &\approx \;\; \frac{\omega}{2} + 2\lambda \mathcal{Q}\left(-\mu_R/\sigma_R\right) + \frac{\lambda}{\pi\sqrt{a\sigma_R^2}} \mathrm{e}^{\frac{-\mu_R^2}{2\sigma_R^2}\left(1-\frac{1}{2a\rho\sigma_R^2}\right)} \\ &\times \sum\nolimits_{i\in C_\infty} (-2)^i \left(\frac{\sqrt{a}\rho^2\sigma_R^2}{\mu_R}\right)^{i+1} \Gamma\left(\frac{i+1}{2}, \frac{\mu_R^2}{2a\rho\sigma_R^4}\right).\end{aligned}$$

# Effects of Phase Quantization

- In practice, an IRS reflecting element only uses a set of discrete phase-shifts due to the associated hardware limitations.
- We investigate the impact of phase-shift quantization assuming that a limited number of discrete phase-shift is available for selection at the $n$th IRS element as $\hat{\theta}_n^* = \pi \hat{q}/2^{b-1}$,
  - $b$ is the number of quantization bits
  - $\hat{q} = \underset{q \in \{0, \pm 1, \cdots, \pm 2^{b-1}\}}{\operatorname{argmin}} |\theta_n^* - \pi q/2^{b-1}|$
  - $\hat{\theta}_n^*$ is the optimal phase-shift
- The difference between unquantized and quantized phase-shift is defined as the phase quantization error: $\epsilon_n = \theta_n^* - \hat{\theta}_n^*$.
- When the number of quantization levels increases, $\epsilon_n$ converges to a uniform distribution as $\epsilon_n \sim \mathcal{U}[-\pi/2^b, \pi/2^b)$.
- The optimal SNR with discrete phase-shift

$$\hat{\gamma}^* = \frac{\bar{\gamma}_R \bar{\gamma}_D \beta_{h^D}^2 \left( \sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I} \mathrm{e}^{j\epsilon_n} \right)^2}{\bar{\gamma}_R \left( \sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I} \mathrm{e}^{j\epsilon_n} \right)^2 + \bar{\gamma}_D \beta_{h^D}^2 + 1}.$$

# Simulation: Outage probability

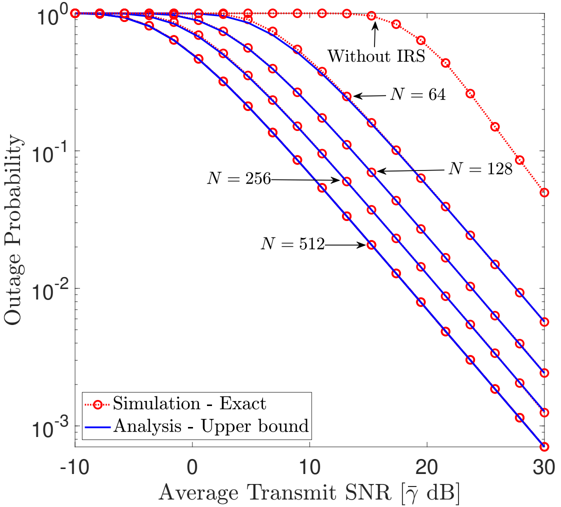



Figure: The outage probability for $N \in \{64, 128, 256, 512\}$ and the threshold SNR is $\gamma_{th} = 0$ dB. .

# Simulation: Average achievable rate

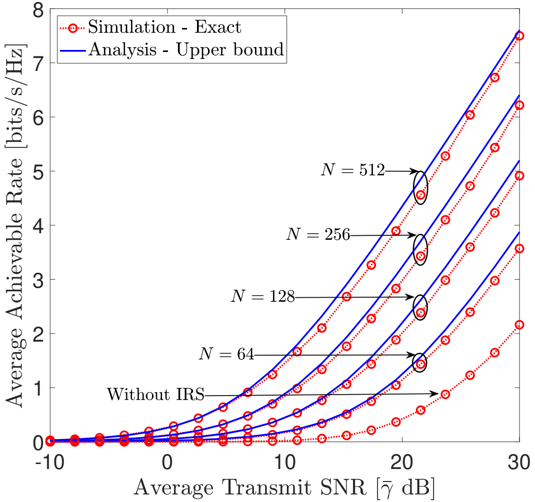



Figure: The average achievable rate for $N \in \{64, 128, 256, 512\}$.

# Simulation: Average BER

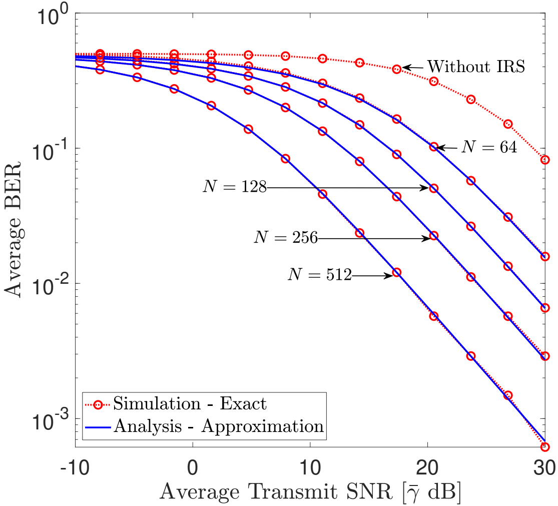



Figure: The average BER of BPSK for $N \in \{64, 128, 256, 512\}$, $\omega = 1$, and $\vartheta = 2$.

# Simulation: Phase-shift quantization

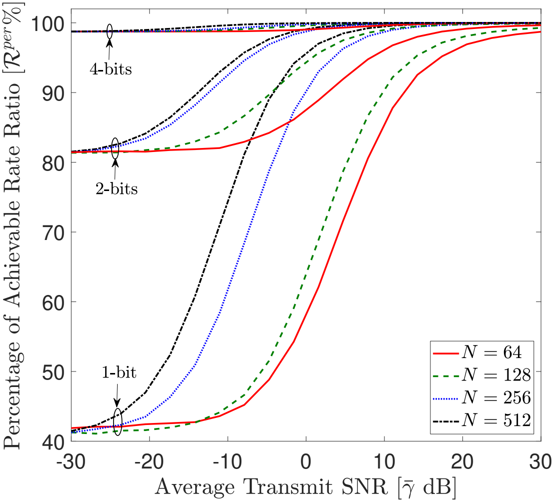



Figure: The effect of phase shift quantization on the average achievable rate for $N \in \{64, 128, 256, 512\}$.

# Conclusions

- The performance of an IRS-assisted relay system has been investigated.
- The optimal SNR that is attained through intelligent phase-shift controlling of the IRS elements has been probabilistically characterized by deriving a tight CDF approximation.
- Thereby, tight approximations/bounds for the fundamental performance metrics, including the average achievable rate, SNR/rate outage probability, and average SER have been derived.
- The impact of phase-shift errors at the IRS has been investigated by adopting discrete phase-shift adjustments.
- The accuracy of our analysis has been validated through the Monte-Carlo simulation.
- A rigorous set of numerical results has been presented to investigate the performance of the proposed IRS-assisted relay system.
- From our numerical results, we reveal that the IRS-assisted relay systems can enhance the end-to-end wireless communication performance.

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# References


1. HC. Liaskos et al., “A New Wireless Communication Paradigm Through Software-Controlled Metasurfaces,” in IEEE Commun. Mag., vol. 56, no. 9, pp. 162–169, 2018.
2. D. L. Galappaththige, D. Kudathanthirige, and G. Amarasuriya Aruma Baduge, “Performance Analysis of Distributed Intelligent Reflective Surface Aided Communications,” in IEEE Global Commun. Conf. (GLOBECOM), May 2020, pp. 1–6,.
3. G. Amarasuriya, C. Tellambura, and M. Ardakani, “Asymptotically-Exact Performance Bounds of AF Multi-Hop Relaying over Nakagami Fading,” in IEEE Trans. Commun., vol. 59, no. 4, pp. 962–967, 2011.
4. E. Björnson, Ö . Ö zdogan, and E. G. Larsson, “Intelligent Reflecting Surface Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?”, in IEEE Wireless Commun. Lett., vol. 9, no. 2, pp. 244–248, 2020.
5. M. Di Renzo et al., “Reconfigurable Intelligent Surfaces vs. Relaying: Differences, Similarities, and Performance Comparison,” in IEEE Open J. Commun. Society, vol. 1, pp. 798–807, 2020.

# Thank you for your attention!

**Questions ??**

alan.devkota@siu.edu
diluka.lg@siu.edu