Reconfigurable Intelligence Surfaces (RIS)-based Wireless Network Design and Analysis

Sanjeev Sharma
Assistant Professor, Department of Electronics Engineering,
IIT (BHU) Varanasi, India

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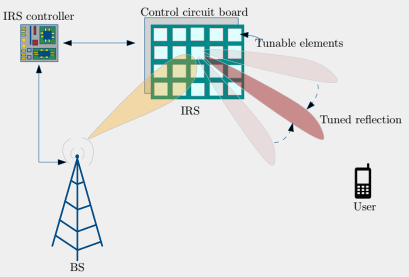
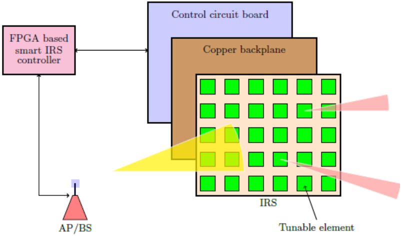
Outline

- Introduction of RIS
- Multiple RIS-aided Wireless System
- Outage Probability Analysis
- Diversity Order Analysis
- Coding Gain Analysis
- Conclusion

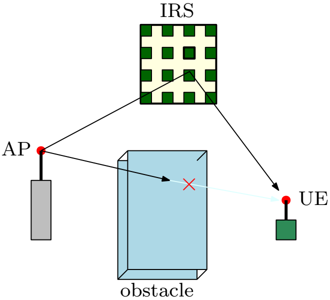
Intelligent Reflecting Surface/Reflecting Intelligent Surface

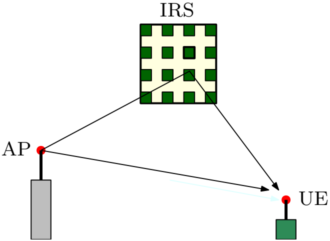


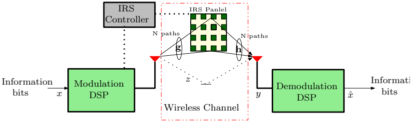


- Channel conditions are estimated at the base station.
- IRS controller **dynamically** tunes $\beta e^{j\theta}$ to receive maximum signal strength.
- IRS manipulates existing channel to a more favourable condition.
- Additional assistance when integrated with existing techniques.

IRS Contd...

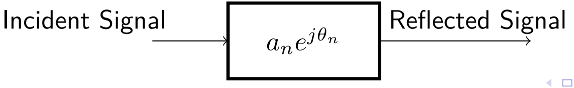






- By considering N reflecting element at the RIS, signal is expressed as

$$\text{Reflected Signal} = \underbrace{\sum_{n=0}^{N-1} a_n e^{j\theta_n}}_{\text{RIS response}} \text{Incident Signal}$$



Current Research areas in IRS

- Resource optimization is IRS-added wireless network.
- Phase optimization of IRS elements is major challenge.
- Performance of IRS has been studied with respect to OFDM, MIMO, massive-MIMO.
- Channel estimation techniques have to be designed individually for each of the modulation technique.
- IRS-design methods and deployment schemes, etc.
- IRS-aided joint sensing and communication, and other fields.
- Multiple IRS-aided system design and analysis.

Multiple IRS

Exploit diversity for multi IRS assisted communication for different fading channels[1]

Outage probability of multiple-IRS-assisted SISO wireless communications over Rician fading channel for selection combining (SC) receiver

- Selection combining: Select the best signal

[1] Outage probability of multiple-IRS-assisted SISO wireless communications over Rician fading by Rahul Kumar, et al. 2023

System Model

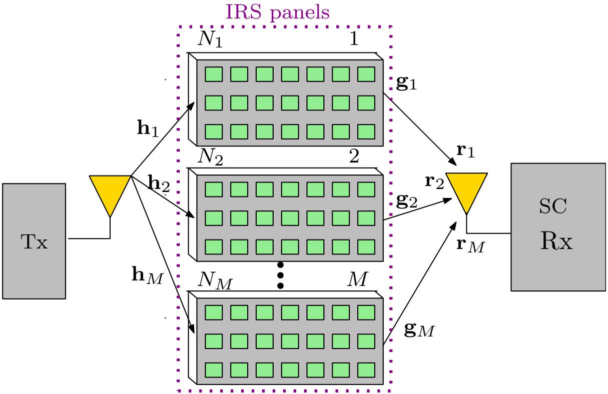


Figure: Multiple-IRS-aided SISO communication system with SC receiver

System Model Contd...

- The m-th received signal can be expressed as

$$r_m = \sqrt{P}\left(\mathbf{g_m}^T \mathbf{\Phi}_m \mathbf{h_m}\right) x_t + n_m, \quad 1 \leq m \leq M$$

- x_t : Tx message with unit energy, P: Tx power
- $\mathbf{h_m} = \left[\mathsf{h}_{m1}, \mathsf{h}_{m2}, \ldots \mathsf{h}_{mN_m}\right]^T$ and $\mathbf{g_m} = \left[\mathsf{g}_{m1}, \mathsf{g}_{m2}, \ldots \mathsf{g}_{mN_m}\right]^T$ are channel coefficients vectors.
- $\mathbf{\Phi}_m = \text{diag}\{[e^{j\theta_{m1}}, e^{j\theta_{m2}}, ..., e^{j\theta_{mN_m}}]\}$: phase shift matrix
- h_{mi} and g_{mi} are modeled as Rician distribution.

Performance Analysis

- The instantaneous optimal signal-to-noise-ratio (SNR) γ_m of m-th received signal can be expressed as

$$\gamma_m = \gamma_0 \left(\sum_{i=1}^{N_m} |h_{mi}| \, |\mathrm{g}_{mi}| \right)^2 ,$$

  where γ_0 represents the transmit SNR.
- The output SNR γ_{sc} at the output of SC receiver can be given as

$$\gamma_{sc} = \max_{1 \le m \le M} \{\gamma_m\} .$$

Outage Probability

The OP of an SISO communication system with SC receiver can be expressed as

$$P_{\text{out}} = \Pr(\gamma_{sc} \le \gamma_{th}) = \Pr\left(\max_{1 \le m \le M} \{\gamma_m\} \le \gamma_{th} \right) = \prod_{m=1}^{M} F_{\gamma_m}(\gamma_{th})$$

Performance Analysis Contd...

Outage Probability

The OP of a SISO communication system with SC receiver can be expressed as

$$P_{\text{out}} \simeq \prod_{m=1}^{M} F_{\gamma_m}(\gamma_{th})$$

$$= \begin{cases} \prod_{m=1}^{M} \left(1 - \Theta_m Q\left(\frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right), & \text{CLT} - \text{BasedMethod} \\ \prod_{m=1}^{M} \frac{\gamma\left(\theta_1+1, \frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}}}{\theta_2}\right)}{\Gamma(\theta_1+1)}, & \text{LSE} - \text{BasedMethod} \end{cases}$$

where $\Theta_m = \left(0.5 + 0.5\text{erf}\left(\sqrt{\frac{\mu_m}{2\sigma_m^2}}\right)\right)^{-1}$, $\theta_1 = \frac{\mu_m^2}{\sigma_m^2} - 1$, and $\theta_2 = \frac{\sigma_m^2}{\mu_m}$.

Performance Analysis Contd...

Asymptotic Outage Probability Expression

The asymptotic OP of the considered SISO wireless system can be given by

$$P_{\text{out}}^{\infty} = \frac{\gamma_{th}^{\sum_{m=1}^{M} N_m}}{\gamma_0^{\sum_{m=1}^{M} N_m}} \prod_{m=1}^{M} \left(\frac{\lambda_m}{\Gamma(2N_m + 1)} \right), \tag{1}$$

where $\lambda_m = \left(12\, d_{h_m}^{\alpha_{h_m}} d_{\mathsf{g}_m}^{\alpha_{\mathsf{g}_m}} \left(1 + K_{h_m}\right) \left(1 + K_{\mathsf{g}_m}\right)\right)^{N_m}$
$\times \exp\left(-N_m \left(K_{h_m} + K_{\mathsf{g}_m}\right)\right)$.

Diversiy Order and Coding Gain

$\mathcal{G}_d = \sum_{m=1}^{M} N_m$ and $\mathcal{G}_c = \gamma_{th}^{-1} \left(\prod_{m=1}^{M} \left(\frac{\lambda_m^{N_m}}{\Gamma(2N_m+1)\gamma_0^{N_m}} \right) \right)^{-\frac{1}{\sum_{m=1}^{M} N_m}}$.

Numerical and Simulation Results

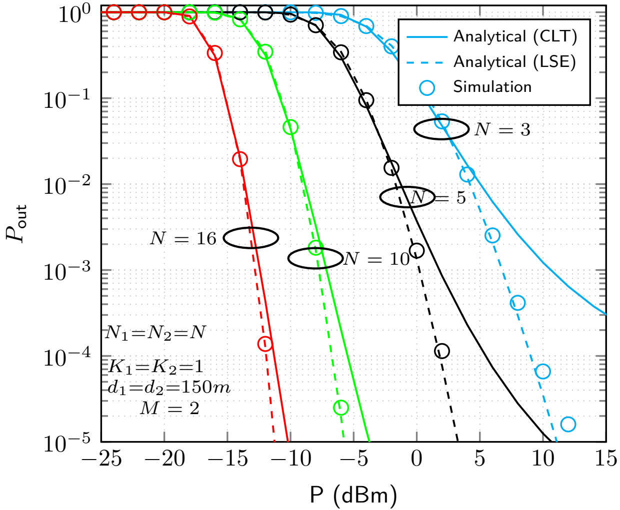


Figure: OP performance with varying N for $M = 2$. The marker, solid and dashed lines denote the simulation, analytical (CLT), and analytical (LSE) results, respectively.

Numerical and Simulation Results Contd...

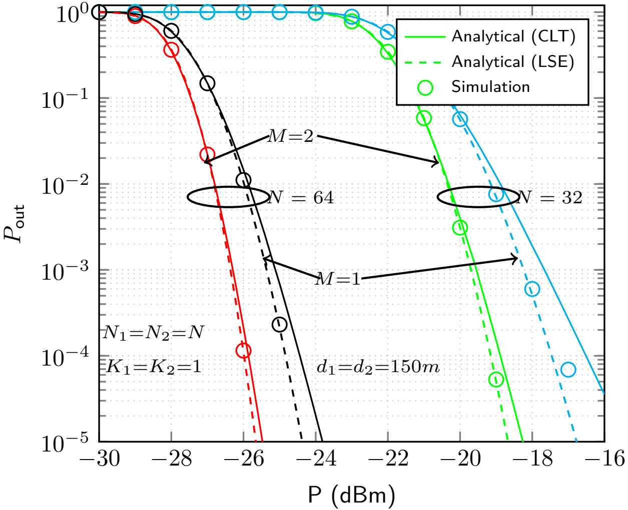


Figure: OP performance with varying both M and N_m. The marker, solid, and dashed lines denote the simulation, analytical (CLT), and analytical (LSE) results, respectively.

Numerical and Simulation Results Contd...

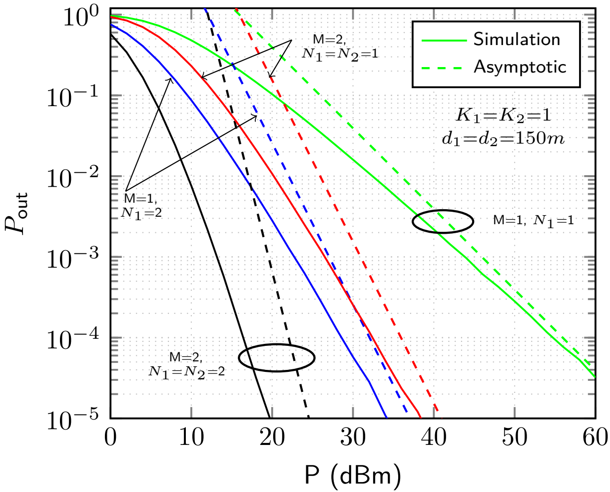


Figure: Asymptotic OP performance with varying both N_m and M. The solid lines and dashed lines denote the simulation and analytical results, respectively.

Numerical and Simulation Results Contd...

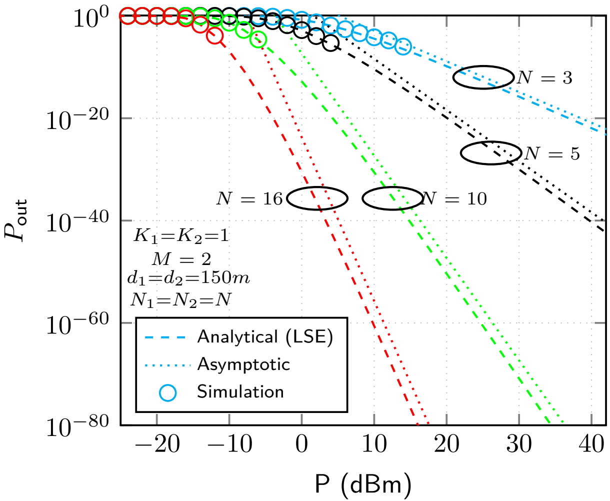


Figure: OP performance with varying N for $M = 2$. The dashed and dotted lines denote the analytical (LSE) and asymptotic results, respectively.

Numerical and Simulation Results Contd...

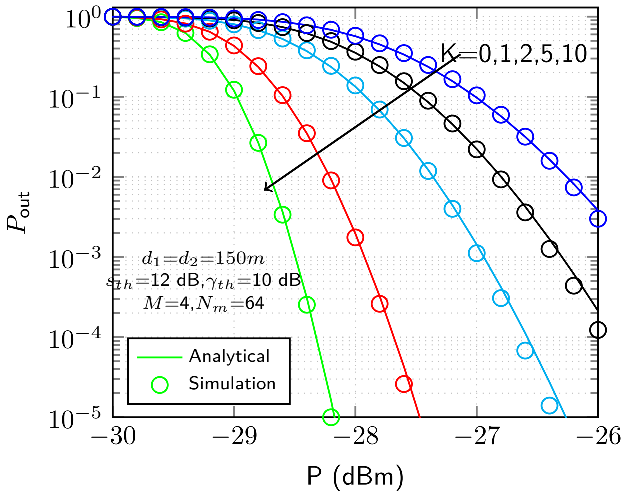


Figure: OP performance with varying the fading parameter K for SEC scheme.. The solid lines and marker denote the analytical and simulation results, respectively.

Numerical and Simulation Results Contd...

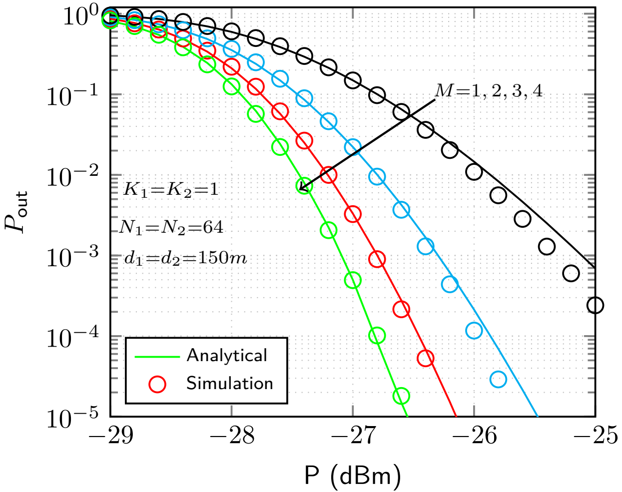


Figure: OP performance with varying the number of IRS panels M. The solid lines and marker denote the analytical and simulation results, respectively.

Numerical and Simulation Results Contd...

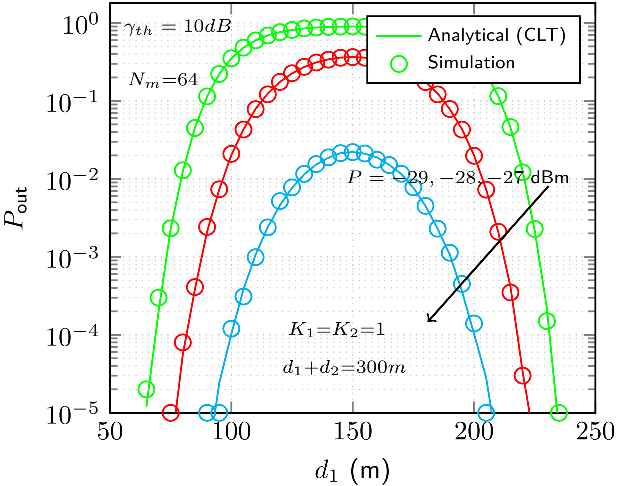


Figure: OP performance w.r.t d_1 for $M = 2$ and fixed $N_m = 64$. The solid lines and marker denote the analytical and simulation results, respectively.

Multiple IRS Contd...

Exploit diversity for multiple IRS assisted communication for different fading channels:

Outage probability analysis of multiple IRS-assisted SISO system with switched diversity under Rician fading[2].

• Switch and Stay Combining: When the received signal power from the selected IRS panel goes below a predetermined threshold, then the received signal branch becomes undesirable and a IRS panel switching is required.

• Switch and Examine Combining: The receiver will repeat the testing until either it finds a permissible IRS panel.

[2]Outage probability analysis of multiple intelligent reflecting surface-assisted single-input single-output system with switched diversity By Rahul Kumar, et al. 2023

System Model

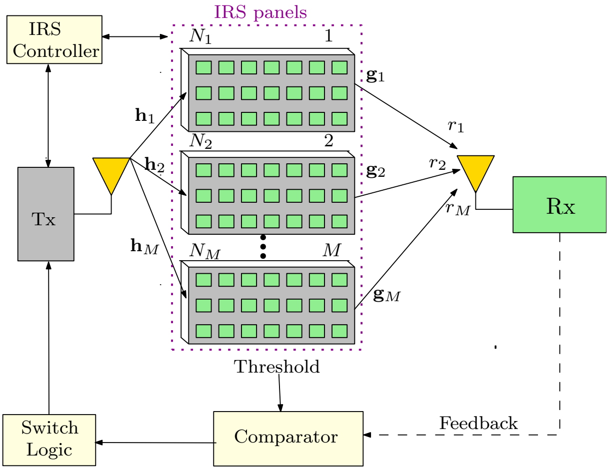


Figure: Multiple-IRS-aided SISO communication system with switched diversity.

Performance Analysis

- The instantaneous optimal SNR γ_m of m-th received signal can be expressed as

$$\gamma_m = \gamma_0 \left(\sum_{i=1}^{N_m} |h_{mi}| \, |\mathrm{g}_{mi}| \right)^2 ,$$

  where γ_0 represents the transmit SNR.
- The IRS panel switching is assumed to be done at the discrete instant of time $t = nT$, where T is in the order of channel coherent time.
- $\gamma_m(n)$ is the received signal power at the receiving antenna at time instant n.
- $\gamma(n)$ is the received signal power after applying the switched diversity.

Performance Analysis Contd...

The Switching Operation of SSC Diversity

The Switching operation of IRS panels using SSC diversity can be expressed as

$$\gamma(n) = \gamma_m(n) \text{ iff } \begin{cases} \gamma(n-1) = \gamma_m(n-1), & \text{and } \gamma_m(n) \geq s_{th} \\ \text{or} & \\ \gamma(n-1) = \gamma_{((m-1)_M)}(n-1), & \text{and } \gamma_{((m-1)_M)}(n) < s_{th} \end{cases}$$

Performance Analysis Contd...

The Switching Operation of SEC Diversity

The Switching Operation of IRS panels using SEC diversity can be expressed as

$$\gamma(n) = \gamma_m(n) \text{ iff}$$

$$\begin{cases}
\gamma(n-1) = \gamma_m(n-1), & \text{and } \gamma_m(n) \geq s_{th} & \\
\text{or} & & \\
\gamma(n-1) = \gamma_m(n-1), & \text{and } \gamma_j(n) < s_{th}, & j = 1, 2, \ldots, M \\
\text{or} & & \\
\gamma(n-1) = \gamma_{((m-1)_M)}(n-1), & \text{and } \gamma_{((m-1)_M)}(n) < s_{th} & \text{and } \gamma_m(n) \leq s_{th} \\
\vdots & & \\
\text{or} & & \\
\gamma(n-1) = \gamma_{((m-l)_M)}(n-1), & \text{and } \gamma_{((m-l+j)_M)}(n) < s_{th} & \text{and } \gamma_m(n) \geq s_{th}, j = 1, 2, \ldots, l \\
\vdots & & \\
\text{or} & & \\
\gamma(n-1) = \gamma_{((m-l)_M)}(n-1), & \text{and } \gamma_{((m-1+j)_M)}(n) < s_{th} & \text{and } \gamma_m(n) \geq s_{th}, j = 1, 2, \ldots, M-1
\end{cases}$$

where $m = 1, 2, 3, \ldots, M$.

Performance Analysis Contd...

Outage Probability of SSC Diversity

The OP of a SISO communication system with SSC diversity at IRS panels can be expressed as

$$P_{\text{out}_{SSC}} = \begin{cases} \left(1 - Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right)\left(1 - Q\left(\frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right), \gamma_{th} < s_{th} \\ \left(Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right) - Q\left(\frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right) + \left(1 - Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right) \times \\ \left(1 - Q\left(\frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right) \text{otherwise} \end{cases}$$

Performance Analysis Contd...

Outage Probability of SEC Diversity

The OP of a SISO communication system with SEC diversity at IRS panels can be expressed as

$$P\text{out}_{SEC} = \begin{cases} \left(1 - Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right)^{M-1} \left(1 - Q\left(\frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right), \gamma_{th} < s_{th} \\ \sum_{j=1}^{M} \left(Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right) - Q\left(\frac{\sqrt{\frac{\gamma_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right) \\ \left(1 - Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right)^{j} + \left(1 - Q\left(\frac{\sqrt{\frac{s_{th}}{\gamma_0}} - \mu_m}{\sigma_m}\right)\right)^{M}, \text{otherwise} \end{cases}$$

Performance Analysis Contd...

Asymptotic Outage Probability Expression

The asymptotic OP of the considered SISO wireless system with SSC diversity at the IRS panels can be given by

$$P^{\infty}_{\text{out}_{SSC}} = \begin{cases} \frac{\lambda_{th}^{N_m} s_{th}^{N_m}}{\gamma_0^{2N_m}} \left(\frac{\lambda_m}{\Gamma(2N_m+1)} \right)^2, & \text{if } \gamma_{th} < s_{th} \\ \frac{\lambda_m(\lambda_{th}^{N_m} - s_{th}^{N_m})}{\Gamma(2N_m+1)\gamma_0^{N_m}} & \text{otherwise} \\ + \frac{\lambda_{th}^{N_m} s_{th}^{N_m}}{\gamma_0^{2N_m}} \left(\frac{\lambda_m}{\Gamma(2N_m+1)} \right)^2, & \end{cases}$$

where $\lambda_m = \left(12\, d_{h_m}^{\alpha_{h_m}} d_{\mathsf{g}_m}^{\alpha_{\mathsf{g}_m}} \left(1 + K_{h_m}\right) \left(1 + K_{\mathsf{g}_m}\right)\right)^{N_m}$
$\times \exp\left(-N_m \left(K_{h_m} + K_{\mathsf{g}_m}\right)\right)$.

Performance Analysis Contd...

Asymptotic Outage Probability Expression

The asymptotic OP of the considered SISO wireless system with SEC diversity at the IRS panels can be given by

$$P^{\infty}_{\text{out}_{SEC}} = \begin{cases} \frac{\lambda_{th}^{N_m} s_{th}^{N_m(M-1)}}{\gamma_0^{MN_m}} \left(\frac{\lambda_m}{\Gamma(2N_m+1)}\right)^M, & \text{if} \gamma_{th} < s_{th} \\ \sum_{j=1}^{M} \frac{\lambda_m(\lambda_{th}^{N_m} - s_{th}^{N_m})}{\Gamma(2N_m+1)\gamma_0^{N_m}} \left(\frac{\lambda_m (s_{th})^{N_m}}{\Gamma(2N_m+1)\gamma_0^{N_m}}\right)^j & \\ + \left(\frac{\lambda_m (s_{th})^{N_m}}{\Gamma(2N_m+1)\gamma_0^{N_m}}\right)^M, & \text{otherwise} \end{cases}$$

where $\lambda_m = \left(12\, d_{h_m}^{\alpha_{h_m}} d_{\mathsf{g}_m}^{\alpha_{\mathsf{g}_m}} \left(1 + K_{h_m}\right) \left(1 + K_{\mathsf{g}_m}\right)\right)^{N_m}$
$\times \exp\left(-N_m \left(K_{h_m} + K_{\mathsf{g}_m}\right)\right)$.

Performance Analysis Contd...

Diversity Order and Coding Gain of SSC

$\mathcal{G}_d = 2N_m$

$G_c = (\lambda_{th} s_{th})^{-\frac{1}{2}} \left(\frac{\lambda_m}{\Gamma(2N_m+1)}\right)^{-\frac{1}{N_m}}$, if $\gamma_{th} < s_{th}$

Diversiy Order and Coding Gain of SEC

$\mathcal{G}_d = MN_m$

$G_c = (\lambda_{th})^{-\frac{1}{M}} (s_{th})^{-\frac{M-1}{M}} \left(\frac{\lambda_m}{\Gamma(2N_m+1)}\right)^{-\frac{1}{N_m}}$, if $\gamma_{th} < s_{th}$.

Numerical and Simulation Results

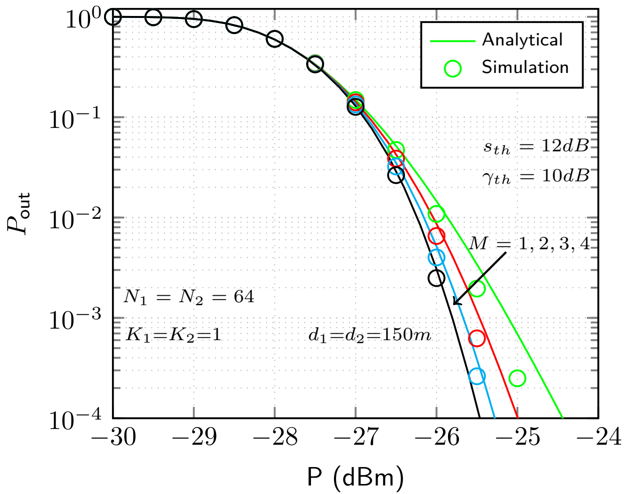


Figure: OP performance w.r.t P (dBm) for without divesity scheme ($M = 1$), SSC scheme ($M = 2$) and SEC scheme ($M = 3, 4$).

Numerical and Simulation Results Contd...

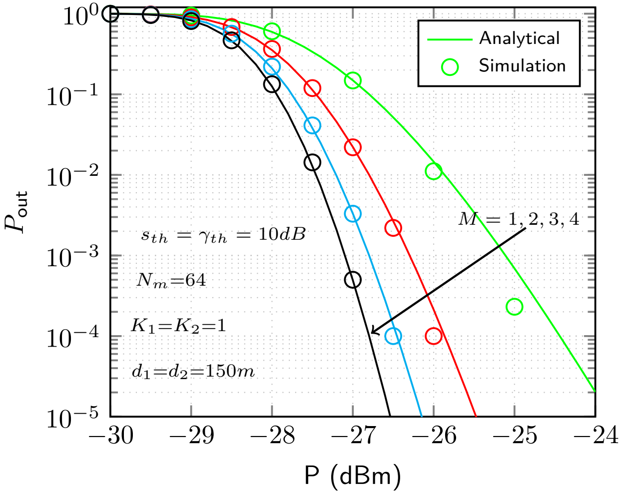


Figure: OP performance w.r.t P (dBm) for without diversity scheme ($M = 1$ and switched diversity schemes ($M = 2, 3, 4$).

Numerical and Simulation Results Contd...

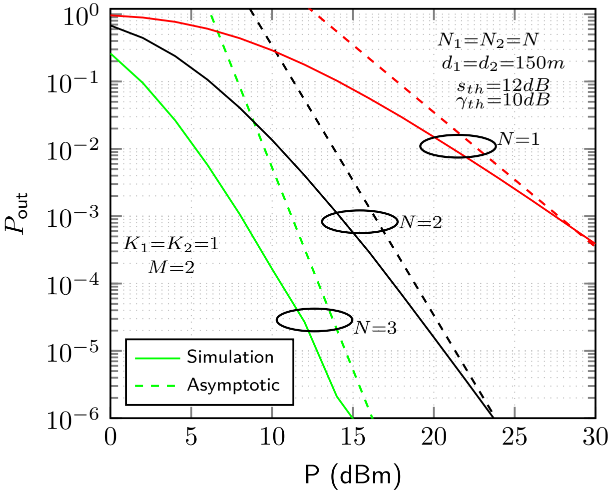


Figure: Asymptotic OP performance with varying the number of IRS elements N_m for SSC scheme.

Numerical and Simulation Results Contd...

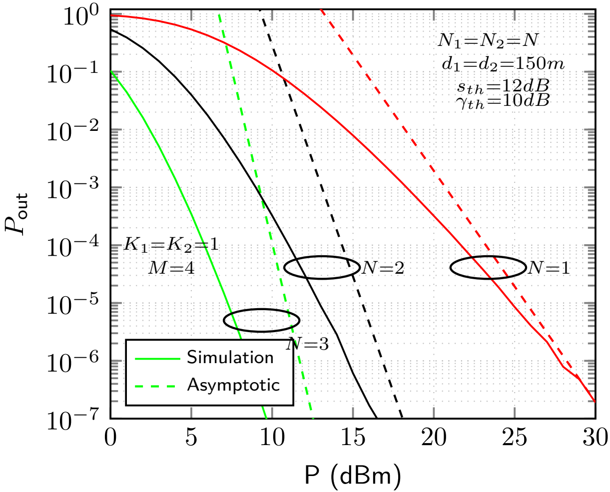


Figure: Asymptotic OP performance with varying the number of IRS elements N_m for SEC scheme.

Numerical and Simulation Results Contd...

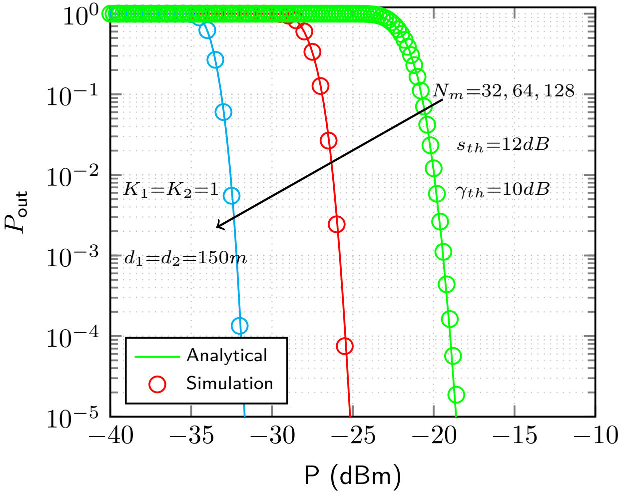


Figure: OP performance with varying the number of IRS elements in the panels $N_m = 32, 64, 128$, $M = 4$ for SEC scheme.

Numerical and Simulation Results Contd...

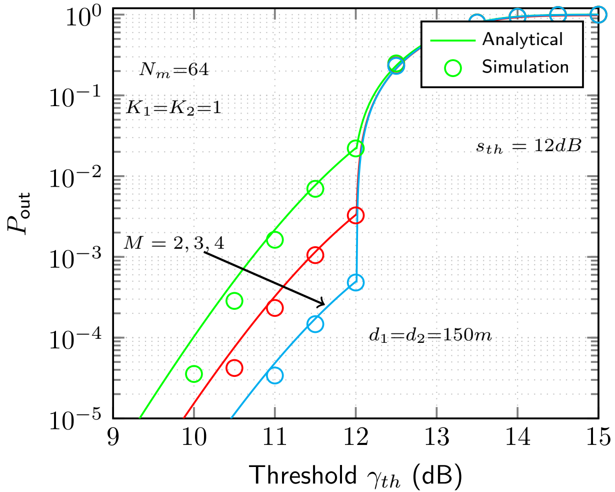


Figure: OP performance w.r.t threshold γ_{th} of SSC for $M = 2$ and SEC for $M = 3, 4$ and fixed $N_m = 64$.

Numerical and Simulation Results Contd...

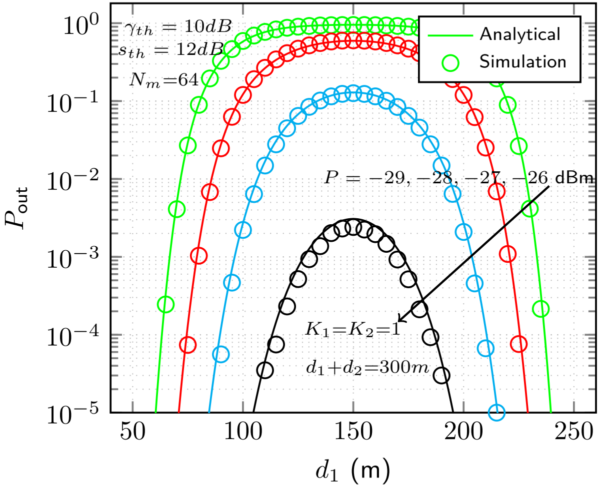


Figure: OP performance w.r.t distance d_1 of SEC for $M = 4$ and fixed $N_m = 64$ for SEC.

Thank You
Questions/Comments??