EEEN60481 Coursework Performance Evaluation of Wireless Communication Systems Using Monte-Carlo Simulations

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Chapter 1

Introduction to Monte Carlo Simulations

Monte Carlo simulations are a class of computational algorithms that rely on repeated random sampling to obtain numerical results (Metropolis and Ulam, 1949; Robert and Casella, 2004). These simulations are particularly useful in solving problems that are deterministic in principle but too complex to solve analytically. The name "Monte Carlo" is a reference to the famous casino in Monaco, symbolizing the use of randomness and the element of chance.

In a Monte Carlo simulation, we typically define a domain of possible inputs, generate random inputs from a probability distribution, perform a deterministic computation using these inputs, and aggregate the results. As the number of simulations (or trials) tends toward infinity, the Monte Carlo estimate of the desired quantity often converges to the correct solution.

Monte Carlo methods are used across various fields—physics, finance, engineering, mathematics, and statistics—due to their flexibility and ease of implementation (Robert and Casella, 2004). Problems such as approximating integrals, simulating complex physical systems (e.g., particle transport, fluid dynamics), pricing financial derivatives, and performing risk analysis can benefit greatly from these methods.

Chapter 2

Results and Discussion

2.1 Performance of a Basic Wireless Communication System Using Monte-Carlo Simulations

This section presents the results obtained from Monte-Carlo simulations of a basic wireless communication system under both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. The LOS scenario employs Rician fading, reflecting the presence of a dominant direct path, whereas the NLOS scenario employs Rayleigh fading, which models purely scattered multipath conditions without a direct line-of-sight component. Such channel models are well-established in wireless communications (Proakis, 2001; Goldsmith, 2005).

2.1.1 Ergodic Capacity

The ergodic capacity, defined as the expected value of the instantaneous channel capacity, provides a measure of the long-term average spectral efficiency of the system. By averaging over a large number of fading realizations, the simulations offer insights into how the wireless link performs under variable channel conditions. Generally, increasing the transmit SNR (γ_t) improves the ergodic capacity, as the channel is better able to distinguish the signal from the noise (Goldsmith, 2005).

2.1.2 Outage Probability

The outage probability is the probability that the instantaneous SNR falls below a given threshold (γ_{th}). A low outage probability indicates a more reliable link, as fewer realizations of the fading channel fail to meet the required quality-of-service criterion. Both LOS and NLOS scenarios experience diminishing outage probabilities as γ_t increases, but the presence of a LOS component (modeled by the Rician distribution) ensures more robust performance (Proakis, 2001).

2.1.3 Simulation Results

Figure 2.1 illustrates the ergodic capacity and outage probability of the system as a function of γ_t, ranging from 20 dB to 60 dB. In the LOS scenario, where the Rician factor K is positive and not negligible, the system consistently outperforms the purely Rayleigh fading (NLOS) scenario. This improvement is evident both in terms of higher ergodic capacity and lower outage probability.

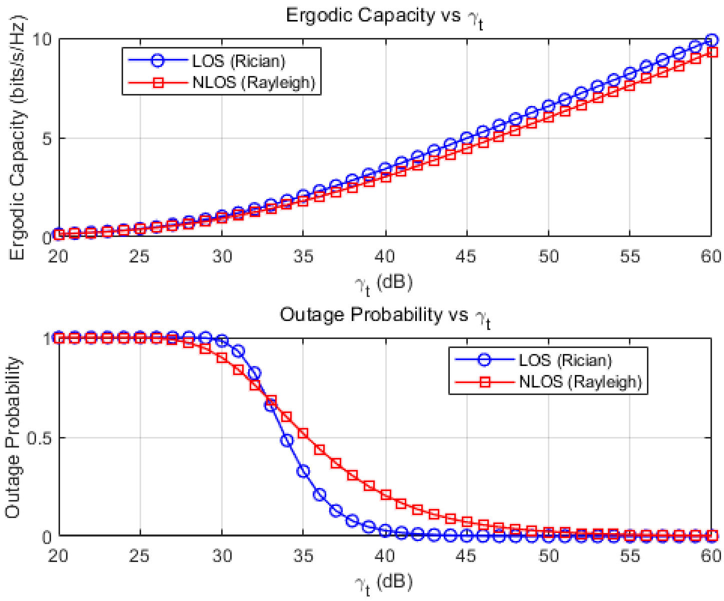

Figure 2.1: Ergodic Capacity and Outage Probability vs. γ_t for LOS (Rician) and NLOS (Rayleigh) fading scenarios.

From the figure, it is observed that:

- **Ergodic Capacity:** As γ_t increases, both LOS and NLOS scenarios show improved capacity. However, the LOS (Rician) scenario yields consistently higher ergodic capacity, particularly at moderate-to-high SNR values.
- **Outage Probability:** At lower γ_t, both scenarios suffer high outage probabilities. As γ_t grows, the outage probability declines, but the LOS scenario achieves a faster reduction and maintains lower outage levels across the entire SNR range.

In summary, the Monte-Carlo simulation results confirm that introducing a LOS component into the fading environment improves both the ergodic capacity and outage probability, indicating more efficient and reliable wireless communication at higher SNR regimes.

2.2 Performance of Intelligent Reflecting Surface (IRS)-assisted Wireless Communication Systems

In this section, we present the simulation results obtained from the IRS-assisted wireless communication scenario. IRS technology represents a new approach to controlling the wireless environment by using a reconfigurable surface equipped with passive reflecting elements (Wu and Zhang, 2019; Basar, 2020). By intelligently configuring the phase shifts of these elements, the IRS can direct and enhance signal propagation, leading to improved performance.

2.2.1 Ergodic Capacity

The ergodic capacity in the IRS-assisted system benefits from the additional degrees of freedom introduced by the reflective elements. As N, the number of IRS elements, increases, more energy is constructively added at the receiver, improving the overall SNR and, consequently, the ergodic capacity.

2.2.2 Outage Probability

Similarly, the outage probability is significantly improved by the IRS. By properly configuring the reflecting elements, one can mitigate fading dips and ensure the received SNR rarely falls below the outage threshold, leading to a more reliable communication link.

2.2.3 Simulation Results

Figure 2.2 illustrates the ergodic capacity and outage probability as functions of γ_t, ranging from 10 dB to 40 dB, for different values of $N = \{25, 50, 100\}$.

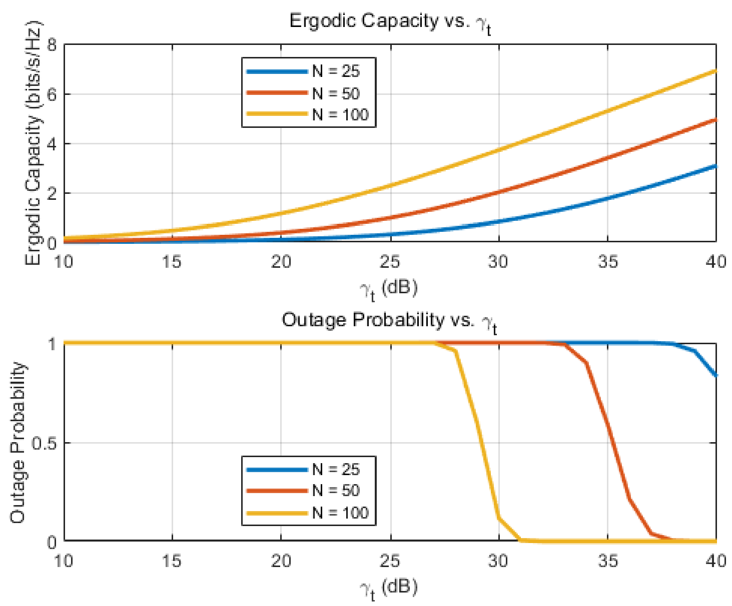

Figure 2.2: Ergodic Capacity and Outage Probability vs. γ_t for different numbers of IRS elements ($N = 25, 50, 100$).

Key observations include:

- Increasing N significantly boosts the ergodic capacity, especially at higher γ_t.
- Outage probability drops steeply with increasing γ_t, and larger N values lead to near-zero outages even at moderate SNR levels.

These results confirm the transformative potential of IRS technology in future wireless communication systems.

Chapter 3

Conclusion and Outcome

In this project, we employed Monte-Carlo simulations to investigate the performance of wireless communication systems under various conditions. The work was divided into two main parts. First, we considered a basic wireless communication system where the direct link between the transmitter and receiver experiences either line-of-sight (LOS) fading (Rician) or non-line-of-sight (NLOS) fading (Rayleigh). Second, we extended the analysis to an intelligent reflecting surface (IRS)-assisted scenario, wherein the presence of a reconfigurable metasurface with multiple passive elements allowed for significant control over the propagation environment.

From the first part of the analysis, it was established that a dominant LOS component improves overall system performance, as evidenced by higher ergodic capacity and lower outage probability compared to the NLOS scenario. Increasing the SNR further enhanced performance, but the LOS-based system consistently outperformed its NLOS counterpart.

The second part introduced the IRS-assisted wireless communication system. By optimally adjusting the phase shifts of its reflecting elements, the IRS can effectively manipulate the propagation environment. Simulations revealed that as the number of IRS elements (N) increased, so did the ergodic capacity, while the outage probability dropped dramatically. Even at moderate SNR values, a sufficiently large IRS configuration could nearly eliminate outages and significantly boost capacity.

Overall, the outcomes of this project confirm the substantial benefits of LOS conditions and advanced technologies such as IRS in modern wireless communications. The Monte-Carlo simulation approach proved invaluable for validating theoretical expectations and gaining insight into complex, stochastic wireless environments. These findings provide useful guidance for future network designs, highlighting how careful management of propagation conditions and the deployment of IRS-assisted solutions can yield enhanced capacity, improved coverage, and robust connectivity in next-generation wireless networks.

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Appendix A

MATLAB Code Implementation

A.1 Performance of a Basic Wireless Communication System Using Monte-Carlo Simulations

This section provides the MATLAB code used to evaluate the performance of a basic wireless communication system under both LOS (Rician) and NLOS (Rayleigh) fading scenarios. The metrics evaluated are the ergodic capacity and outage probability as functions of the transmit SNR (γ_t).

```matlab
clear; clc; close all;

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Question 1: Basic Wireless Communication System
%
% This code performs Monte-Carlo simulations to obtain ergodic capacity and
% outage probability under LOS (Rician) and NLOS (Rayleigh) fading.
%
% Parameters:
%   ht = 10 m, hu = 6 m, dx = 80 m
%   Gt_dBi = 20 dBi, Gr_dBi = 20 dBi
%   f = 900 MHz, gamma_th_dB = 4 dB, K_dB = 8 dB (Rician factor)
%   N = 1e6 (realizations)
%   gamma_t_dB: 20:60 dB
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Given Parameters
ht = 10; hu = 6; dx = 80;
Gt_dBi = 20; Gr_dBi = 20;
f = 900e6; c = 3e8; lambda = c/f;
gamma_th_dB = 4; gamma_th = 10^(gamma_th_dB/10);
K_dB = 8; K = 10^(K_dB/10);

Gt = 10^(Gt_dBi/10); Gr = 10^(Gr_dBi/10);
r = sqrt(dx^2 + (ht - hu)^2);
PL_r = Gt * Gr * (lambda/(4*pi*r))^2;

N = 1e6;
```

```matlab
gamma_t_dB_vec = 20:60;
gamma_t_lin_vec = 10.^(gamma_t_dB_vec/10);

% Pre-allocate
ergodic_capacity_LOS = zeros(length(gamma_t_lin_vec),1);
outage_prob_LOS = zeros(length(gamma_t_lin_vec),1);
ergodic_capacity_NLOS = zeros(length(gamma_t_lin_vec),1);
outage_prob_NLOS = zeros(length(gamma_t_lin_vec),1);

% Channel generation
h_LOS = sqrt(K/(K+1)) + sqrt(1/(2*(K+1)))*(randn(N,1)+1j*randn(N,1));
h_NLOS = (randn(N,1)+1j*randn(N,1))/sqrt(2);

h_LOS_mag_sq = abs(h_LOS).^2;
h_NLOS_mag_sq = abs(h_NLOS).^2;

for idx = 1:length(gamma_t_lin_vec)
    gamma_t_lin = gamma_t_lin_vec(idx);
    SNR_LOS = gamma_t_lin * PL_r * h_LOS_mag_sq;
    SNR_NLOS = gamma_t_lin * PL_r * h_NLOS_mag_sq;

    ergodic_capacity_LOS(idx) = mean(log2(1 + SNR_LOS));
    ergodic_capacity_NLOS(idx) = mean(log2(1 + SNR_NLOS));

    outage_prob_LOS(idx) = mean(SNR_LOS <= gamma_th);
    outage_prob_NLOS(idx) = mean(SNR_NLOS <= gamma_th);
end

% Plot results
figure;
subplot(2,1,1);
plot(gamma_t_dB_vec, ergodic_capacity_LOS, 'b-o', 'LineWidth',1); hold on;
plot(gamma_t_dB_vec, ergodic_capacity_NLOS, 'r-s', 'LineWidth',1);
grid on; xlabel('\gamma_t (dB)'); ylabel('Ergodic Capacity (bits/s/Hz)');
title('Ergodic Capacity vs \gamma_t');
legend('LOS (Rician)','NLOS (Rayleigh)','Location','Best');

subplot(2,1,2);
plot(gamma_t_dB_vec, outage_prob_LOS, 'b-o', 'LineWidth',1); hold on;
plot(gamma_t_dB_vec, outage_prob_NLOS, 'r-s', 'LineWidth',1);
grid on; xlabel('\gamma_t (dB)'); ylabel('Outage Probability');
title('Outage Probability vs \gamma_t');
legend('LOS (Rician)','NLOS (Rayleigh)','Location','Best');
```

Listing A.1: MATLAB code for basic wireless communication system performance

A.2 Performance of IRS-Assisted Wireless Communication Systems

In this section, we provide the MATLAB code for the IRS-assisted wireless communication scenario. The IRS is equipped with N reflecting elements, and by optimally adjusting the phase shifts, we aim to improve the system's ergodic capacity and reduce outage probability. The parameters, including $N = \{25, 50, 100\}$ and γ_t ranging from 10 to 40 dB, are used to illustrate the performance gains offered by the IRS.

```
clear; clc; close all;

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Question 2: IRS-Assisted Wireless Communication System
%
% This code runs Monte-Carlo simulations to evaluate the ergodic capacity
% and outage probability of an IRS-assisted system for different values of N.
%
% Parameters:
%   N = {25, 50, 100}
%   Gt_dBi = 10 dBi, Gr_dBi = 10 dBi
%   L = 2 m, W = 2 m
%   dh = 25 m, dg = 25 m, phi = 30
%   gamma_th_dB = 10 dB
%   gamma_t_dB = 10:40 dB
%
% Channels:
%   h_i, g_i ~ CN(0,1)
% Optimal Phase Shifts:
%   SNR = gamma_t * PL * (sum |h_i||g_i|)^2
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

N_values = [25, 50, 100];
Gt_dBi = 10; Gr_dBi = 10;
Gt = 10^(Gt_dBi/10); Gr = 10^(Gr_dBi/10);

L = 2; W = 2;
dh = 25; dg = 25;
phi_deg = 30; phi = deg2rad(phi_deg);

gamma_th_dB = 10;
gamma_th = 10^(gamma_th_dB/10);

gamma_t_dB_vec = 10:40;
gamma_t_lin_vec = 10.^(gamma_t_dB_vec/10);

% Path-Loss:
% PL = Gt * Gr * ((L*W)/(4*pi *dh*dg))  * cos (phi)
PL = Gt * Gr * ((L*W)/(4*pi^2*dh*dg))^2 * cos(phi)^2;

Nreal = 1e6;

```

```
% Pre-allocate
ergodic_capacity = zeros(length(N_values), length(gamma_t_lin_vec));
outage_prob = zeros(length(N_values), length(gamma_t_lin_vec));

for n_idx = 1:length(N_values)
    N_irs = N_values(n_idx);

    % Channels
    h = (randn(N_irs, Nreal) + 1j*randn(N_irs, Nreal))/sqrt(2);
    g = (randn(N_irs, Nreal) + 1j*randn(N_irs, Nreal))/sqrt(2);

    abs_h = abs(h);
    abs_g = abs(g);

    sum_abs_hg = sum(abs_h.*abs_g, 1);

    for gt_idx = 1:length(gamma_t_lin_vec)
        gamma_t_lin = gamma_t_lin_vec(gt_idx);
        SNR_samples = gamma_t_lin * PL * (sum_abs_hg.^2);

        ergodic_capacity(n_idx, gt_idx) = mean(log2(1 + SNR_samples));
        outage_prob(n_idx, gt_idx) = mean(SNR_samples <= gamma_th);
    end

    clear h g abs_h abs_g sum_abs_hg
end

% Plot results
figure;
legendStrings = cell(length(N_values), 1);
for n_idx = 1:length(N_values)
    subplot(2,1,1);
    plot(gamma_t_dB_vec, ergodic_capacity(n_idx,:), 'LineWidth',2);
   hold on; grid on;
    xlabel('\gamma_t (dB)');
    ylabel('Ergodic Capacity (bits/s/Hz)');
    title('Ergodic Capacity vs. \gamma_t');
    legendStrings{n_idx} = sprintf('N = %d', N_values(n_idx));

    subplot(2,1,2);
    plot(gamma_t_dB_vec, outage_prob(n_idx,:), 'LineWidth',2); hold on;
    grid on;
    xlabel('\gamma_t (dB)');
    ylabel('Outage Probability');
    title('Outage Probability vs. \gamma_t');
end

subplot(2,1,1);
legend(legendStrings, 'Location', 'Best');
subplot(2,1,2);
legend(legendStrings, 'Location', 'Best');
```

Listing A.2: MATLAB code for IRS-assisted wireless communication system performance