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PAPER

```
% Title: Multi-RIS-aided Wireless Systems: Statistical
 Characterization and Performance Analysis
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% Online: https://github.com/trinhudo/Multi-RIS
% Version: 12-Sep-2021

% Multiple RISs with detailed phase-shift configuration
% --ERA scheme: all RISs participate
% --ORA scheme: only the best RIS participates
% --Analysis is based on Gamma distribution

tic
% rng('default');
```

SETTING

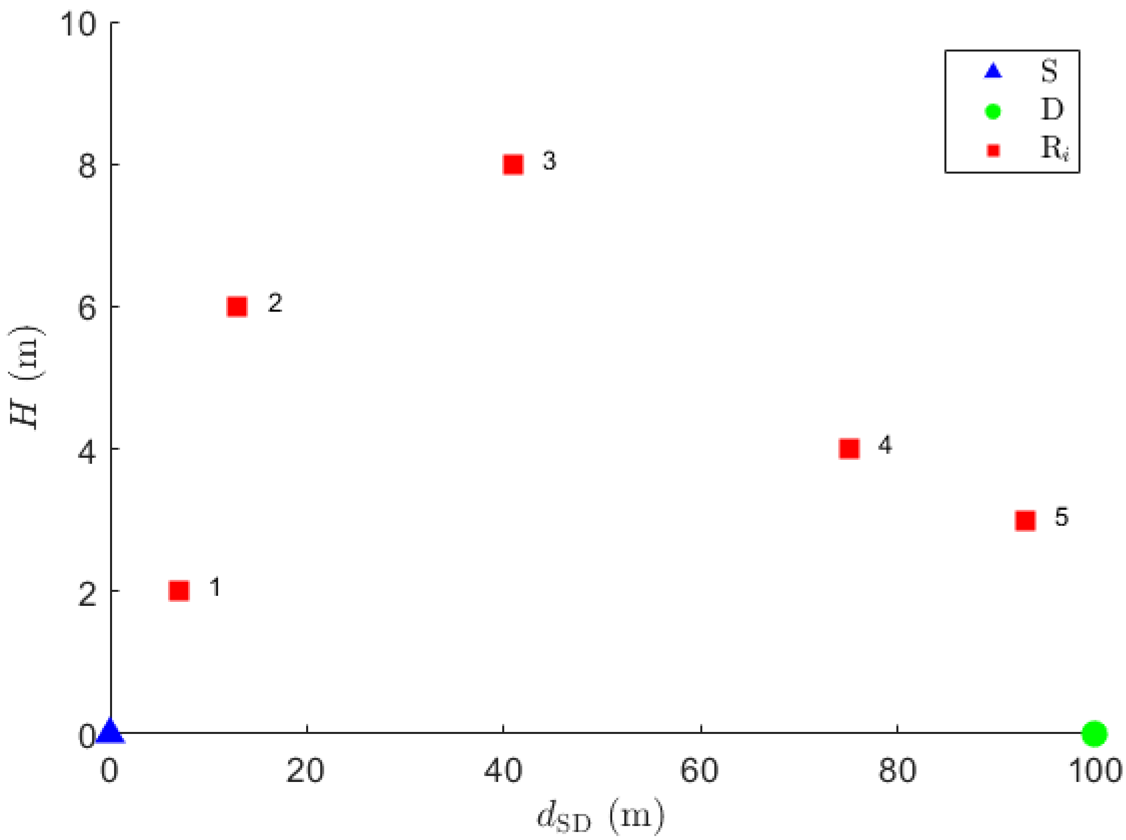
```
clear all
close all

sim_times = 1e5; % Number of simulation trails

R_th = 1; % Predefined target spectral efficiency [b/s/Hz]

SNR_th = 2^R_th-1; % Predefined SNR threshold

N_RIS = 5; % Number of distributed RISs

L_single = 25; % Number of elements at each RIS

L = L_single*ones(1,N_RIS); % all RISs

kappa_nl = 1; % Amplitude reflection coefficient
```

```
% Network area
x_area_min = 0;
x_area_max = 100; % in meters
y_area_min = 0;
y_area_max = 10;

% Source location
x_source = x_area_min;
y_source = y_area_min;

% Destination location
x_des = x_area_max;
y_des = y_area_min;

% Random location setting
% x_RIS = x_area_min + (x_area_max-x_area_min)*rand(N_RIS, 1); %
 [num_RIS x 1] vector
% y_RIS = y_area_min + (y_area_max-y_area_min)*rand(N_RIS, 1);

%Location setting D1
x_RIS = [7; 13; 41; 75; 93];
y_RIS = [2; 6; 8; 4; 3];

% Compute location of nodes
pos_source = [x_source, y_source];

pos_des = [x_des, y_des];
pos_RIS = [x_RIS, y_RIS]; % [num_RIS x 2] matrix

% Compute distances
d_SR = sqrt(sum((pos_source - pos_RIS).^2 , 2)); % [num_RIS x 1]
 vector
d_RD = sqrt(sum((pos_RIS - pos_des).^2 , 2));
d_SD = sqrt(sum((pos_source - pos_des).^2 , 2));
```

NETWORK TOPOLOGY

```
figure;

scatter(x_source, y_source, 100, 'b^', 'filled'); hold on
scatter(x_des, y_des, 100, 'go', 'filled'); hold on
scatter(x_RIS, y_RIS, 100, 'rs', 'filled'); hold on

for kk = 1:N_RIS
    text(x_RIS(kk)+3, y_RIS(kk)+0.1, num2str(kk));
    hold on
end

xlabel('$d_{\rm SD}$ (m)', 'Interpreter', 'Latex')
ylabel('$H$ (m)', 'Interpreter', 'Latex')
axis([x_area_min x_area_max y_area_min y_area_max])
legend('$\rm S$', '$\rm D$', '$\mathrm{R}_i$',...
```

```
    'Interpreter', 'Latex',...
    'Location', 'best')

set(gca, 'LooseInset', get(gca, 'TightInset')) % remove plot padding
set(gca,'fontsize',13);
hold off

% Path-loss model
% ---------------

% Carrier frequency (in GHz)
fc = 3; % GHz

% 3GPP Urban Micro in 3GPP TS 36.814
% NLoS path-loss component based on distance, x is in meter
pathloss_NLOS = @(x) db2pow(-22.7 - 26*log10(fc) - 36.7*log10(x));

antenna_gain_S = db2pow(5); % Source antenna gain, dBi
antenna_gain_RIS = db2pow(5); % Gain of each element of a RIS, dBi
antenna_gain_D = db2pow(0); % Destination antenna gain, dBi

% Noise power and Transmit power P_S
% ---------------------------------

% Bandwidth
BW = 10e6; % 10 MHz

% Noise figure (in dB)
noiseFiguredB = 10;

% Compute the noise power in dBm
sigma2dBm = -174 + 10*log10(BW) + noiseFiguredB; % -94 dBm
sigma2 = db2pow(sigma2dBm);

P_S_dB = -5:25; % Transmit power of the source, dBm, e.g., 200mW =
 23dBm

SNRdB = P_S_dB - sigma2dBm; % Average transmit SNR, dB = dBm - dBm,
 bar{rho} = P_S / sigma2
```



SIMULATION | ERA SCHEME

```
% Nakagami scale parameter
m_0 = 2.5 + rand; % S->D, scale parameter, heuristic setting

m_h = 2.5 + rand(N_RIS, 1); % S->R

m_g = 2.5 + rand(N_RIS, 1); % R->D

% Nakagami spread parameter

Omega_0 = 1; % Normalized spread parameter of S->D link
Omega_h = 1; % Normalized spread parameter of S->RIS link
Omega_g = 1; % Normalized spread parameter of RIS->D link

% Path-loss

path_loss_0 = pathloss_NLOS(d_SD)*antenna_gain_S; % S->D link

path_loss_h = pathloss_NLOS(d_SR) * ...
    antenna_gain_S*antenna_gain_RIS*L_single; % Source -> RIS

path_loss_g = pathloss_NLOS(d_RD) * ...
    antenna_gain_RIS*L_single*antenna_gain_D; % RIS -> Des
```

```
% Phase of channels

phase_h_SD = 2*pi*rand(1, sim_times); % domain [0,2pi)
phase_h_SR = 2*pi*rand(N_RIS, L_single, sim_times); % domain [0,2pi)
phase_g_RD = 2*pi*rand(N_RIS, L_single, sim_times); % domain [0,2pi)

phase_h_SR_eachRIS = zeros(L_single, sim_times);
phase_g_RD_eachRIS = zeros(L_single, sim_times);

% Channel modeling

h_SD = sqrt(path_loss_0) * ... % need sqrt because path-loss is
 outside of random()
    random('Naka', m_0, Omega_0, [1, sim_times]) .* ...
    exp(1i*phase_h_SD);

h_SR = zeros(N_RIS,L_single,sim_times); % S to RIS channel
g_RD = zeros(N_RIS,L_single,sim_times); % RIS to D channel

for nn = 1:N_RIS
    phase_h_SR_eachRIS = squeeze(phase_h_SR(nn,:,:)); % random() just
 uses 2D
    phase_g_RD_eachRIS = squeeze(phase_g_RD(nn,:,:)); % random() just
 uses 2D

    for kk=1:L(nn)
        h_SR(nn,kk,:) = sqrt(path_loss_h(nn)) .* ... % need sqrt
 because path-loss is outside of random()
            random('Naka', m_h(nn), Omega_h, [1, sim_times]) .* ...
            exp(1i*phase_h_SR_eachRIS(kk,:));

        g_RD(nn,kk,:) = sqrt(path_loss_g(nn)) .* ... % need sqrt
 because path-loss is outside of random()
            random('Naka', m_g(nn), Omega_g, [1, sim_times]) .* ...
            exp(1i*phase_g_RD_eachRIS(kk,:));
    end
end

% Phase-shift Configuration for ERA scheme
%-----------------------------------------

h_ERA_cascade = zeros(N_RIS, sim_times); % matrix of cascade channel
 S-via-RIS-to-D

for ss = 1:sim_times % loop over simulation trials
    phase_shift_config_ideal = zeros(L_single,1);
    phase_shift_config_ideal_normalized = zeros(L_single,1);
    phase_shift_complex_vector = zeros(L_single,1);

    for nn=1:N_RIS % loop over each RIS
        for ll = 1:L_single % loop over each elements of one RIS
            % Unknown domain phase-shift
            phase_shift_config_ideal(ll) = ...
```

```
                phase_h_SD(ss) - phase_h_SR(nn,ll,ss) -
 phase_g_RD(nn,ll,ss);
            % Convert to domain of [0, 2pi)
            phase_shift_config_ideal_normalized(ll) =
 wrapTo2Pi(phase_shift_config_ideal(ll));
            phase_shift_complex_vector(ll) =
 exp(1i*phase_shift_config_ideal_normalized(ll));
        end

        phase_shift_matrix = kappa_nl .*
 diag(phase_shift_complex_vector);

        % Cascade channel (complex, not magnitude)
        h_ERA_cascade(nn,ss) =  h_SR(nn,:,ss) * phase_shift_matrix *
 g_RD(nn,:,ss).'; % returns a number
    end
end

h_ERA_e2e_magnitude = abs(h_SD + sum(h_ERA_cascade,1)); % direct +
 cascade channels

Z_ERA = h_ERA_e2e_magnitude; % RV Z in the analysis

Z2_ERA = Z_ERA.^2; % RV Z^2
```

SIMULATION | ORA SCHEME (BEST RIS SELECTION)

```
% Simple simulation
%-------------------

% V_M_ORA = max(h_e2e_RIS_path, [], 1); %V_M for the best RIS
% R_ORA   = abs(h_SD + V_M_ORA); %Magnitude of the e2e channel
% R2_ORA  = R_ORA.^2; %Squared magnitude of the e2e channel

% Detailed simulation
%---------------------

h_ORA_cascade = zeros(1, sim_times);

[~,idx] = max(h_ERA_cascade,[],1);

for ss = 1:sim_times
    phase_shift_config_ideal = zeros(L_single,1);
    phase_shift_config_ideal_normalized = zeros(L_single,1);
    phase_shift_complex_vector = zeros(L_single,1);
    for ll = 1:L_single % loop over each elements of one RIS
        % Unknown domain phase-shift
        phase_shift_config_ideal(ll) = phase_h_SD(ss) -
 phase_h_SR(idx(ss),ll,ss) - phase_g_RD(idx(ss),ll,ss);
        phase_shift_config_ideal_normalized(ll) =
 wrapTo2Pi(phase_shift_config_ideal(ll));
```

```
        phase_shift_complex_vector(ll) =
 exp(1i*phase_shift_config_ideal_normalized(ll));
    end

    phase_shift_matrix = kappa_nl .* diag(phase_shift_complex_vector);

    % e2e channel coefficient (complex number, not magnitude)
    h_ERA_cascade(idx(ss),ss) =  h_SR(idx(ss),:,ss) *
 phase_shift_matrix * g_RD(idx(ss),:,ss).';

    h_ORA_cascade(ss) = h_ERA_cascade(idx(ss),ss);
end

h_ORA_e2e_magnitude = abs(h_SD + h_ORA_cascade);

R_ORA = h_ORA_e2e_magnitude; % RV R in the analysis

R2_ORA = h_ORA_e2e_magnitude.^2; % RV R^2
```

ANALYSIS | ERA SCHEME | GAMMA DISTRIBUTION

```
Omg_0 = Omega_0*path_loss_0;
Omg_h = Omega_h*path_loss_h;
Omg_g = Omega_g*path_loss_g;

lambda = sqrt(m_h./Omg_h .* m_g./Omg_g) ./ kappa_nl; % lambda_nl

% Working on h0
%--------------

%The k-th moment of h0
E_h0_k = @(k) gamma(m_0+k/2)/gamma(m_0)*(m_0/Omg_0)^(-k/2);

%CDF of h0
F_h0 = @(x) gammainc(m_0*double(x).^2/Omg_0, m_0, 'lower');

%PDF of h0
f_h0 = @(x) 2*m_0^m_0/gamma(m_0)/Omg_0^m_0*double(x).^(2*m_0-1).*exp(-
m_0/Omg_0.*double(x).^2);

% Working on U_nl
%----------------

%The k-moment of U_nl
E_U_nl_k = @(k,n) lambda(n)^(-k)*gamma(m_h(n)+0.5*k)...
    * gamma(m_g(n)+0.5*k) / gamma(m_h(n)) / gamma(m_g(n));

%Parameter of the approximate Gamma distribution of U_nl
alpha_U= @(n) E_U_nl_k(1,n)^2/(E_U_nl_k(2,n)-E_U_nl_k(1,n)^2);
beta_U = @(n) E_U_nl_k(1,n)/(E_U_nl_k(2,n)-E_U_nl_k(1,n)^2);
```

```
%PDF of U_nl
f_U_nl = @(x,n) beta_U(n)^alpha_U(n)/gamma(alpha_U(n))...
    * x.^(alpha_U(n)-1) .* exp( -beta_U(n)*x );

% Working on V_n
%---------------

%The k-moment of V_n
E_V_n_k = @(k,n) gamma(L(n) * alpha_U(n)+k) ...
    / gamma(L(n) * alpha_U(n)) * beta_U(n)^(-k);

%PDF of V_n
f_V_n = @(v,n) vpa(beta_U(n)^(sym(L(n)*alpha_U(n)))/
gamma(sym(L(n)*alpha_U(n))))...
    * v.^(L(n)*alpha_U(n)-1) .* exp(-beta_U(n)*v);

%CDF of V_n
F_V_n = @(v,n) gammainc(beta_U(n)*double(v),L(n)*alpha_U(n),'lower');

% Working on T
%-------------

% The 1st moment of T
E_T_1 = 0;

for nn = 1:N_RIS
    for kk = 1:L(nn)
        E_T_1 = E_T_1 + E_U_nl_k(1,nn);
    end
end

%The 2nd  moment of T

E_T_2 = 0;

for nn = 1:N_RIS
    tmpA = 0;
    for kk = 1:L(nn)
        tmpA = tmpA + E_U_nl_k(1,nn);
    end
    for ii = nn+1:N_RIS
        tmpB = 0;
        for kk = 1:L(ii)
            tmpB = tmpB + E_U_nl_k(1,ii);
        end
        E_T_2 = E_T_2 + 2 * tmpA * tmpB;
    end
end

for nn = 1:N_RIS
    tmpC = 0;
    for kk = 1:L(nn)
        tmpC = tmpC + E_U_nl_k(2,nn);
    end
```

```
    tmpD = 0;
    for kk = 1:L(nn)
        for v = (kk+1):L(nn)
            tmpD = tmpD + 2 * E_U_nl_k(1,nn) * E_U_nl_k(1,nn);
        end
    end
    E_T_2 = E_T_2 + tmpC + tmpD;
end

% Working on Z
%------------

% The 1st moment of Z
E_Z_1 = E_h0_k(1) + E_T_1;

% The 2nd moment of Z in ERA
E_Z_2 = E_h0_k(2) + E_T_2 + 2*E_h0_k(1)*E_T_1;

% Parameter of the approximate Gamma distribution of Z
alpha_Z = E_Z_1^2/(E_Z_2 - E_Z_1^2);
beta_Z = E_Z_1/(E_Z_2 - E_Z_1^2);

% CDF of Z in ERA
F_Z_Gamma = @(z) gammainc(z*beta_Z, alpha_Z, 'lower');

% PDF of Z in ERA
f_Z_Gamma = @(z) 1/gamma(alpha_Z)*(beta_Z)^alpha_Z...
    * z.^(alpha_Z-1) .* exp( -z*beta_Z );

% CDF of Z^2 in ERA
F_Z2_Gamma = @(z) F_Z_Gamma(sqrt(z));

% Asymptotic analysis
%--------------------

% %Asymptotic CDF of Z
% F_Z_Gamma_asymp = @(z) (z*beta_Z)^alpha_Z/gamma(alpha_Z+1);
%
% %Asymptotic CDF of Z^2
% F_Z2_Gamma_asymp= @(z) F_Z_Gamma_asymp(sqrt(z));
```

ANALYSIS | ORA SCHEME | GAMMA DISTRIBUTION

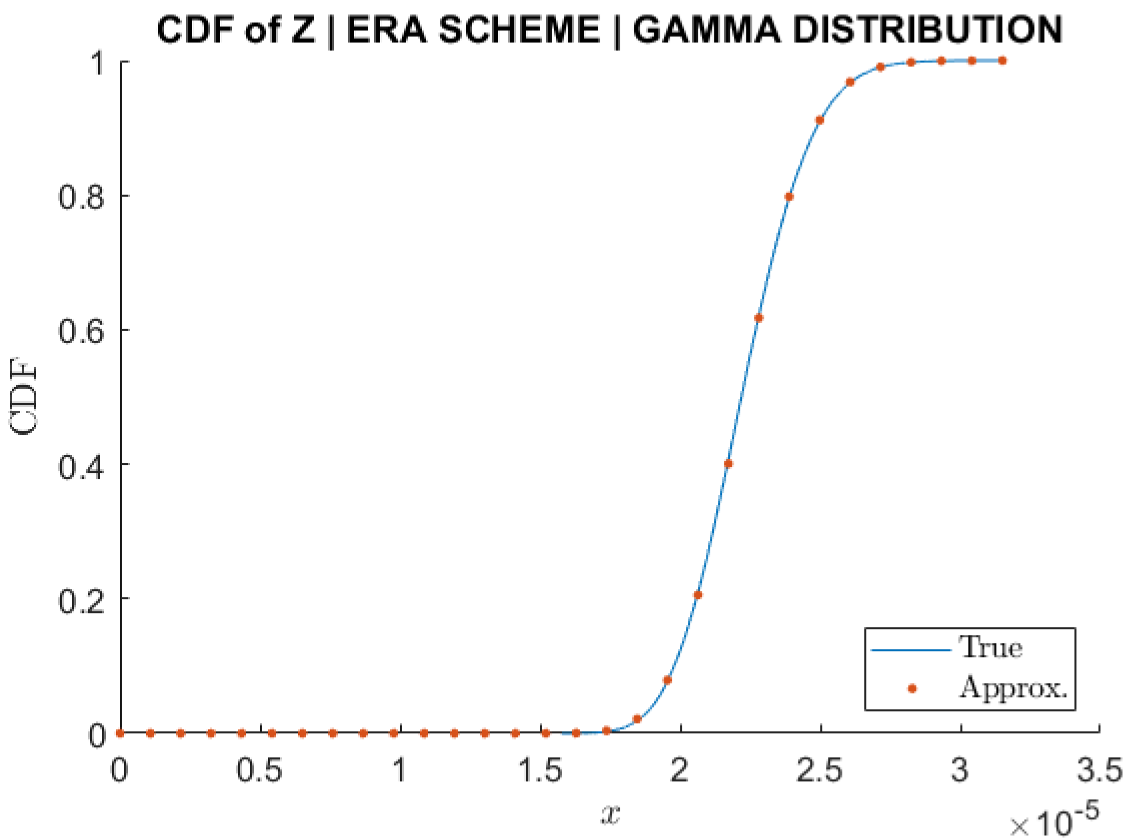
```
% Working on M_V ( max V_n )
%--------------------------

% CDF of V_M in ORA
F_M_V = @(x) 1;
for k = 1:N_RIS
    F_M_V = @(x) F_M_V(x) .* F_V_n(x,k);
end
```

```
M = 100; %Number of steps in M-staircase approximation

% CDF of R in ORA
F_R = @(r) 0;
for m = 1:M
    F_R = @(r) F_R(r)...
        + (F_h0(m/M*r) - F_h0((m-1)/M*r)) .* F_M_V((M-m+1)/M*r);
end

% CDF of R^2 in ORA
F_R2_Gamma = @(r) F_R(sqrt(r)); % for using in e2e SNR of the ORA
 scheme

% Asymptotic analysis
%--------------------

% %Asymptotic of R^2
% LAlpha_arr = zeros(1,N_RIS);
% Beta_arr  = zeros(1,N_RIS);
%
% for n = 1:N_RIS
%     LAlpha_arr(n) = L(n)*alpha_U(n);
%     Beta_arr(n) = beta_U(n);
% end
%
% M1 = 1e3; m_arr = 1:M1;
% fM = sum( ((m_arr-1)/M1).^(2*m0-1).*(1-(m_arr-1)/
M1).^sum(LAlpha_arr) )/M1;
%
% F_R_Gamma_asymp = @(r) (2*m0)/gamma(m0+1)*(m0/Omg0)^(m0)...
%     * prod( Beta_arr.^(LAlpha_arr) ./ gamma(LAlpha_arr+1) .*
 r.^LAlpha_arr )...
%     * r.^(2*m0) * fM;
% F_R2_asymp = @(r) F_R_Gamma_asymp(sqrt(r));
```

CDF of Z | ERA SCHEME | GAMMA DISTRIBUTION

```
figure;

[y, x] = ecdf(Z_ERA); hold on;
domain_Z = linspace(0, max(x), 30);

plot(x, y); hold on;
plot(domain_Z, F_Z_Gamma(domain_Z), '.', 'markersize', 10); hold on;

title('CDF of Z | ERA SCHEME | GAMMA DISTRIBUTION')
xlabel('$x$', 'Interpreter', 'Latex')
ylabel('CDF','Interpreter', 'Latex')
legend('True',...
    'Approx.',...
```

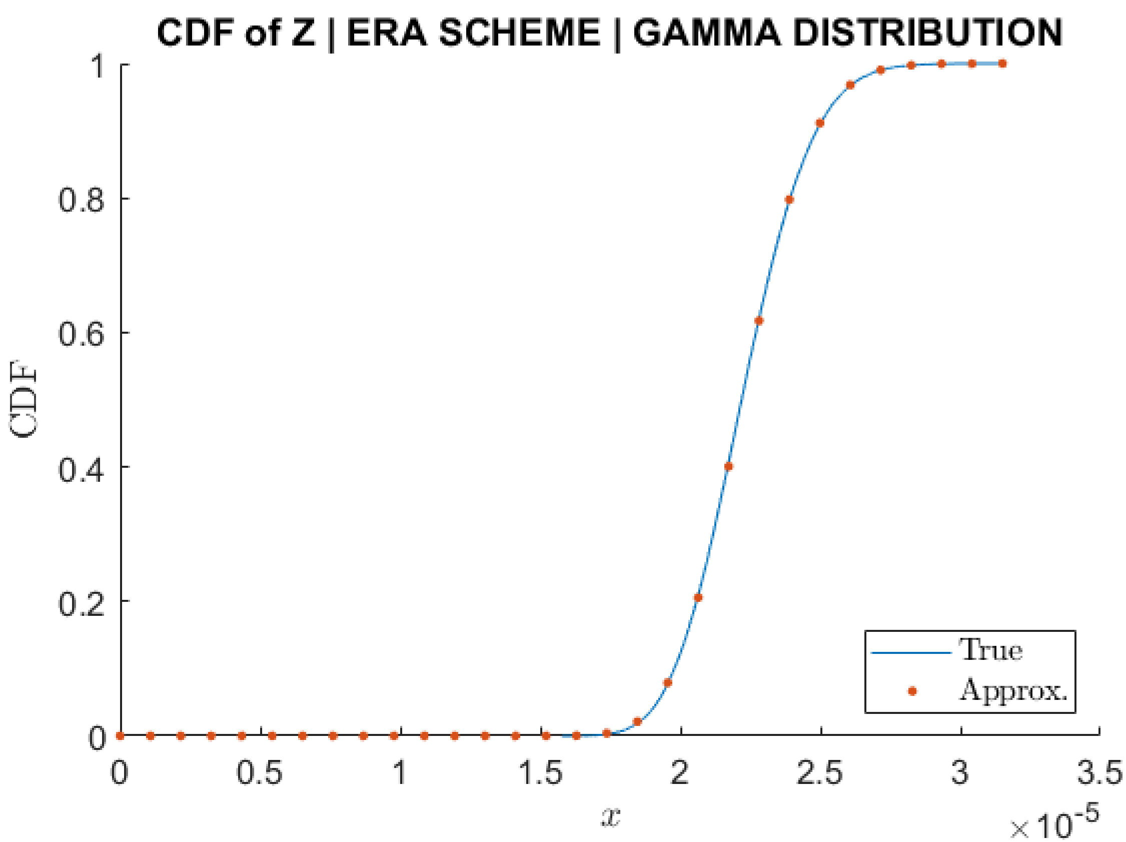
```
    'location', 'se',...
    'Interpreter', 'Latex');

% x0 = 100; y0 = 100; width = 300; height = 250;
% set(gcf,'Position', [x0, y0, width, height]); % plot size
set(gca, 'LooseInset', get(gca, 'TightInset')) % remove plot padding
set(gca,'fontsize',13);
```

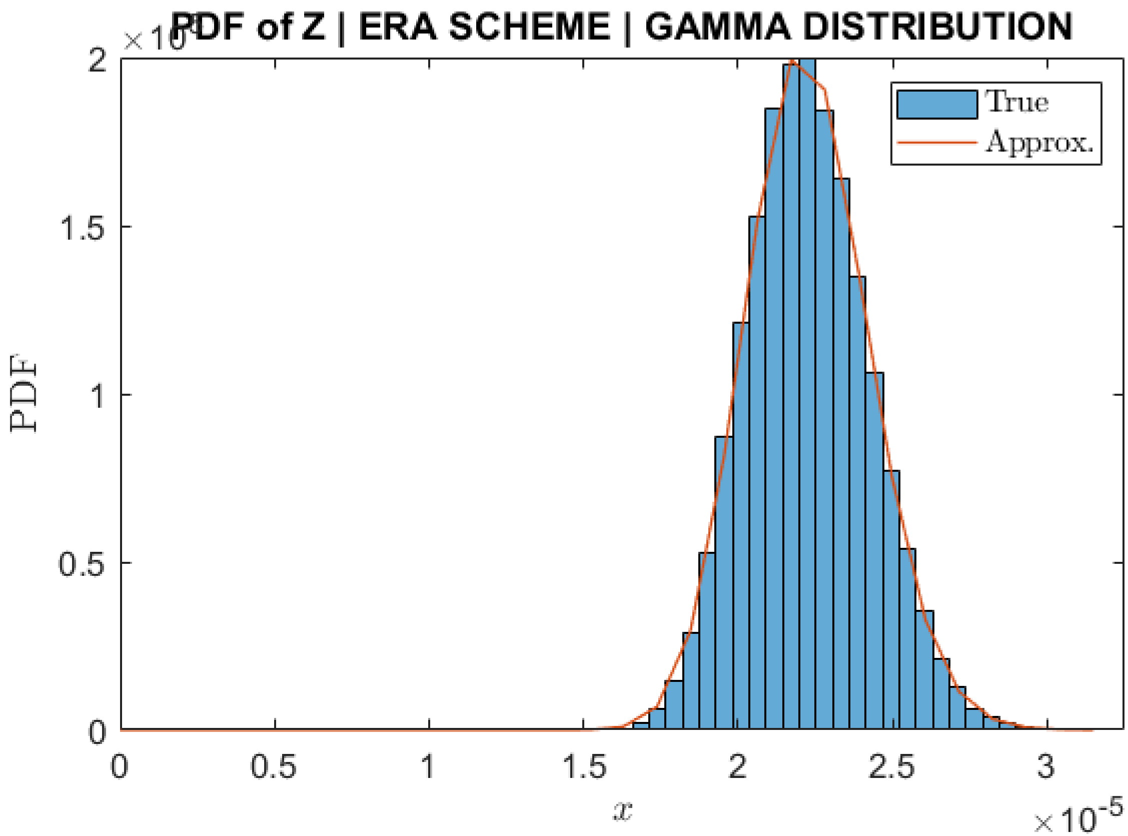


PDF of Z | ERA SCHEME | GAMMA DISTRIBUTION

```
% Non-symbolic PDF of Z and Z^2
%-------------------------------

% f_Z = @(z) 1/gamma(alpha_Z)*(beta_Z)^alpha_Z...
%     * z.^(alpha_Z-1) .* exp( -z*beta_Z );
% f_Z2 = @(z) 1./(2*sqrt(z)) .* f_Z(sqrt(z));

figure;

number_of_bins = 30;
histogram(h_ERA_e2e_magnitude,
 number_of_bins, 'normalization', 'pdf'); hold on;
% histfit(h_ERA_e2e_magnitude, number_of_bins, 'gamma'); hold on;
```

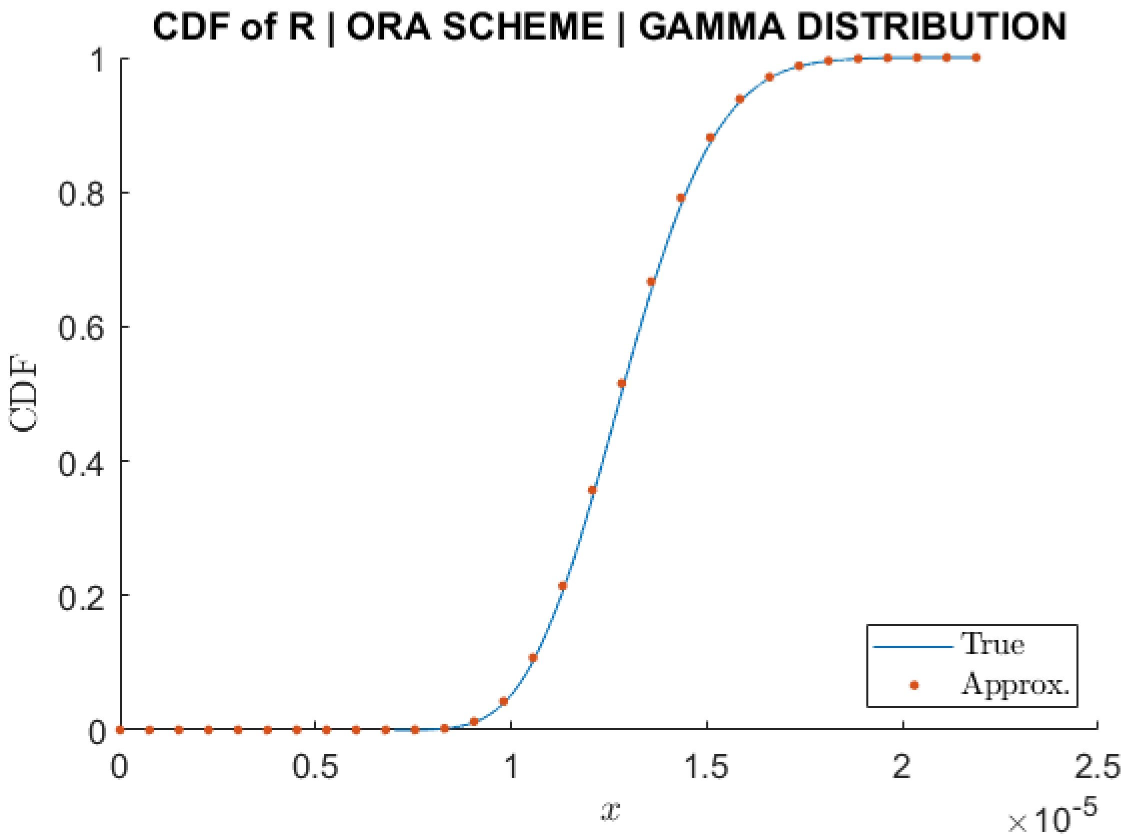
```
% Symbolic PDF of Z
syms sbl_az sbl_bz sbl_z
symbolic_f_Z(sbl_az,sbl_bz,sbl_z) = 1/
gamma(sbl_az)*(sbl_bz)^sbl_az ...
    * sbl_z^(sbl_az-1) * exp( - sbl_z*sbl_bz );

plot(domain_Z, double(vpa(symbolic_f_Z(alpha_Z, beta_Z,
 domain_Z))),...
    'linewidth', 1); hold on;

title('PDF of Z | ERA SCHEME | GAMMA DISTRIBUTION')
xlabel('$x$', 'Interpreter', 'Latex')
ylabel('PDF', 'Interpreter', 'Latex')
legend('True',...
    'Approx.',...
    'location', 'ne',...
    'Interpreter', 'Latex');

set(gca, 'LooseInset', get(gca, 'TightInset')) % remove plot padding
set(gca,'fontsize',13);
```





CDF of R | ORA SCHEME | GAMMA DISTRIBUTION

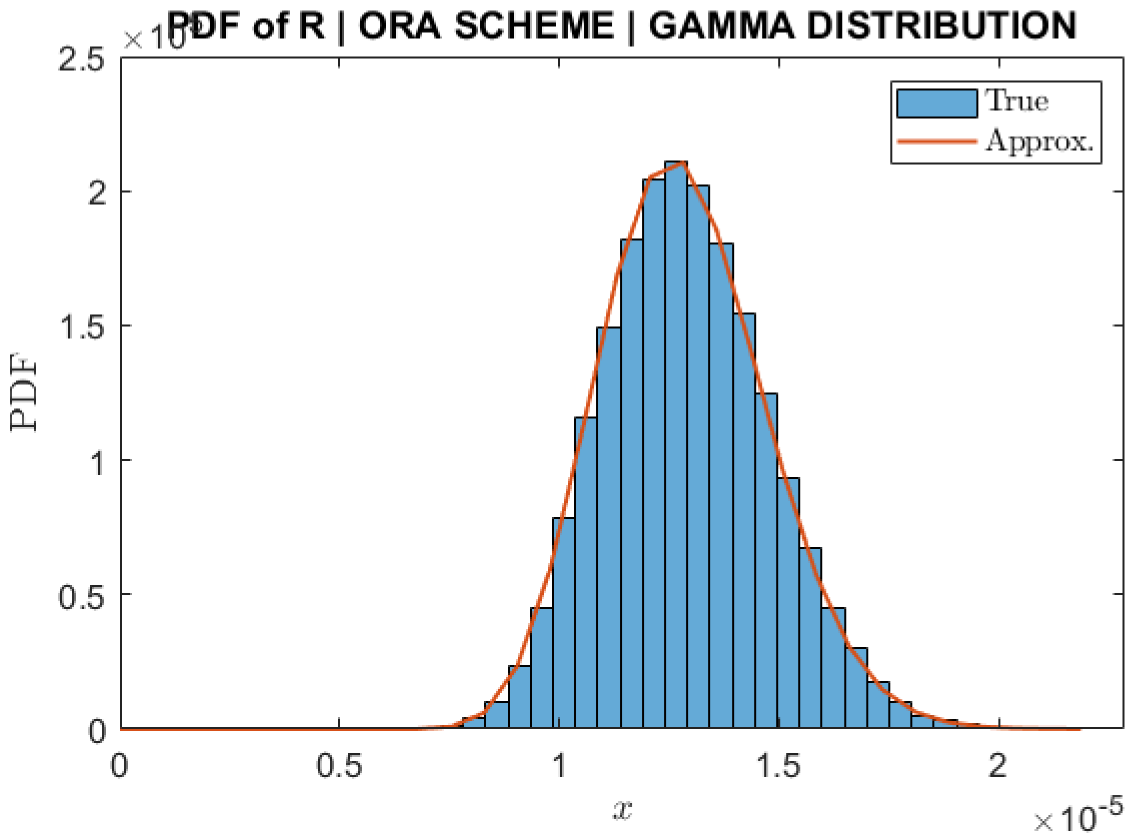
```
figure;

[y, x] = ecdf(R_ORA); hold on;
domain_R = linspace(0, max(x), 30);

plot(x, y); hold on;
plot(domain_R, F_R(domain_R), '.', 'markersize', 10); hold on;

title('CDF of R | ORA SCHEME | GAMMA DISTRIBUTION')
xlabel('$x$', 'Interpreter', 'Latex')
ylabel('CDF', 'Interpreter', 'Latex')
legend('True',...
    'Approx.',...
    'location', 'se',...
    'Interpreter', 'Latex');

set(gca, 'LooseInset', get(gca, 'TightInset')) %remove plot padding
set(gca,'fontsize',13);
```



PDF of R | ORA SCHEME | GAMMA DISTRIBUTION

```
f_M_V = @(x) 0; % CDF of M_v in ORA

for nn = 1:N_RIS
    func_tmp = @(x) 1;
    for t = 1:N_RIS
        if (nn ~= t)
            func_tmp = @(x) func_tmp(x) .* F_V_n(x,t);
        end
    end
    f_M_V = @(x) f_M_V(x) + f_V_n(x,nn) .* func_tmp(x);
end

M = 100; %Number of steps in M-staircase approximation

f_R = @(r) 0; % PDF of R in ORA


for m = 1:M
    f_R = @(r) f_R(r)...
        + ((m/M)*f_h0(m/M*r) - ((m-1)/M)*f_h0((m-1)/M*r))...
        .*F_M_V((M-m+1)/M*r)...
```

```
        + (F_h0(m/M*r)- F_h0((m-1)/M*r))...
        .*((M-m+1)/M).*f_M_V((M-m+1)/M*r);
end

f_R2 = @(r) 1./(2*sqrt(r)).*f_R(sqrt(r)); % PDF of R^2 in ORA

figure;

histogram(R_ORA, number_of_bins, 'normalization', 'pdf'); hold on;
plot(domain_R, double(vpa(f_R(sym(domain_R)))), 'linewidth', 1.5);
 hold on;

title('PDF of R | ORA SCHEME | GAMMA DISTRIBUTION')
xlabel('$x$', 'Interpreter', 'Latex')
ylabel('PDF', 'Interpreter', 'Latex')
legend('True ',...
    'Approx.',...
    'location', 'ne',...
    'Interpreter', 'Latex');

set(gca, 'LooseInset', get(gca, 'TightInset')) %remove plot padding
set(gca,'fontsize',13);
```



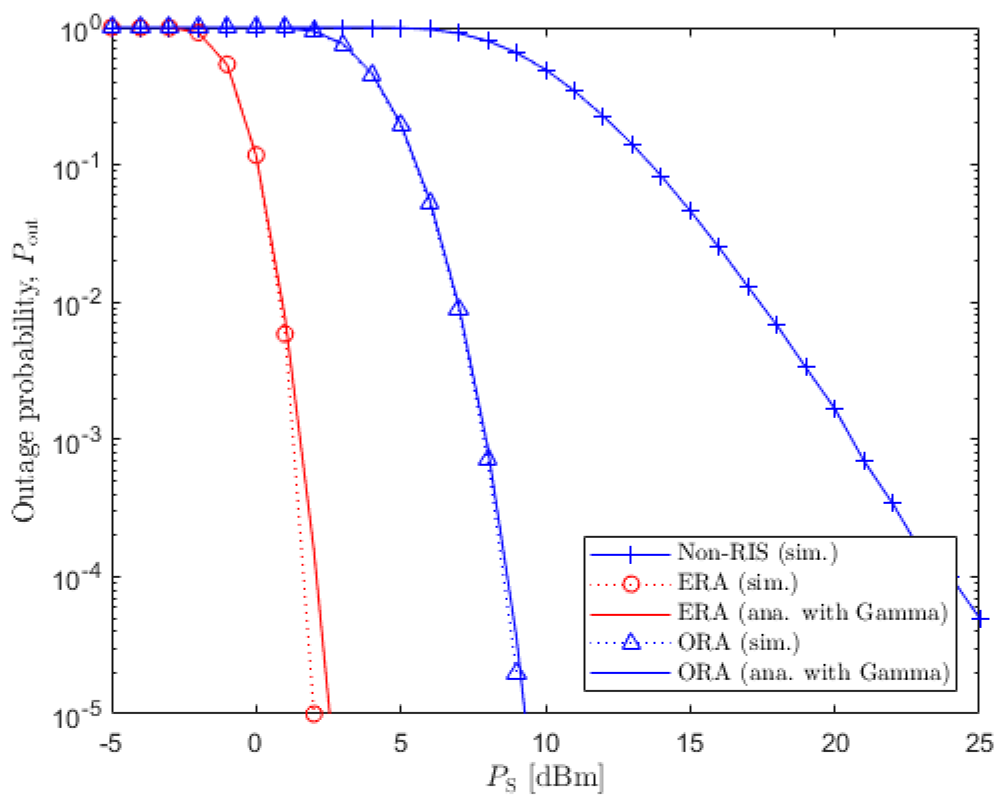
OUTAGE PROBABILITY

```
OP_non_RIS_sim = zeros(length(SNRdB),1); % should be column vector
```

```
OP_ERA_sim = zeros(length(SNRdB),1);
OP_ERA_ana = zeros(length(SNRdB),1);
OP_ORA_sim = zeros(length(SNRdB),1);
OP_ORA_ana = zeros(length(SNRdB),1);

SNR_h0 = abs(h_SD).^2;

for idx = 1:length(SNRdB)

    avgSNR = db2pow(SNRdB(idx)); % i.e., 10^(SNRdB/10)

    OP_non_RIS_sim(idx) = mean(avgSNR*SNR_h0 < SNR_th);

    % ERA scheme

    OP_ERA_sim(idx) = mean(avgSNR*Z2_ERA < SNR_th);

    OP_ERA_ana(idx) = F_Z2_Gamma(SNR_th/avgSNR);

    %ORA scheme

    OP_ORA_sim(idx) = mean(avgSNR*R2_ORA < SNR_th);

    OP_ORA_ana(idx) = F_R2_Gamma(SNR_th/avgSNR);

    fprintf('Outage probability, SNR = % d \n', round(SNRdB(idx)));
end

figure;

semilogy(P_S_dB, OP_non_RIS_sim, 'b+-'); hold on;
semilogy(P_S_dB, OP_ERA_sim, 'ro:'); hold on;
semilogy(P_S_dB, OP_ERA_ana, 'r-'); hold on;
semilogy(P_S_dB, OP_ORA_sim, 'b^:'); hold on;
semilogy(P_S_dB, OP_ORA_ana, 'b-'); hold on;

xlabel('$P_{\rm S}$ [dBm]', 'Interpreter', 'Latex');
ylabel('Outage probability, $P_{\rm out}$', 'Interpreter', 'Latex');
legend('Non-RIS (sim.)',...
    'ERA (sim.)', ...
    'ERA (ana. with Gamma)',...
    'ORA (sim.)', ...
    'ORA (ana. with Gamma)',...
    'Location','se',...
    'Interpreter', 'Latex');
axis([-Inf Inf 10^(-5) 10^(0)]);
```

```
Outage probability, SNR =  89
Outage probability, SNR =  90
Outage probability, SNR =  91
Outage probability, SNR =  92
Outage probability, SNR =  93
Outage probability, SNR =  94
Outage probability, SNR =  95
```

```
Outage probability, SNR =  96
Outage probability, SNR =  97
Outage probability, SNR =  98
Outage probability, SNR =  99
Outage probability, SNR =  100
Outage probability, SNR =  101
Outage probability, SNR =  102
Outage probability, SNR =  103
Outage probability, SNR =  104
Outage probability, SNR =  105
Outage probability, SNR =  106
Outage probability, SNR =  107
Outage probability, SNR =  108
Outage probability, SNR =  109
Outage probability, SNR =  110
Outage probability, SNR =  111
Outage probability, SNR =  112
Outage probability, SNR =  113
Outage probability, SNR =  114
Outage probability, SNR =  115
Outage probability, SNR =  116
Outage probability, SNR =  117
Outage probability, SNR =  118
Outage probability, SNR =  119
```



ERGODIC CAPACITY

```
EC_non_RIS_sim = zeros(length(SNRdB),1); % should be column vector
EC_ERA_sim = zeros(length(SNRdB),1);
EC_ERA_ana = zeros(length(SNRdB),1);
EC_ORA_sim = zeros(length(SNRdB),1);
EC_ORA_ana = zeros(length(SNRdB),1);

syms az bz rho % Inputs: az = alpha_Z, bz = beta_Z, rho = snr

EC_RIS(az, bz, rho) = 1/gamma(az)/log(2)*2^(az-1)/sqrt(pi)...
    * meijerG(0, [1/2,1], [az/2,az/2+1/2,0,0,1/2], [], (bz/2)^2/rho);

func_EC_ORA_Gamma = @(x,c) (1/log(2)).*(1./(1+x).*(1 - F_R(sqrt(x./
c))));

for idx = 1:length(SNRdB)
    avgSNR = db2pow(SNRdB(idx)); % 10^(SNRdB(idx)/10)

    EC_non_RIS_sim(idx) = mean(log2(1 + avgSNR*SNR_h0));

    EC_ERA_sim(idx) = mean(log2(1+avgSNR*Z2_ERA));

    EC_ERA_ana(idx) = double(vpa(EC_RIS(alpha_Z, beta_Z, avgSNR)));

    EC_ORA_sim(idx) = mean(log2(1+avgSNR*R2_ORA));

    EC_ORA_ana(idx) = integral(@(x) func_EC_ORA_Gamma(x,avgSNR), 0,
 Inf);

    fprintf('Ergodic capacity, SNR = % d \n', round(SNRdB(idx)));
end

figure;

plot(P_S_dB, EC_non_RIS_sim, 'b+-'); hold on;
plot(P_S_dB, EC_ERA_sim, 'ro:'); hold on;
plot(P_S_dB, EC_ERA_ana, 'r-'); hold on;
plot(P_S_dB, EC_ORA_sim, 'bs:'); hold on;
plot(P_S_dB, EC_ORA_ana, 'b-'); hold on;

xlabel('$P_{\rm S}$ [dBm]', 'Interpreter', 'Latex');
ylabel('Ergodic capacity [b/s/Hz]', 'Interpreter', 'Latex');
legend('Non-RIS (sim.)',...
    'ERA (sim.)',...
    'ERA (ana. with Gamma)',...
    'ORA (sim.)',...
    'ORA (analytical)',...
    'Interpreter', 'Latex',...
    'Location','NW');

toc
```

```
Ergodic capacity, SNR =  89
Ergodic capacity, SNR =  90
Ergodic capacity, SNR =  91
Ergodic capacity, SNR =  92
Ergodic capacity, SNR =  93
Ergodic capacity, SNR =  94
Ergodic capacity, SNR =  95
Ergodic capacity, SNR =  96
Ergodic capacity, SNR =  97
Ergodic capacity, SNR =  98
Ergodic capacity, SNR =  99
Ergodic capacity, SNR =  100
Ergodic capacity, SNR =  101
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Ergodic capacity, SNR =  109
Ergodic capacity, SNR =  110
Ergodic capacity, SNR =  111
Ergodic capacity, SNR =  112
Ergodic capacity, SNR =  113
Ergodic capacity, SNR =  114
Ergodic capacity, SNR =  115
Ergodic capacity, SNR =  116
Ergodic capacity, SNR =  117
Ergodic capacity, SNR =  118
Ergodic capacity, SNR =  119
Elapsed time is 179.881284 seconds.
```

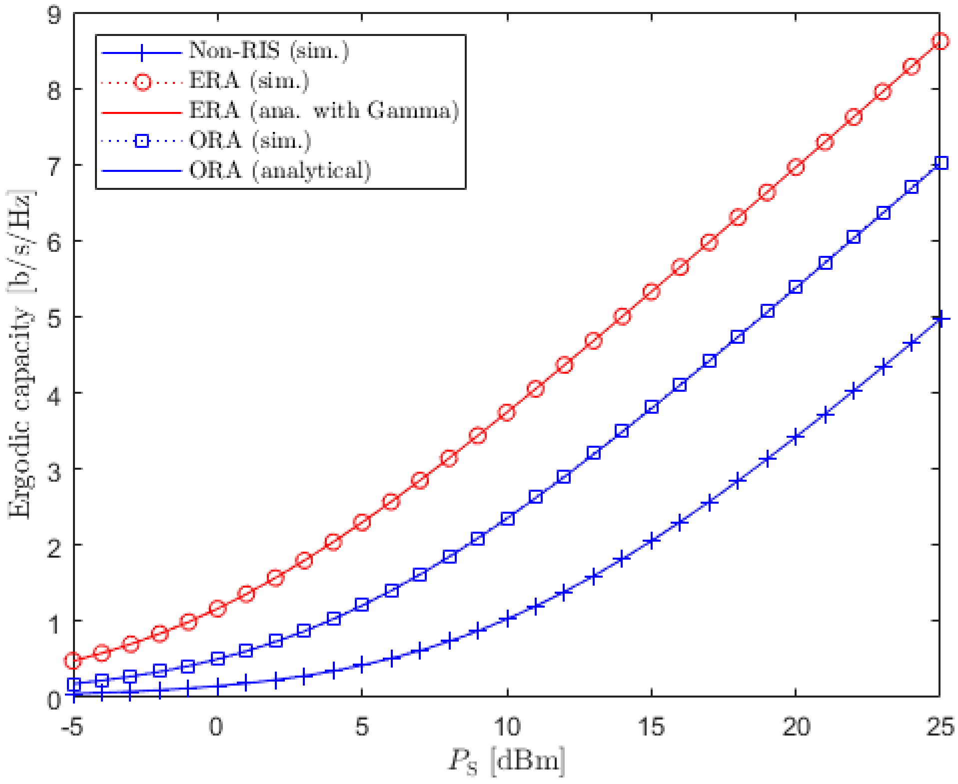

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