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Homework 2

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ECE 233: Wireless Communications System Design, Modeling, and Implementation

Summer 2024

Part 1: Capacity gain in MIMO system

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Parameters

```
lambda = 0.06;  % ???
Nt_Nr = {[8, 8], [16, 16]};  % Cell array for pairs
dt = lambda / 2;
dr = lambda / 2;
L = 6;
SNR = -10:2:20;
num_MC = 1000;
x = randn(max(Nt_Nr{2}), 1) + 1j * randn(max(Nt_Nr{2}), 1);  % Random signal
noise_var = 10.^(-SNR / 10); % Noise variance calculation
qam = 4;
```

Plotting for (Nt, Nr) = (8, 8) and (16, 16)

```
for idx = 1:length(Nt_Nr)
    Nt = Nt_Nr{idx}(1);
    Nr = Nt_Nr{idx}(2);

    % Initialize storage for achievable rates (Monte Carlo averaging)
    rate_ZF_rich_avg = zeros(1, length(SNR));
    rate_LMMSE_rich_avg = zeros(1, length(SNR));
    rate_SVD_rich_avg = zeros(1, length(SNR));

    rate_ZF_sparse_avg = zeros(1, length(SNR));
    rate_LMMSE_sparse_avg = zeros(1, length(SNR));
    rate_SVD_sparse_avg = zeros(1, length(SNR));

    % Monte Carlo Trials
    for MC_id = 1:num_MC
        % Generate channels
        Hr = calculateRichChannel(Nr, Nt);  % Rich channel
        Hs = calculateSparseChannel(Nr, Nt, L, dt, dr, lambda);  % Sparse
channel

        % Generate symbols to transmit through transmit antennas
        input_bits = randi([0 1],Nt*log2(qam),1);
        x = qammod(input_bits, qam, 'InputType', 'bit', 'UnitAveragePower',
true);

        for snr_idx = 1:length(SNR)
```

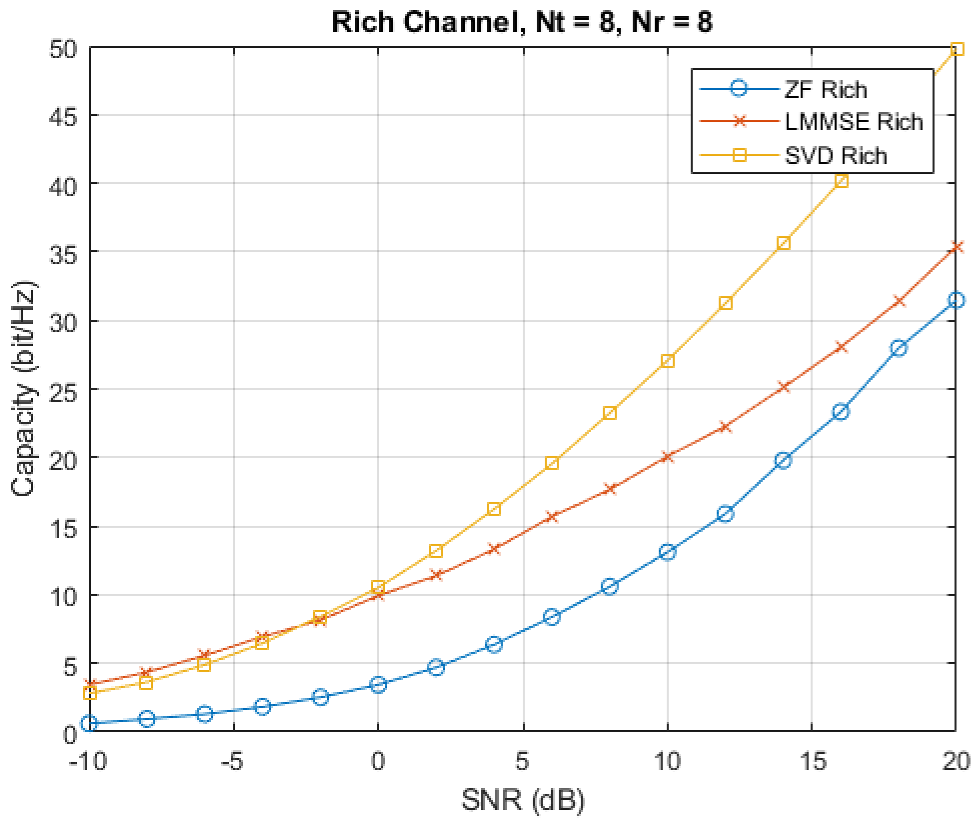
```
            snr_dB = SNR(snr_idx);
            SNR_linear = 10^(snr_dB / 10);  % Convert to linear scale
            noise_var = 1 / SNR_linear;  % Adjust noise variance based on SNR

            % ZF Combining
            [W_ZF_rich, capacity] = calculateZFCombiner(Hr, x, Nt, Nr,
SNR_linear);
            rate_ZF_rich_avg(snr_idx) = rate_ZF_rich_avg(snr_idx) + capacity;

            [W_ZF_sparse, capacity] = calculateZFCombiner(Hs, x, Nt, Nr,
SNR_linear);
            rate_ZF_sparse_avg(snr_idx) = rate_ZF_sparse_avg(snr_idx) +
capacity;

            % LMMSE Combining
            [W_LMMSE_rich, capacity] = calculateLMMSECombiner(Hr, x, Nt, Nr,
SNR_linear, noise_var);
            rate_LMMSE_rich_avg(snr_idx) = rate_LMMSE_rich_avg(snr_idx) +
capacity;

            [W_LMMSE_sparse, capacity] = calculateLMMSECombiner(Hs, x, Nt,
Nr, SNR_linear, noise_var);
            rate_LMMSE_sparse_avg(snr_idx) = rate_LMMSE_sparse_avg(snr_idx)
+ capacity;

            % SVD Combining
            [W_SVD_rich, capacity] = calculateSVDCombiner(Hr, x, Nt, Nr,
SNR_linear);
            rate_SVD_rich_avg(snr_idx) = rate_SVD_rich_avg(snr_idx) +
capacity;

            [W_SVD_sparse, capacity] = calculateSVDCombiner(Hs, x, Nt, Nr,
SNR_linear);
            rate_SVD_sparse_avg(snr_idx) = rate_SVD_sparse_avg(snr_idx) +
capacity;
        end
    end

    % Average over the Monte Carlo trials
    rate_ZF_rich_avg = rate_ZF_rich_avg / num_MC;
    rate_LMMSE_rich_avg = rate_LMMSE_rich_avg / num_MC;
    rate_SVD_rich_avg = rate_SVD_rich_avg / num_MC;

    rate_ZF_sparse_avg = rate_ZF_sparse_avg / num_MC;
    rate_LMMSE_sparse_avg = rate_LMMSE_sparse_avg / num_MC;
    rate_SVD_sparse_avg = rate_SVD_sparse_avg / num_MC;

    % Plotting results for this (Nt, Nr) pair
    figure;
    plot(SNR, rate_ZF_rich_avg, '-o', 'DisplayName', 'ZF Rich');
    hold on;
    plot(SNR, rate_LMMSE_rich_avg, '-x', 'DisplayName', 'LMMSE Rich');
    plot(SNR, rate_SVD_rich_avg, '-s', 'DisplayName', 'SVD Rich');
    title(['Rich Channel, Nt = ', num2str(Nt), ', Nr = ', num2str(Nr)]);
```

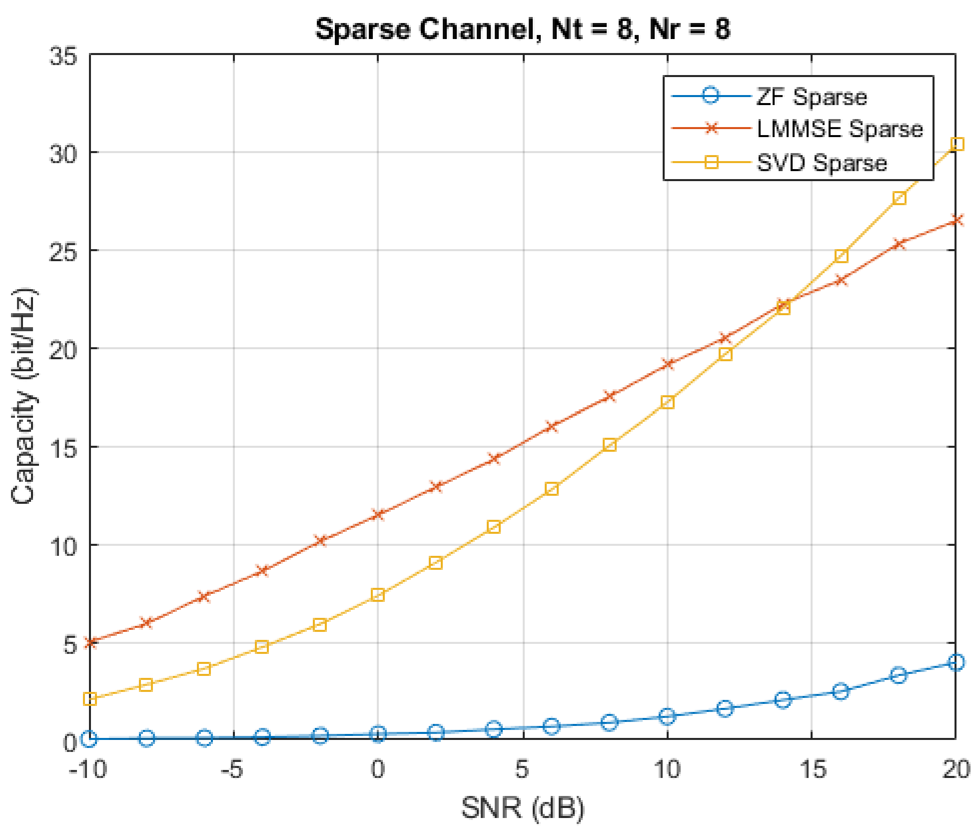
```
    xlabel('SNR (dB)');
    ylabel('Capacity (bit/Hz)');
    legend;
    grid on;

    figure;
    plot(SNR, rate_ZF_sparse_avg, '-o', 'DisplayName', 'ZF Sparse');
    hold on;
    plot(SNR, rate_LMMSE_sparse_avg, '-x', 'DisplayName', 'LMMSE Sparse');
    plot(SNR, rate_SVD_sparse_avg, '-s', 'DisplayName', 'SVD Sparse');
    title(['Sparse Channel, Nt = ', num2str(Nt), ', Nr = ', num2str(Nr)]);
    xlabel('SNR (dB)');
    ylabel('Capacity (bit/Hz)');
    legend;
    grid on;
end
```

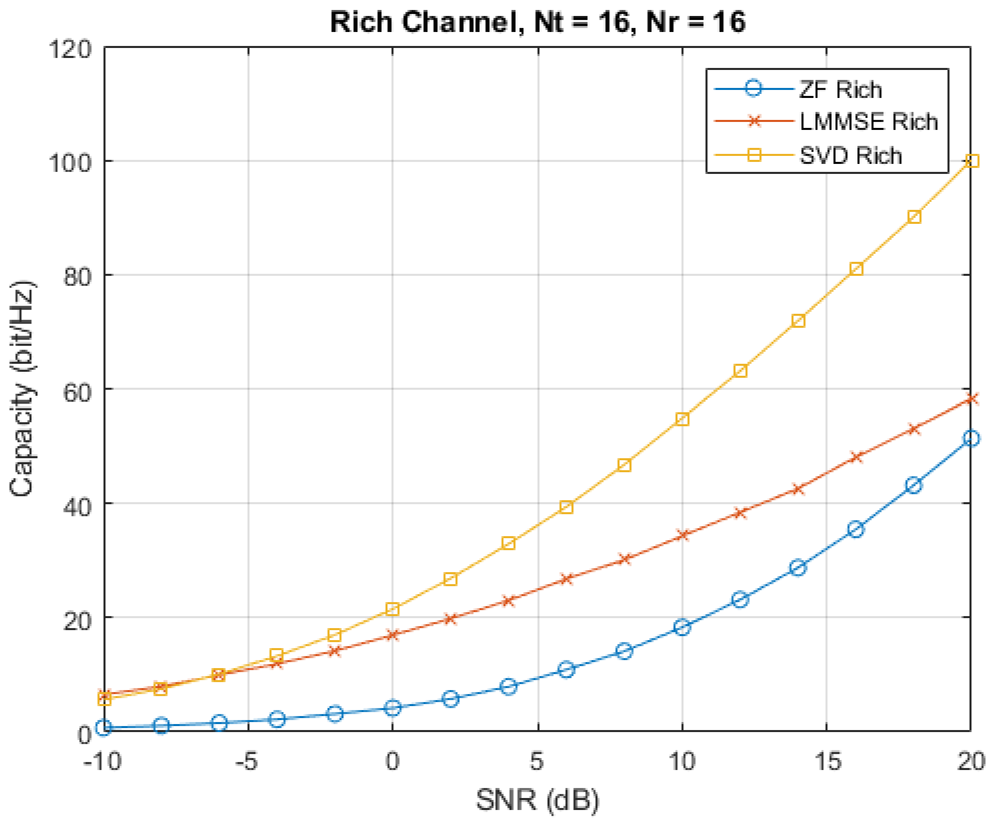
Functions

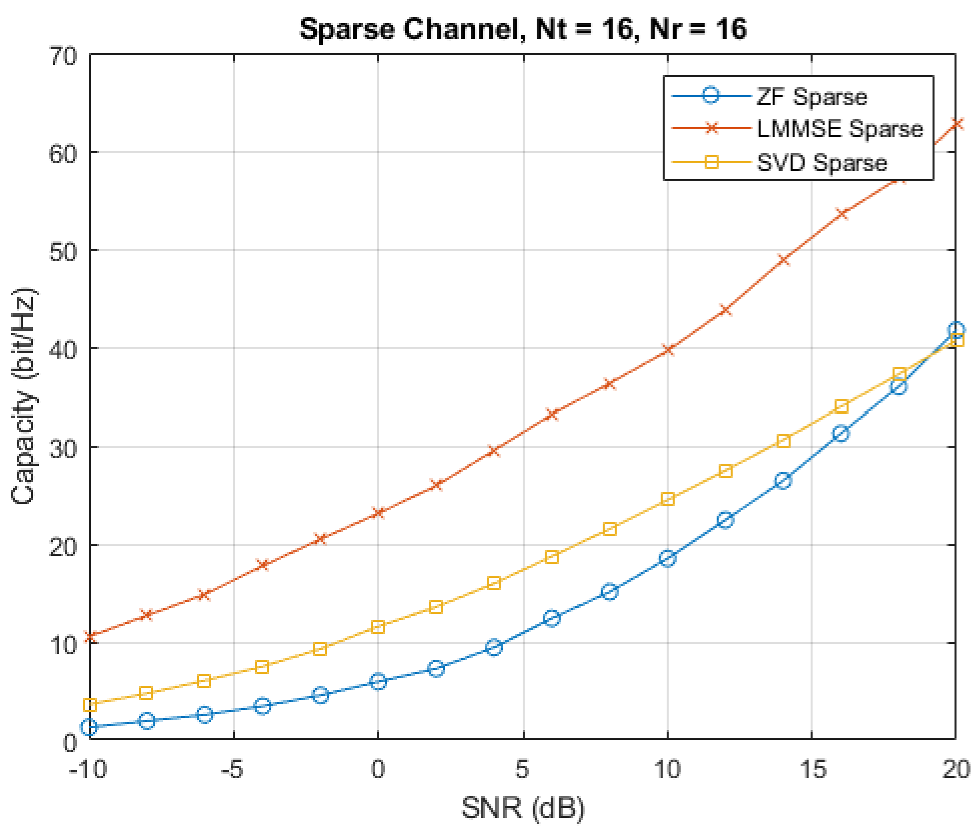
```
function Hr = calculateRichChannel(Nr, Nt)
    % Generate real and imaginary parts independently from N(0, 1/2)
    real_part = sqrt(1/2) * randn(Nr, Nt);
    imag_part = sqrt(1/2) * randn(Nr, Nt);

    % Combine to form complex Gaussian elements
    Hr = real_part + 1j * imag_part;
end

function Hs = calculateSparseChannel(Nr, Nt, L, dt, dr, lambda)
    Hs = zeros(Nr, Nt);  % Initialize the sparse channel matrix

    scale_factor = sqrt(Nt * Nr / L);

    for i = 1:L
        % Generate path gain (complex Gaussian random variable)
        alpha_i = sqrt(1/2) * (randn() + 1i*randn());   % N(0, 1) complex
normal

        % Generate AoA (theta_i) and AoD (phi_i) uniformly in [-pi/2, pi/2]
        theta_i = (-pi/2) + (pi) * rand();
        phi_i = (-pi/2) + (pi) * rand();

        % Calculate aRx(theta_i) spatial response vector
        aRx = sqrt(1/Nr) * exp(-1i * pi * (0:(Nr-1))' * sin(theta_i));

        % Calculate aTx(phi_i) spatial response vector
        aTx = sqrt(1/Nt) * exp(-1i * pi * (0:(Nt-1))' * sin(phi_i));

        % Update the sparse channel matrix
        Hs = Hs + alpha_i * (aRx * aTx');
    end

    Hs = scale_factor * Hs;
```

```
end

function capacity = calculateCapacity(x_hat, n_hat)
    x_hat = abs(x_hat).^2;
    n_hat = abs(n_hat).^2;
    capacity = sum(log2((x_hat./n_hat) + 1));
end

function [W_ZF, capacity] = calculateZFCombiner(H, x, Nt, Nr, SNR_linear)
    W_ZF = pinv(H);

    % Generate complex noise with noise power corresponding to SNR
    noise_power = (norm(H*x, 'fro')^2)/SNR_linear;
    noise = sqrt(1/2) * (randn(Nr,1) + 1j*randn(Nr,1));
    noise = (noise/norm(noise, 'fro')) * sqrt(noise_power);

    capacity = calculateCapacity(W_ZF*H*x, W_ZF*noise);
end


function [W_LMMSE, capacity] = calculateLMMSECombiner(H, x, Nt, Nr,
SNR_linear, noise_var)
    % Calculate the LMMSE combining matrix
    W_LMMSE = inv(H'*H+(1/SNR_linear)*eye(Nt))*H';

    % Generate complex noise with noise power corresponding to SNR
    noise_power = (norm(H*x, 'fro')^2)/SNR_linear;
    noise = sqrt(1/2) * (randn(Nr,1) + 1j*randn(Nr,1));
    noise = (noise/norm(noise, 'fro')) * sqrt(noise_power);

    capacity = calculateCapacity(W_LMMSE*H*x, W_LMMSE*noise);
end


function [W_SVD, capacity] = calculateSVDCombiner(H, x, Nt, Nr, SNR_linear)
    % Perform SVD on the channel matrix H
    [U, S, V] = svd(H); % H = UEV^H

    % W_SVD = U^H
    W_SVD = U';

    noise_power = (norm(H*V*x, 'fro')^2)/SNR_linear;
    noise = sqrt(noise_power) * sqrt(1/2) * (randn(Nr,1) + 1j*randn(Nr,1));
    noise = (noise/norm(noise, 'fro')) * sqrt(noise_power);

    capacity = calculateCapacity(W_SVD*H*V*x, W_SVD*noise);
end
```


Rich Channel, Nt = 8, Nr = 8
ZF Rich
LMMSE Rich
SVD Rich
Capacity (bit/Hz)
SNR (dB)
50
45
40
35
30
25
20
15
10
5
0
-10
-5
0
5
10
15
20


Sparse Channel, Nt = 8, Nr = 8
ZF Sparse
LMMSE Sparse
SVD Sparse
Capacity (bit/Hz)
SNR (dB)
35
30
25
20
15
10
5
0
-10
-5
0
5
10
15
20


Rich Channel, Nt = 16, Nr = 16
ZF Rich
LMMSE Rich
SVD Rich
Capacity (bit/Hz)
SNR (dB)
0
20
40
60
80
100
120
-10
-5
0
5
10
15
20


Sparse Channel, Nt = 16, Nr = 16
ZF Sparse
LMMSE Sparse
SVD Sparse
Capacity (bit/Hz)
SNR (dB)
0
10
20
30
40
50
60
70
-10
-5
0
5
10
15
20

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Part 2: Interference mitigation techniques for antenna array

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Parameters

```
N = 16; % Number of antennas
phi1 = 30 * pi / 180; % Angle for UE-1 in radians
phi2 = 40 * pi / 180; % Angle for UE-2 in radians.
true_phi2 = 40;
delta_phi1 = 1 * pi / 180; % Angle for UE-2 in radians
phi_range = -90:0.2:90;
T = 1000; % Number of symbols
P_s1 = 1; % Power of signal s1(t)
P_s2 = 10; % Magnitude of signal s2(t)
sigma2 = 1e-3; % Noise power
num_MC = 1000;
num_MC_faster = 10;
SNR_dB = -20:10:40; % SNR range in dB
zeta = 0.0001;
```

Setup

```
noise_power_dB = -SNR_dB; % Noise Power dB = -SNR dB
SNR = 10.^(SNR_dB/10); % SNR_dB --> SNR linear scale
```

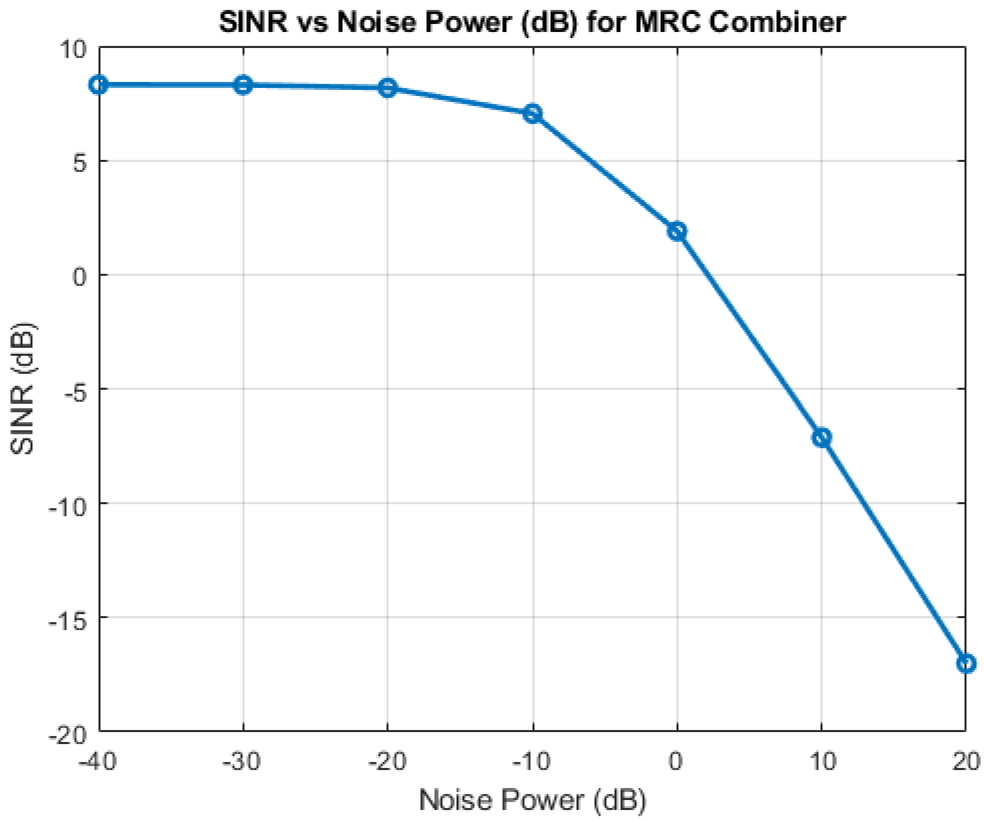
```
% Channel vectors for UE-1 and UE-2
h1 = calculate_ULA_response(N, phi1); % N x 1 channel vector for UE-1
h2 = calculate_ULA_response(N, phi2);  % N x 1 channel vector for UE-2

% Generate 4-QAM symbols for s1(t) and s2(t)
s1 = calculate_QAM_symbols(T, P_s1);  % 4-QAM symbols for UE-1
s2 = calculate_QAM_symbols(T, P_s2);  % 4-QAM symbols for UE-2
```

(a) MRC combiner

```
% Combiner
mrc = generate_MRC_combiner(h1);

% Calculate SINR over SNR
SINR_dB_mrc = zeros(size(SNR_dB)); % Preallocate SINR in dB

% Number of noise power values
num_vals = length(noise_power_dB);
for idx = 1:num_vals
    % Calculate noise power from SNR
    sigma2 = 1 / SNR(idx);

    % Initialize accumulators for SINR across trials
    SINR_accum = 0;

    for trial = 1:num_MC
        % Generate noise matrix for each trial
        n = generate_noise(N, T, sigma2);

        % Generate received signal
        x = calculate_received_signal_array(h1, h2, s1, s2, N, T, n);

        % Compute SINR for the MRC combiner
        SINR_trial_dB = calculate_SINR(mrc, x, h1, h2, s1, s2, n, T);

        % Accumulate SINR results over trials
        SINR_accum = SINR_accum + 10^(SINR_trial_dB / 10); % Convert to
linear scale for averaging
    end

    % Average SINR over trials and convert back to dB
    mean_SINR = SINR_accum / num_MC;
    SINR_dB_mrc(idx) = 10 * log10(mean_SINR); % Convert back to dB
end
```

Plot of the SINR vs σ2

```
plot_SINR_over_noise_power(SINR_dB_mrc, noise_power_dB, "MRC Combiner");
```



(b) MVC combiner

```
% Calculate SINR over SNR
SINR_dB_mvc = zeros(size(SNR_dB)); % Preallocate SINR in dB

% Number of noise power values
num_vals = length(noise_power_dB);
for idx = 1:num_vals
    % Calculate noise power from SNR
    sigma2 = 1 / SNR(idx);

    % Initialize accumulators for SINR across trials
    SINR_accum = 0;

    for trial = 1:num_MC
        % Generate noise matrix for each trial
        n = generate_noise(N, T, sigma2);

        % Generate received signal
        x = calculate_received_signal_array(h1, h2, s1, s2, N, T, n);

        % Compute SINR for the MRC combiner
        mvc = generate_MVC_combiner(x, h1, N, T);
        SINR_trial_dB = calculate_SINR(mvc, x, h1, h2, s1, s2, n, T);
```

```
        % Accumulate SINR results over trials
        SINR_accum = SINR_accum + 10^(SINR_trial_dB / 10); % Convert to
linear scale for averaging
    end

    % Average SINR over trials and convert back to dB
    mean_SINR = SINR_accum / num_MC;
    SINR_dB_mvc(idx) = 10 * log10(mean_SINR); % Convert back to dB
end
```

Plot of the SINR vs σ2

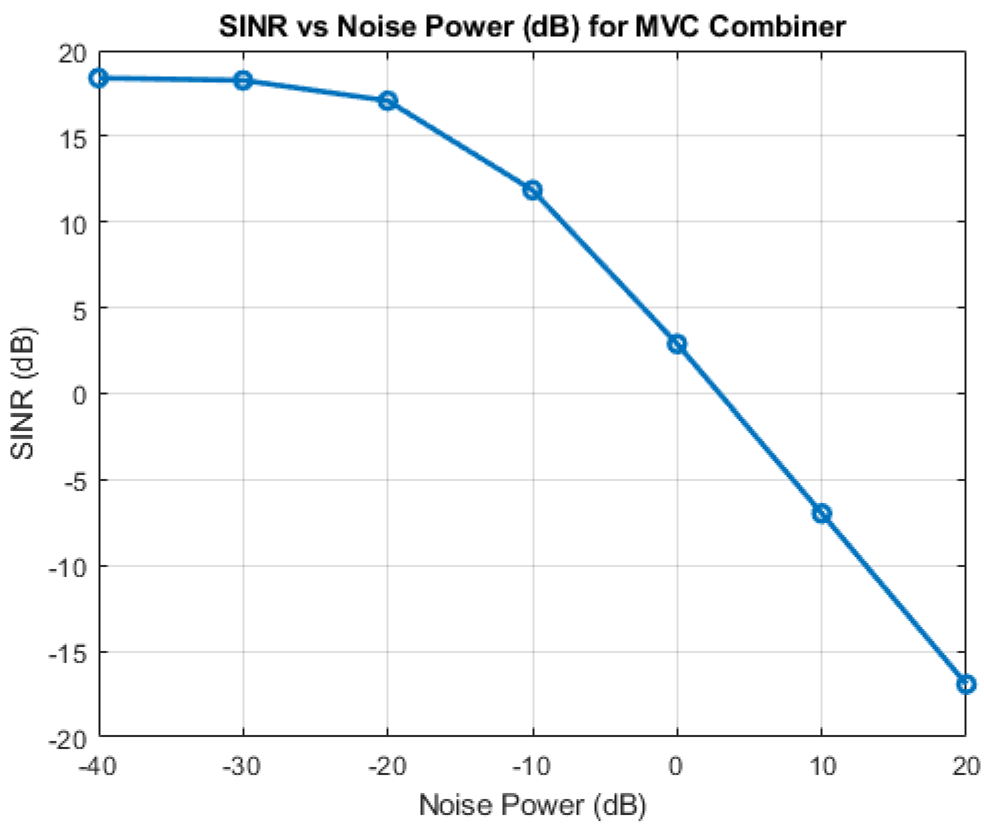
```
plot_SINR_over_noise_power(SINR_dB_mvc, noise_power_dB, "MVC Combiner");
```

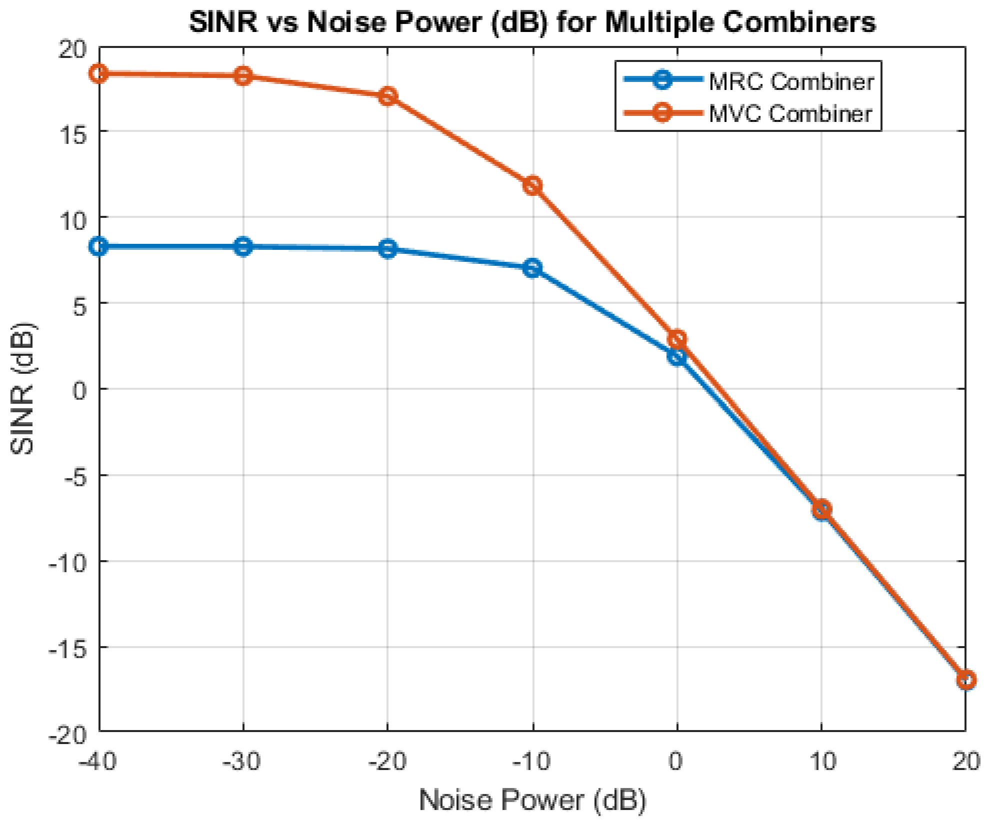
MRC and MVC Combiners

```
SINR_dB_list = {SINR_dB_mrc, SINR_dB_mvc};
combiner_names = {"MRC Combiner", "MVC Combiner"};
plot_SINR_over_noise_power_compare(SINR_dB_list, noise_power_dB,
combiner_names)
```

Explanation

As you can see between the MRC and MVC, initially, the MVC has a higher SINR than the MRC. However, at approximately Noise Power = 0 dB, they merge into similar SINR values. Both trend similarly.





(c) MVC with imperfect channel estimation

```
% Calculate SINR over SNR
SINR_dB_imperfect_mvc = zeros(size(SNR_dB)); % Preallocate SINR in dB

% Number of noise power values
num_vals = length(noise_power_dB);
for idx = 1:num_vals
    % Calculate noise power from SNR
    sigma2 = 1 / SNR(idx);

    % Initialize accumulators for SINR across trials
    SINR_accum = 0;

    for trial = 1:num_MC
        % Generate noise matrix for each trial
        n = generate_noise(N, T, sigma2);

        % Generate received signal
        x = calculate_received_signal_array(h1, h2, s1, s2, N, T, n);

        % Compute SINR for the MRC combiner
        imperfect_mvc = generate_imperfect_MVC(x, N, T, delta_phi1, phi1);
        SINR_trial_dB = calculate_SINR(imperfect_mvc, x, h1, h2, s1, s2, n,
T);
```

```
        % Accumulate SINR results over trials
        SINR_accum = SINR_accum + 10^(SINR_trial_dB / 10); % Convert to
        % linear scale for averaging
    end

    % Average SINR over trials and convert back to dB
    mean_SINR = SINR_accum / num_MC;
    SINR_dB_imperfect_mvc(idx) = 10 * log10(mean_SINR); % Convert back to dB
end
```

Plot of the SINR vs σ2

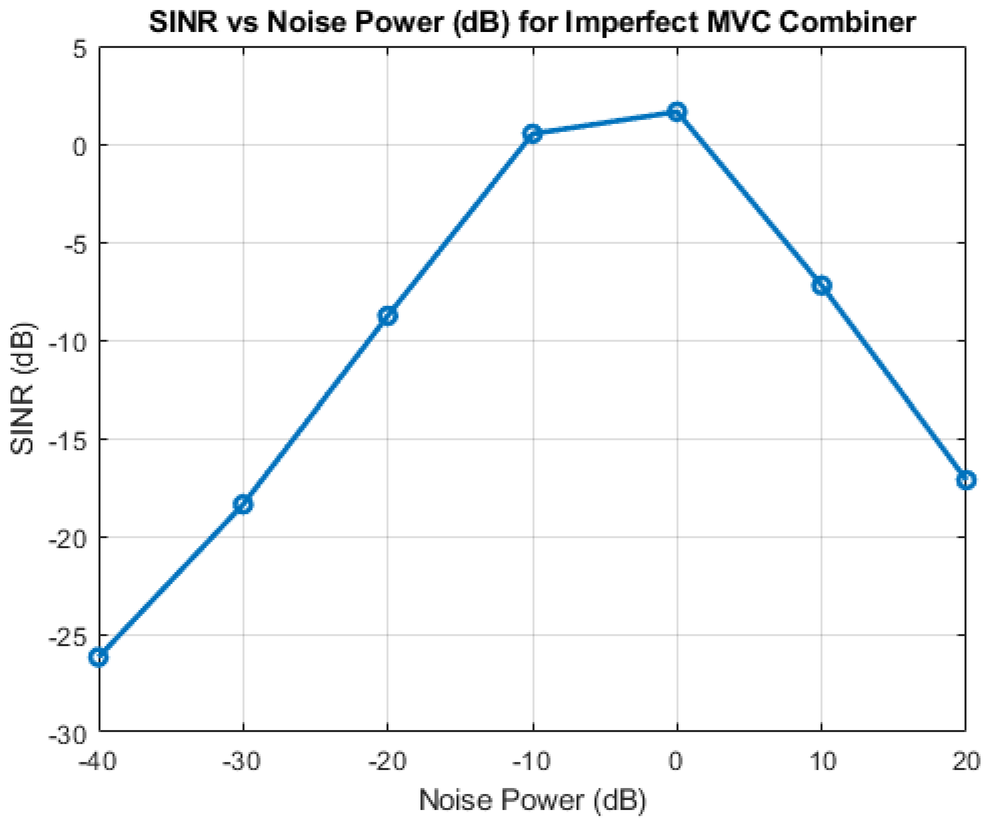
```
plot_SINR_over_noise_power(SINR_dB_imperfect_mvc, noise_power_dB, "Imperfect
MVC Combiner");
```

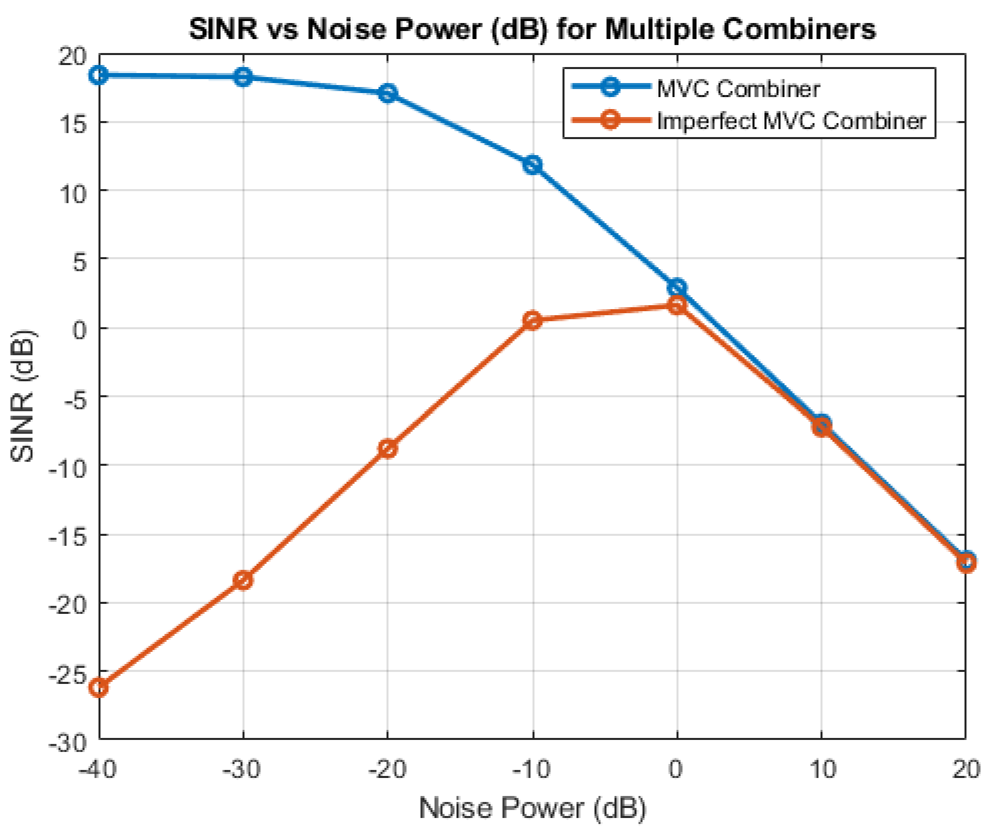
MRC, MVC, and Imperfect MVC Combiners

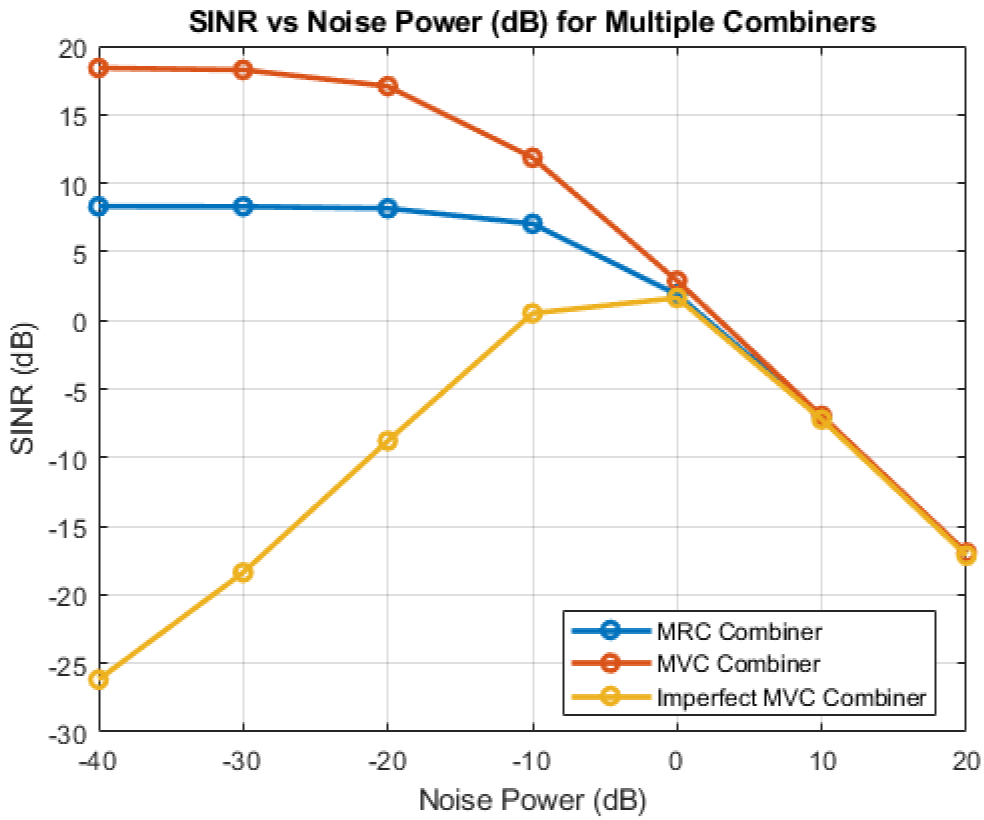
```
SINR_dB_list = {SINR_dB_mvc, SINR_dB_imperfect_mvc};
combiner_names = {"MVC Combiner", "Imperfect MVC Combiner"};
plot_SINR_over_noise_power_compare(SINR_dB_list, noise_power_dB,
combiner_names)

SINR_dB_list = {SINR_dB_mrc, SINR_dB_mvc, SINR_dB_imperfect_mvc};
combiner_names = {"MRC Combiner", "MVC Combiner", "Imperfect MVC Combiner"};
plot_SINR_over_noise_power_compare(SINR_dB_list, noise_power_dB,
combiner_names)
```

Explanation

In comparison to the MVC and MRC which decreases as Noise Power (dB) increases, the Imperfect MVC Combiner starts out with a low SINR value and increases until it merges with the MRC and MVC combiners at Noise Power = 0 dB and then all three decreases.


SINR vs Noise Power (dB) for Imperfect MVC Combiner
SINR (dB)
Noise Power (dB)
5
0
-5
-10
-15
-20
-25
-30
-40
-30
-20
-10
0
10
20


SINR vs Noise Power (dB) for Multiple Combiners
MVC Combiner
Imperfect MVC Combiner
SINR (dB)
Noise Power (dB)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-40
-30
-20
-10
0
10
20



(d) A variant of the minimum variance combiner: estimation of h2

```
num_vals = length(noise_power_dB);
estimates = zeros(num_vals, 1);
for idx = 1:num_vals
    sigma2 = 1/SNR(idx);

    estimated_phi2 = 0;
    for trial = 1:num_MC_faster
        % Generate noise matrix for each trial
        n = generate_noise(N, T, sigma2);

        % Generate received signal
        x = calculate_received_signal_array(h1, h2, s1, s2, N, T, n);

        % get estimated phi2 for each trial
        [w_phi, r_phi, phi2_hat] = estimate_phi2(x, N, T, phi_range);
        estimated_phi2 = estimated_phi2 + phi2_hat;
    end
    estimated_phi2 = estimated_phi2 / num_MC_faster;
    estimates(idx) = estimated_phi2;

    % Plot E|w(phi)'x(t)|^2 vs phi, for each sigma
```

```
    figure;
    plot(phi_range, r_phi, 'LineWidth', 2);
    xlabel('phi (degrees)');
    ylabel('E|w(\phi)''x(t)|^2');
    title(['Plot for noise power = ', num2str(noise_power_dB(idx)), ' dB']);
    grid on;
end
```

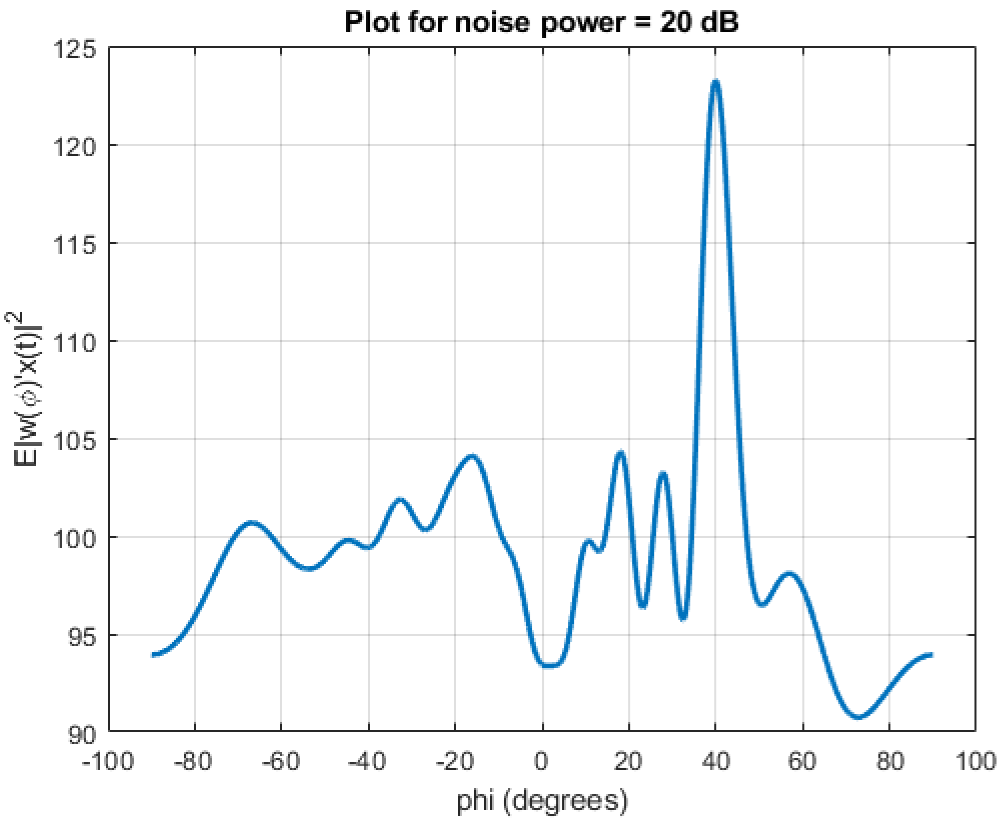
Compare estimated phi2 with true phi2

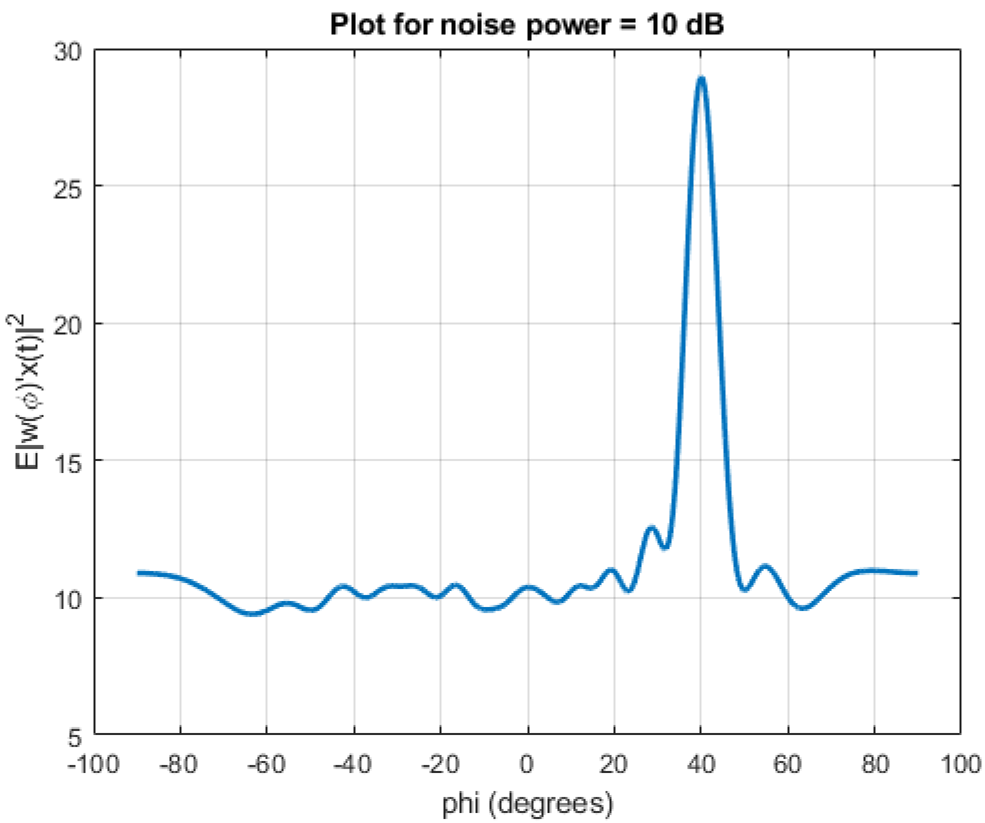
```
estimates
errors = abs(estimates - true_phi2); % Calculate the absolute error

figure;
plot(noise_power_dB, errors, '-o', 'LineWidth', 2);
xlabel('Noise power (dB)');
ylabel('Absolute Error (degrees)');
title('Error between Estimated \phi_2 and True \phi_2 = 40^\circ');
grid on;
```

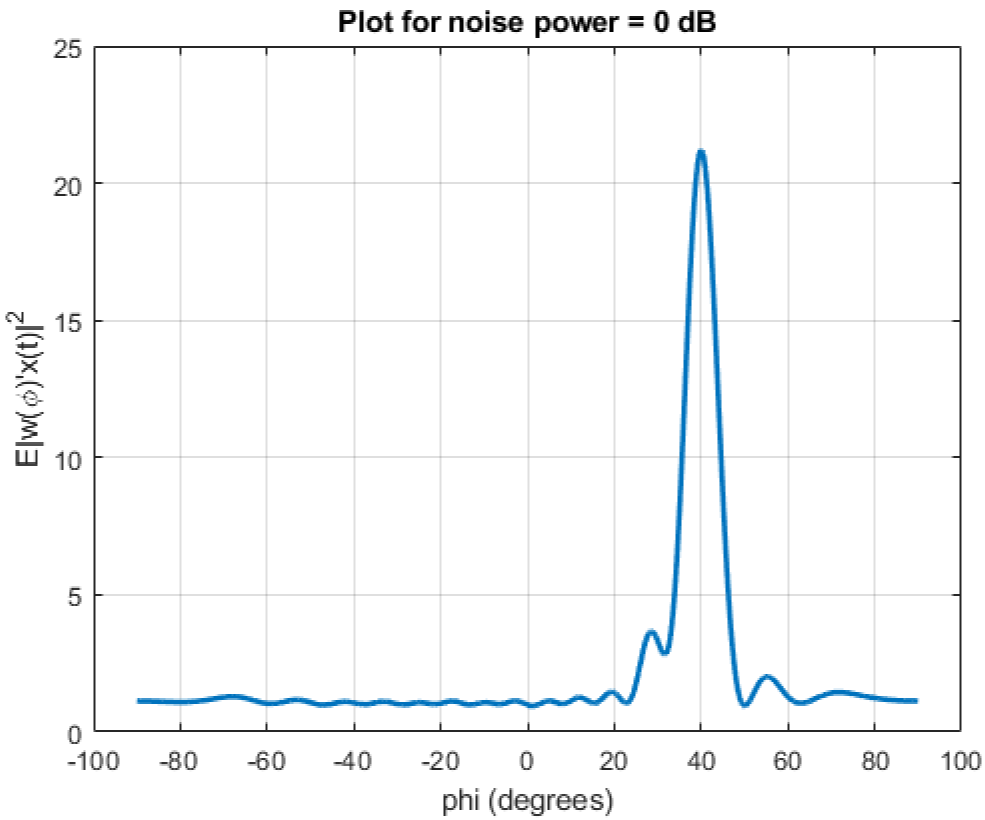
Explanation

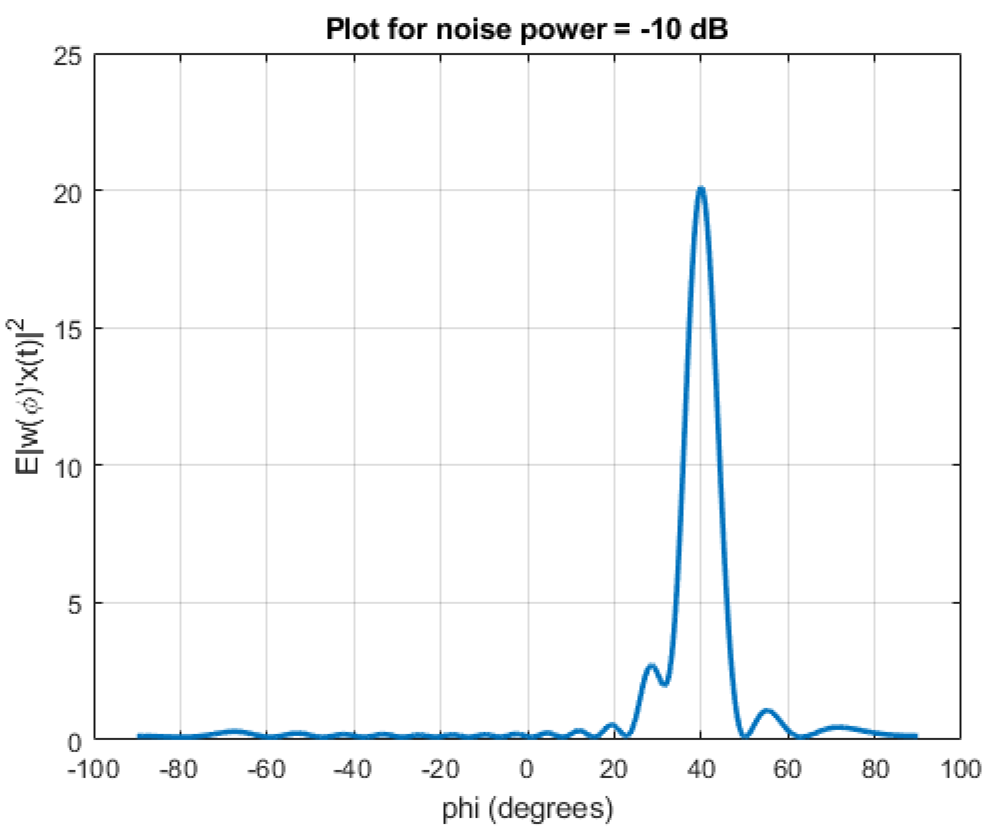
As you can see in the listed estimates, and the errors between the estimated phi2 and true phi2 values, they are relatively accurate estimates for the best phi2. Generally, sometimes the error can increase a little bit when the Noise Power (dB) is greater than 0. This procedure does give a perfect estimate for phi2 as you can see most have negligible error values.

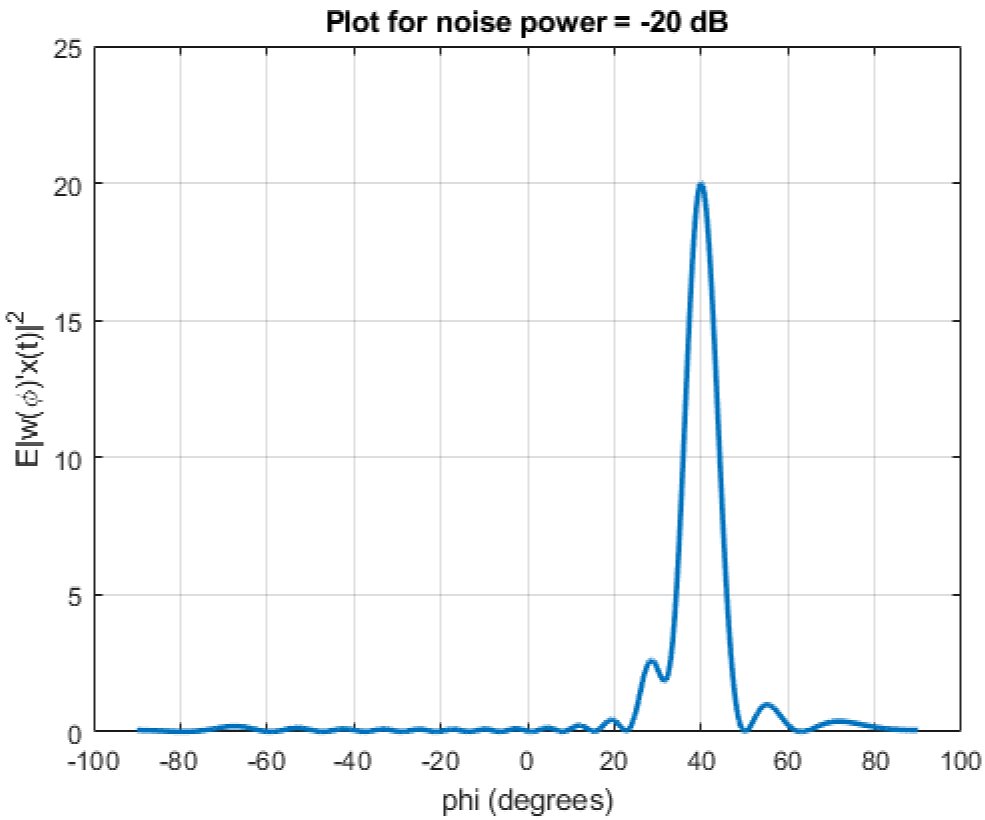
```
estimates =

   40.0200
   39.9800
   40.0000
   40.0000
   40.0000
   40.0000
   40.0000
```

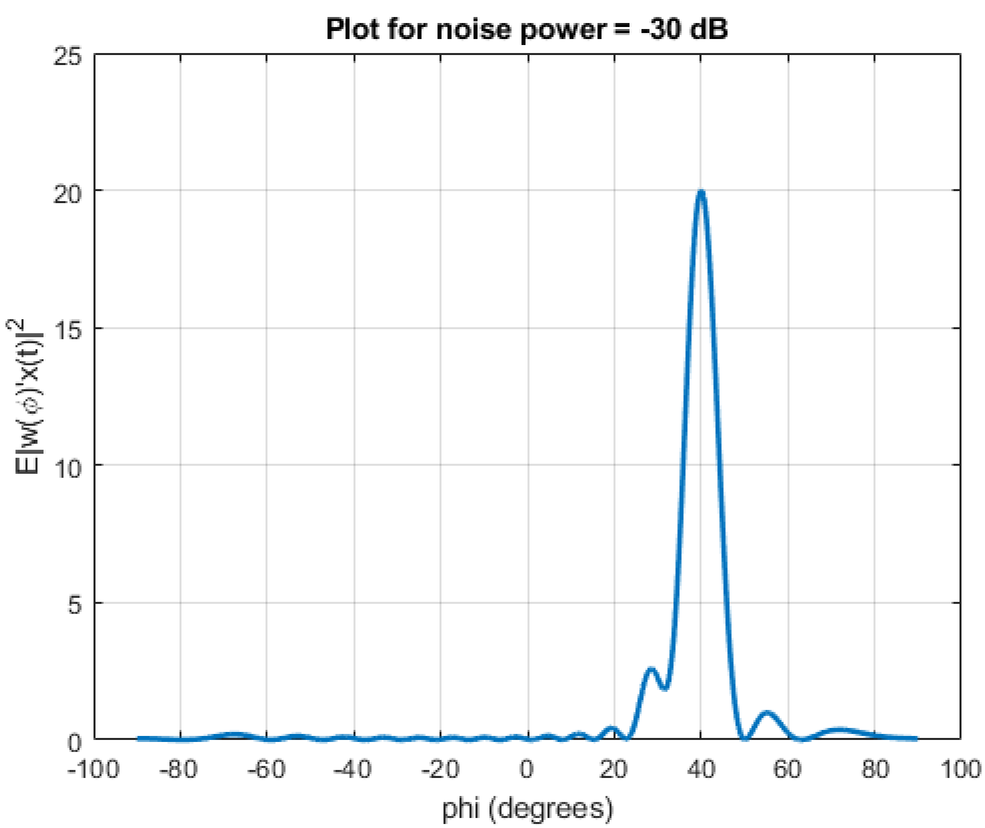

Plot for noise power = 20 dB
125
120
115
110
105
100
95
90
E|w(φ)'x(t)|²
-100
-80
-60
-40
-20
0
20
40
60
80
100
phi (degrees)

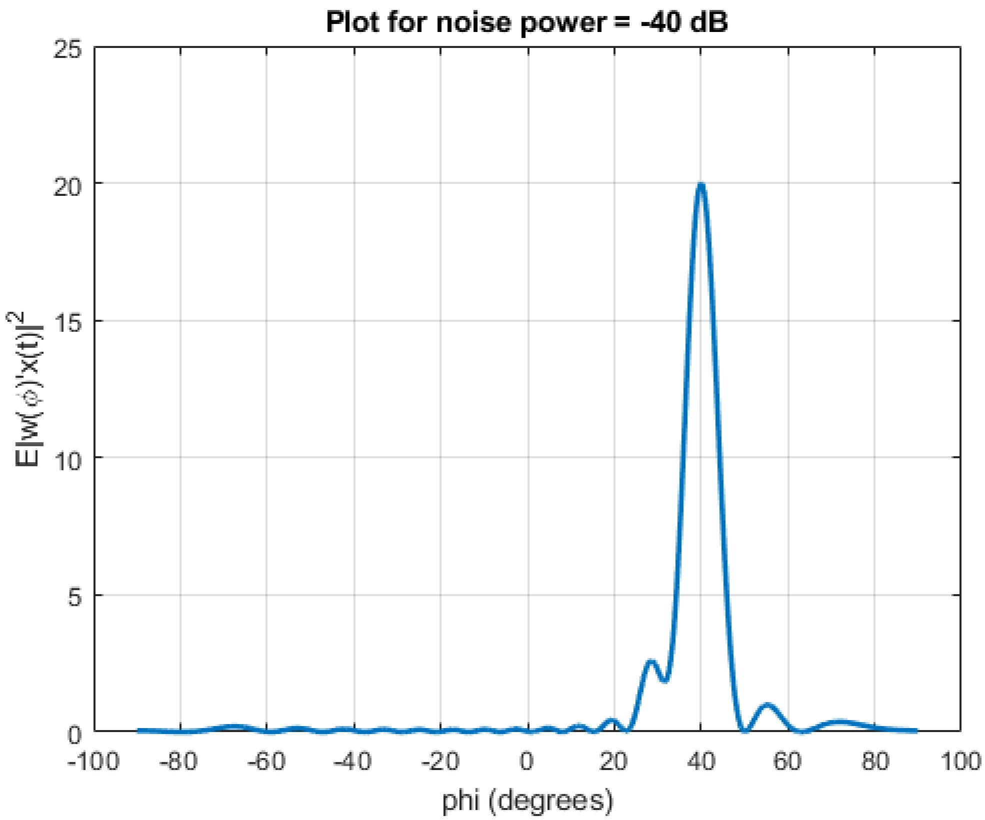

Plot for noise power = 10 dB
30
25
20
15
10
5
E|w(φ)'x(t)|²
-100
-80
-60
-40
-20
0
20
40
60
80
100
phi (degrees)

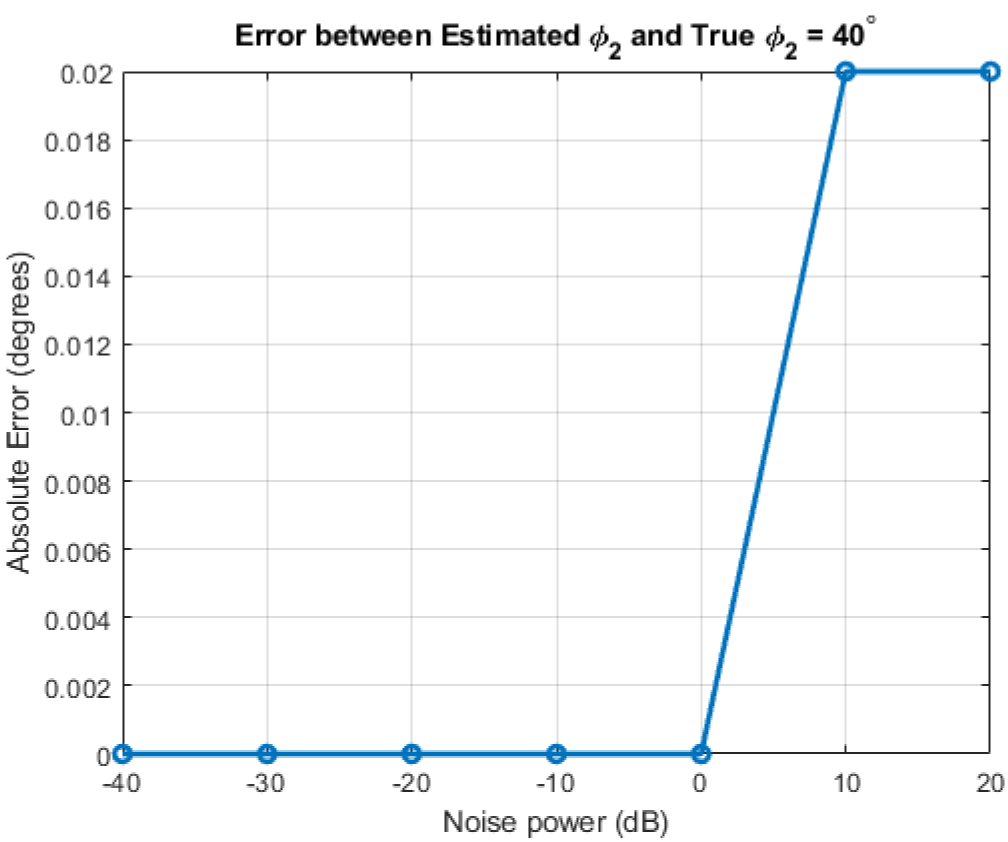

Plot for noise power = 0 dB
E|w(ϕ)'x(t)|²
phi (degrees)
25
20
15
10
5
0
-100
-80
-60
-40
-20
0
20
40
60
80
100


Plot for noise power = -10 dB
E|w(ϕ)'x(t)|²
phi (degrees)
25
20
15
10
5
0
-100
-80
-60
-40
-20
0
20
40
60
80
100


Plot for noise power = -20 dB
E|w(ϕ)'x(t)|^2
phi (degrees)


Plot for noise power = -30 dB
E|w(ϕ)'x(t)|^2
phi (degrees)


Plot for noise power = -40 dB
25
20
15
10
5
0
-100
-80
-60
-40
-20
0
20
40
60
80
100
phi (degrees)
E|w(φ)'x(t)|²


Error between Estimated φ₂ and True φ₂ = 40°
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-40
-30
-20
-10
0
10
20
Noise power (dB)
Absolute Error (degrees)

(e) A variant of the minimum variance combiner: low-rank approximation

```
% Calculate SINR over SNR
SINR_dB_low_rank_mvc = zeros(size(SNR_dB)); % Preallocate SINR in dB

% Number of noise power values
num_vals = length(noise_power_dB);
for idx = 1:num_vals
    % Calculate noise power from SNR
    sigma2 = 1 / SNR(idx);

    phi2_hat = estimates(idx) * pi / 180;
    [low_rank_mvc, h2_hat] = generate_low_rank_MVC(N, T, delta_phi1, phi1,
phi2_hat, zeta);

    % Initialize accumulators for SINR across trials
    SINR_accum = 0;
    for trial = 1:num_MC
        % Generate noise matrix for each trial
        n = generate_noise(N, T, sigma2);

        % Generate received signal
        x = calculate_received_signal_array(h1, h2, s1, s2, N, T, n);

        % Compute SINR for the MRC combiner
        SINR_trial_dB = calculate_SINR(low_rank_mvc, x, h1, h2, s1, s2, n,
T);

        % Accumulate SINR results over trials
        SINR_accum = SINR_accum + 10^(SINR_trial_dB / 10); % Convert to
linear scale for averaging
    end

    % Average SINR over trials and convert back to dB
    mean_SINR = SINR_accum / num_MC;
    SINR_dB_low_rank_mvc(idx) = 10 * log10(mean_SINR); % Convert back to dB
end
```

Plot of the SINR vs σ2

```
plot_SINR_over_noise_power(SINR_dB_low_rank_mvc, noise_power_dB, "Low-Rank
MVC Combiner");
```

Imperfect MVC and Low-Rank MVC Combiners

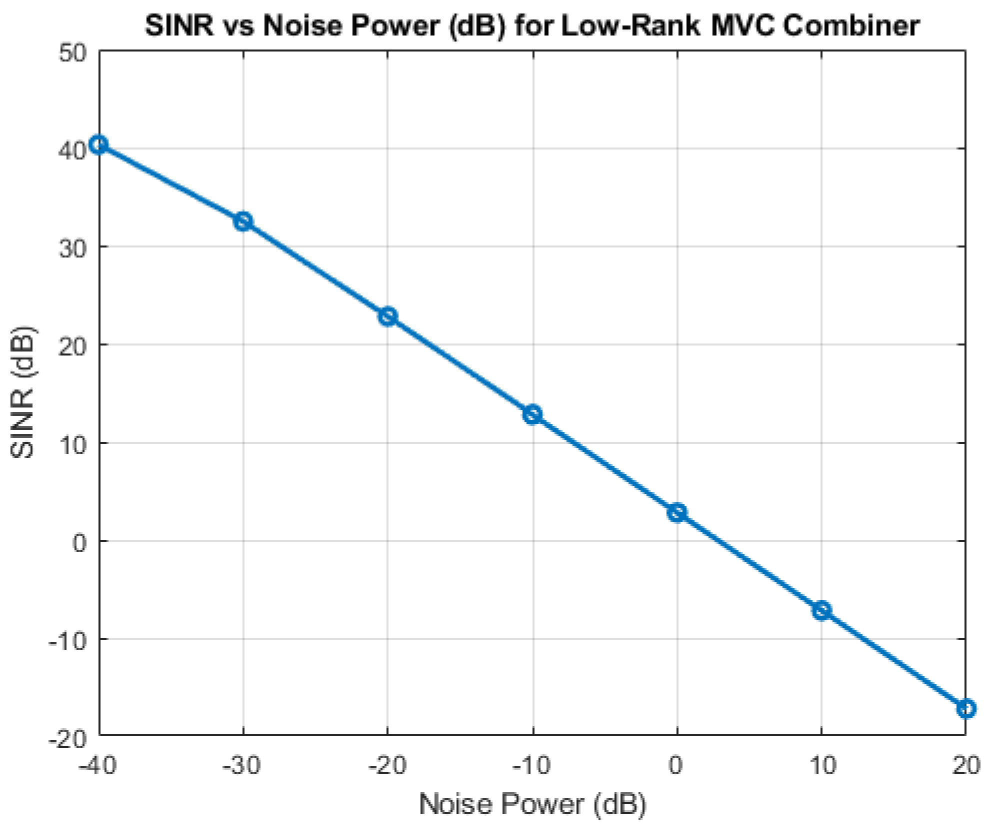
```
SINR_dB_list = {SINR_dB_imperfect_mvc, SINR_dB_low_rank_mvc};
combiner_names = {"Imperfect MVC Combiner", "Low-Rank MVC Combiner"};
plot_SINR_over_noise_power_compare(SINR_dB_list, noise_power_dB,
combiner_names)
```

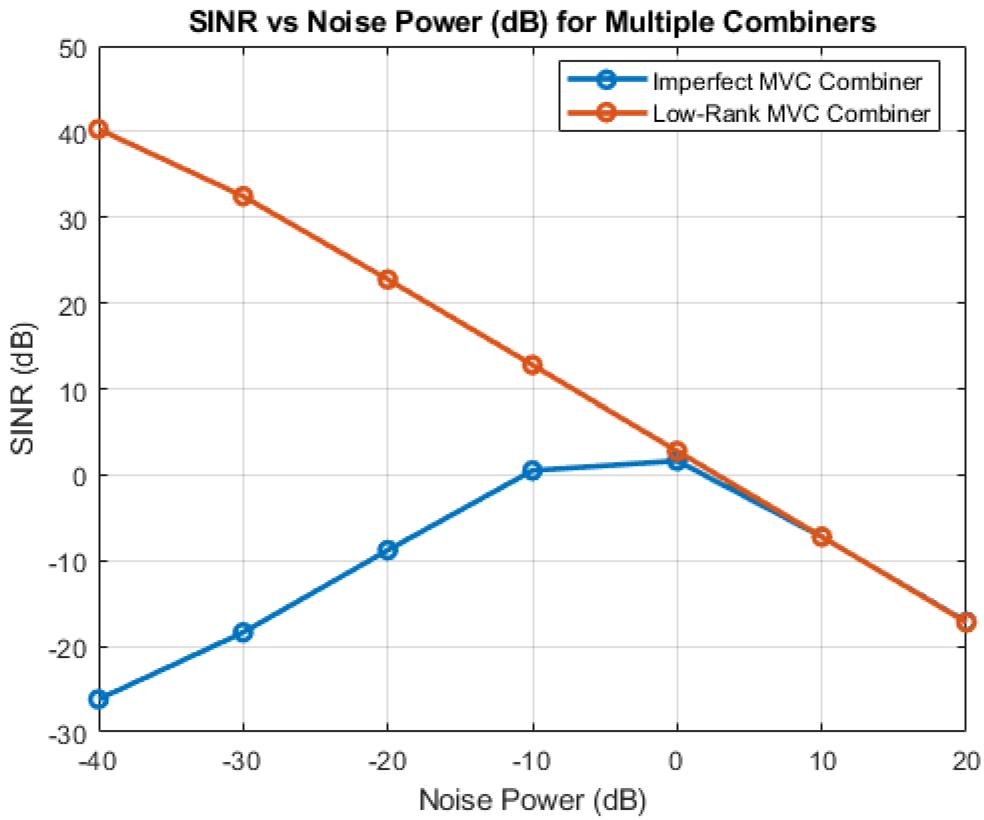
All combiners

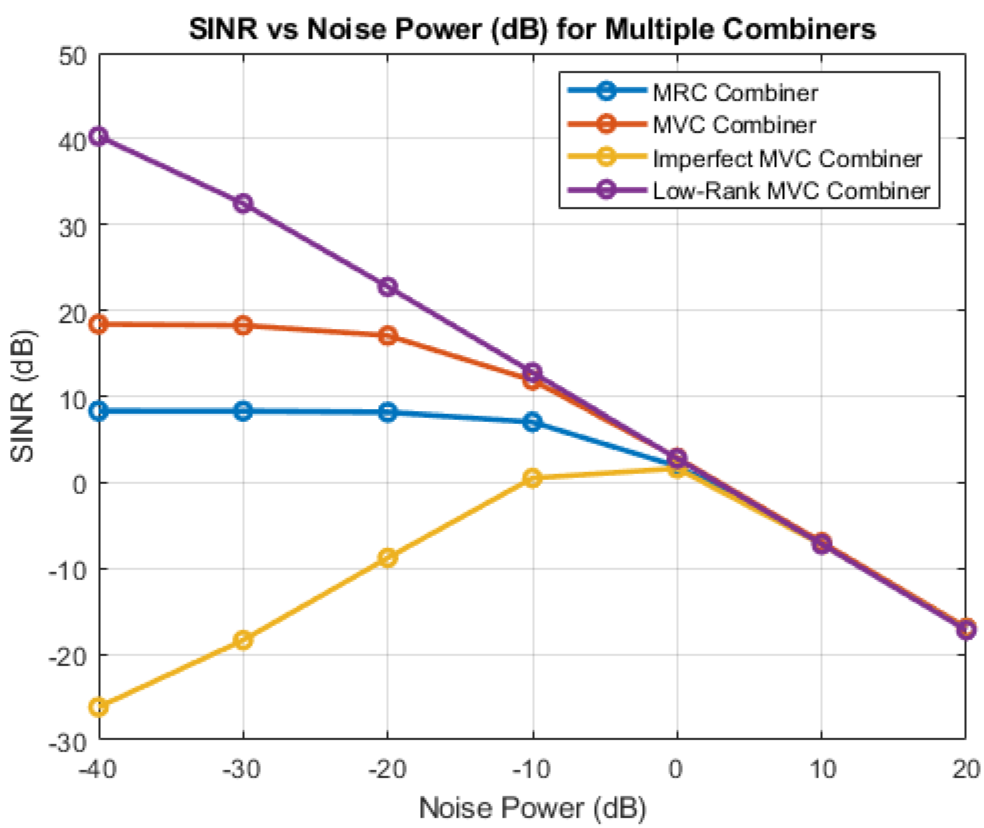
```
SINR_dB_list = {SINR_dB_mrc, SINR_dB_mvc, SINR_dB_imperfect_mvc,
SINR_dB_low_rank_mvc};
combiner_names = {"MRC Combiner", "MVC Combiner", "Imperfect MVC Combiner",
"Low-Rank MVC Combiner"};
plot_SINR_over_noise_power_compare(SINR_dB_list, noise_power_dB,
combiner_names)
```

Explanation

The Low-Rank MVC combiner, unlike the Imperfect MVC Combiner, starts out the highest and starts merging with the other combiners at approximately Noise Power = 0 dB. The Imperfect MVC Combiner starts out with a low SINR value and increases until it merges with the MRC and MVC combiners at Noise Power = 0 dB. The Low-Rank MVC combiner is more of a negative linear trend while the imperfect MVC trends up and then down. All of the combiners trend in the same direction once they merge at approximately Noise Power = 0 dB.




SINR vs Noise Power (dB) for Multiple Combiners
Imperfect MVC Combiner
Low-Rank MVC Combiner
SINR (dB)
Noise Power (dB)
50
40
30
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
20


SINR vs Noise Power (dB) for Multiple Combiners
MRC Combiner
MVC Combiner
Imperfect MVC Combiner
Low-Rank MVC Combiner
SINR (dB)
Noise Power (dB)
50
40
30
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
20

Functions

```
function h = calculate_ULA_response(N, phi)
    % Channel vectors
    h = 1/sqrt(N) * exp(-1j * pi * (0:N-1)' * sin(phi));  % N x 1 channel
vector
end

function s = calculate_QAM_symbols(T, P)
    % Generate 4-QAM symbols
    s = sqrt(P) * (randi([0 1], T, 2) * 2 - 1 + 1j * (randi([0 1], T, 2) * 2
- 1));  % 4-QAM symbols
end

function X = calculate_received_signal_array(h1, h2, s1, s2, N, T, n)
    % Initialize the received signal matrix X
    X = zeros(N, T);

    % Loop through each time step and compute the received signal for each t
    for t = 1:T
        % Calculate the received signal at time t
        X(:, t) = h1 * s1(t) + h2 * s2(t) + n(:, t);
    end
end


function n = generate_noise(N, T, sigma2)
    % Generate NxT complex Gaussian noise with variance sigma2
    n_real = sqrt(sigma2/2) * randn(N, T); % Real part
    n_imag = sqrt(sigma2/2) * randn(N, T); % Imaginary part

    % Combine the real and imaginary parts to form complex noise
    n = n_real + 1i * n_imag;
end

function [s1_hat, target_signal, interference, noise] =
compute_combined_signal(w, x, h1, h2, s1, s2, n, T)
    % Initialize output variables
    s1_hat = zeros(1, T);
    target_signal = zeros(1, T);
    interference = zeros(1, T);
    noise = zeros(1, T);

    % Loop over each time step
    for t = 1:T
        % Define the target signal component
        target_signal(t) = w' * h1 * s1(t);

        % Define the interference component
        interference(t) = w' * h2 * s2(t);

        % Define the noise component
        noise(t) = w' * n(:, t);
```

```
        % Estimate the combined signal (s1_hat) as the sum of the target,
interference, and noise
        s1_hat(t) = target_signal(t) + interference(t) + noise(t);
    end
end

function SINR_dB = calculate_SINR(w, x, h1, h2, s1, s2, n, T)
    [s1_hat, target_signal, interference, noise] =
compute_combined_signal(w, x, h1, h2, s1, s2, n, T);

    % Initialize signal and interference+noise power accumulators
    signal_power_sum = 0;
    interference_plus_noise_power_sum = 0;

    % Loop through each time step
    for t = 1:T
        % Calculate target signal contribution
        signal_component = abs(target_signal(t))^2;

        % Calculate interference and noise contribution
        interference_plus_noise_component = abs(interference(t) +
noise(t))^2;

        % Accumulate power
        signal_power_sum = signal_power_sum + signal_component;
        interference_plus_noise_power_sum =
interference_plus_noise_power_sum + interference_plus_noise_component;
    end

    % Compute the average power of signal and interference+noise
    avg_signal_power = signal_power_sum / T;
    avg_interference_plus_noise_power = interference_plus_noise_power_sum /
T;

    % Calculate the SINR (ratio of average signal power to
interference+noise power)
    SINR = avg_signal_power / avg_interference_plus_noise_power;

    % Convert to dB
    SINR_dB = 10 * log10(SINR);
end

function w = generate_MRC_combiner(h1)
    w = h1;
end

function w = generate_MVC_combiner(x, h, N, T)
    % Initialize the autocorrelation matrix R
    R = zeros(N, N);

    % Summing over 1000 realizations to compute R
    for i = 1:T
        % Accumulate the outer product of each received signal vector
```

```
        R = R + (x(:, i) * x(:, i)');
    end

    % Take the average
    R = R / T;

    % Compute the MVC combiner weights
    w = R \ h; % Equivalent to inv(R) * h1, but numerically more stable
end

function w = generate_imperfect_MVC(x, N, T, delta_phi, phi)
    h1_hat = (1 / sqrt(N)) * exp(-1j * pi * (0:N-1).' * sin(delta_phi +
phi));
    w = generate_MVC_combiner(x, h1_hat, N, T);
end

function [w_phi, r_phi, phi2_hat] = estimate_phi2(x, N, T, phi_range)
    w_phi = zeros(N, length(phi_range));
    r_phi = zeros(1, length(phi_range));

    for idx = 1:length(phi_range)
        deg = phi_range(idx);

        phi = deg * pi / 180;

        % compute w(phi)
        w_phi(:, idx) = (1/sqrt(N)) * exp(-1j * pi * (0:N-1)' * sin(phi));

        R = 0;
        for i = 1:T
            R = R + abs(w_phi(:, idx)' * x(:, i)).^2;
        end
        R = R / T;
        % Take the average
        r_phi(idx) = abs(R); % expected power = E|w(phi)' * x(t)|^2
    end
    [~, max_idx] = max(r_phi);  % Take absolute value to consider the
magnitude
    phi2_hat = phi_range(max_idx);   % Best angle estimate in DEGREES
end

function [w, h2_hat] = generate_low_rank_MVC(N, T, delta_phi1, phi1,
phi2_hat, zeta) % make sure all phi values are in radians
    % h2_hat
    h2_hat = (1/sqrt(N)) * exp(-1j * pi * (0:N-1)' * sin(phi2_hat));

    % R = h2_hat * h2_hat' + zeta*I
    R = zeros(N, N);
    for i = 1:T
        % Accumulate the outer product of each received signal vector
        R = h2_hat * h2_hat';
    end
    R = R / T;
    R = R + zeta * eye(N);
```

```
    % w = R(zeta) \ h1_hat
    h1_hat = (1 / sqrt(N)) * exp(-1j * pi * (0:N-1).' * sin(delta_phi1 +
phi1));
    w = R \ h1_hat;
end

function plot_SINR_over_noise_power(SINR_dB, noise_power_dB, combiner_name)
    plot_title = sprintf('SINR vs Noise Power (dB) for %s', combiner_name);

    figure;
    plot(noise_power_dB, SINR_dB, '-o', 'LineWidth', 2);
    xlabel('Noise Power (dB)');
    ylabel('SINR (dB)');
    title(plot_title);
    grid on;
end

function plot_SINR_over_noise_power_compare(SINR_dB_list, noise_power_dB,
combiner_names)
    % Check that the number of combiners matches the SINR data provided
    num_combiners = length(combiner_names);

    % Create a figure for the plot
    figure;

    % Plot each combiner's SINR data
    for i = 1:num_combiners
        plot(noise_power_dB, SINR_dB_list{i}, '-o', 'LineWidth', 2);
        hold on;  % Retain the current plot when adding new plots
    end

    % Add labels and title
    xlabel('Noise Power (dB)');
    ylabel('SINR (dB)');
    title('SINR vs Noise Power (dB) for Multiple Combiners');

    % Add a legend for the combiners
    legend(combiner_names, 'Location', 'Best');

    % Display the grid
    grid on;
end
```

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