Report about CSI and its utility in indoor localization

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Channel State Information is essential for OFDM communication. By sending a pre-defined traning sequence, channel state informaion could be obtained from the received side and could be used to restore the received signal distorted by multipath, doppler effect, etc. Indoor localization is widely studied recently, lab project like Spot-Fi from Stanford, Chronos from MIT, Splicer from NTU, etc are published. Some are said to be decimeter-level in simple lab environment.

However when trying the implmentation of Sport-Fi, It is found really difficult to correctly estimate AoA and ToF. The technology is currently not ready for commercial use.

In this report, I will summarize the current findings related to CSI.

Loading CSI data

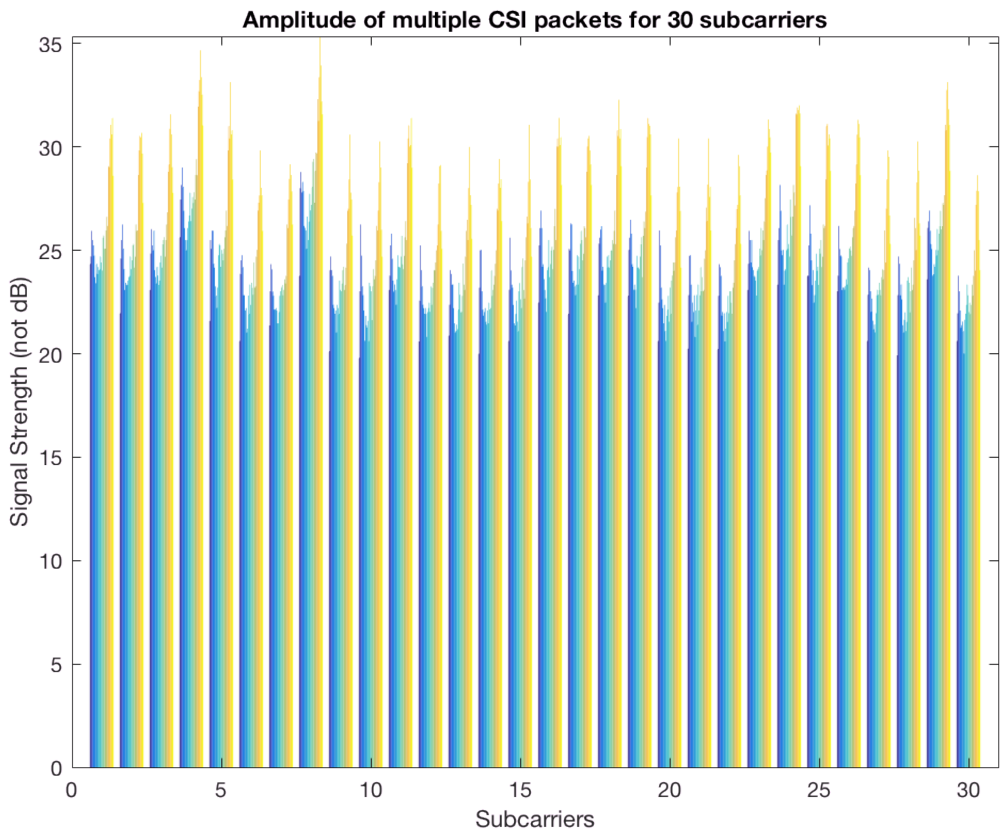
Here we load CSI data from one measurement, with Rx-to-Tx distance 3.2 meters, LOS angle 45 degree, measurement on August 4, 2017.

```
clear
close all
% load csi_trace
%%%%%%%%%%
raw_csi_trace = read_bf_file('csi-data/csi-20170804-320-7-45-2.dat');
% csi_trace = read_bf_file('csi-0605-2.dat');
%% load csi_trace
% csi_trace = csi_trace;
%%%%%%%%%%
sample_idxes = 2017:2116; % take a period as an example
sample_csi_trace= raw_csi_trace(sample_idxes);
idx = 1;
csi_frame = sample_csi_trace{idx};
csi_frame_2 = sample_csi_trace{idx+1};
csi_matrix = squeeze(csi_frame.csi(1,:,:));
csi_matrix_2 = squeeze(csi_frame_2.csi(1,:,:));
```

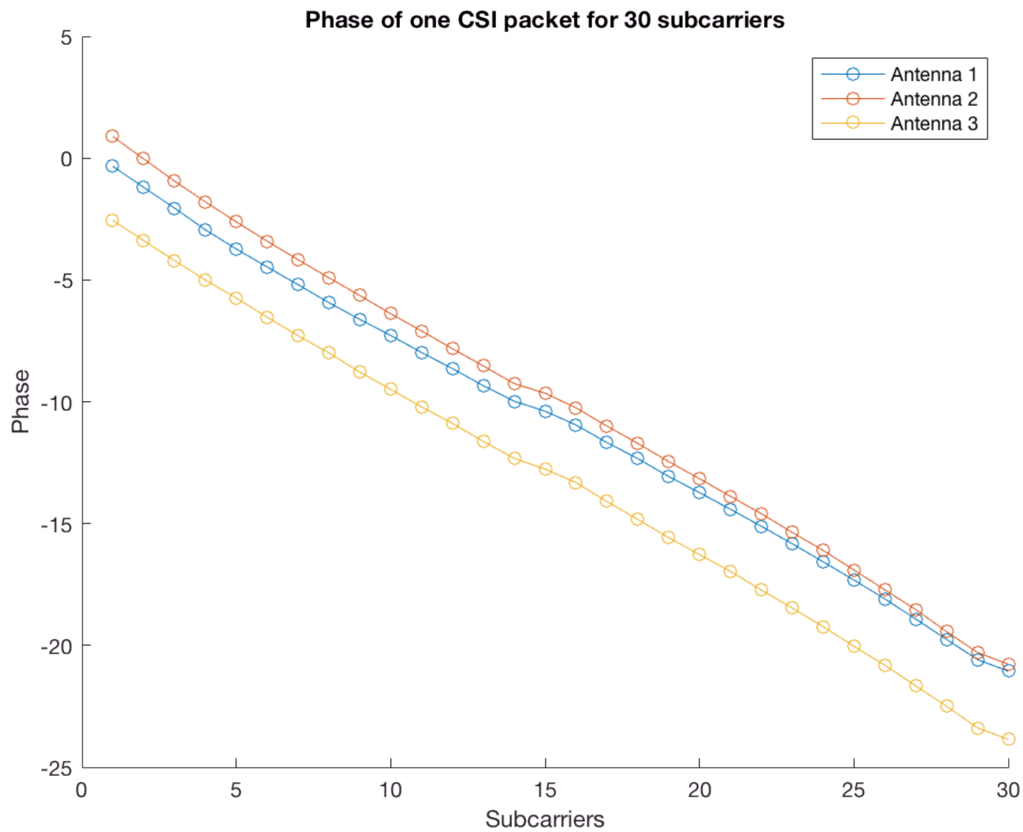
Inspect the csi data

Plot Basic amplitude and phases

```
csi_matrix_for_stability_plot = zeros(length(sample_csi_trace),3,30);
for i=1:length(sample_csi_trace)
   csi_matrix_for_stability_plot(i,:,:) = squeeze(sample_csi_trace{i}.csi(1,:,:));
end

amp_multi = abs(csi_matrix_for_stability_plot);
figure(11), bar(squeeze(amp_multi(1:30,1,:)))
axis([0 31 -inf inf])
title('Amplitude of multiple CSI packets for 30 subcarriers')
xlabel('Subcarriers')
ylabel('Signal Strength (not dB)')
```



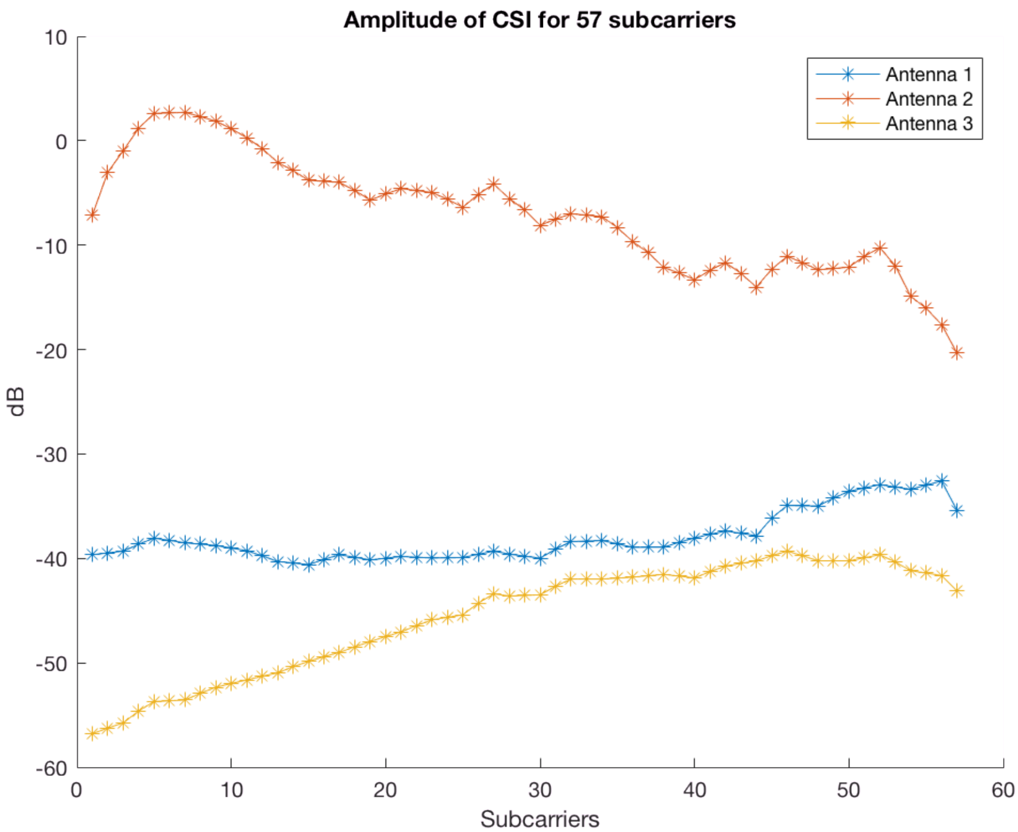

```
amp = abs(csi_matrix);
fi = angle(csi_matrix);
fii = csi_phase_smooth(fi,csi_frame.Nrx);

figure(12),clf
hold on
x_sc = 1:30;
plot(x_sc,squeeze(fii(1,:)),'-o')
plot(x_sc,squeeze(fii(2,:)),'-o')
plot(x_sc,squeeze(fii(3,:)),'-o')
legend('Antenna 1','Antenna 2','Antenna 3');
title('Phase of one CSI packet for 30 subcarriers')
xlabel('Subcarriers')
ylabel('Phase')
hold off
```



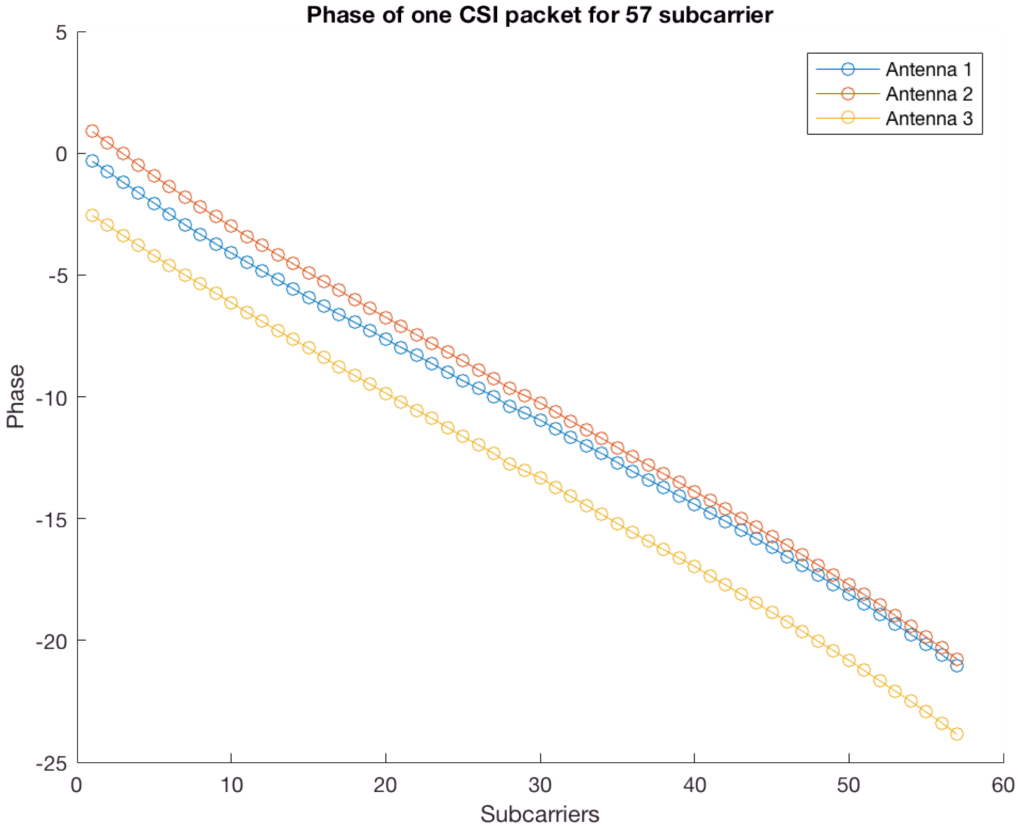
Extend 30 subcarrier to 57 subcarrier by interpolation

Reconstruct the whole spectrum of received signal (also impulse response)

```
e_csi = csi_extend_57(csi_matrix);
x_sc = 1:57;
amp = abs(e_csi);
amp = amp - 44 - csi_frame.agc; % check get_total_rss for more information

% plot amplitude in dB scale
figure(21),clf
hold on
plot(squeeze(amp(1,:)),'-*')
plot(squeeze(amp(2,:)),'-*')
plot(squeeze(amp(3,:)),'-*')
legend('Antenna 1','Antenna 2','Antenna 3');
hold off
title('Amplitude of CSI for 57 subcarriers')
xlabel('Subcarriers')
ylabel('dB')
```




```
fi = angle(e_csi);
fii = csi_phase_smooth(fi,csi_frame.Nrx);


figure(22),clf
hold on
plot(x_sc,squeeze(fii(1,:)),'-o')
plot(x_sc,squeeze(fii(2,:)),'-o')
plot(x_sc,squeeze(fii(3,:)),'-o')
legend('Antenna 1','Antenna 2','Antenna 3');
title('Phase of one CSI packet for 57 subcarrier')
xlabel('Subcarriers')
ylabel('Phase')
hold off
```

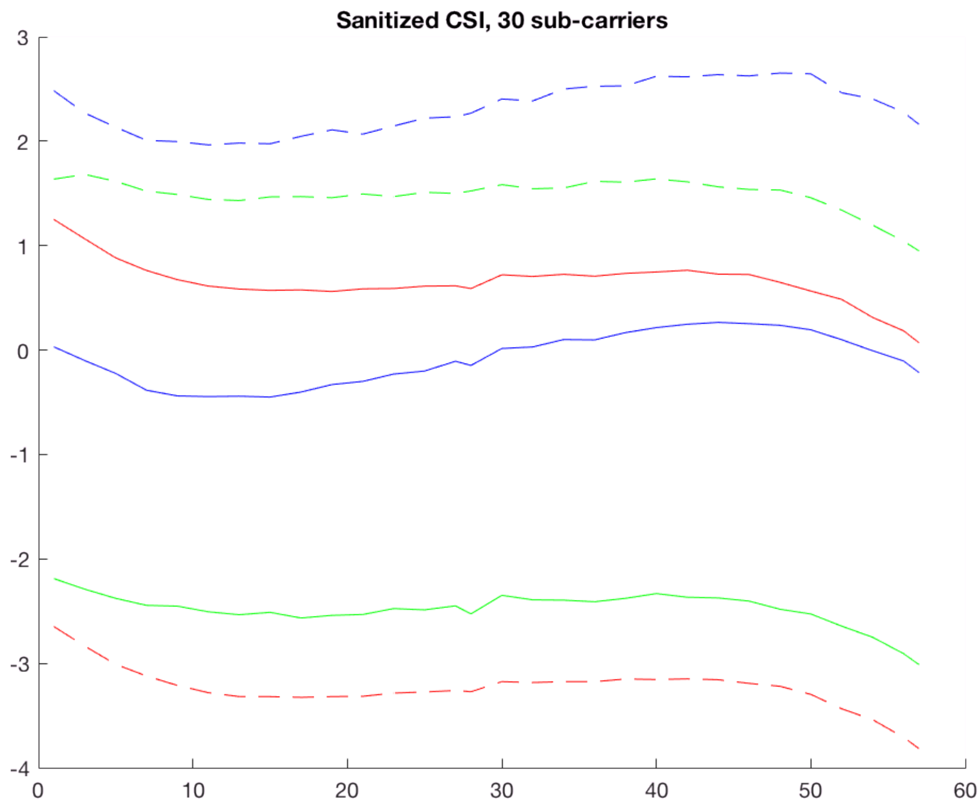


Sanitizing ToF Estimates

Sanitizing ToF according to Spot-Fi. This is not used in real implmentation, because it will bring peak of ToF back to 0 strangly (need further study later).

```
x_sc = 1:57;

e_csi = csi_extend_57(csi_matrix);
amp = abs(e_csi);
fi = angle(e_csi);
fii = csi_phase_smooth(fi,csi_frame.Nrx);

a = polyfit([x_sc-1 x_sc-1 x_sc-1],[fii(1,:) fii(2,:) fii(3,:)],1);

e_csi_2 = csi_extend_57(csi_matrix_2);
amp_2 = abs(e_csi_2);
fi_2 = angle(e_csi_2);
fii_2 = csi_phase_smooth(fi_2,csi_frame_2.Nrx);
a_2 = polyfit([x_sc-1 x_sc-1 x_sc-1],[fii_2(1,:) fii_2(2,:) fii_2(3,:)],1);


figure(31),clf
a(2) = 0;
a_2(2) = 0;
hold on
plot(x_sc,fii(1,:) - polyval(a,x_sc,1),'b-')
plot(x_sc,fii(2,:) - polyval(a,x_sc,1),'r-')
```

```
plot(x_sc,fii(3,:) - polyval(a,x_sc,1),'g-')

plot(x_sc,fii_2(1,:) - polyval(a_2,x_sc,1),'b--')
plot(x_sc,fii_2(2,:) - polyval(a_2,x_sc,1),'r--')
plot(x_sc,fii_2(3,:) - polyval(a_2,x_sc,1),'g--')
hold off
title('Sanitized CSI, 30 sub-carriers')
```




```
% This part is currently not used for data progress
% fi = fii - [polyval(a,x_sc,1); polyval(a,x_sc,1); polyval(a,x_sc,1)];
% [csi_matrix_real,csi_matrix_imag] = pol2cart(fi,amp);
% csi_matrix = csi_matrix_real + 1j*csi_matrix_imag;
```

Smoothed CSI Matrix

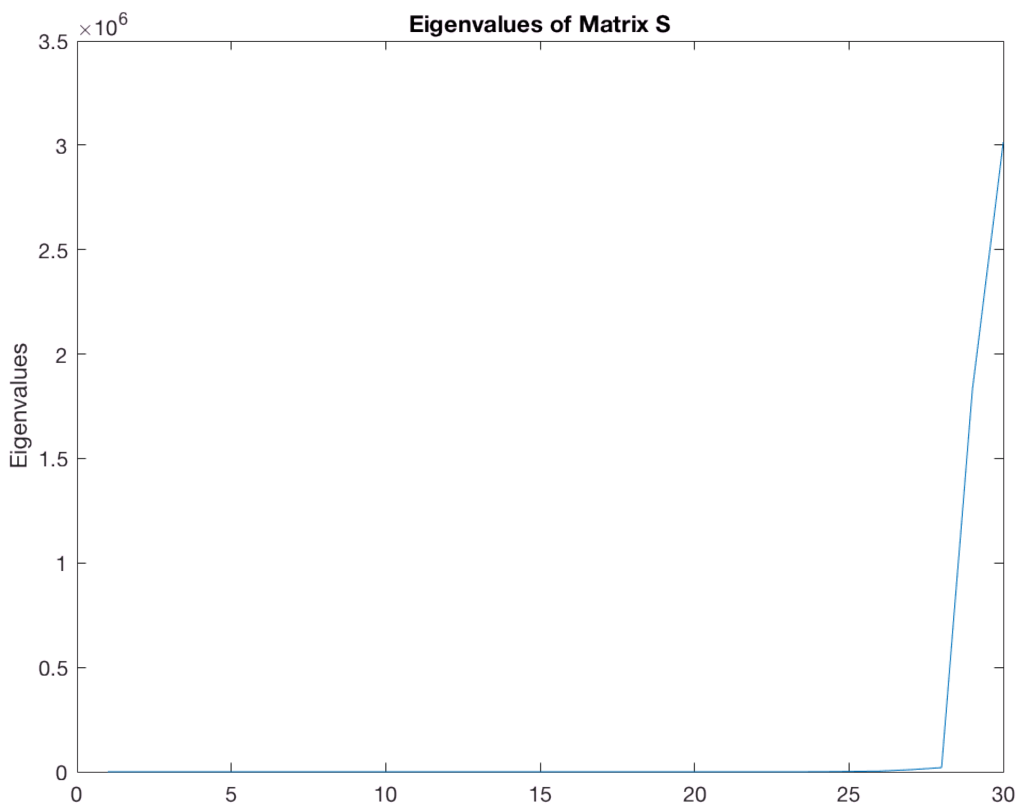
Construct smoothed CSI matrix according to Spot-Fi by taking sub-carriers as psedo antennas to extend antenna amount for MUSIC algorithm. A basic assumption of MUSIC algorithm is, the amount of antennas must be greater than that of multipaths.

```
% idx = 3;
% csi_matrix(:,:,idx);
e_csi = csi_extend_57(csi_matrix);
smoothed_csi = zeros(30,86);

for i=1:15
    smoothed_csi(i,:) = [e_csi(1,i:i+42),e_csi(2,i:i+42)];
end
```

```
for i=16:30
    smoothed_csi(i,:) = [e_csi(2,i-15:i+27),e_csi(3,i-15:i+27)];
end
```

MUSIC algorithm, calculating noise space

```
MUSIC_S = smoothed_csi * smoothed_csi';

[EigenVector1, EigenValue1] = eig(MUSIC_S);
EigenValueList1 = diag(EigenValue1);

[~, order] = sort(EigenValueList1);

EigenVector = EigenVector1(:,order);

figure(51);
plot(EigenValueList1)
title('Eigenvalues of Matrix S')
ylabel('Eigenvalues')
```




```

```

MUSIC algorithm, extracting steering matrix

M sensors, D multipath, N zero eigenvalues

M = N + D

Empirically, D=6~8 (significant reflectors according to SpotFi, Chapter 3.1)

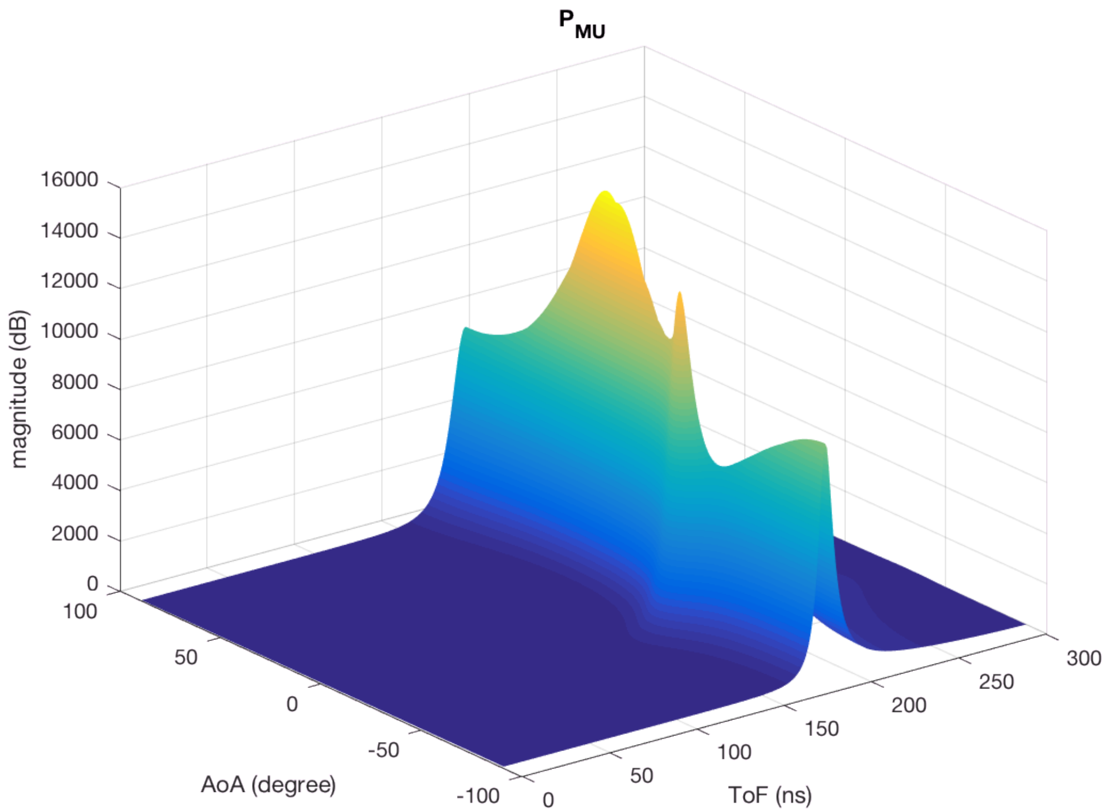
```
EigenValueThreshold = max(EigenValueList1) * 1e-4;
NoiseVectorIdx=find(EigenValueList1<EigenValueThreshold);

En = EigenVector(:,NoiseVectorIdx);

degrees = -90:0.5:90; % linspace
[~,deg_tot] = size(degrees);
tofs = 1e-9:1e-9:300e-9;
[~,tof_tot] = size(tofs);

c = 3e8; % speed of light
f = 2.412e9; % central frequency, all on channel 1
fs = 312.5e3; % frequency diff between consecutive subcarriers
d = 0.07;  % 7 cm between antennas
SP = zeros(deg_tot,tof_tot);

tic
for deg_idx = 1:deg_tot
    deg = degrees(deg_idx);
    theta = deg*pi/180;
    phi = exp(-1j*2*pi*d*sin(theta)*f/c);
    for tof_idx = 1:tof_tot
        tof = tofs(tof_idx);
        omega = exp(-1j*2*pi*fs*tof);
        half = omega.^((0:14)');
        a = [half;
            half.*phi];

        % SP(deg_idx,tof_idx)=(a'*a)/(a'*En*En'*a);
        SP(deg_idx,tof_idx)=1/(a'*En*En'*a);
    end
end
toc
```

```
Elapsed time is 138.722388 seconds.
```

Find most likely AoA and ToF

Peeks of P_{MU} represent a pair of AoA and ToF to a possible multipath.

```
Pmu=abs(SP);
Pmu_max=max(Pmu);
% Pmu_db = 10*log10(Pmu./Pmu_max);

figure(71)
surf(tofs*1e9,degrees,Pmu)
xlabel('ToF (ns)')
ylabel('AoA (degree)')
zlabel('magnitude (dB)')
title('P_{MU}')
grid on
shading interp;
```




```
Pmu_mirror = [Pmu; flipud(Pmu)];
maxima = find_maxima(Pmu_mirror);
rads = degrees'*pi/180;

for k=1:size(maxima,1)
    if maxima(k,1)<=length(rads)
        AoA = rads(maxima(k,1))*180/pi;
        ToF = maxima(k,2);
        fprintf('   AoA=%d  ToF=%d ns\n',ceil(AoA),ToF);
    end
end
```

```
AoA=-28  ToF=173 ns
AoA=-14  ToF=180 ns
AoA=12  ToF=183 ns
AoA=18  ToF=184 ns
```

An overall implementation for AoA estimation

In this implementation, it takes from dataset No. 2017 to dataset No.2047. Ideally, the estimations should be stable for a fixed emmiter and receiver. However, ToF estimation seems vary a lot, and AoA seems hard to estimate.

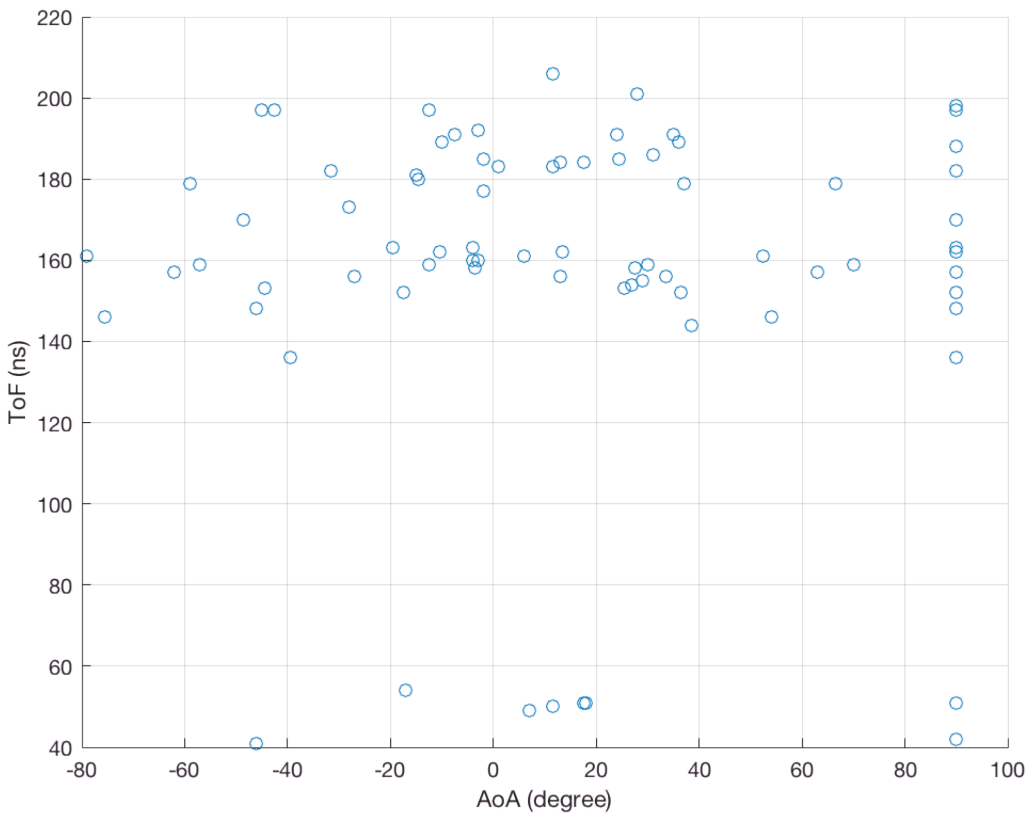
```
csi_trace = read_bf_file('csi-data/csi-20170804-320-7-45-2.dat'); % 72000pkt in 45s
% aoas = zeros(1,length(csi_good))
% csi_trace = csi_trace_30;
% load mat_csi_30_simulated_1.mat
% csi_trace = csi_trace_30;

dataset = [];
countdown = 30;

for idx=2017:length(csi_trace)
    if csi_trace{idx}.Nrx == 3
        countdown = countdown - 1;
        for tx=1:1 % csi_trace{idx}.Ntx
            e_csi = csi_extend_57(csi_trace{idx}.csi(tx,:,:));
            % do estimation
            [tofs, rads, Pmu] = csi_find_aoa_spotfi_sp1(csi_trace{idx},e_csi);
%             figure(10);
%             surf(tofs*1e9,rads*180/pi,Pmu)
%             xlabel('ToF (ns)')
%             ylabel('AoA (degree)')
%             zlabel('magnitude (dB)')
%             grid on
%             shading interp;
%             drawnow;
%             pause(0.8);
            Pmu_mirror = [Pmu; flipud(Pmu)];
            maxima = find_maxima(Pmu_mirror);
            fprintf('idx %d: \n',idx);
            for k=1:size(maxima,1)
                if maxima(k,1)<=length(rads)
                    AoA = rads(maxima(k,1))*180/pi;
                    ToF = maxima(k,2);
                    fprintf('    AoA=%d  ToF=%d ns\n',ceil(AoA),ToF);
                    dataset(end+1,:) = [AoA,ToF,Pmu(maxima(k,1),maxima(k,2))];
    %             else
    %                 fprintf('idx %d: miss\n',idx);
                end
            end
        end
    end
    if countdown <= 0
        break;
    end
end
```

```
idx 2017:
    AoA=-28  ToF=173 ns
    AoA=-14  ToF=180 ns
    AoA=12  ToF=183 ns
    AoA=18  ToF=184 ns
idx 2018:
    AoA=90  ToF=188 ns
    AoA=-7  ToF=191 ns
    AoA=-3  ToF=192 ns
idx 2019:
    AoA=-42  ToF=197 ns
    AoA=90  ToF=198 ns
    AoA=12  ToF=206 ns
```

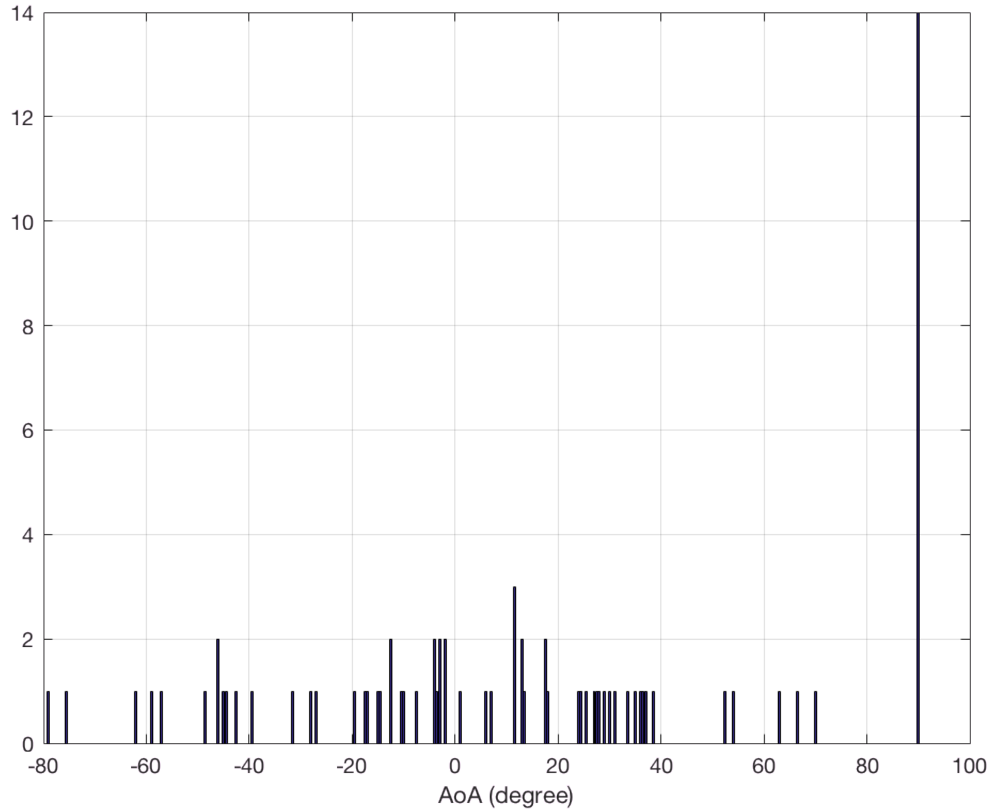
```
idx 2020:
   AoA=36  ToF=189 ns
   AoA=-12  ToF=197 ns
idx 2021:
   AoA=37  ToF=179 ns
   AoA=-10  ToF=189 ns
idx 2022:
   AoA=39  ToF=144 ns
idx 2023:
   AoA=90  ToF=152 ns
   AoA=-44  ToF=153 ns
   AoA=-12  ToF=159 ns
   AoA=-4  ToF=160 ns
idx 2024:
   AoA=7  ToF=49 ns
   AoA=12  ToF=50 ns
   AoA=18  ToF=51 ns
idx 2025:
   AoA=-3  ToF=160 ns
   AoA=90  ToF=163 ns
idx 2026:
   AoA=-75  ToF=146 ns
   AoA=54  ToF=146 ns
idx 2027:
   AoA=-46  ToF=41 ns
   AoA=90  ToF=42 ns
   AoA=18  ToF=51 ns
idx 2028:
   AoA=90  ToF=157 ns
   AoA=-3  ToF=158 ns
idx 2029:
   AoA=-17  ToF=152 ns
   AoA=6  ToF=161 ns
   AoA=14  ToF=162 ns
idx 2030:
   AoA=-46  ToF=148 ns
   AoA=90  ToF=148 ns
idx 2031:
   AoA=-62  ToF=157 ns
   AoA=63  ToF=157 ns
   AoA=-4  ToF=163 ns
idx 2032:
   AoA=-45  ToF=197 ns
   AoA=90  ToF=197 ns
idx 2033:
   AoA=-48  ToF=170 ns
   AoA=90  ToF=170 ns
idx 2034:
   AoA=-59  ToF=179 ns
   AoA=67  ToF=179 ns
   AoA=-31  ToF=182 ns
   AoA=-2  ToF=185 ns
idx 2035:
```

```
    AoA=1  ToF=183 ns
    AoA=14  ToF=184 ns
    AoA=25  ToF=185 ns
    AoA=31  ToF=186 ns
 idx 2036:
    AoA=28  ToF=158 ns
    AoA=30  ToF=159 ns
    AoA=-79  ToF=161 ns
    AoA=53  ToF=161 ns
    AoA=90  ToF=162 ns
    AoA=-19  ToF=163 ns
 idx 2037:
    AoA=-39  ToF=136 ns
    AoA=90  ToF=136 ns
 idx 2038:
    AoA=14  ToF=156 ns
 idx 2039:
    AoA=-14  ToF=181 ns
    AoA=35  ToF=191 ns
 idx 2040:
    AoA=28  ToF=201 ns
 idx 2041:
    AoA=-2  ToF=177 ns
    AoA=90  ToF=182 ns
 idx 2042:
    AoA=90  ToF=51 ns
    AoA=-17  ToF=54 ns
 idx 2043:
    AoA=37  ToF=152 ns
    AoA=-10  ToF=162 ns
 idx 2044:
    AoA=26  ToF=153 ns
    AoA=27  ToF=154 ns
    AoA=29  ToF=155 ns
    AoA=34  ToF=156 ns
    AoA=-57  ToF=159 ns
    AoA=70  ToF=159 ns
 idx 2045:
    AoA=24  ToF=191 ns
 idx 2046:
    AoA=-27  ToF=156 ns
    AoA=90  ToF=157 ns
```

```
figure(81);
scatter(dataset(:,1),dataset(:,2));
xlabel('AoA (degree)')
ylabel('ToF (ns)')
grid on
```




```
figure(82);
statistic = tabulate(dataset(:,1));
bar(statistic(:,1),statistic(:,2));
xlabel('AoA (degree)')
ylabel('')
grid on
```




```
save csi-20170804-320-7-45-2-result-2017-2116.mat dataset
```

Additional: Simulation

A brief simulation.

```
%% Basic simulation for 3 antennas

% Number of Paths D=8
D = 2;
% incident angle and weight for each path
incident_angle = [72 30];

num_of_pkt = 1;
% csi_simulated_pkt = zeros(num_of_pkt,3,57);

for pkt=1:num_of_pkt

    incident_attenuation = (randn([1 D])+1j*(randn([1 D])));
    % incident_attenuation = [10+0.2j 3-0.5j];
    % incident_attenuation = [10 20 30 40 50 60 70 80];
    % set 45 degree as the major direction
    %incident_attenuation(3) = 5;
    % set time of flight, 1ns~0.3m, 10ns~3m, 100ns~30m
    % tof = randi([1 50],[D 1]) * 1e-9;
```

```
% tof = [200 100 120 130 140 150 160 170]' .* 1e-9;
tof = [50 80]' .* 1e-9;
% tof(3) = 15e-9;

% % Number of Paths D=2
% D = 2;
% M = 3;
% % Set incident angle and weight for each path
% incident_angle = [17 20];
% incident_attenuation = (randi([2 6],[1 2])+1j*(randi([2 4],[1 2])));
% % set 45 degree as the major direction
% % incident_attenuation(2) = 30 + 30j;
% % set time of flight, 1ns~0.3m, 10ns~3m, 100ns~30m
% tof = randi([8 40],[1 2]) * 1e-9;
% % tof(3) = 20e-9;

%% Fomulate steering matrix and incident quanties, given by the number of multipath
c = 3e8; % speed of light
f = 2.412e9; % central frequency
fs = 312.5e3; % 312.5 kHz
d = 0.07; % the minimal distance in between is 0.012
twopi = 2*pi;
deg2rad = pi/180;
phiD = exp(-1j*twopi*d*sin(incident_angle*deg2rad)*f/c);  % 1*D
omega = exp(-1j*twopi*fs*tof);   % D*1

csi_cell.timestamp_low = 4;
csi_cell.bfee_count = 1;
csi_cell.Nrx = 3;
csi_cell.Ntx = 1;
csi_cell.rssi_a = 39;
csi_cell.rssi_b = 36;
csi_cell.rssi_c = 33;
csi_cell.noise = -78;
csi_cell.agc = 24;
csi_cell.perm = [1 2 3];
csi_cell.rate = 8454;
csi_cell.csi = zeros(1,3,30);

A = [ones(1,D)
    phiD
    phiD.^2];

F = zeros(D,57);
FF = omega.^(0:56);

for row=1:D
   F(row,:) = incident_attenuation(row).*FF(row,:);
end

%% Simulate CSI measurements

X1 = A*F;
snr = 25;
X  = awgn(X1,snr,'measured');

%% Spoi-fi solution
csi_simulated = X;
% csi_find_aoa_spotfi_sp1 is the same as stated in MUSIC algorithm
[tofs, rads, Pmu] = csi_find_aoa_spotfi_sp1(csi_cell,csi_simulated);
```

```
    figure(91);
    surf(tofs*1e9,rads*180/pi,Pmu)
    xlabel('ToF (ns)')
    ylabel('AoA (degree)')
    zlabel('magnitude (dB)')
    title('P_{MU}')
    shading interp;
    Pmu_mirror = [Pmu; flipud(Pmu)];
    maxima = find_maxima(Pmu_mirror);
    for k=1:size(maxima,1)
        if maxima(k,1)<=length(rads)
            AoA = rads(maxima(k,1))*180/pi;
            ToF = maxima(k,2);
            fprintf('    AoA=%d  ToF=%d ns\n',ceil(AoA),ToF);
        end
    end
end
```

```
AoA=-55  ToF=51 ns
AoA=73  ToF=51 ns
AoA=30  ToF=80 ns
```