Massive Notes 1.3

Key Points : Ways to Improve the Spectral Efficiency; Increase the Transmit Power

1. Ways to Improve the Spectral Efficiency

1. There are different ways to improve the per-cell SE in cellular networks. Consider **a two-cell network** where the average channel gain between a BS and every UE in a cell is identical, as shown below.

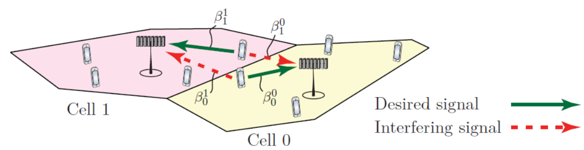

Figure 1: A two-cell network.

2.1. β_0^0 denotes the average channel gain from a UE in cell 0 to its serving BS;
2.2. β_1^0 denotes the average channel gain from a UE in cell 1 to BS in cell 0 (i.e., β_1^0 is the interfering signals);
2.3. β_1^1 denotes the average channel gain from a UE in cell 1 to its serving BS;
2.4. β_0^1 denotes the average channel gain from a UE in cell 0 to BS in cell 1 (i.e., β_0^1 is the interfering signals).

3. The average channel gains are **positive dimensionless quantities** that are often very small since **the signal energy decays quickly with the propagation distance**; values in the range from -70 dB to -120 dB are common within the serving cell, while the interfering signals are even smaller.

4. Suppose $\beta_0^0 = \beta_1^1$ and $\beta_1^0 = \beta_0^1$, we can define the **ratio** $\bar{\beta}$ between the inter-cell and intra-cell channel gains as

$$\bar{\beta} = \frac{\beta_1^0}{\beta_0^0} = \frac{\beta_0^1}{\beta_0^0} = \frac{\beta_1^0}{\beta_1^1} = \frac{\beta_0^1}{\beta_1^1} \tag{1}$$

5. Typically we have $0 \leq \bar{\beta} \leq 1$, where $\bar{\beta} \approx 0$ corresponds to a **negligibly weak inter-cell interference** and $\bar{\beta} \approx 1$ means that **the inter-cell interference is as strong as the desired signals** (which may happen for UEs at the cell edge).

2. Increase the Transmit Power(1)

6. The SE naturally depends on **the strength of the received desired signal**, represented by **the average SNR** (i.e., $\frac{p\mathbb{E}\{|h|^2\}}{\sigma^2}$), the average SNR of a UE in cell 0 therefore is

$$\mathrm{SNR}_0 = \frac{p}{\sigma^2}\beta_0^0 \tag{2}$$

where p denotes the UE's transmit power and σ^2 is the noise power. SNR_0 plays a key role in this topic.

7. Suppose there is one active UE per cell and that each BS and UE is equipped with a **single patch antenna** with a size that is smaller than the wavelength. Channel is **flat-fading** (i.e., the coherence bandwidth of the channel is larger than the signal bandwidth), so **the symbol-sampled complex-baseband** signal $y_0 \in \mathbb{C}$ received at the BS in cell 0 is

$$y_0 = \underbrace{h_0^0 s_0}_{\text{Desired signal}} + \underbrace{h_1^0 s_1}_{\text{Interfering signal}} + \underbrace{n_0}_{\text{Noise}} \tag{3}$$

where $n_0 \sim \mathcal{N}_{\mathbb{C}}(0, \sigma^2)$, and the scalars $s_0, s_1 \sim \mathcal{N}_{\mathbb{C}}(0, p)$ represents the information signals (e.g., QAM signals) transmitted by the desired and interesting UEs, respectively. We consider one model of LoS propagation and one model of NLoS propagation. In single-antenna LoS propagation, we have

$$h_i^0 = \sqrt{\beta_i^0} \quad \text{for} \quad i = 0, 1 \tag{4}$$

8. Since **phase rotation** does not affect the SE, it can be neglected. The channel gain β_i^0 can be interpreted as the macroscopic **large-scale fading** in LoS propagation, caused by distance-dependent pathloss. This parameter is **constant** if the transmitter and receiver are **fixed**, while it **changes** if the transmitter and/or receiver **move**.

9. **Microscopic** movements (at the order of the **wavelength**) can be modeled as **phase-rotations** in h_i^0

10. **Large** movements (at the order of **meters**) lead to **substantial** changes in β_i^0. We often consider a fixed value of h_i^0.

11. In NLoS propagation environments, the channel responses are **random variables** that change over **time** and frequency, and it there is **sufficient scattering** between the UEs and the BS, then

$$h_i^0 \sim \mathcal{N}_{\mathbb{C}}(0, \beta_i^0) \quad \text{for} \quad i = 0, 1 \tag{5}$$

(5) is called **Rayleigh Fading** because the magnitude $|h_i^0|$ is a **Rayleigh distributed random variable**.

12. The transmitted signal reaches the receiver through **many different paths** and the **superimposed** received signals can either **reinforce** or **cancel** each other. When the number of paths is **large**, the **central limit theorem** motivates the use of a **Gaussian distribution**.

13. **Small-scale fading**: a microscopic effect caused by **small variations** in the propagation environment (e.g., movement of the transmitter, receiver, or other objects). The phenomenon that 12 talk about is small-scale fading.

14. **Large-scale fading**: the variance β_i^0 is interpreted as the macroscopic large-fading, which includes **distance-dependent pathloss**, **shadowing**, **antenna gains**, and **penetration losses** in NLoS propagation.

3. Increase the Transmit Power(2): LoS case

15. Suppose the BS in cell 0 knows the channel responses. An **achievable** UL SE for the desired UE in the LoS case is

$$\mathrm{SE}_0^{\mathrm{LoS}} = \log_2\big(1 + \frac{1}{\bar{\beta} + \frac{1}{\mathrm{SNR}_0}}\big) = \log_2\big(1 + \frac{1}{\bar{\beta} + \frac{\sigma^2}{p\beta_0^0}}\big) \tag{6}$$

where $\bar{\beta} = \frac{\beta_1^0}{\beta_0^0}$ and $\mathrm{SNR}_0 = \frac{p}{\sigma^2}\beta_0^0$, so we have the SINR expression of SE

$$\mathrm{SE}_0^{\mathrm{LoS}} = \log_2\big(1 + \frac{\overbrace{p\beta_0^0}^{\text{Signal power}}}{\underbrace{p\beta_1^0}_{\text{Interference power}} + \underbrace{\sigma^2}_{\text{Noise power}}}\big) \tag{7}$$

16. If we increase p, the SE can be improved. However, the SE will NOT increase indefinitely with p. In the LoS, we have

$$\mathrm{SE}_0^{\mathrm{LoS}} \to \log_2\left(1 + \frac{1}{\bar{\beta}}\right) = \log_2\left(1 + \frac{\beta_0^0}{\beta_1^0}\right) \quad \text{as} \quad p \to \infty \tag{8}$$

where the limit is completely determined by **the strength of the interference**. This is due to the fact that the desired UE and the interfering UE both increase their transmit powers.

Program 1: LoS

Listing 1: LoS.m

```
%Empty workspace and close figures
close all;
clear;

%Define the SNR range for analytical curves
SNRdB = -10 : 0.1 : 50;
SNR = 10 .^ (SNRdB/10);

%Define the different beta_bar values (strength of inter-cell interference)
betabar = [1e-1, 1e-3]';

%Preallocate matrices for storing the simulation results
SE_LoS = zeros(length(betabar), length(SNR));

%% Go through different strengths of the interference
for b = 1 : length(betabar)

    %Compute SE under line-of-sight (LoS) propagation as in (1.17)
    SE_LoS(b, :) = log2(1 + 1 ./ (betabar(b) + 1 ./ SNR));

end

%% Plot the simulation results
figure;
hold on; box on;

plot(SNRdB, SE_LoS(1, :), 'r--', 'LineWidth', 1.5);
plot(SNRdB, SE_LoS(2, :), 'b-.', 'LineWidth', 1.5);

xlabel('SNR [dB]');
ylabel('Average SE [bit/s/Hz]');

legend('beta = 0.1, LoS', 'beta = 0.001, LoS', 'Location', 'SouthEast');
ylim([0, 10]);
```

Output 1:

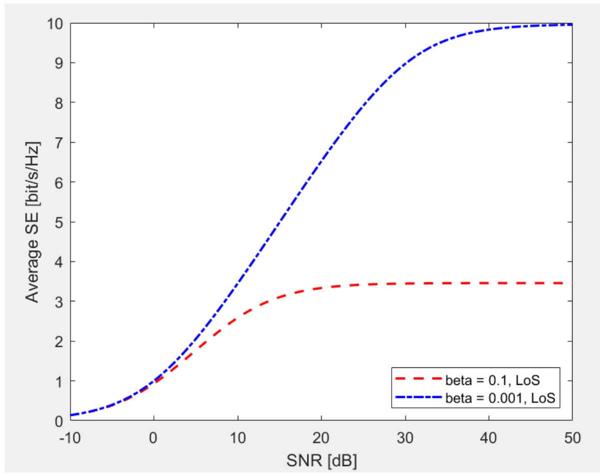

Figure 2: Average UL SE as a function of the SNR for different cases of inter-cell interference strength in LoS model.(END)