Massive Notes 1.5

Key Points : Increasing Cell Density; Obtain an Array Gain

1. Increasing Cell Density:

1. From the previous notes, we have already known that simply increasing transmit power is not a smart move to achieve a higher SE. Another way to increase the SNR to obtain a higher SE is **increasing the cell density** D but to keep the transmit power fixed.

2. The concept of increasing cell density is not complicated. Since we often assume the average gain is **inversely proportional** to the propagation distance to some fixed *pathloss* exponent in channel modeling, if we increase D, then **the distance to the desired BS and the interfering BSs are reduced**.

3. But this method does have disadvantages. when the distance to the desired BS and the interfering BSs are reduced, **the inter-cell interference increase at roughly the same pace**. Therefore, like simply increasing transmit power, the interference-limited SE limit can be also obtained when we increase D. However, cell densification is a suitable way to improve the hotspot tier. It is noteworthy that if the channel model change (e.g., the pathloss exponent reduce to free-space propagation scenario, 2), increasing D is useless because **the sum power of the interfering signals increase faster than the desired signal power**.

2. Obtain an Array Gain(1): LoS case

4. Instead of increasing the UL transmit power or cell densification, the BS can **deploy multiple receive antennas to collect more energy from the EM waves**. It is more convenient to equip the BSs with multiple antennas than the UEs, because the latter are typically compact commercial end-user products powered by batteries and relying on low-cost components.

5. We now suppose the BS in cell 0 is equipped with an array of M antennas. The channels responses from the desired and interfering UEs can then be represented by the vectors $\mathbf{h}_0^0 \in \mathbb{C}^M$ and $\mathbf{h}_1^0 \in \mathbb{C}^M$, respectively. The mth element of each vector is the channel response observed at the mth BS antenna, for $m = 1, \ldots, M$. Remember the scalar received UL signal is

$$y_0 = \underbrace{h_0^0 s_0}_{\text{Desired signal}} + \underbrace{h_1^0 s_1}_{\text{Interfering signal}} + \underbrace{n_0}_{\text{Noise}} \tag{1}$$

so we extend (1) to a received vector $\mathbf{y}_0 \in \mathbb{C}^M$ as

$$\mathbf{y}_0 = \underbrace{\mathbf{h}_0^0 s_0}_{\text{Desired signal}} + \underbrace{\mathbf{h}_1^0 s_1}_{\text{Interfering signal}} + \underbrace{\mathbf{n}_0}_{\text{Noise}} \tag{2}$$

where $\mathbf{n}_0 \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}_M, \sigma^2 \mathbf{I}_M)$ is the receiver noise over the BS array.

6. Figure 1 shows a LoS horizontal **uniform linear array** (**ULA**) case.

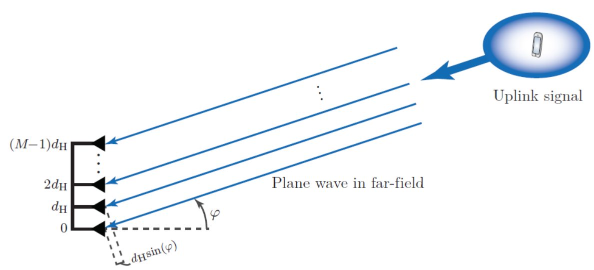

Figure 1: LoS propagation between a transmitting single-antenna UE and a BS equipped with a ULA with M antennas.

7. Consider SIMO, there are M antennas in the ULA, and if λ refers to the wavelength at the carrier frequency, then the antenna spacing is λd_H meters, where $d_H \in (0, 0.5]$. We also assume that the UEs are located at fixed locations in the **far-field** of the BS array, which leads to the following deterministic channel response

$$\mathbf{h}_i^0 = \sqrt{\beta_i^0}\left[1, e^{2\pi j d_H \sin(\varphi_i^0)}, \ldots, e^{2\pi j d_H (M-1)\sin(\varphi_i^0)}\right] \quad \text{for} \quad i = 0, 1 \tag{3}$$

where $\varphi_i^0 \in [0, 2\pi)$ is the **azimuth angle** to the UE, relative to the **boresight** of the array at the BS in cell 0, and β_i^0 denotes the **macro-scopic large-scale fading**. We don't consider the common phase rotation of all elements since this phenomenon does not affect the SE. But it is worth noting that when we comparing two adjacent antennas, one of them observes a signal that has traveled $d_H \sin\varphi$ longer than the other one. This leads to the array response in (3) with **phase rotations** that are multiples of $d_H \sin\varphi$.

3. Obtain an Array Gain(2): NLoS case

8. Now let's consider the NLoS case, suppose the channel response is **spatially uncorrelated over the array**. Therefore

$$\mathbf{h}_i^0 \sim \mathcal{N}_{\mathbb{C}}\big(\mathbf{0}_M, \beta_i^0 \mathbf{I}_M\big) \quad \text{for} \quad i = 0, 1 \tag{4}$$

where β_i^0 describes the **macroscopic large-scale fading**, while the randomness and Gaussian distribution account for the **small-scale fading**.

9. This channel model is called **uncorrelated Rayleigh fading** or **Independent and identically distributed (i.i.d) Rayleigh fading**, because the elements in $\mathbf{h}_i^0$ are **uncorrelated**, **independent** and **have Rayleigh distributed magnitudes**.

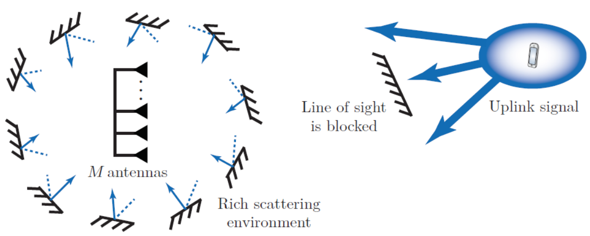

Figure 2: NLoS propagation with uncorrelated Rayleigh fading between a transmitting single-antenna UE and a BS equipped with an array of M antennas.

10. As shown in figure 2, Uncorrelated Rayleigh fading is a tractable model for **rich scattering conditions**, where the BS array is **surrounded by many scattering objects**, as compared to the number of antennas. We assume the average channel gain β_i^0 is the same for all BS antennas. It is reasonable if the distance between the BS and UE is much larger than the distance between the BS antennas. But the thing will be different when M is large. Fortunately, we don't consider this situation right now.

11. From figure 2 we also can see that the LoS path is blocked, but the signal finds multiple other paths via scattering objects. The BS is surrounded by many scattering objects so that **the UE location has no impact on the spatial directivity of the received signal**. (END)