Guidance on Link Level Simulation

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Matlab Codes

- Data_Rate/main.m
- Channel_Model/channel.m
- Transmissions/image_transfer.m

1 Data Rate and Number of Antenna Elements

Question 1: What is the SNR and data rate observed at a given distance for a given transmit power, antenna gain and channel bandwidth?
Answer: We compute the SNR and data rate in bits per second according to the following equation:

$$R = B \log_2(1 + \mathrm{SNR}), \tag{1}$$

where B is the channel bandwidth, R is the data rate, while $\eta = \frac{R}{B}$ denotes the spectral efficiency in bit/s/Hz.

From the Friis equation, the ratio of the received power to the transmit power is given by:

$$\frac{P_r}{P_t} = \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}\ , \tag{2}$$

where G_t and G_r are the transmit and receiver antenna gains, respectively, λ is the wavelength, d is the distance between the antennas and L is the system loss. For a free space propagation, without antenna gains ($G_t = G_r = 1$) and no system loss ($L = 1$), we have:

$$\frac{P_r}{P_t} = \left(\frac{c}{4\pi d f}\right)^2\ , \tag{3}$$

where $f = c/\lambda$ is the carrier frequency and c is the speed of light. In order to arrive at the solution, we first compute the propagation pathloss the signal experienced as it traversed through the channel, which is defined as $PL = -10\log_{10}\left(\frac{P_r}{P_t}\right) = 10\log_{10}\left(\frac{P_t}{P_r}\right)$. Hence, the free space path loss in Eq. (3) at distance d_0 is given by:

$$PL_F(d_0) = 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi d_0}{c}\right)\ . \tag{4}$$

The general propagation loss can be modeled as [1, 2, 3]:

$$PL = 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi d_0}{c}\right) + 10n\log_{10}\left(\frac{d}{d_0}\right) + \mathcal{S}, \tag{5}$$

where d is the distance at which data rate is measure, $\mathcal{S}$ is the shadowing effect, while n is the pathloss exponent, which depends on the environment under consideration. A more detailed analysis on pathloss models is given in [1, 2, 3]. At free space, the pathloss exponent is given by $n = 2$. Furthermore, the reference distance d_0 is the distance at which (or closer to which), the path loss inherits the characteristics of free-space loss. Note that d_0 must be properly determined for different propagation environments. For example, d_0 is typically set as 1km for a cellular system with a large coverage (e.g., a cellular system with a cell radius greater than 10 km). However, it could be 100m or 1m, respectively, for a macro-cellular system with a cell radius of 1km or a micro-cellular system with an extremely small radius [2].

The antenna gain can be computed as:

$$G = G_E A_F, \tag{6}$$

where G_E is the single element antenna gain, while A_F is the array factor, which is given by the number of antenna elements in the best case beamforming scenario. In other words, the total antenna gain from both the transmitter and receiver can be computed as:

$$G_t G_r = G_{t,E} A_{t,F} \; G_{r,E} A_{r,F} \;, \tag{7}$$

where the subscript $_t$ and $_r$ denotes the transmitter and receiver, respectively, while we $A_{t,F} = N_t$ and $A_{r,F} = N_r$. Hence, the multiplications of $N_t N_r$ can be computed as:

$$N_t N_r = \frac{G_t \; G_r}{G_{t,E} \; G_{r,E}} = 10^{\frac{G_t^{\text{dBi}} + G_t^{\text{dBi}} - G_{t,E}^{\text{dBi}} - G_{r,E}^{\text{dBi}}}{10}} \;, \tag{8}$$

where $G_{t,E}^{\text{dBi}} = 10\log_{10}(G_{t,E})$ and $G_{r,E}^{\text{dBi}} = 10\log_{10}(G_{r,E})$.

The total received power $P_r^{\text{dBm}} = 10\log_{10}(P_r)$ for a transmit power of $P_t^{\text{dBm}} = 10\log_{10}(P_t)$ and for transmit and receive antenna gains of $G_t^{\text{dBi}} = 10\log_{10}(G_t)$ and $G_r^{\text{dBi}} = 10\log_{10}(G_r)$, respectively, can be expressed as from Eq. (2), Eq. (5) and Eq. (8) as:

$$\begin{aligned} P_r^{\text{dBm}} &= P_t^{\text{dBm}} - \text{PL} + G_t^{\text{dBi}} + G_r^{\text{dBi}}, & (9) \\ P_r^{\text{dBm}} &= P_t^{\text{dBm}} - \text{PL} + G_{t,E}^{\text{dBi}} + G_{r,E}^{\text{dBi}} + 10\log_{10}(N_t N_r), & (10) \end{aligned}$$

where again N_t and N_r denote the number of antenna elements at the transmitter and receiver, respectively. Having obtained the received power, the $\text{SNR} = P_r/N_0$ is computed as the ratio of received power P_r and noise power N_0. Then by plugging the SNR into Eq. (1), we can evaluate the corresponding data rate.

Question 2: What is the number of antenna elements required to achieve a target data rate, at a given distance for a given transmit power and channel bandwidth?

Answer: From Eq. (1) we have:

$$\begin{aligned} P_r &= (2^{R/B} - 1) N_0 & (11) \\ P_r^{\text{dBm}} &= 10\log_{10}(2^{R/B} - 1) + N_0^{\text{dBm}} \;, & (12) \end{aligned}$$

which gives the required received power for a given target transmission rate of R. Let the required received power in Eq. (12) be denoted as $P_{r,*}^{\text{dBm}}$, while the received power without antenna gain ($G_t^{\text{dBi}} = G_r^{\text{dBi}} = 0$) in Eq. (9) be represented as $P_{r,0}^{\text{dBm}} = P_t^{\text{dBm}} - \text{PL}$. Then, the required antenna gain for attaining a certain target rate R is given by $G_t^{\text{dBi}} + G_r^{\text{dBi}} = P_{r,*}^{\text{dBm}} - P_{r,0}^{\text{dBm}}$, which gives the number of transmit and receive antenna elements based on Eq. (8).

Typical values for the parameters in the Matlab code are: transmit power of around 20-40 dBm, and shadowing of around 20 dB for mmWave systems. The gain of antenna element is assumed to be 10 dBi in this exercise but you can change it depending on the standard. Furthermore, we assumed that the pathloss exponent n to be equal to 2. However, pathloss exponent value is contingent on the channel environment. The noise is given by KTB, where K is the Boltzmann constant, and T is the temperature in Kelvin scale. At around 300 K, the noise is around -174 dBm/Hz. The frequency is in GHz, distance is in meters. For more information, please refer to [1].

2 Channel Model

In this exercise, we analyze the IEEE802.11 channel model. More explicitly, we study by taking snap shots of Frequency response of the channel for each time. In order to do so, we first define the delay spread, which is the the difference between the time of arrival of the earliest significant multipath component and the last multipath component. The delay spread is typically quantified in terms of root mean square (RMS) metric, as defined in Eq. (1.20) of [2]. Depending on the sampling period T_s the number of multipaths may be defined. A higher sampling rate is more likely to cause a higher number of multipaths from the transmitter to the receiver. The normalized channel power is spread across the multipaths. Therefore, to study the power distribution of the channel, we need to investigate the power delay profile. In this example, we employ IEEE802.11 model in the Matlab code. Furthermore, the number of paths is defined by using Rayleigh fading channel model (ray model), as detailed in Chapter 1 on page 24 of [2].

Having obtained the channel in time domain, we then employ FFT to transform the channel into frequency domain. The size of the FFT depends on the number of subcarriers in the system model considered. We have set the number of subcarriers to 128, as a design example. Note that this is only for a snap shot. To obtain multiple snap shots, we assumed the channel to vary in time according to Jakes' model, which is a function of Doppler frequency. Changing the Doppler frequency would vary the channel fading in the time domain. To see variations in the frequency domain, we should vary the RMS value of the delay spread or by changing sampling time of the signal.

3 Transmissions

In this exercise, an image is transmitted over a simple binary symmetrical channel (BSC) with a given probability of error (probability_of_flipping). The image is first converted to bits, then the bits are corrupted by the BSC. At the receiver, the corrupted bit sequence is converted back to image. This Matlab code can be used to evaluate the system's transmission reliability. Two images are provided, namely ngc6543a.jpg and satya.jpg. However, you can use your own image as well.

References

[1] Ibrahim Hemadeh, K. Satyanarayana, Mohammed El-Hajjar, and Lajos Hanzo, "Millimeter-wave communications: Physical channel models, design considerations, antenna constructions, and link-budget", *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, 2018.

[2] Cho, et al., "MIMO-OFDM Wireless Communications with Matlab", IEEE Press, John Wiley & Sons 2010.

[3] A. Goldsmith, "Wireless Communications", Cambridge University Press, 2005.