Communication Channels

PROJECT REPORT:

CHANNEL MODELING FOR 5G SMALL CELLS

JiaLun Kou

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Prof. Dr. Ir. Philippe De Doncker

Engineering Sciences

CONTENTS

CHAPTER 1 THEORETICAL FOUNDATIONS

1.1 Effective Height

To calculate the induced voltage at the receiver, the radiated fields of the different rays must be computed. the effective height of the receiver is used to find the induced voltage as follows:

$$\vec{h}_e(\theta,\phi) = -\frac{\lambda}{\pi}\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta}\vec{1}_z \tag{1.1}$$

The effective hight allows us to obtain the radiated fields, for **Transmitter side**, we assume in the far-field (radiated electric field is plane wave),:

$$\begin{cases}\vec{h}_e^{TX}(\theta^{TX},\phi^{TX}) = \left(\vec{h}_e(\theta,\phi)\vec{1}_\theta\right)\vec{1}_\theta + \left(\vec{h}_e(\theta,\phi)\vec{1}_\phi\right)\vec{1}_\phi \ , \ \left(\vec{1}_z \perp \vec{1}_\phi\right) \\ \vec{E}(r) = jZ_0 I_a \frac{\beta}{4\pi}\frac{e^{-j\beta r}}{r}\vec{h}_e^{TX}(\theta^{TX},\phi^{TX})\end{cases}$$

$$\vec{E}(r) = j\frac{Z_0 I_a}{2\pi}\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\frac{e^{-j\beta r}}{r}\vec{1}_\theta \tag{1.2}$$

1.2 Antenna Gain

In order to get $G_{TX}(\theta)$, the Radiated intensity should be first deduced:

$$U(\theta) = r^2 S(r,\theta) = r^2\frac{\left|\vec{E}(r)\right|^2}{2Z_0} = Z_0\frac{|I_a|^2}{8\pi^2}\left(\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\right)^2 \tag{1.3}$$

Then we could get total radiated power:

$$P_{ar} = \int_0^{2\pi}\int_0^{\pi} U(\theta)\sin\theta d\theta d\phi$$

$$\left(\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\right)^2 \approx \sin^3\theta \tag{1.4}$$

$$P_{ar} = Z_0\frac{|I_a|^2}{4\pi}\frac{3\pi}{8}$$

Antenna directivity

$$D(\theta) = \frac{U(\theta)}{P_{ar}/4\pi} = \frac{16}{3\pi}\sin^3\theta \tag{1.5}$$

We assume $\eta = 1$, ($\theta_{rx} = \theta_{tx}$ Since BS and UE at the same height, when $\theta = \frac{\pi}{2}$, Gain reach to maximum), The gain of the antenna, which is dependent on θ, is equal to:

$$G_{TX}(\theta_{tx}) = G_{RX}(\theta_{rx}) = \eta D(\theta) = \frac{16}{3\pi}\sin^3\theta$$
$$G_{TX,\max} = \frac{16}{3\pi} * \left(\sin\left(\frac{\pi}{2}\right)\right)^3 = 1.69765 \qquad (1.6)$$

To deduce the transmitted power, the given maximal EIRP of 0.25W was used.

$$EIRP = P_{TX,\max} \cdot G_{TX} \qquad (1.7)$$

$$P_{TX,\max} = \frac{EIRP}{G_{TX,\max}} = \frac{0.25}{1.69765} = 0.147262W \qquad (1.8)$$

1.3 Electric field and Received power

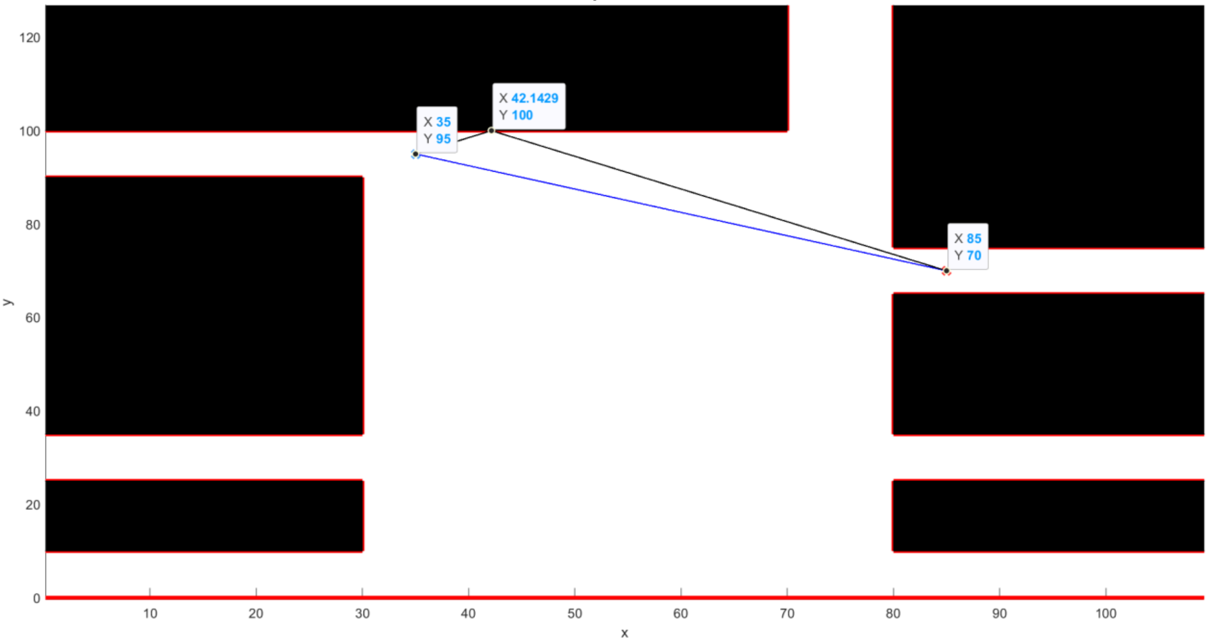


Figure 1: Specific case that will be used for validation (max 1 reflection)

Blue ray = LOS + Ground reflection, Black ray = Single reflection

Validation Parameters: $H_{TX} = H_{RX} = 2m$

$$C = 3 \cdot 10^8 (m/s), f_{carrier} = 26GHZ,$$
$$\beta = \frac{2\pi f_{carrier}}{C} = 544.543$$
$$\varepsilon_r = 4, \ \ EIRP = 0.25W,$$
$$TX = (35, 95), RX = (85, 70),$$
$$r = \sqrt{(35-85)^2 + (95-70)^2} = 55.9017m$$

1.3.1 LOS WAVE

First, We calculate electric field amplitude in the simplest case:

$$\begin{cases} S(r,\theta,\phi) = G_{TX}(\theta_{TX},\phi)\dfrac{P_{TX}}{4\pi r^2} \\ S(r,\theta,\phi) = \dfrac{\left|\vec{E}(r)\right|^2}{2Z_0} \end{cases} \tag{1.9}$$

$$E = \frac{\sqrt{60G_{TX}(\theta_{TX})P_{TX}}}{r} = \frac{\sqrt{60EIRP}}{r}$$

The amplitude of the LOS wave is given by (1.9) while its phase is due to the propagation distance only, so that the complex amplitude of this LOS wave is:

$$\begin{cases} \theta_{TX} = \dfrac{\pi}{2} + \operatorname{atan}\dfrac{h_{TX-}h_{RX}}{r} = \dfrac{\pi}{2} \\ G_{TX}(\theta_{TX}) = \dfrac{16}{3\pi}\sin^3(\theta_{TX}) = 1.69765 \\ r_{los} = \sqrt{r^2 + (h_{TX-}h_{RX})^2} = r = 55.9017 \\ E_{los} = Ee^{-j\beta r_{los}} = \sqrt{60G_{TX}(\theta_{TX})P_{TX}}\dfrac{e^{-j\beta\cdot r_{los}}}{r_{los}} \\ \quad = 0.0271 + 0.0638i \ = \ equal\ to\ simulation\ result \end{cases} \tag{1.10}$$

1.3.2 SINGLE REFLECTION OF A BUILDING

A reflected wave is a LOS wave with an extra (attenuation) factor that depends on the relative permittivity which is equal to 4 in this case. The attenuation factor represents a perpendicular reflection.

$$\begin{cases} \theta_{incident} = \dfrac{\pi}{2} - \operatorname{atan}\left(\dfrac{(100-95)}{(42-35)}\right) = 0.950547 \\ \theta_{incident-simulation} = 0.9601 \\ G_{TX}(\theta_{TX}) = 1.69765 \\ r_{ref} = \sqrt{(42-85)^2 + (100-130)^2} + \sqrt{5^2+7^2} = 61.0332 \\ r_{simulation} = 61.0328 \\ \Gamma_{\perp} = \dfrac{\cos\theta_i - \sqrt{\varepsilon_r}\sqrt{1-\dfrac{1}{\varepsilon_r}\sin^2\theta_{incident}}}{\cos\theta_i + \sqrt{\varepsilon_r}\sqrt{1-\dfrac{1}{\varepsilon_r}\sin^2\theta_{incident}}} = -0.5173 \\ \Gamma_{\perp simulation} = -0.5217 \end{cases} \tag{1.11}$$

$$E_{ref} = \Gamma_{\perp}\sqrt{60G_{TX}(\theta_{TX})P_{TX}}\frac{e^{-j\beta\cdot r_{ref}}}{r_{ref}} = 0.0316 - 0.0090i$$

$$E_{ref-simulation} = 0.0331 - 0.0015i$$

To calculate the angles, the reflection point must be found first. This is done by finding the intersection of the line between the image of the transmitter and the receiver, and the horizontal walls. Basic geometry can than be used to find the angles. As shown in **Figure 1**, the reflection points **A= (42,100)**

To calculate the distance travelled by the wave, the image point of the transmitter is found by reflecting the transmitter over the wall. The total distance travelled is then the distance between the image point and the receiver. In validation case, the image point **B=(85,130)**

1.3.3 GROUND REFLECTION

$$\begin{cases} r_{gnd} = \sqrt{{r_{los}}^2 + (h_{TX} + h_{RX})^2} = \sqrt{55.9017^2 + (2+2)^2} = 56.0446 = r_{gnd-simulation} \\ \theta_{TX,gnd} = \dfrac{\pi}{2} + \operatorname{atan}\dfrac{h_{TX+}h_{RX}}{r_{los}} = \dfrac{\pi}{2} + \operatorname{atan}\left(\dfrac{4}{55.9017}\right) = 1.6422 = \theta_{TX,gnd\text{-}simulation} \\ G_{TX}(\theta_{TX,gnd}) = \dfrac{16}{3\pi}\sin^3\theta_{TX,gnd} = \dfrac{16}{3*\pi}*(\sin(1.6422))^3 = 1.68471 = G_{TX}(\theta_{TX,gnd})_{\ simulation} \\ \theta_{incident} = \dfrac{\pi}{2} - \operatorname{atan}\dfrac{h_{TX+}h_{RX}}{r_{los}} = \dfrac{\pi}{2} - \operatorname{atan}\left(\dfrac{4}{55.9017}\right) = 1.4994 = \theta_{incident\text{-}simulation} \\ \Gamma_{\parallel} = \dfrac{\cos\theta_{incident} - \dfrac{1}{\sqrt{\varepsilon_r}}\sqrt{1 - \dfrac{1}{\varepsilon_r}\sin^2\theta_{incident}}}{\cos\theta_{incident} + \dfrac{1}{\sqrt{\varepsilon_r}}\sqrt{1 - \dfrac{1}{\varepsilon_r}\sin^2\theta_{incident}}} = -0.7172 = \Gamma_{\parallel\text{-}simulation} \\ E_{gnd} = \Gamma_{\parallel}\sqrt{60 G_{TX}(\theta_{TX,gnd}) P_{TX}}\dfrac{e^{-j\beta\cdot r_{gnd}}}{r_{gnd}} = -0.0151 + 0.0472i = E_{gnd\text{-}simulation} \end{cases}$$

(1.12)

1.3.4 RECEIVED POWER

Total electric field at receiver:

$$E_{total} = \sqrt{60 G_{TX}(\theta_{TX}) P_{TX}}\left(\frac{e^{-j\beta\cdot r_1}}{r_1} + \Gamma_{\perp}\frac{e^{-j\beta\cdot r_2}}{r_2} + \ldots.\right) \quad (1.13)$$

$$\begin{cases} P_{RX} = A_e(\theta,\phi)S(r) = A_e(\theta,\phi)\dfrac{|E_{total}|^2}{2Z_0} \\ Z_0 = 120\pi\ ,\ R_a = \dfrac{720\pi}{32},\ \dfrac{Z_0}{\pi R_a} = \dfrac{16}{3\pi} \end{cases} \quad (1.14)$$

$$P_{RX} = \frac{\lambda^2}{4\pi} G_{RX}\frac{|E_{total}|^2}{2Z_0} \quad (1.15)$$

$$P_{RX} = \left(\frac{\lambda}{4\pi}\right)^2 G_{RX} G_{TX} P_{TX}\left|\frac{e^{-j\beta\cdot r}}{r} + \ldots.\right|^2 \quad (1.16)$$

A function **Powercalculate** () was written that calculates the total received power due to all the MPC's according to formula (1.16), but with a slight modification. $G_{RX}\ and\ G_{TX}$ are not equal for every MPC. In case of a ground reflection, this MPC arrives at a different angle than the other components, therefore the gain will be different. The formula of (1.16) then becomes:

$$P_{RX} = \left(\frac{\lambda}{4\pi}\right)^2 P_{TX}\left|\sqrt{G_{RX}(\theta_1)G_{TX}(\theta_1)}\frac{e^{-j\beta\cdot r_1}}{r_1} + \Gamma_{\parallel}\sqrt{G_{RX}(\theta_2)G_{TX}(\theta_2)}\frac{e^{-j\beta\cdot r_2}}{r_2} + \ldots.\right|^2 \quad (1.17)$$

$$P_{RX} = \left(\frac{\lambda}{4\pi}\right)^2 P_{TX,\max} \left| \frac{E_{los}\sqrt{G_{RX}\left(\frac{\pi}{2}\right)G_{TX}\left(\frac{\pi}{2}\right)}}{\sqrt{60EIRP}} + \frac{E_{ref}\sqrt{G_{RX}\left(\frac{\pi}{2}\right)G_{TX}\left(\frac{\pi}{2}\right)}}{\sqrt{60EIRP}} + \frac{E_{gnd}\sqrt{G_{RX}(\theta_{RX,gnd})G_{TX}(\theta_{TX,gnd})}}{\sqrt{60EIRP}} \right|^2$$

$$P_{RX} = \left(\frac{\lambda}{4\pi}\right)^2 * 0.1472 * |0.0119 + 0.0280i + 0.0139 - 0.0039i + -0.0067 + 0.0208i|^2 = 2.9547e-10$$

$$P_{RX\text{-}simulation} = 3.3257e-10$$

(1.18)

1.3.5 DELAY SPREAD AND RICE FACTOR

The delay spread is the maximal time difference between the first ray to arrive and the last one. The time of arrival can be obtained from the distance travelled by a ray, using the speed of light $\tau_i = \frac{d_i}{c}$.

$$\sigma_\tau = \max|\tau_i - \tau_j| \quad \forall i,j$$
$$= \max\left|\frac{r_{los}}{c}, \frac{r_{ref}}{c}, \frac{r_{gnd}}{c}\right|$$
$$= \frac{r_{ref}}{c} - \frac{r_{los}}{c} = \frac{61.0332 - 55.9017}{3*10^8} = 1.7105 \times 10^{-8} \qquad (1.19)$$
$$\sigma_{\tau,simulation} = 1.7104e-08$$

In particular, when there is only one ray (diffraction) $\sigma_\tau = 0$ and when there is only LOS and ground reflection with $d_{direct} \gg 2h \, : \, d_{direct} \approx d_{ground} \; so \; that \; \sigma_\tau \approx 0$, this phenomenon will be seen at **impulse response chapter**.

The rice factor is the ratio between the squared direct ray amplitude a0 and the sum of all the other N squared rays amplitudes:

$$K = \frac{a^2{}_{los}}{\sum_{i=1}^{N} a^2{}_i}$$
$$= \frac{E^2{}_{los}}{E^2{}_{ref} + E^2{}_{gnd}} \qquad (1.20)$$
$$= \frac{0.0048}{0.0011 + 0.0025} = 1.33333$$
$$K_{simulation} = 1.3512$$

if there is no LOS, K = 0.

1.3.6 DIFFRACTION WAVE

The diffraction coefficient for the Knife-edge model can be approximated with d1 >> h and d2 >> h:

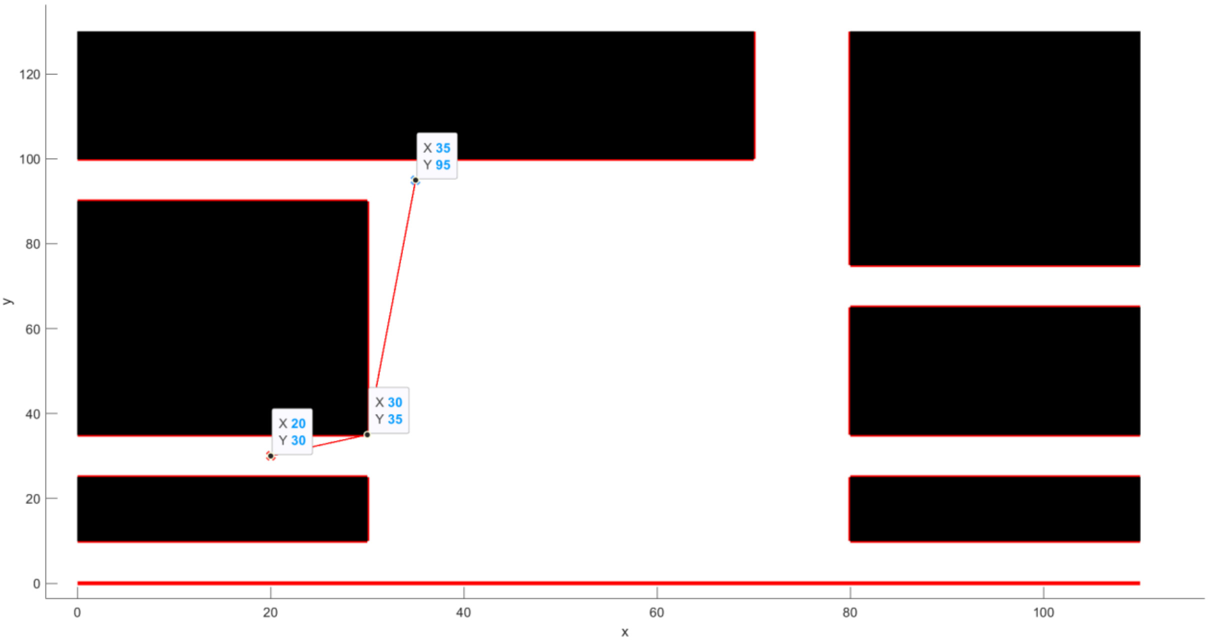


Figure 2: Specific case that will be used for validation (diffraction ray)

$$\begin{cases} \Delta r = \left(\sqrt{10^2+5^2}+\sqrt{5^2+60^2}\right)-\left(\sqrt{15^2+65^2}\right)=4.67999 \\ v=\sqrt{\frac{2}{\pi}\beta\Delta r}=\sqrt{\frac{2}{\pi}*544.543*4.67999}=40.279 \\ F(v)=\frac{1+j}{2}\int_v^\infty e^{-j\frac{\pi u^2}{2}du} \\ =\frac{1+j}{2}\left(\left(\int_0^\infty \cos\left(\frac{\pi}{2}u^2\right)du-j\int_0^\infty \sin\left(\frac{\pi}{2}u^2\right)\right)-\left(\int_0^v \cos\left(\frac{\pi}{2}u^2\right)du-j\int_0^v \sin\left(\frac{\pi}{2}u^2\right)\right)\right) \\ =\frac{1+j}{2}\left(\left(\frac{1}{2}-j\frac{1}{2}\right)-(C(v)-jS(v))\right)=\frac{1+j}{2}\left(\left(\frac{1}{2}-C(v)\right)-j\left(\frac{1}{2}-S(v)\right)\right)=0.0046+0.0064i \end{cases}$$

(1.21)

$$E_{diff}=F(v)\sqrt{60G_{TX}(\theta_{TX})P_{TX}}\frac{e^{-j\beta\cdot r}}{r}=2.4726e-4-2.1004e-4i \qquad (1.22)$$

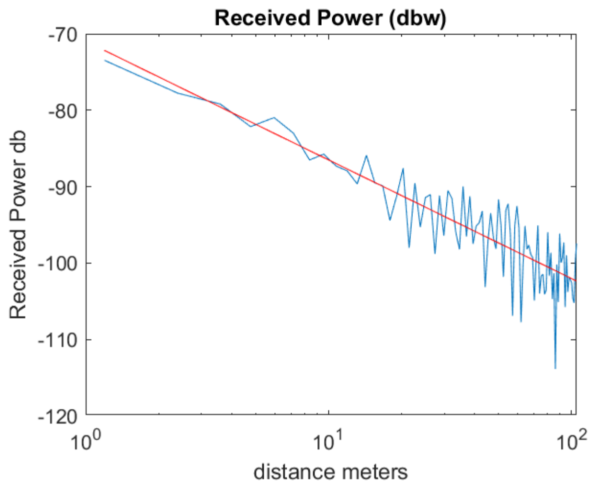
1.3.7 SNR

The receiver noise figure is given and equal to 12 dB, k is a constant, B equals 200 MHz and T has been arbitrarily chosen as 290 K.

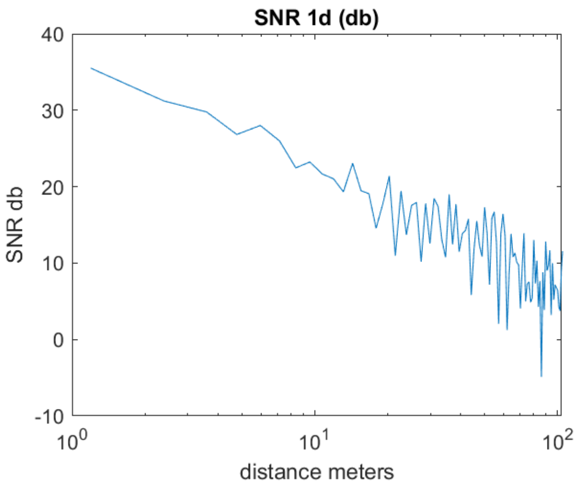
$$P_{noise}=F_{dB}+10\log(kTB)=-108.9701dB \qquad (1.23)$$

1.4 1D-plots and Heatmap

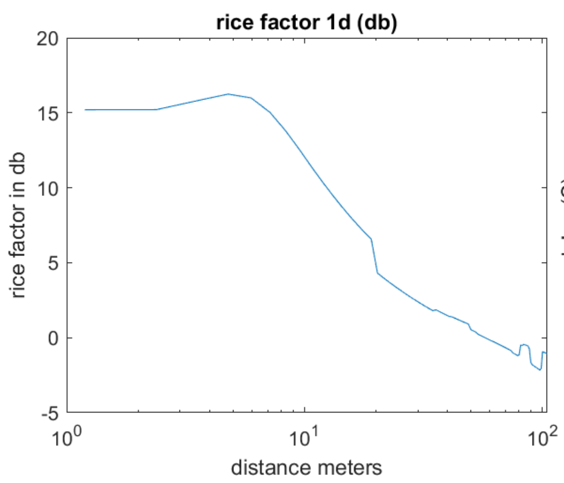
1.4.1 1D PLOTS



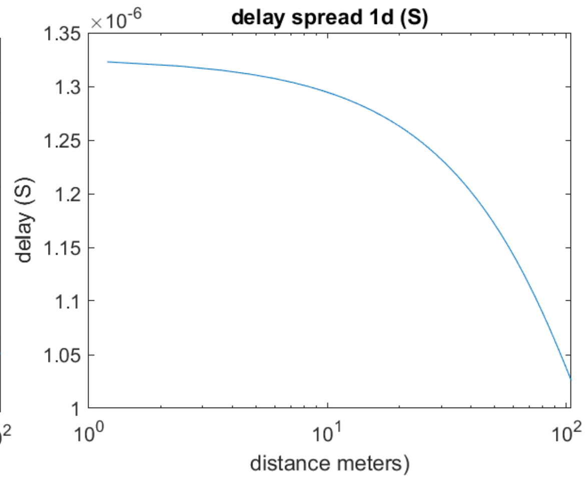
(a)



(b)



(c)



(d)

For the received power and the SNR: In order to calculate path loss exponent (**this will be used to derive path loss model in chapter 3**), The linear regression was applied to predict average power. it can be seen that there is a lot of variability as opposed to the average received power. This is due to the interference of the LOS and the reflected rays.

$$P_{RX}(d) = P_{RX}(d_0) - 10n\log\frac{d}{d0}$$
$$d_0 = 10,\ n = slop/-10 = -15.520/-10 = 1.552 \tag{1.24}$$

The path loss exponent of n= 1.5520 which is lower than the path loss exponent of **free space propagation** (n = 2).

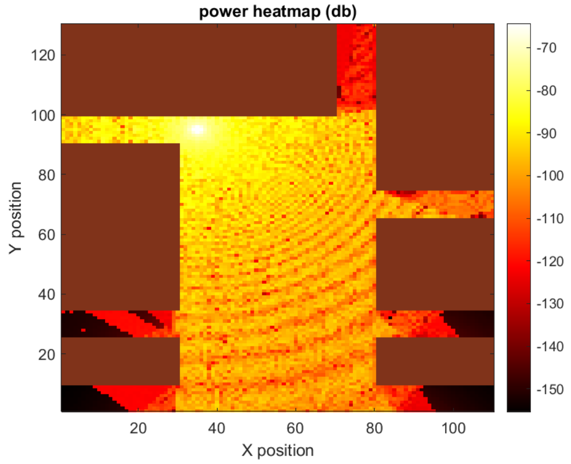
This can easily be understood by looking at the rice factor plot. There it is seen that starting from a distance around 90m to 100m, the rice factor (in dB) is less than zero, meaning that the reflected rays contribute more to the received power than the LOS ray. This combined with the fact that the relative path length difference between the LOS ray and the reflected rays becomes smaller for larger distances means more power is received at larger distances than for a **free space propagation model**.

Since the noise conditions are assumed to be identical for every location, the SNR curve is identical to the received power curve up to a constant difference based on the noise power.

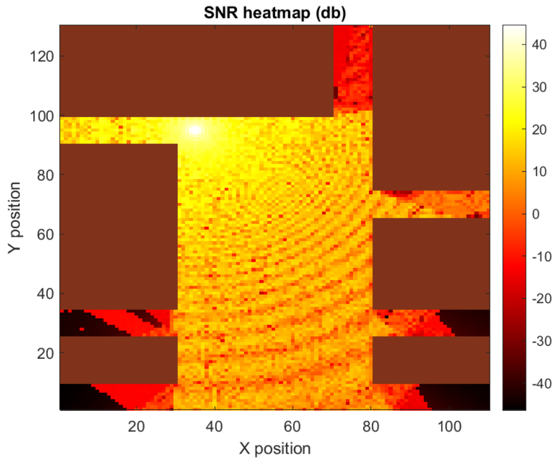
The Delay Spread can be seen to be decreasing for increasing distance. This is due to the earlier mentioned fact that the relative path length difference of the LOS and the reflected rays decreases for further distances.

Similarly, to the Delay Spread plot, the Rice Factor plot also shows a general downward trend. This is because of the same reason as for the Delay spread.

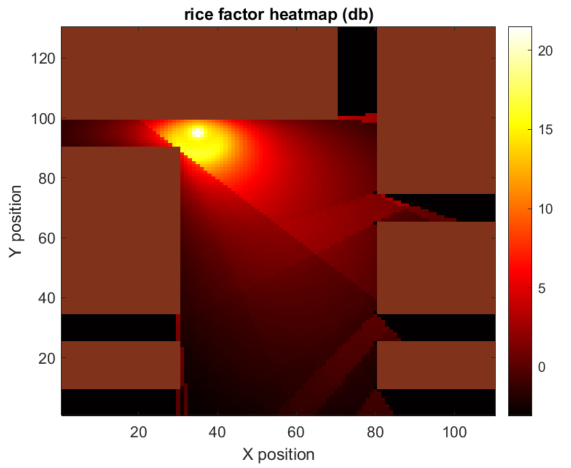
1.4.2 HEAT MAP



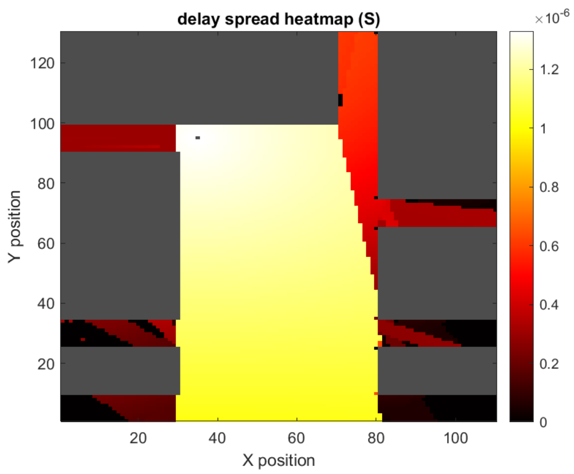
(a)



(b)



(c)



(d)

For **Received power and SNR heat map**:

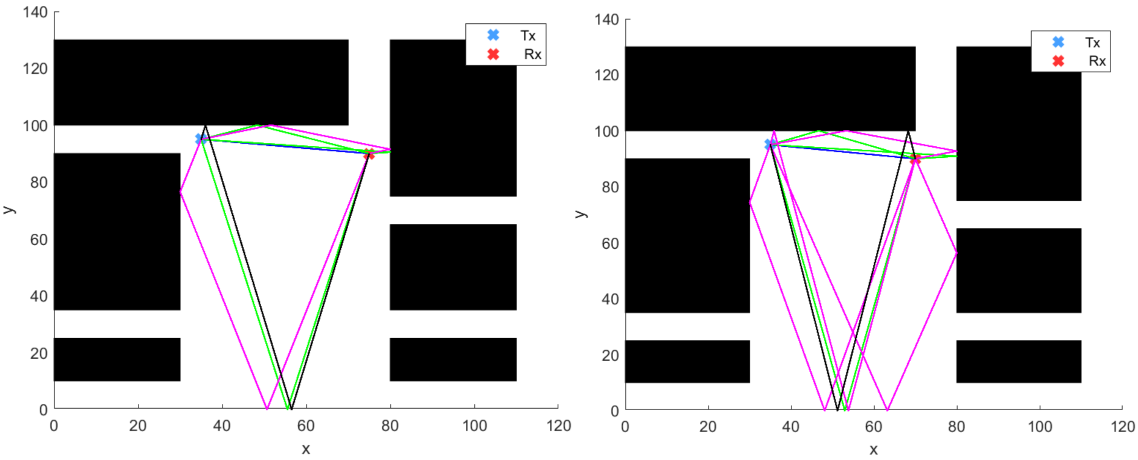
Visually, this figure corresponds to what we observed in 1D plot. Close to the transmitter, the received power is high. When moving away from this transmitter, the power decreases. In the LOS case, interference patterns between the ground ray and reflected ray can be seen as concentric circles.

For **Rice factor heatmap**

Combine with the 1d plot, At 10 m distance from the transmitter, the Rice factor is around 15 dB, At around 18 m from the transmitter, we could see the rice factor increase to 17 dB, and then it start to decreases , at 90m distance from transmitter , the Rice factor changes sign and the power of the multipaths becomes higher than the LOS power.

For **delay spread heatmap**

As expected, the delay spread is higher close to the BS, because the difference of the path lengths- between the reflection and the direct ray is relatively higher than in the case where we are far away from the BS.



(a) Rx= (75,90) max propagation lengths =199.0603 (b) Rx= (70,90) max propagation lengths 406.0825

As shown in above figure, the Black line is the ray of maximum length propagation, we could see the left figure max propagation length is nearly twice than the right one, so this is why we could see a suddenly change at top right corner.

It is also clear that the rays don't reach too deep into the streets.

CHAPTER 2 IMPULSE RESPONSE

The analyses of the time of arrival of each rays have to be done only for some points but for multiple bandwidths, from narrowband to 200MHz. The narrowband limit is $B \ll \triangle f_c$ with the coherent bandwidth $\triangle f_c = \dfrac{1}{\sigma_\tau}$

2.1 Theoretical analyses

Physical impulse responses:

For the physical impulse responses, we have to consider the time of arrival of each ray, which is directly proportional to the travelled distance: $\tau_i = \frac{d_i}{c}$ We can then visualise the impulses due to each ray.

$$h(\tau) = \sum_{\mathrm{n}=1}^{\mathrm{N}} a_n e^{j\phi_n} e^{-j2\pi f_c \tau_n} \delta(\tau - \tau_n) \;\; with \;\; a_n = \sqrt{\frac{P_{RX_n}}{P_{TX}}} \qquad (2.1)$$

TDL impulse responses:

The UE does not have infinite bandwidth, and for a bandwidth B it would need a sampling frequency $f_s = 2B$ which result in sample taps of duration $\Delta\tau = \frac{1}{2B}$. Knowing that the expression of a band-limited signal is $x(t-\tau) = \sum_{l=-\infty}^{\infty} x(t - l\Delta\tau)\sin c(2B(\tau - l\Delta\tau))$, we can compute the Tapped Delay Line (TDL) impulse response:

$$\begin{aligned} h_{TDL}(\tau, t) &= \sum_{l=0}^{L} h_l(t)\delta(\tau - l\triangle\tau) \\ h_l(t) &= \sum_{n=1}^{N} \alpha_n(t)\sin c(2B(\tau_n - l\Delta\tau)) \end{aligned} \qquad (2.2)$$

Uncorrelated scattering TDL impulse responses:

If we consider that the value of $\sin c$ is not negligible only when $\tau_n l\Delta\tau$, we can do a first approximation to obtain:

$$h_l(t) \approx \sum_{\tau_n \in tap \;\; l} \alpha_n(t) = \sum_{\tau_n \in tap \;\; l} a_n(t) e^{j\phi_n(t)} e^{-j2\pi f_c \tau_n} \qquad (2.3)$$

2.2 Physical impulse response simulation

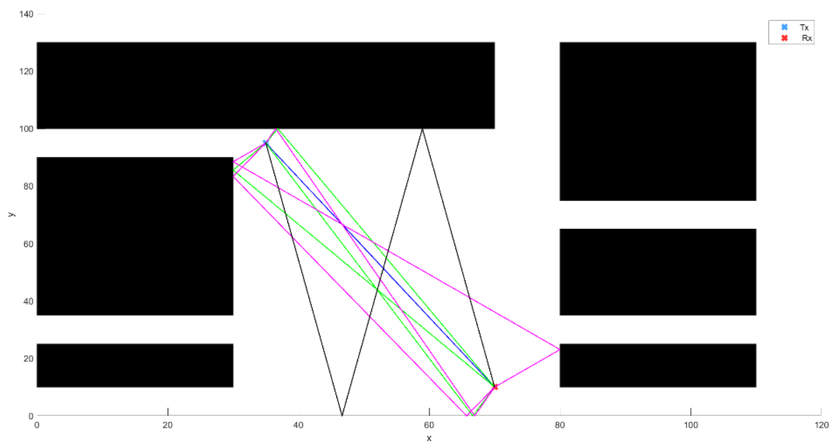


Figure 3 : Rx=(70,10) Los & Gnd (blue) ;single reflect(green) ;double reflect(pink & black)

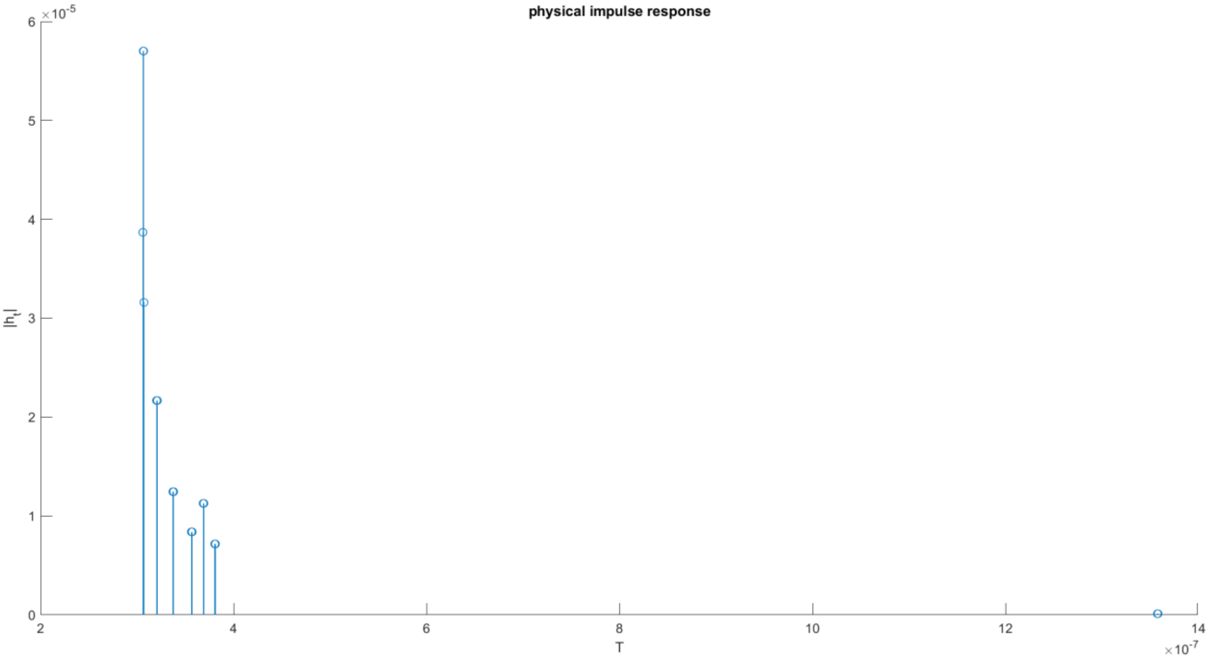


Figure 4

As shown in **Figure 3 and Figure 4**, First, we could see there is little difference in time arrival between the LOS and ground reflected wave (as we discuss in delay spread). Then the first, second reflections arrive. The attenuation factor decreases also as expected, with the increase of reflection times and distance, we could see the amplitude of rays become smaller and smaller, At end, around t=13*10^-7s, this is the ray of maximum length propagation, witch amplitude is nearly equal to 0.

2.2 TDL impulse response

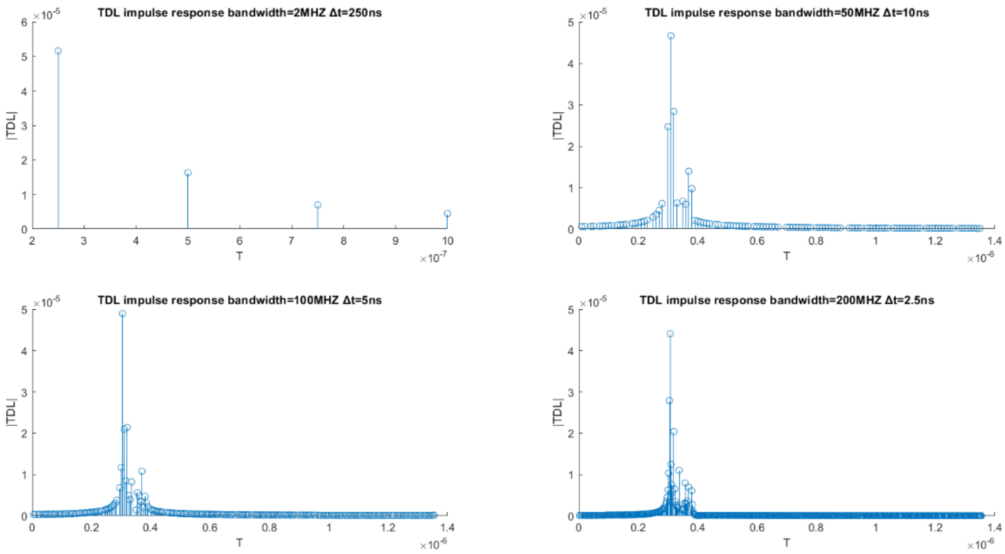


Figure 5

Due to the $\mathrm{sin}c$ function, each ray will contribute to every tap. The used bandwidth will have influence on how far the taps are from each other. And we also could see when we increase the bandwidth , the leakage of impulse response decrease , therefore The bigger the BW, the better the correct taps are highlighted.

2.3 US TDL impulse response

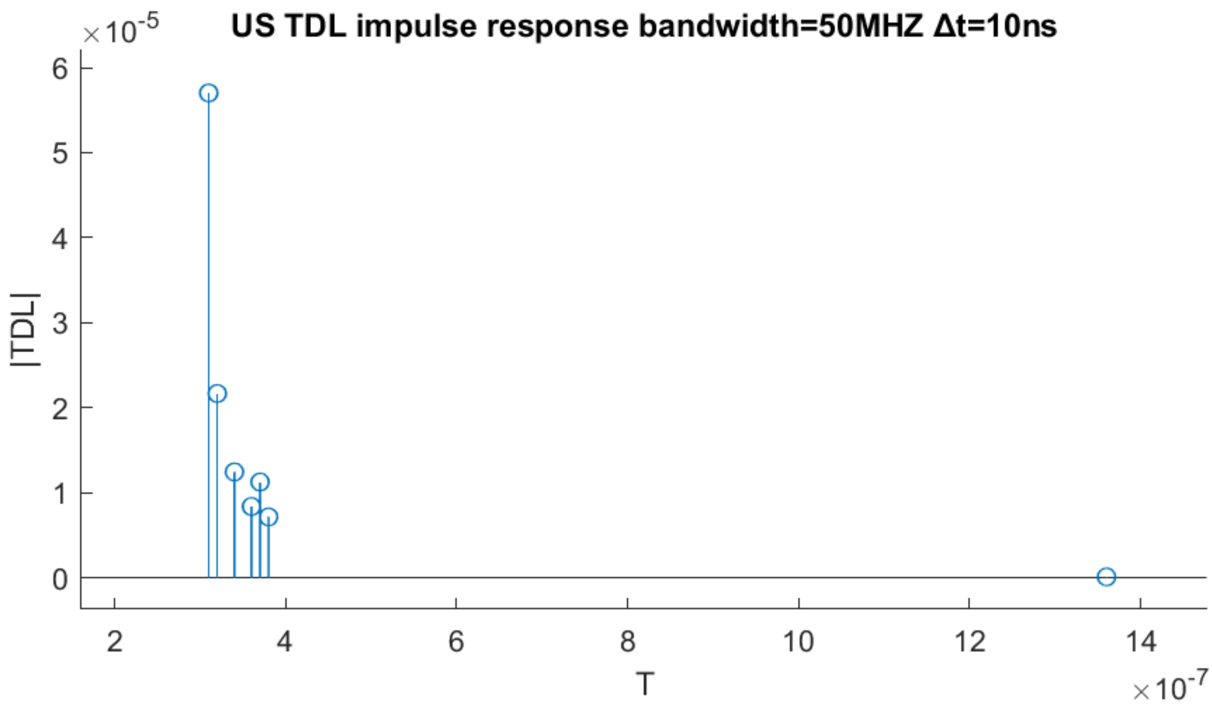


Figure 6

The TDL impulse response can be approximated by the uncorrelated scattering assumption given by formula (2.3). Instead of using a sinc, all the amplitudes between two consecutive taps will be summed. the US TDL looks very similar to the physical impulse response with the only exception that the LOS and ground reflected wave are summed up in the same tap. This is because the ground reflected wave arrives very closely after the LOS wave.

CHAPTER 3 PROPOGATION MODEL

3.1 Path loss model

With the path loss exponent $n = 1.552$ (we already derived it in chapter 1),

$d_0 = 10m$, $P_{RX}(d_0) = -73.5383dB$,

The path loss model can be expressed as (in decibel scale):

$$L_0(d_0) = P_{TX,\max} - P_{RX}(d_0) = 10*\log 10(0.147262) - (-73.5383) = 65.2192dB$$

$$L_0(d) = L_0(d_0) + 10n\log\frac{d}{d_0} \tag{3.1}$$

$$= 65.2192 - 15.52\log\frac{d}{d_0}$$

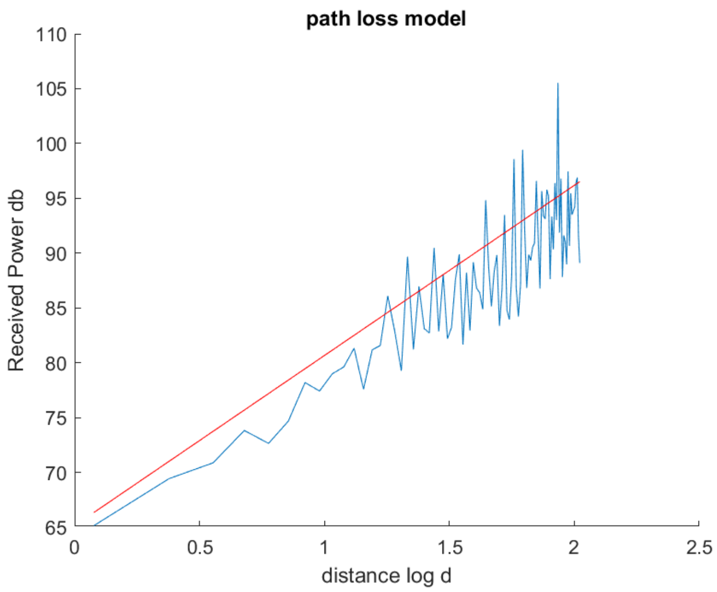


Figure 7: 1D plot path loss

3.2 Fading variability

The fading variability can also be computed as the variance of the power P_{RX} around the mean $\bar{P}_{RX}$ (the linear approximation):

$$\sigma^2{}_L = \frac{1}{N}\sum_{n=1}^{N}\left(P_{RX,i} - \bar{P}_{RX,i}\right)^2 \tag{3.2}$$

That gives us $\sigma = 3.7932dB$. That allow us to consider random normal distribution L_{σ_L} with zero mean and variance σ_L:

$$L_d = L_0(d) + L_{\sigma_L} \tag{3.3}$$

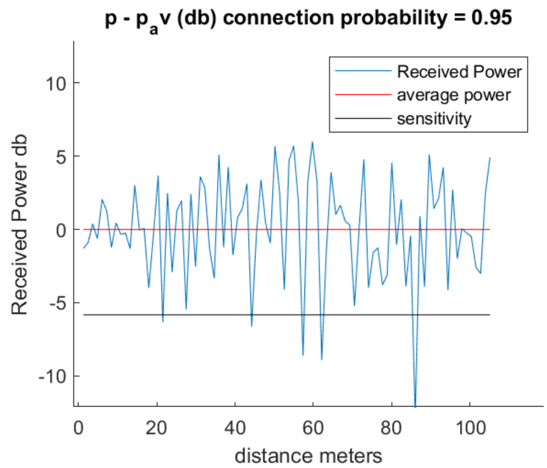


Figure 8

3.3 Cell range

For a certain required connection probability, a fade margin can be determined using

$$\gamma = \sigma\sqrt{2}\cdot erfc^{-1}(2\cdot(1-p)) \qquad (3.4)$$
$$p = 0.95, \gamma = 6.2393dB$$

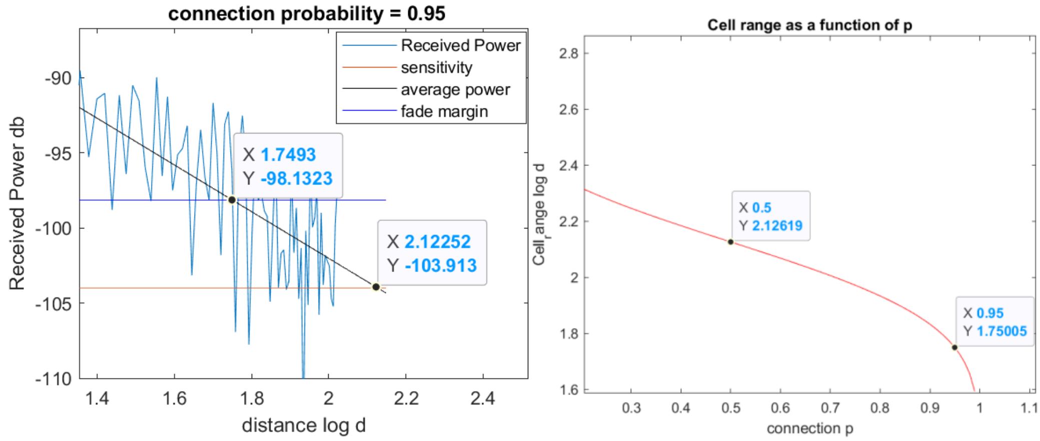


Figure 9: **(a)** **(b)**

To know Cell range as a function of connection probability at cell edge, a minimum Received power has to be determined first, the project description specifies that the target SNR at the receiver should be 5dB, Since the SNR is just the received power divided by the noise power, therefore minimum Received power could be deduced:

$$P_{RX,\min imum} = SNR_{target} + P_{noise} \qquad (3.5)$$
$$= 5 + (-108.9701) = -103.97dB$$

$$P_{RX,\min imum,add\ \gamma} = P_{RX,\min imum} + \gamma = -103.97 + 6.2393 = -97.7307 \qquad (3.6)$$

First, We look at the **Figure 9**(a) , when we don't consider fade margin , the maximum Cell range is around 2.12 with log scale , then after adding fade margin on minimum Received power , the maximum Cell range decrease to 1.7493 with log scale. Combine equation (1.24) with (3.6) , we could derive:

$$d = d_0 * 10^{(P_{RX,\min imum,add\ \gamma} - P_{RX}(d_0))/-10n} \tag{3.7}$$

The plot based on this could be seen in **Figure 9**: (b) , when we increase the connection probability , the maximum Cell range will decrease .

3.4 full connection probability throughout the whole cell

The full connection probability throughout the whole cell in function of the fade margin is given by:

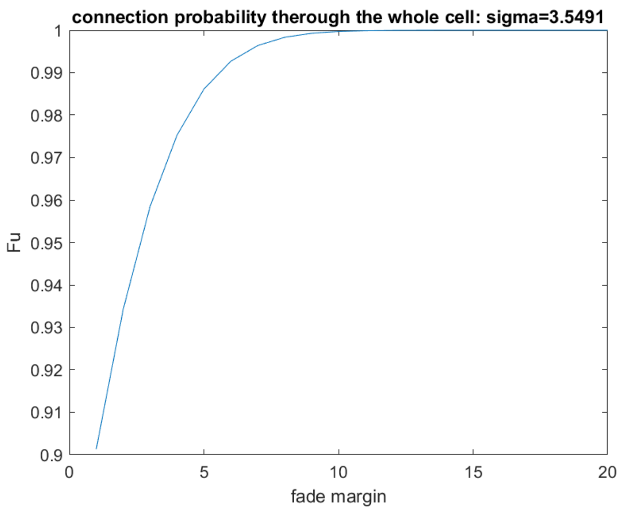


Figure 10

$$a = \frac{\gamma}{\sqrt{2}\sigma_L}$$

$$b = \frac{1}{\sqrt{2}\sigma_L} 10n \log e \tag{3.8}$$

$$F_u = 1 - \frac{1}{2} erfc(a) + \frac{1}{2} e^{\frac{2a}{b} + \frac{1}{b^2}} erfc\left(a + \frac{1}{b}\right)$$

We could see when we need more connection probability, the more fade margin will be added.

3.5 Conclusion

All the requirements for this project were met. By using the divide and conquer approach, small pieces of code were written and once verified further built upon. This ensured the obtained results were correct. the main pieces of code like calculating the power have been extensively verified (as they are the building blocks for the rest of the report) and should therefore be correct. Overall I feel like this project has been a success and made me gain more insight in the theory learned during the classes.