Bachelorarbeit

Channel Selection for Wearable Wireless Devices in the THz Range

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Declaration

To the best of my knowledge and belief this work was prepared without aid from any other sources except where indicated. Any reference to material previously published by any other person has been duly acknowledged. This work contains no material which has been submitted or accepted for the award of any other degree in any institution.

Erlangen, July 31, 2017

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Contents

Abstract

Wearable wireless devices (WWDs) carried on the human body are expected to play an important rule in future body area networks. Recent works have indicated that the THz (Terahertz) band ($0.1 - 10$ THz) possesses attractive properties for the development of such systems, especially for reducing the interference when multiple WWD bearers exist in closed proximity. In this thesis, we consider a system of WWDs where each device selects a channel from a set of K orthogonal channels, with a bandwidth of approximately 2 GHz per channel, located in the THz Band. The goal is to investigate how the frequencies choices of these channels influence the performance of a WWD system for different user densities.To this end, the cumulative distribution function (CDF) of the signal-to-noise-interference-plus-noise ratio (SINR)of the users in such scenarios for different frequency choices will be analyzed.

Los dispositivos inalámbricos portátiles (WWDs) que se usan sobre el cuerpo humano jugarán un papel muy importante en las redes de area corporal. Recientes trabajos han indicado que la banda de ($0.1 - 10$) THz (Terahercios) posee propiedades muy atractivas para el desarrollo de estos sistemas, especialmente para reducir la interferencia cuando múltiples WWDs están muy próximos. En este trabajo fin de grado, consideramos un sistema de dispositivos inalámbricos portátiles donde cada sistema selecciona un canal de un conjunto de K canales ortogonales, con una banda de 2 GHz por canal, localizados en la banda de THz. El objetivo es investigar cómo la elección de frecuencia de estos canales influye la representación de los sistemas de WWD para diferentes densidades de usuarios. Para finalizar, la función de distribución acumulada (CDF) de la signal-to-interference-plus-noise ratio(SINR) de los usuarios cuando estos eligen diferentes frecuencias en escenarios será analizado.

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Glossary

Abbreviations

CDF	Cumulative Density Function
EM	Electromagnetic
ET	Transversal Electric
ISI	Intersymbol-Interference
LOS	Line-of-sight
MLSE	Maximum-Likelihood Sequence Estimation
MA	Molecular Absorption
NLOS	Non-line-of-Sight
PAM	Pulse Amplitud Modulation
RH	Relative Humidity
RS	Random Selection
SCS	Single Channel Selection
SNR	Signal-to-Noise Ratio
SINR	Signal-to-Interference-Plus-Noise Ratio
THz	Terahertz
WWD	Wearable Wireless Devices

Constants

c = 2.99979×10^{8} [m/s], Speed of Light
K_B = $1.3806 \times 10^{-}(23)$ [J/K], Boltzmann's Constant
N_A = $6.0221 \times 10^{(}23)$ [molecule/mol], Avogadro Constant
T_K^0 = 296 [K], Reference Temperature
μ_0 = $4\pi \times 10^{-}(12)$ [F/m], Permitivity in Vacuum
Z_0 = 377[Ω], Free Space Wave Impedance

Symbols

$\alpha(f)$	Extinction Coefficient [cm^{-}1]
BW	Bandwidth [Hz]
f	Frequency [Hz]
Γ	Fresnel Reflection Coefficient
$h_c(t)$	Continuous-Time Channel Impulse Response
$h[u]$	Discrete-Time Channel Impulse Response
$\kappa(f)$	Molecular Absorption Coefficient [cm^{-}1]

L_{abs}^{dB}	Molecular Absorption Loss [dB]
L_{free}^{dB}	Free-Space Propagation Loss [dB]
$n_r(f)$	Index of Refraction
N_0	Power Spectral Density of Noise [W/Hz]
r	Path Length [m]
ρ	Scattering Coefficient
$\tau(f,r)$	Transmittance
T_0	Reference Temperature [K]
T	Temperature of the Medium [K]
$\tau(f,r)$	Transmittance
τ	Delay of the Path [s]
θ_i	Incident Angle
θ_r	Reflected Angle
$Z(f)$	Wave Impedance [Ω]

Chapter 1

Introduction

Currently, wearable wireless devices are expanding fast in our society. Devices such as smartphones and tablets will see explosive growth and high adoption rates over the next years. For this reason, wearables will need to be more sophisticated, capturing what the users can see, hear or even feel. Today, all signs indicate that wearables will be the "next big thing" within the mobile ecosystem. It is expected to see a big amount of new wearable devices, such as smartphone-compatible watches, innovative healthcare solutions and many variations of smartglasses. Consequently, it is expected that in 2018 the wearable industry will have revenues around 5- 30 billion dollars [3].

Due to the development of this technology, the communications between wireless devies must be analyzed to find a way for a realization with low-latency high-speed data connections in order to enable truly demanding use cases [3].

A WWD can be defined as an electronic device that can be carried on the human body, this characteristic will allow WWDs to be soon a mainstream technology for the costumers. It is important to say that WWD will have a huge importance in the medical field as well, applications such as telemedicine and the constant monitoring of patients for example with heart diseases, diabetes, etc. could be performancedmore accurately[1].

Nowadays, already available commercial WWDs use the unlicensed bands around [2.4-5] GHz [3]. Until now, these bands are enough for low data rate but when there are many users the band becomes overcrowded, for instance: in public transportation, in public events, in public places, etc. Furthermore, it has to be considered that the number of persons is greater than the amount of mobile phones so this makes the situation more challenging.

Because of the limited bandwidth and the great interference present in the range of $[2.4-5]$ GHz these bands are inadequate to support the cases mentioned before. They will also not support high date rates required for WWDs.

Another aspect to contemplate is how far frequencies can be reused without provoking interferences depending on the propagation characteristics of the frequency band used.

To fulfill the necessary requirements to have a reliable communication link between the WWDs the frequency band between 0.1 THz to 10 THz will be studied in this research.

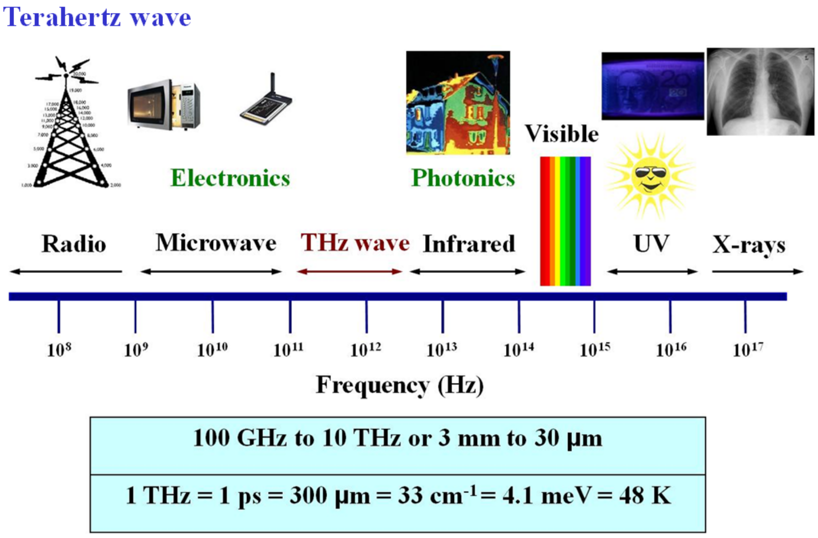

Figure 1.1: Electromagnetic Spectrum

The propagation characteristic of the EM waves over the THz channel have been studied in [4] [5] [1]. Based mostly on [1], this thesis will analyze the reliability of the communication link when there are several users in an indoor scenario. Right now, it is unknown how much bandwidth will be required by a WWD but based on the requirements needed currently, it is expected that a data rate of 1 Gbps will be enough to fulfill the needs of the users.

In Chapter 2, the propagation of EM waves through the THz channel as well as the molecular absorption, the free-space propagation and noise will be described. The user model, indoor scenario and the digital communication system are described for the communication between WWDs in Chapter 3. In Chapter 4, the SINR will be analyzed to know how the aspects described in the previous chapters affect the communication link. In Chapter 5, the best channels performance will be shown. Finally, the thesis is concluded in Chapter 6.

Chapter 2

Line-of-Sight Propagation and Molecular Absorption in the THz Channel

The main characteristics of the line-of-sight(LOS)propagation in the THz frequency band will be analyzed in this chapter, focusing on the features that can be exploited to construct a reliable communication channel. The usage of the THz band for "long" distances will be investigated, this term refers only to a few meters because of the huge attenuation characteristics of this band. In this research, the molecular absorption will be exploited and it has to be mentioned that this phenomenon is relatively fixed for a specific frequency but its impact depends on several factors like temperature, atmospheric conditions, etc. This work is focused on short distance communications between WWDs, furthermore the THz band will provide the requirements of WWDs in terms of bandwidth and interference attenuation, where the role of the path loss is truly important[1].

2.1 Path-loss Model

When an EM wave goes through the medium it suffers a path-loss which depends on the frequency and the distance between the transmitter and receiver. On the other hand,the molecular absorption effect plays an important role if it is considered in the transmission when the THz band is exploited. Thus, the formula to describe the total attenuation considering a communication link in the THz band is:

$$L(f,r) = L_{free}(f,r) \cdot L_{abs}(f,r), \tag{2.1}$$

where $L_{free}(f,r)$ represents the free-space propagation loss, $L_{abs}(f,r)$ describes the molecular absorption loss, f is the frequency and r is the distance between transmitter and receiver. These contributions will be analyzed meticulously in the subsequent sections.

2.1.1 Free-space Propagation Loss

The free-space propagation loss is only the propagation of the EM wave through the medium and it can be written as:

$$L_{free}(f,r) = \left(\frac{4 \cdot \pi \cdot f \cdot r}{c}\right)^2, \tag{2.2}$$

where c is a constant which describes the speed of the light. The frequency will have values between $[0.1 - 10]$ THz, so this makes the propagation loss very large in this range. Another important parameter in the equation is the distance r, which can be controlled and it should be very low in comparison to the frequency. Then, the loss caused by the frequency could be compensated by the effect of the distance. Figure (2.1), shows the result of Equation (2.2) for the free-space propagation loss.

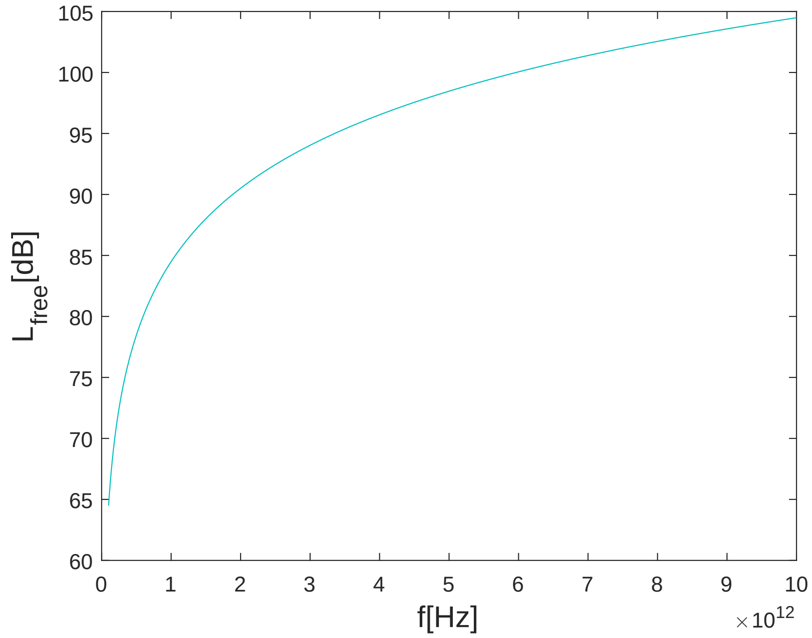

Figure 2.1: Free-space propagation loss for r=0.4 m

2.1.2 Molecular Absorption Loss

The molecular absorption phenomenon is caused when the selected frequency for the transmission of EM waves is around the same value as the resonant frequency for internal vibration modes in a molecule [5]. Then, the absorbed energy is converted to kinetic energy. The molecular absorption depends on several factors such as temperature, atmospheric conditions, physical properties of the molecules, etc. This phenomenon does not have any specific value for a given frequency. A mathematical way to know its value is through the transmittance of the medium. Thus, the molecular absorption loss can be expressed by:

$$L_{abs}(f,r) = \frac{1}{\tau(f,r)}. \tag{2.3}$$

In Equation (2.3), it is observed that this event is no more than the transmittance of the medium. The fraction of energy that is able to pass through the medium is called transmittance. According to [5] its calculation can be made using the Beer-Lambert Law given bye:

$$\tau(f,r) = e^{-k(f)\cdot r}. \tag{2.4}$$

It can be observed that the transmittance is directly dependent on the distance and implicitly connected with the frequency through the absorption coefficient $k(f)$. T his factor contains specific information about the frequency and the external factors that are related with molecular absorption. See the following equation:

$$k(f) = \sum_{i,g} k^{i,g}(f) \tag{2.5}$$

A deep explanation about this has been done in [1], [5]. According with their description, the molecular absorption will suffer an important impact if parameters such as pressure, temperature or relative humidity have a variation even if this is insignificant. The absorption coefficient (2.5) is the sum of all the individual absorption coefficients of molecules of a single isotopologue [1] "i" of a gas "g" a[5]. Given different climatic conditions the molecular absorption will change, but this research is focusing only on normal climatic conditions for t=23°C and RH= 40% (Relative Humidity)because the normal weather represents well the indoor conditions. In Figure 2.2, a representation of this phenomenon in normal conditions can be observed by using Equation (2.2) and it is noticeable that values for molecular absorption are extremely high for some frequencies. In Figure 2.3, it can be observed that for low frequencies the MA absorption does not play an important role, but for high frequencies the impact is very noticeable. Furthermore, for some frequency intervals the MA is irrelevant. Here, in this figure the distance r is 0.4 m, the green line is under the MA influence while the red line is without MA.

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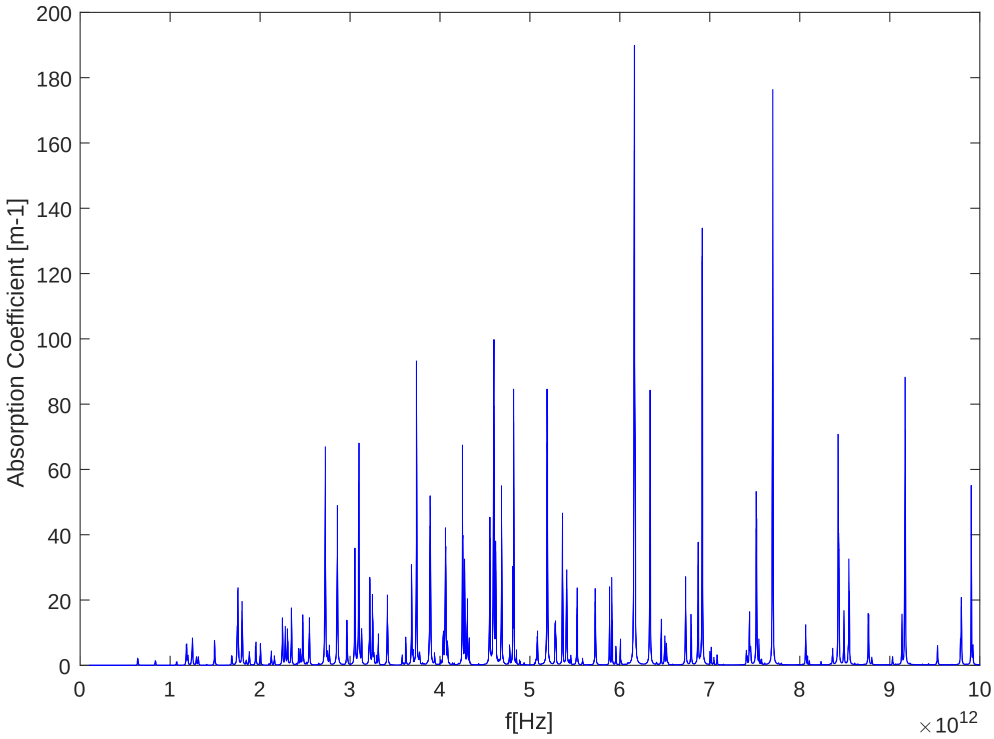
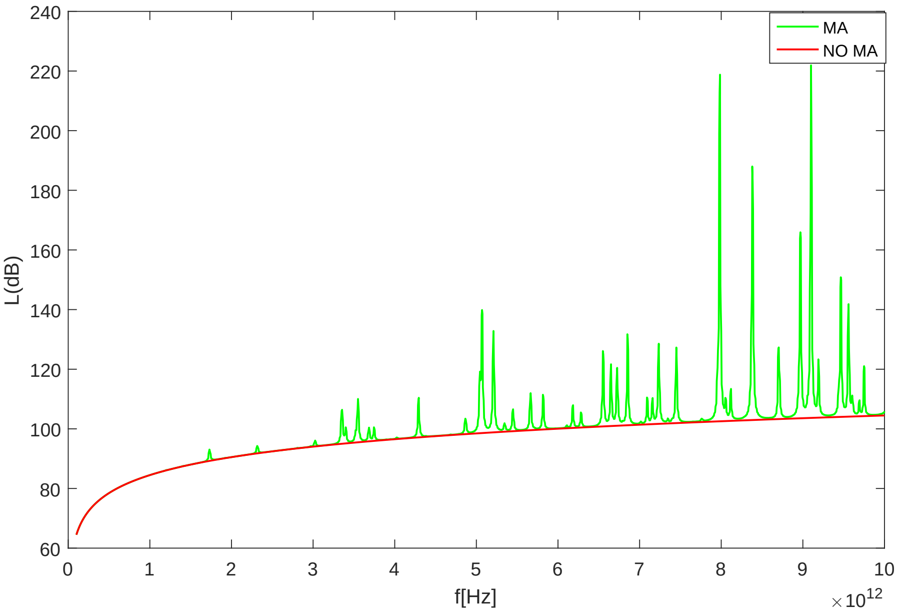
[1] A molecule that only differs from another in its isotopic composition



(a) Normal weather for t=23°C and RH= 40%

Figure 2.2: Molecular absorption



(a) Distance between desired receiver and desired transmitter for r= 0.4 m

Figure 2.3: Molecular absorption for a short distance

2.1.3 Transparency and Molecular Absorption Windows

During the communication through the THz band it is necessary to work with the molecular absorption and the free propagation loss at the same time. Then, built a reliably communication link under this conditions is especially complicated. In Figure 2.2 can be observed that there are certain zones where the molecular absorption is almost negligible. These zones or gaps are called "*transparent windows*", which are defined as a group of consecutive frequencies with transmittance of the medium higher than 95% [1]. These windows are not used for this research, because they are suitable for long distances transmissions and not for short distances.

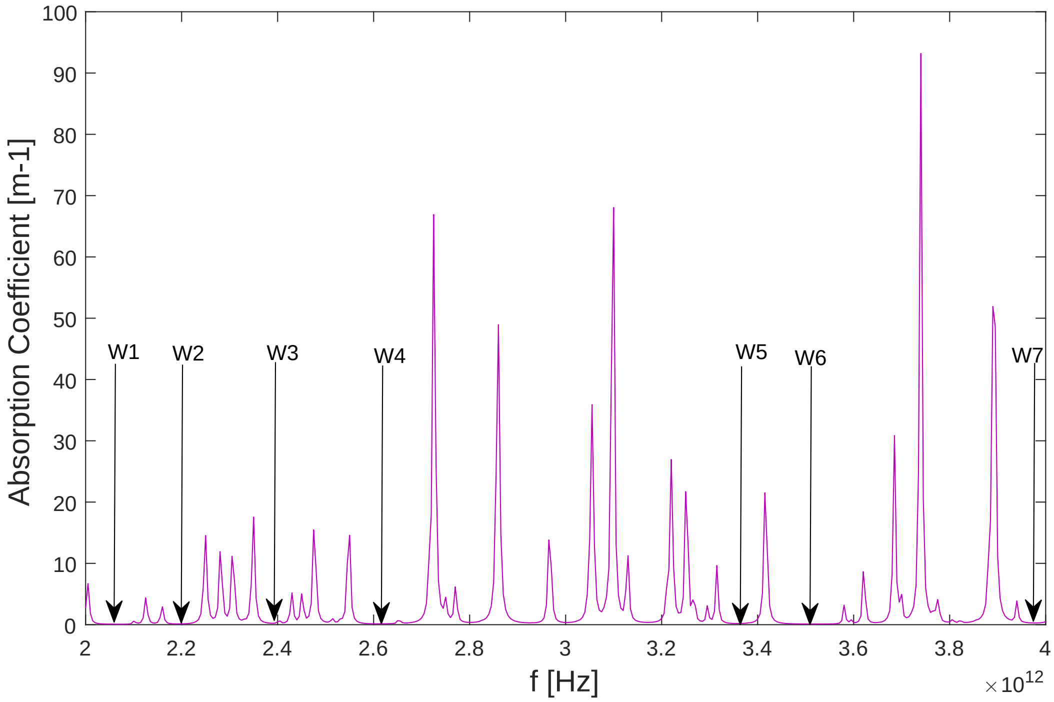


Figure 2.4: Transparency windows

The usage of these windows for transmission provide the opportunity to avoid the molecular absorption effect and only deal with the free-space propagation loss. In a transparency window, a higher area could be covered due to molecular absorption does not play a significant role. In Figure 2.4 a range between [2—4] THz is analyzed to identify the transparency windows and seven windows are found. Previously, the transparency windows were found but there exist other segments where the molecular absorption is considerably noticeable. These segments are known as "*molecular absorption windows* " and it seems that these windows are not useful. It is important to highlight that if the distance between transmitter and receiver is very short, the molecular absorption influence is almost negligible [1]. Thus, the transmission depends mostly on the free propagation loss and it is as if the communication link is built in a transparency window.

Nonetheless, if the distance is considerably high then the attenuation grows exponentially. This event is beneficial when simultaneous transmissions from different devices are created at the same time, making that the interference decreases efficiently and improving the transmission. It is needed to take into account that variations in the distance, temperature or in the relative humidity (RH) could modify the properties of these windows in terms of height and width. Then, it is difficult to know how much bandwidth is occupied at a given time.

In Figure 2.5, the main molecular absorption windows can be observed. The range [2—4] THz is examined and 19 windows are found. Then, in comparison with the number of transparency windows the amount of molecular absorption windows is higher.

Due to the fact that new applications in WWDs do not require a high area coverage but they demand a high data rate, the molecular absorption windows can be exploited to fulfill these requirements.

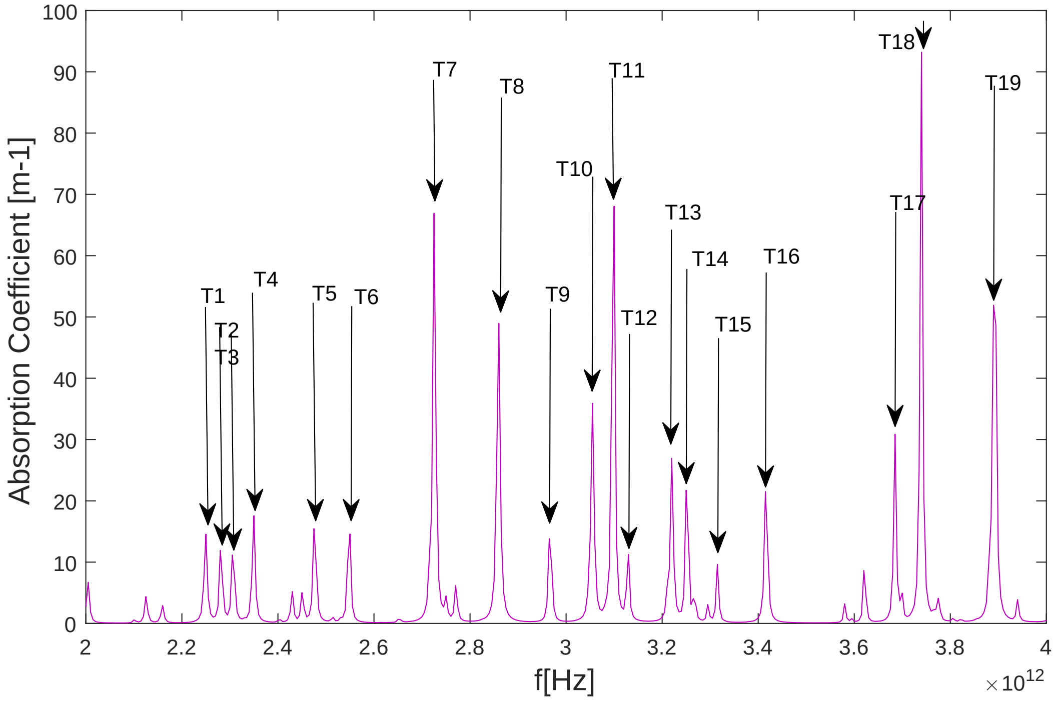


Figure 2.5: Molecular absorption windows

2.2 Noise Under the Influence of Molecular Absorption

The molecular absorption phenomenon attenuates the EM signals and besides also inserts noise during the transmission. This noise is added when the internal vibrations in the molecules are transformed into EM emissions, which are at the same frequency as the ones who are absorbed [1].

The ambient noise is formed by thermal and molecular noise:

- Thermal noise: assumed to be white. Its power spectral density is described by:

  $$N_{0_{thermal}}(f) = K_B \cdot T_{sys}, \tag{2.6}$$

  where K_B defines the Boltzmann constant,T_{sys} denotes the system electronic temperature.

- Molecular noise: in this case, white noise approximation is valid when the signal bandwidth is small. The power spectral density of the molecular noise can be defined as:

  $$N_{0_{mol}}(f,r) = K_B \cdot T_{mol}(f,r), \tag{2.7}$$

  where $T_{mol}(f,r)$ is the molecular noise temperature which is dependent on frequency and distance. See Equation below:

  $$T_{mol}(f,r) = T_0 \cdot (1 - \tau(f,r)) = T_0 \cdot (1 - e^{-k(f)\cdot r}), \tag{2.8}$$

  where T_0 and $\tau(f,r)$ are the reference temperature and the transmittance of the medium (2.4), respectively.

According to the studies done in [1], it can be concluded that principally the thermal noise contributes to the noise power. Furthermore, the overall noise power spectral density can be denoted as:

$$N_0(f,r) = N_{0_{thermal}}(f) + N_{0_{mol}}(f,r), \tag{2.9}$$

and if it is assumed that $T_{sys} = T_0 = 293K$ then:

$$N_0(f,r) = K_B \cdot (T_0 + T_0 \cdot (1 - e^{-k(f)})), \tag{2.10}$$

In this thesis, to consider the molecular absorption effect the noise will be computed as:

$$N_{thermal}(f) = 2 \cdot K_B \cdot T_{sys}, \tag{2.11}$$

In Equation (5.3), it is assumed that each frequency has MA influence, which is not correct. It has been observed that certain frequencies are not affected by molecular absorption. Thus, a pessimistic analysis is assumed.

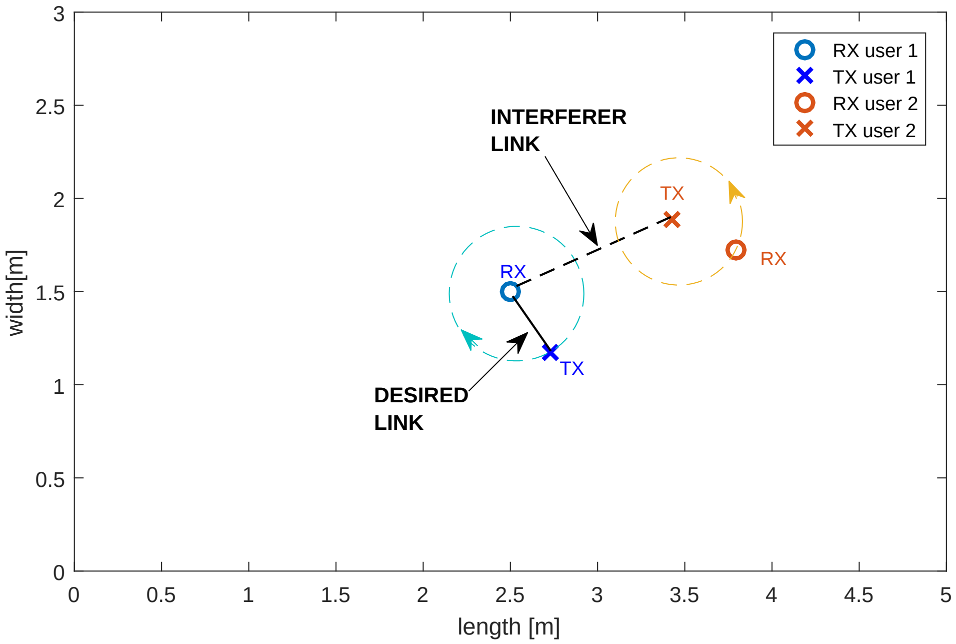
Chapter 3

System Model and Digital Communication System

The system model of the communication link will be designed: the user and his WWD, the indoor scenario, covering all the probable characteristics which could affect the communication transmission. The propagation of the EM is analyzed in detail in terms of LOS and NLOS, focusing on the reflected waves, building materials and their scattering effects. These factors help to describe the NLOS more accurately. Furthermore, the continuous-time and discrete-time impulse responses of the channel are obtained considering the events mentioned before.

3.1 User Model

It is important to remember that the high attenuation characteristics of the propagation medium, and variations in distance will cause a meaningful impact in the performance of the communication. The users will be designed in a two-dimensional space although, this type of representation does not provide many variations in comparison with a tree-dimensional space, it can help to understand how it works in the real life. The most basic and important component is the user, which is equipped with two wearable devices: transmitter ("*desired transmitter*") and receiver ("*desired receiver*"). Furthermore, the communication link between them will be designated as "*desired link*". Considering the practical applications available nowadays, the LOS link between the *desired receiver* and *desired transmitter* will be always available. The distance between *desired receiver* and *desired transmitter* is short, which can imitate the use of a WWD carried on the human body. Similarly, the interferer user has the same characteristics. Thus, the communication link between *desired receiver* and *interferer transmitter* will be denominated "*interferer link*". This description can be observed in Figure 3.1.



(a) Two users in a room size 5 m x 3 m

Figure 3.1: User model: Desired and interferer link

3.2 Scenario for the Wearable Wireless Devices

Once described how the users are, the area where the WWD devices will be hosted is described. The scenario will be indoors, where the obstacles and the multipath propagation coming from the reflections are the dominant factors that influence the propagation channel.

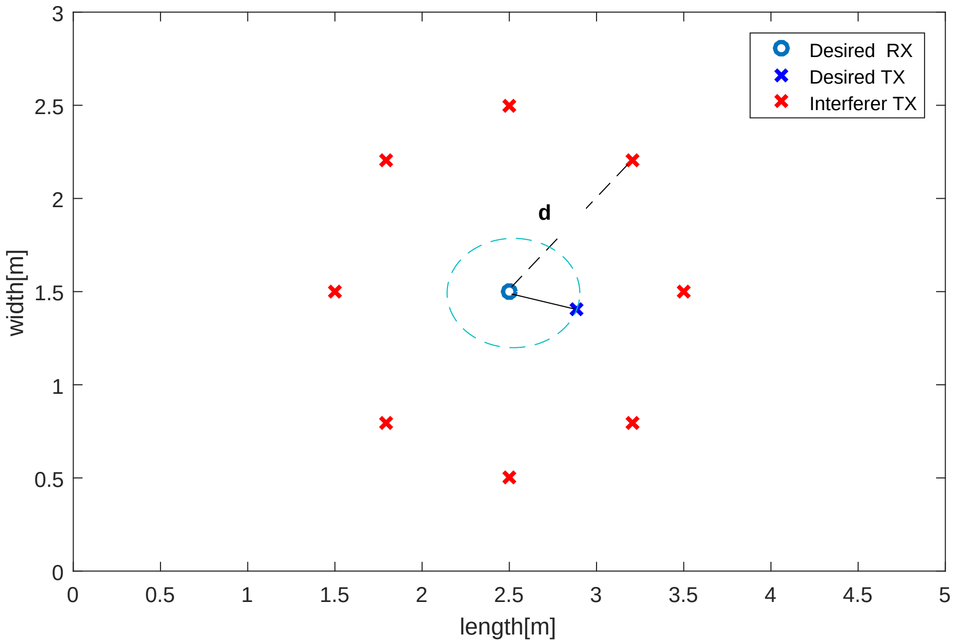


Figure 3.2: Scenario model

In this research, the most simple and typical scenario in a two-dimensional space will be considered: a rectangular room, which is specified by its length and width.

For the first analysis, there will be a desired user located in the middle of a room and the interferer users will be distributed uniformly in a circle (See also Figure 3.2). The position of the *desired receiver* is fixed while his corresponding *desired interferer* is located in a distance of 0.4 m and it is moving around the *desired receiver*. In the case of the interferer users, it is considered that the position of the interferer transmitters is fixed in a certain distance 'd' and their corresponding receivers are moving around them. In Figure 3.2 the interferer receivers are not drawn because they are not important for this analysis. The interferer transmitters are separated in a distance "*d*" from the *desired receiver* (*interferer link*) and different distances such as d=1 m, d=5 m and d=10 m will be considered.

For the second analysis, the users will be distributed randomly in a room. Moreover, it is important to mention that the distance between transmitters and receivers for both cases, desired as well as interferer users, is 0.4m.

It is considered that each WWD is equipped with one omnidirectional antenna, as a consequence, the irradiated EM waves will reach the locations free of obstacles with direct LOS.

When a signal travels though a medium and hits a surface with a different EM characteristics, some parts of its energy is absorbed or refracted inside the surface of the material. While another part of the energy is reflected. This is known as reflection phenomenon and repeats several times until the path loss absorbed all the remaining energy.

Due to the high path-loss characteristics of the THz band, only the first order reflection has importance in the analysis. The rest of reflections will be contemplated as negligible. Then, two types of signals will be considered: LOS component and NLOS component. The LOS is the direct communication link as well known as *desired link* and the NLOS, which is the reflection occurring from the wall or from objects. In this testing, only the reflections from the walls are considered. This description can be observed in Figure 3.3

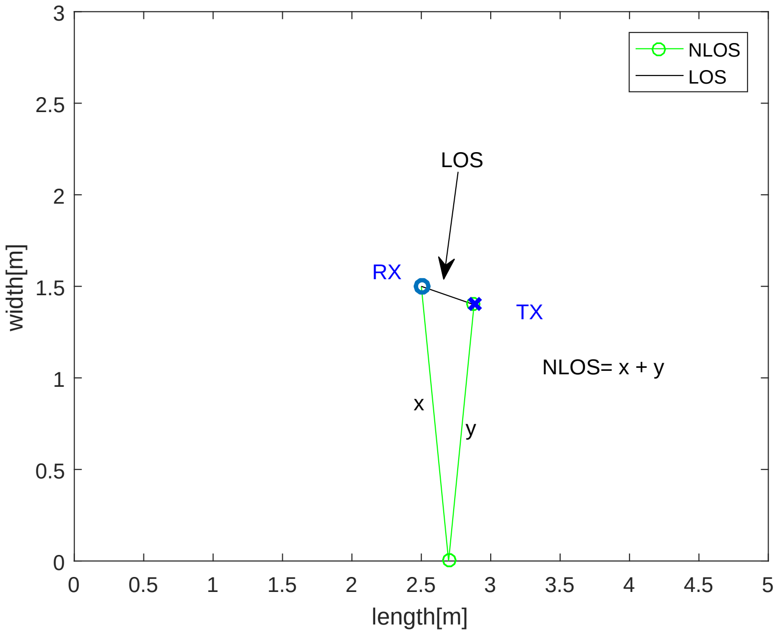


Figure 3.3: LOS and NLOS: desired receiver and desired transmitter

3.2.1 Assumptions

For the analysis in this thesis the following assumptions have been made:

- The users will have a totally smooth surface, then because of this specular reflection takes place. For materials, which have a totally smooth surface, the incident wave will be perfectly reflected in its specular direction but if the surface is rough, then this effect will not occur. When there is a reflection from a smooth surface, all the energy is reflected and concentrated in the specular direction. The term specular means that the directions of the incoming and outgoing EM waves make the same angle with respect to the surface normal. In the case of a rough surface, the irregularity of the material causes a diffuse scattering which distributes the energy from the incident wave in multiple directions. Consequently, the power in the specular direction is reduced (See also Figure 3.4). Regrettably, a part of the remaining energy could reach the receiver through the non-specular component.

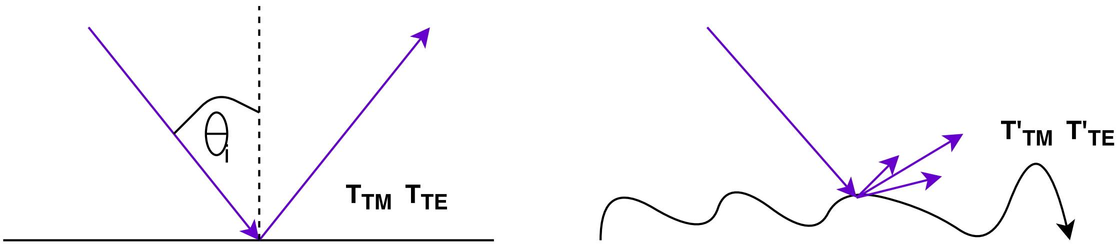


Figure 3.4: Refelction from a smooth(left) and from a rough(right) surface

- The user has his own *desired transmitter* and *desired receiver*.
- The users are not blocking each other.
- The room and users are modeled in a 2-D indoor scenario.
- The desired signal is stronger than reflections.
- If the number of users increases the interferences increase as well.

3.2.2 Fresnel Reflection Coefficient

Considering that the highest amount of energy of the strongest reflection is created when the EM waves are polarized using the transverse electric (TE) mode [2], a transmission with TE mode is assumed. A material with a totally smooth surface is assumed and the Fresnel reflection coefficient for the TE mode is shown in the following:

$$\Gamma_{TE} = \frac{Z \cdot \cos\theta_i - Z_0 \cdot \cos\theta_t}{Z \cdot \cos\theta_i + Z_0 \cdot \cos\theta_t}, \tag{3.1}$$

Here, θ_i and θ_t are the angle of incidence and reflection respectively. On the other hand, $Z_0 = 377\ \Omega$ represents the free space wave impedance and Z the wave of impedance of the reflecting material. This can be calculated with the following expression:

$$Z(f) = \sqrt{\frac{\mu_0}{\varepsilon_0(n^2(f) - (\frac{\alpha(f)\cdot c}{4\cdot\pi\cdot f})^2 - j \cdot \frac{2\cdot n(f)\cdot\alpha(f)\cdot c}{4\cdot\pi\cdot f})}} \tag{3.2}$$

where μ_0 and ε_0 are the free space permeability and permitivity, c the speed of light and f the frequency of the incident wave. Moreover, θ_t is determined using:

$$\theta_t = arcsin(sin(\theta_i) \cdot \frac{n_1}{n_2}) \tag{3.3}$$

For the current analysis, a totally smooth surface of the material is assumed . Hence, the most important estimation will be the refracted wave component which is related to the characteristics of the material according to

$$\frac{sin\theta_1}{sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}, \tag{3.4}$$

where θ_1, θ_2 represent the incident angle and the refracted angle respectively. v is the phase velocity, λ is the wavelength and n is the refractive index for a certain material.

If the EM wave is transmitted trough vacuum, then $n = 1$ and the expression for the refractive index for the material n_2 is defined by

$$n_2(f) = \frac{c}{\nu}, \tag{3.5}$$

where c is the speed of light in the vacuum and ν represents the speed of light in a certain medium. Furthermore, the extinction coefficient also known as absorption coefficient is conformed by μ_f and ρ_m represents the attenuation coefficient and the mass density of the material respectively. The ratio of both defines the Equation (3.6).

$$\alpha(f) = \frac{\mu(f)}{\rho_m}, \tag{3.6}$$

In previous researches, two materials were investigated: *concrete plaster* and *ingrain plaster* [1] [2]. These materials fit perfectly the requirements for the current analysis. The characterization of these materials has been elaborated for a limited range of frequencies $[0.1 - 1]$ THz. According to previous results, for this thesis the *ingrain paper* which variation of refractive index is up to 1.5 will be assumed. It is important to mentioned that for this material the variation is random and is around 40 cm^{-1} (extinction coefficient). Therefore, if the frequency f goes from $[1 - 10]$ THz the $\alpha(f)$ coefficient will be mostly dominated by the frequency due to the high difference between them [1]. As a result, the extinction coefficient has not effect on the overall reflection coefficient. For more information the interested reader is referred to [1] and [2].

3.3 Continuous-time Channel

Various parameters relevant for the communication channel in the THz band have been described before. In this part of the chapter, the continuous-time impulse response is modeled. The impulse response is composed to five taps: one is the LOS link that corresponds to the direct path between desired transmitter and desired receiver and the other four are reflections from the inner walls in the room which represent the NLOS link. It has to be known that the speed rate of the impulse response in relation to the speed of the fading is faster that the taps of the channel [1]. Furthermore, due to the high attenuation that EM waves suffer when they are traveling through a terahertz channel a big difference in power is expected at the receiver between the LOS and the NLOS links. The following equations will described the continuous impulse response of LOS and NLOS transmission:

$$h_{c_{k,i}}(t) = \sum_{l=0}^{5} \nu_{k,i} \cdot \delta(t - \tau_{k,i}(l)), \tag{3.7}$$

where $h_{c_{k,i}}$ represents communication channel of the user U_i under the influence of the interference from the users U_k, the time delay between taps is denoted by l, while ν is given by:

$$\nu_{c_{k,i}} = \sqrt{L_{k,i}(l)} \cdot \Gamma(\theta_{k,i}(l)) \cdot e^{-j \cdot \Delta\phi_{k,i}(l)}, \tag{3.8}$$

where ν contains the effects of the total path-loss L (See Equation 2.1 in Chapter 2), the scattering surface of the material along with the reflection coefficient denoted by Γ, and the phase shifting between signals, which is expressed by:

$$\Delta\phi_{k,i}(l) = \frac{2 \cdot \pi \cdot f}{c} \cdot (r_{k,i}(l) - r_{k,i}). \tag{3.9}$$

A representation of the continuous-time impulse response can be observed in Figure 3.6 and Figure 3.5.

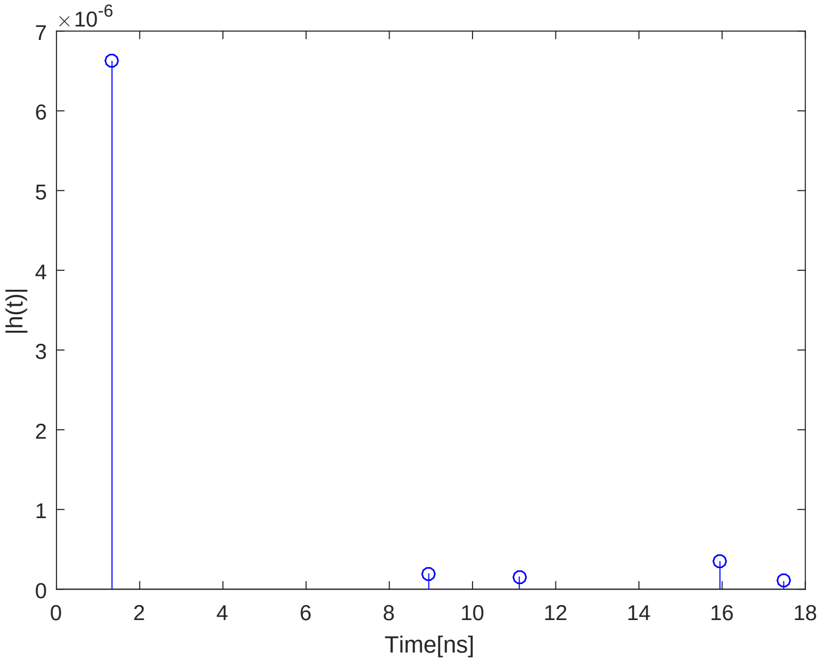


Figure 3.5: Magnitude of the channel impulse response for the desired user.

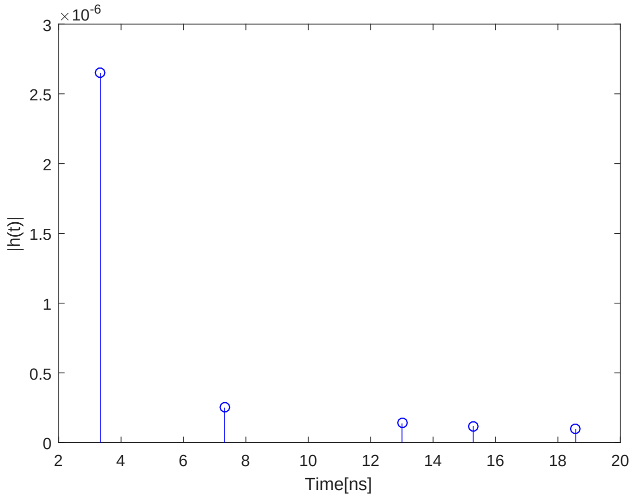


Figure 3.6: Magnitude of the channel impulse response for the interferer user

In Figure 3.5, the first sample represents the LOS and the remaining four represents the NLOS.

3.4 Discrete-time Channel

Previously, the continuous-time impulse response has been developed. Now, the digital communication channel that describes the effect of transmit pulse shaping and receive filtering will be formulated. It is expected that the frequency selectivity of the discrete-time channel will depend on the symbol rate, room size and position of the users.

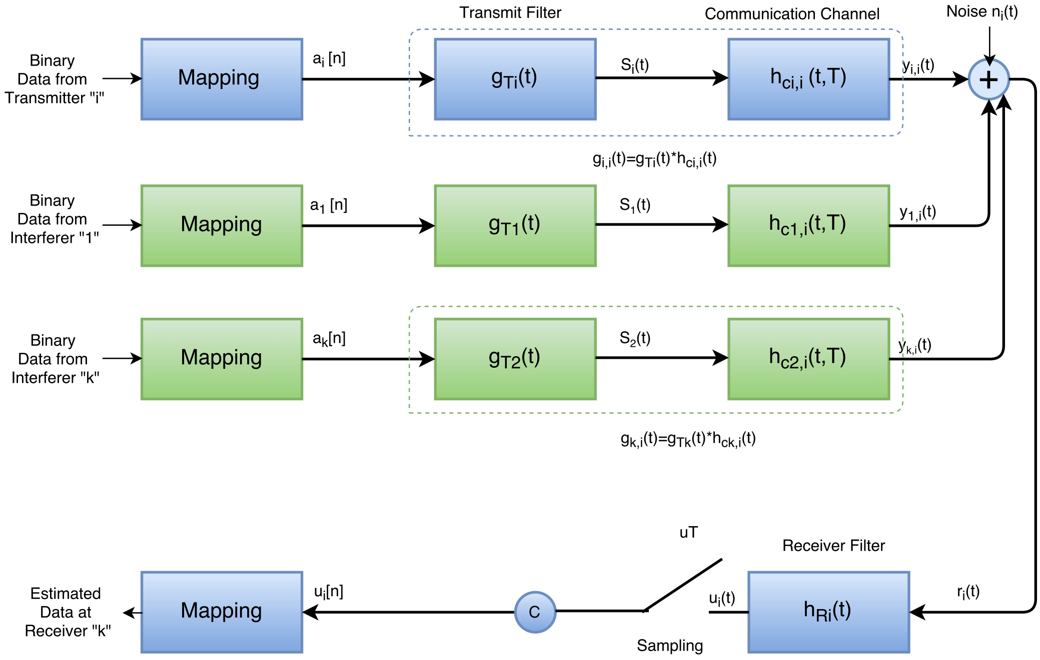


Figure 3.7: Digital communication scheme of user "i" under interference of "k" users

3.4.1 Transmit and Receiver Filter

The transmit filter [6] is modeled through a root cosine function $g_T(t)$ and it is described by the following equation:

$$g_{c_k}(\alpha,t)=\sqrt{\frac{E_T}{T}}\cdot\frac{(4\cdot\alpha t/T)\cdot cos(\pi(1+\alpha)\cdot\frac{t}{T})+sin(\pi(1-\alpha)\cdot\frac{t}{T})}{(\pi t/T)\cdot(1-(4\alpha t/T)^2)},\tag{3.10}$$

where α, T and E_T represent the roll of factor which means the excess of bandwidth, the symbol period and the energy of the pulse response, respectively. Following the scheme represented in Figure 3.7, the transmit signal can be specified as

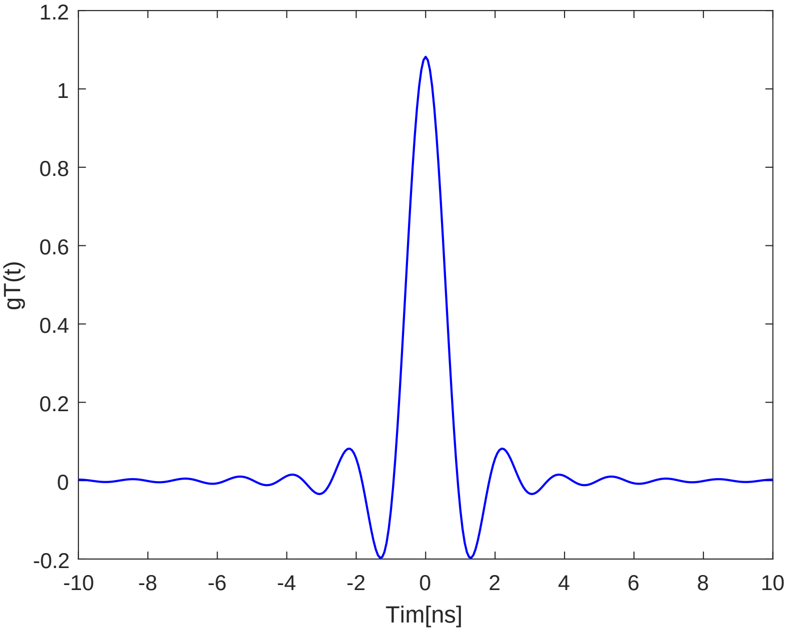


Figure 3.8: Transmit filter with $\alpha = 0.3$

$$s_i(t)=\sum_{n=-\infty}^{\infty}a_i[n]\cdot g_{T_i}(t-nT)\tag{3.11}$$

Because of the choice for the transmit filter, the square-root-cosine was used as the receiver input filter. This is used to minimize the intersymbol interference (ISI).

3.4.2 Discrete-time Impulse Response

Then, the discrete-time impulse response after the sampling can be calculated following the next formulas:

$$h_C(\tau,t)=\sum_{i=1}^{N_p}\nu_i(t)\delta(\tau-\tau_i),\tag{3.12}$$

$$h[\mu,\kappa]=C\sum_{i=1}^{N_p}\int_{-\infty}^{+\infty}\nu_i(\kappa T-\xi)h_R(\xi)g_T(\mu T-\tau_i-\xi)d\xi, \tag{3.13}$$

$$C=\frac{1}{\sqrt{\frac{E_T}{T}}}, \tag{3.14}$$

where C is used in order to guarantee a dimensionless signal(dimension $1/V$) and T is the symbol period.

- If the following assumption is made:
  Fading is slow compared to the duration of the impulse response $h_R(\xi)$. Then,

  $$h[\mu,\kappa]\approx C\sum_{i=1}^{N_p}\nu_i(\kappa T)\int_{-\infty}^{+\infty}h_R(\xi)g_T(\mu T-\tau_i-\xi)d\xi=C\sum_{i=1}^{N_p}\nu_i(\kappa T)\gamma(\mu T-\tau_i) \tag{3.15}$$

  with

  $$\gamma(t)=h_R(t)*g_T(t), \tag{3.16}$$

  which is the impulse response contain a cascade of transmit and received filter which analytical expression is

  $$\gamma(t)=g_c(\alpha,t)*g_c^\star(\alpha,-t)=E_T\frac{cos(\pi\alpha t/T)}{1-(2\alpha t/T)^2}sinc(\frac{\pi t}{T}), \tag{3.17}$$

  where E_T is the energy of transmit pulse (dimensions V^2) and can be calculated with

  $$E_T=\int_{-\infty}^{+\infty}\mid g_T(t)\mid^2 dt=\int_{-\infty}^{+\infty}\mid G_T(f)\mid^2 df. \tag{3.18}$$

  E_T can be used for normalization of C. Furthermore, with Equation 3.15 the discrete-time impulse responses for the desired and interferer link can be calculated.

Figure 3.10 and Figure 3.10 show some ISI due to the effect of multipath propagation over the communication channel, but its impact is not very important because of the big difference between the taps corresponding to the LOS and NLOS link.

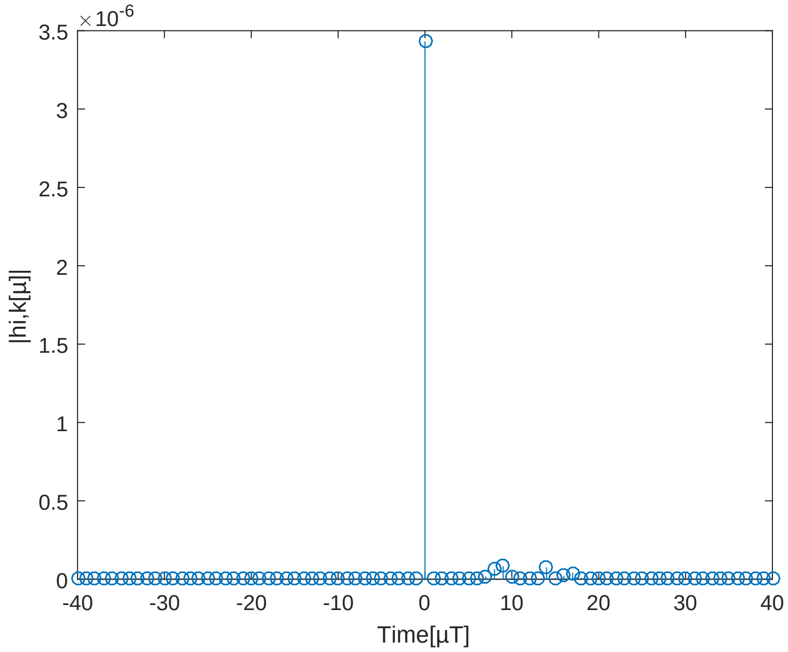


Figure 3.9: Magnitude of the channel impulse response for the desired user.

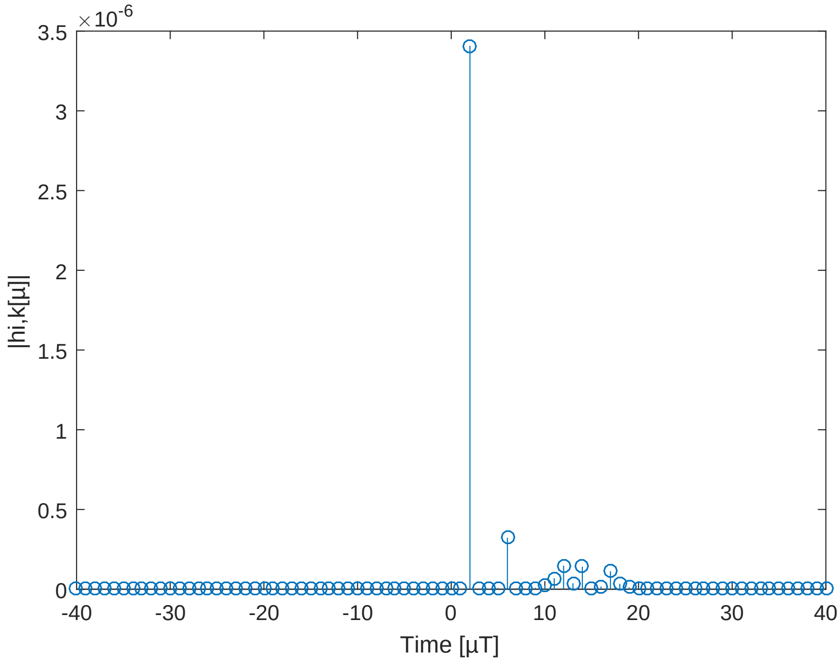


Figure 3.10: Magnitude of the channel impulse response for the interferer user

Chapter 4

SINR Analysis

Once the communication system have been designed, the impact of the interference in the THz communications has to be simulated using the aspects mentioned in the previous chapters. The most important parameter to analyze is the SINR, which helps to evaluate the quality of the link for the entire analysis.

4.1 Signal-to-Interference-Plus-Noise Ratio

The impacts because MA and high free-space propagation that make the terahertz band special have been explained in the Chapter 2. These effects do not affect all frequencies equally, and they are present only for certain frequencies depending on the characteristics of the medium.

As was mentioned before, only the MA for normal weather is analyzed and based on those results the most convenient frequencies to carry out the SINR analysis are found. To have a reliable connection, the distance between the desired transmitter and the desired receiver must be short enough to defeat the effects of the free-space propagation and molecular absorption loss. If Equation (2.2) and Equation (2.3) are analyzed, it can be seen that the distance is one of the most important factors. Nonetheless, the distance between *interferer transmitter* and *desired receiver* is greater than the distance between *desired transmitter* and *desired receiver*. This is because the interferer device is carried by different users U_k and normally the separation distance between users is higher than the distance between WWD of user U_i.

Ideally, the goals to achieve the best possible SINR for each user. For instance, the maximum value of the SINR is reached when only one user is considered in an indoor scenario. The best communication channel available for this user is the one who experiments less free-space propagation and minimum molecular absorption. Nevertheless, if another user is included and both use the same frequency, the SINR will decrease significantly because at this particular frequency the effects of the path-loss are minimized, which means that both users interfer each other. If more users are added and use the same frequency, the interference power will be high enough to corrupt all the communication links. At this point, the total path-loss plays an important role, limiting the power of the interference and improving the performance of the desired link.

4.2 SINR Estimation

To determine the SINR, the use of a Maximun-Likelihood Sequence Estimation (MLSE) will be considered to get the most of the energy from all the multipath signals, this is made to avoid issues with the ISI. The SINR is expressed by the following equation

$$SINR_i = \frac{\sum_u |h_{i,i}[u]|^2 \cdot P}{\sigma_{n_i}^2 + \sum_{k\in F_i} \sum_u |h_{k,i}[u]|^2 \cdot P}, \tag{4.1}$$

where P represents the signal power that is applied at the transmitters, $\sigma_{n_i}^2$ is the variance of the noise at the receiver, $h_{i,i}[u]$ and $h_{k,i}[u]$ are the discrete-time channel impulse responses for the desired and the interferer link, respectively. F_i constitute the total number of interferers U_k sharing the same frequency as user U_i.

4.3 Results

Once the communication system has been described, it is proceeded to analyze the communication behavior considering the aspects describe previously such as molecular absorption, path loss, surface of the material, size of the room, user distribution, etc.
In this part, the room size is 21.5 m x 21 m. The reason is because the interferer users will be located in a considerable "large distance". As was mentioned in Chapter 3, the interferer transmitters are distributed in a circle around the desired receiver with a distance "d". Three distances are considered: 1 m, 5 m and 10 m. For theses distances, 8 interferer transmitters are contemplated. It is important to mention that the desired receiver has his desired transmitter located at a distance of 0.4 m for the current analysis. Furthermore, $P_t = 30$ dBm will be used because in previous researches it has been demonstrated that at this power, data rates in the order of Tbps can be achieved for distances up to 1 m [4].
The next Figures 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 describe the behavior of the communication link with 8 interferer users located at a distance of 1 m, 5 m or 10 m.

On each figure: in SNRLOS, the NLOS components are not assume. It is only considered the LOS between *desired transmitter* and *desired receiver*. In SNRLOS + MA, the same assumptions are made but the molecular absorption play an important role in this part.

In SINRLOS, the LOS between *desired receiver* and *interferer transmitter* is considered. In SINRLOS + MA, the same assumptions as before but the MA is applied. For all the cases described before, all users transmit at the same frequency. It is a mono-frequency transmission. Only the path-loss and molecular absorption are playing a role. Reflections are not assumed.

Finally,in the TrueSINR-discrete the Equation 4.1 is used. The discrete impulse response for desired users and interferes users is calculated. The LOS and NLOS components are taking in account.The calculations are made from [0.1-10] THz. The carrier frequencies are taking as: 100 GHz, 105 GHz, 110 GHz and so on. The BW used is 1.3 GHz and symbol period is 1 GHz.

It is observed that for certain frequencies the SINR decreases significantly because of the MA.

If Figure 4.3 shows that the frequency should not be chosen close to the peak, the best is around the peak.

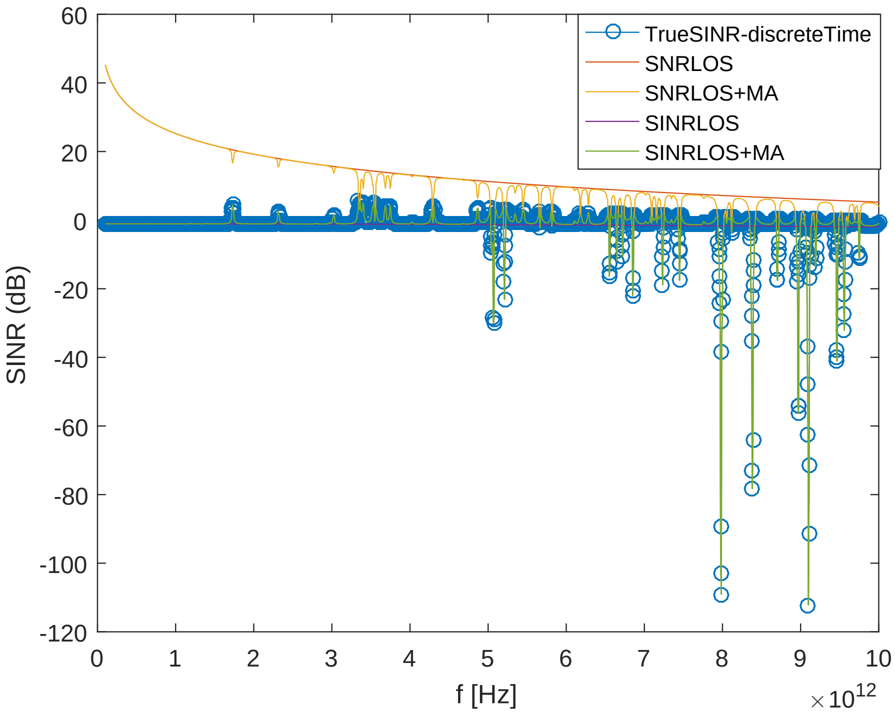


Figure 4.1: d=1 m, 1 desired user and 8 interferer transmitters.

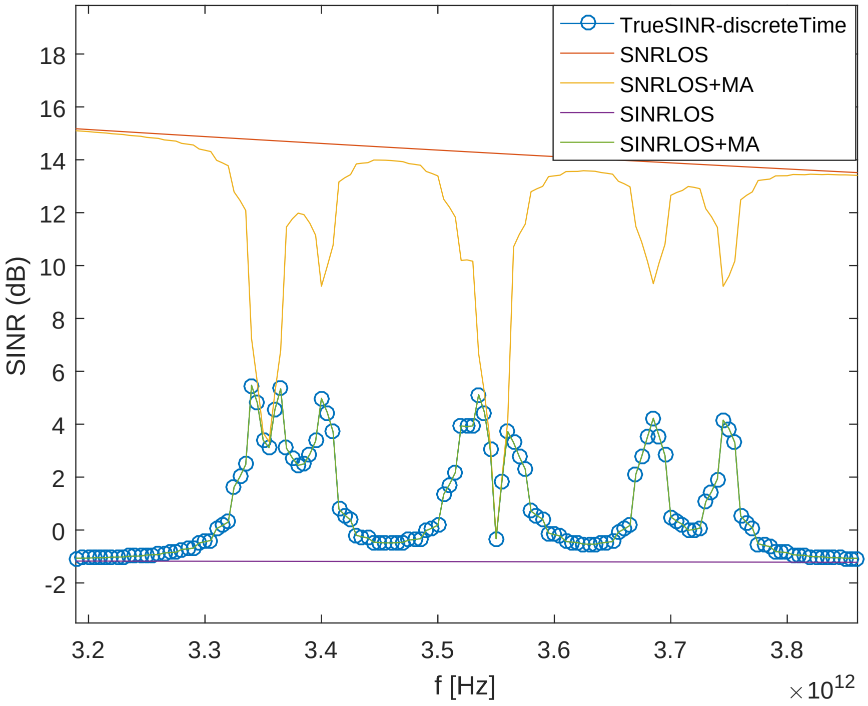


Figure 4.2: d=1 m, 1 desired user and 8 interferer transmitters.

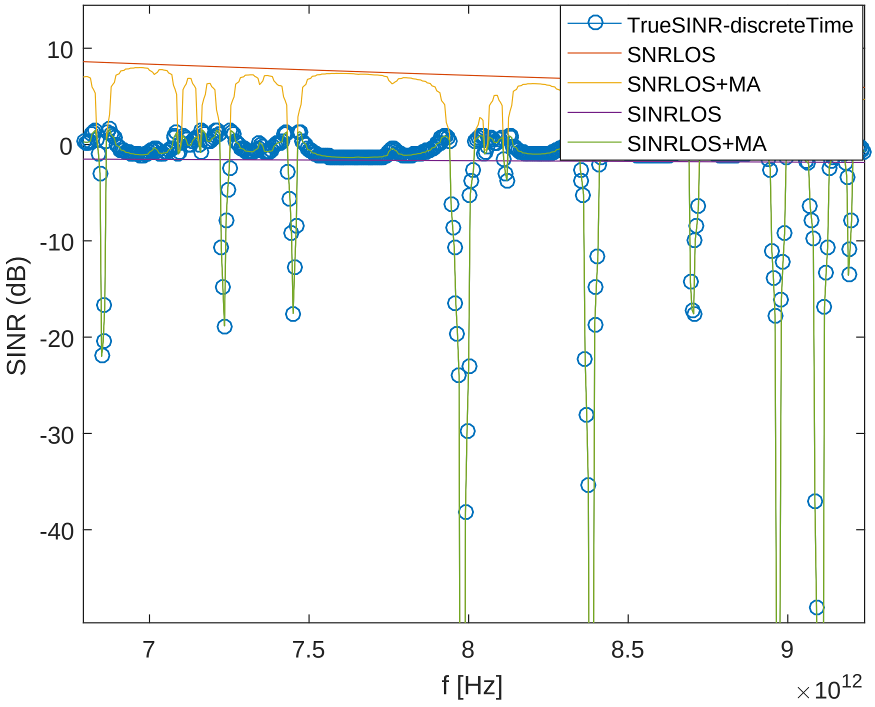


Figure 4.3: d=1 m, 1 desired user and 8 interferer transmitters.

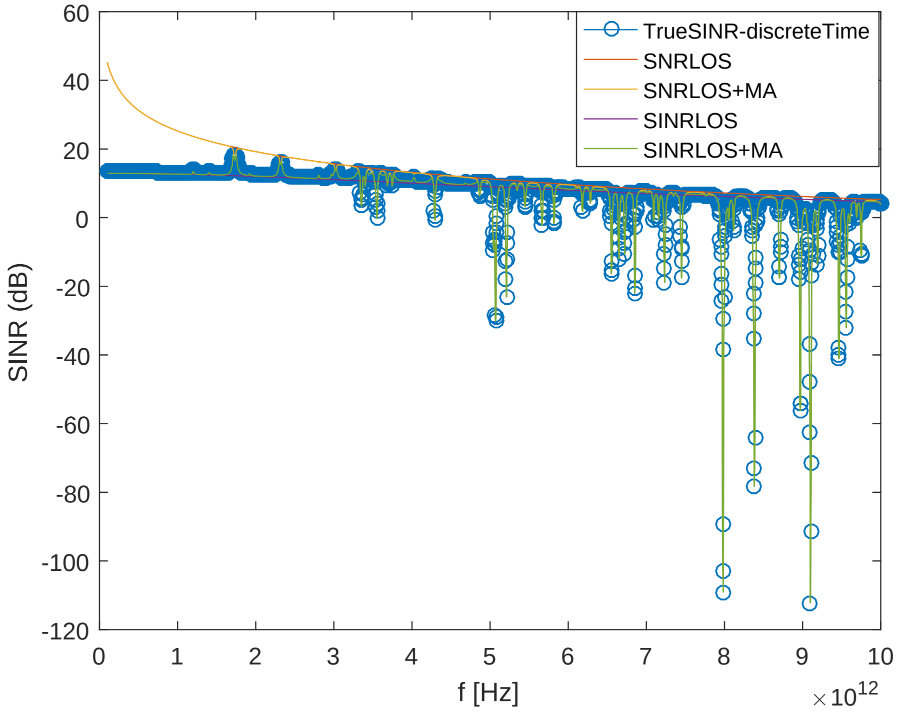


Figure 4.4: d=5 m, 1 desired user and 8 interferer transmitters.

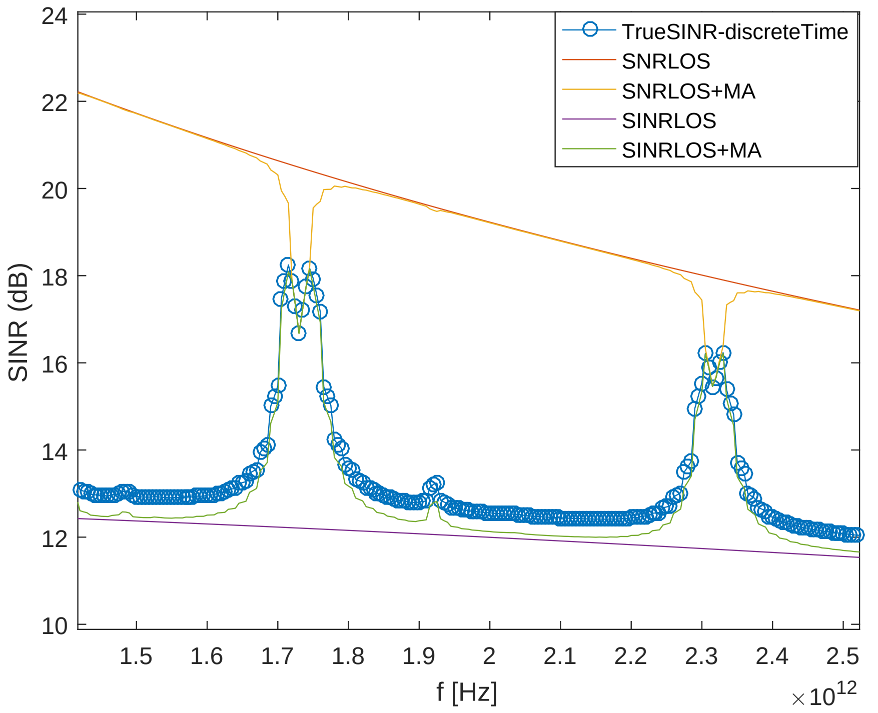


Figure 4.5: d=5 m, 1 desired user and 8 interferer transmitters.

In Figure 4.5, it is observed that the reflected path contributes a bit more.

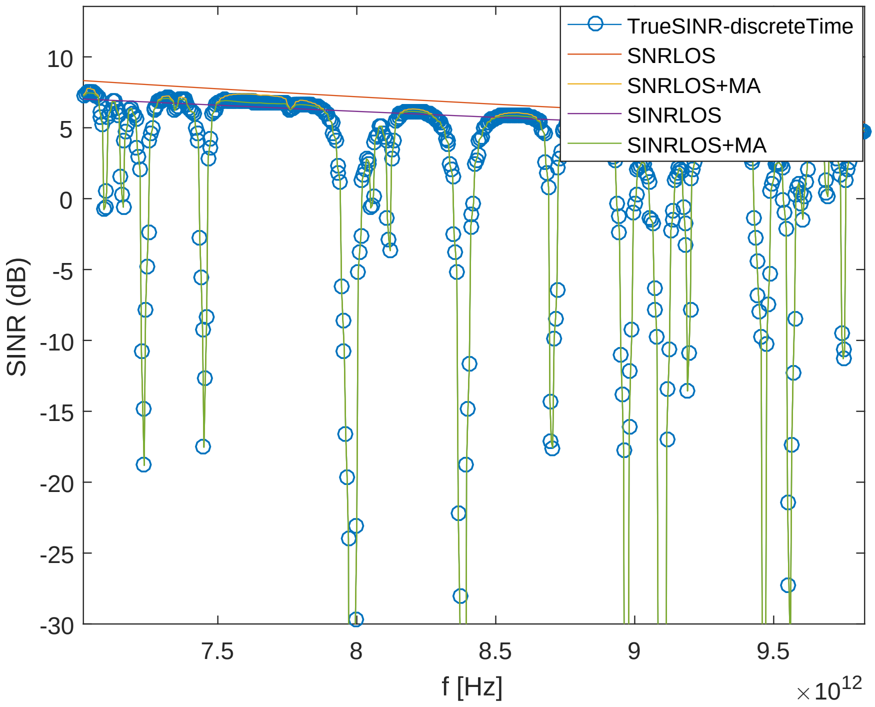


Figure 4.6: d=5 m, 1 desired user and 8 interferer transmitters.

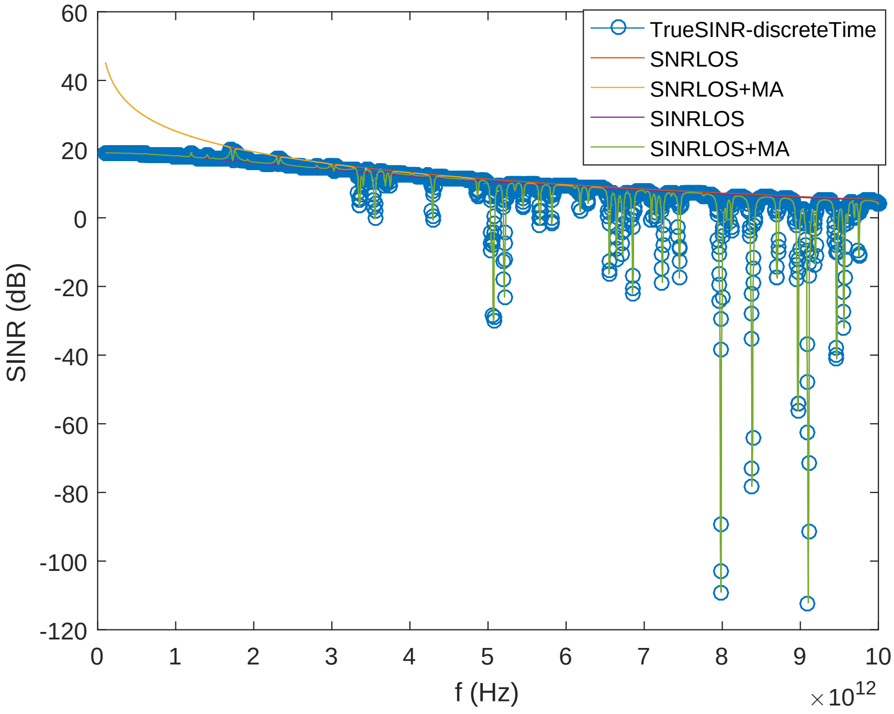


Figure 4.7: d=10 m, 1 desired user and 8 interferer transmitters.

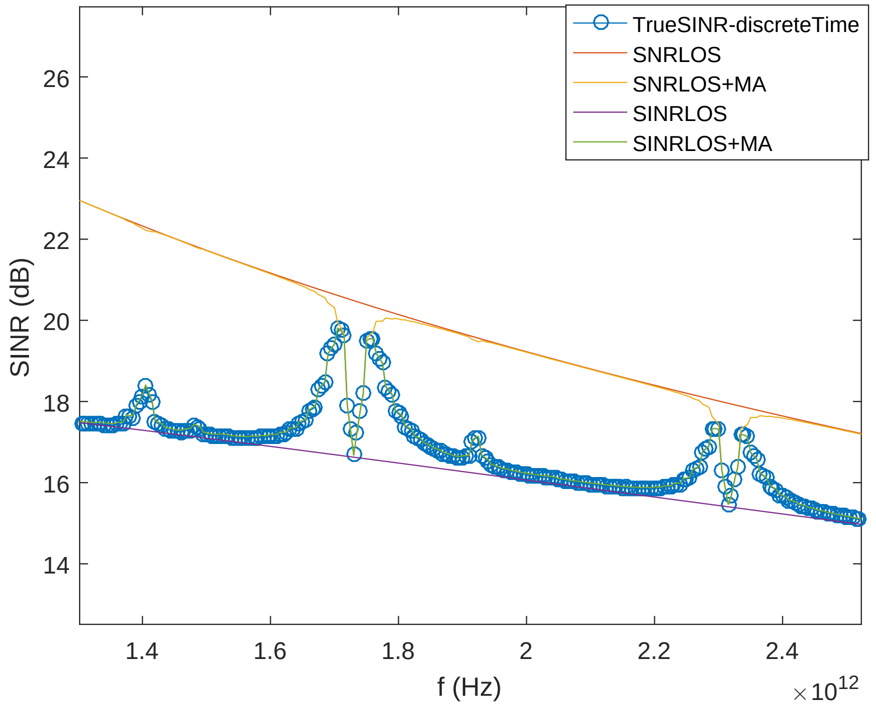


Figure 4.8: d=10 m, 1 desired user and 8 interferer transmitters.

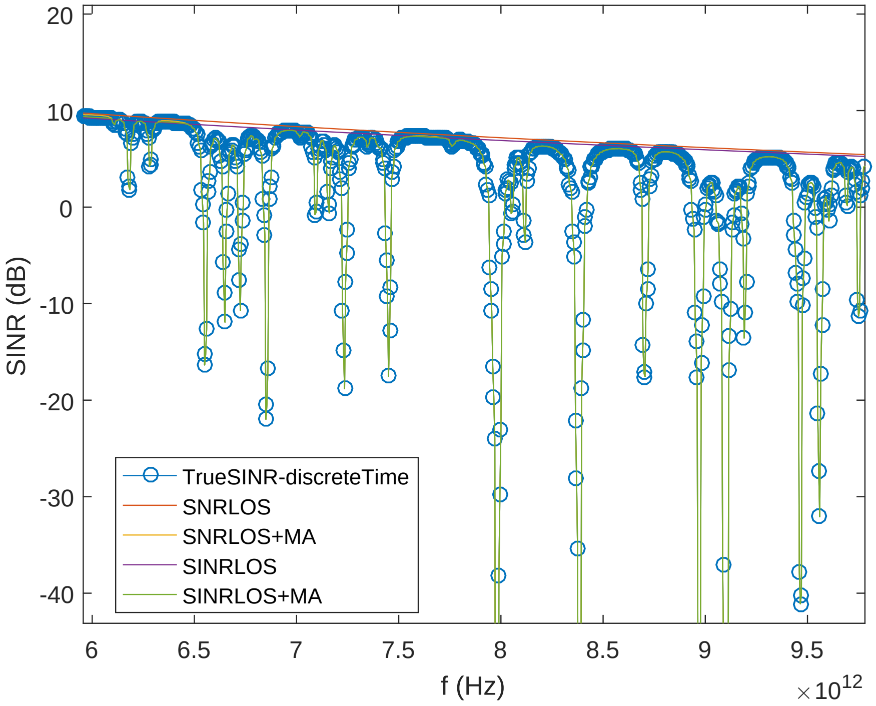


Figure 4.9: d=10 m, 1 desired user and 8 interferer transmitters.

It can be observed that the interferer is weak for higher distances such as for 5 m and 10 m. In fact, for d= 10 m the interferences are negligible. If the distance increases, the interference decreases. Observing the results, the interferences are higher the closer are the interference users are to the desired user. The consequence is that the communication quality suffers a significant reduction. However, the molecular absorption helps to reduce the interferences. The molecular absorption can be "destructive" for some cases, for example, in the high frequencies the SINR achieves very low values and does not allow to create a reliable communication channel. The MA phenomenon benefits the lower frequencies as can be observed in the previous figures, helps to increases the SINR for certain frequencies which can be used to create a adequate communication channel. Then, because of this it is easier to fulfill the requirements for the WWD. These frequencies, which take advantage of this benefit, will be found out in the next chapter.

Chapter 5

Performance Comparison

In this Chapter, the channels which are the best to have a reliable communication link will be analyzed. Moreover, all the aspects mentioned in previous chapters will be considered such as molecular absorption, number of users, room dimentions ,etc. As well, it will be investigated what channels are the best for low and high densities of users.

5.1 Analysis for Different Number of Users and Number of Channels

Now, the location of the users is different , they are randomly distributed in a room whose dimensions are l= 5 m and w =3 m. Each user has his own transmitter and receiver and the distance between them is 0.4 m. The transmitter does not have a fixed position, it revolves around the receiver (See also Figure 5.1). The Equation To find out the best frequencies for a reliable communication link for the wearable wireless devices, the next formula to calculate the SINR is used:

$$\mathrm{SINR}(f,K,N) = \frac{P_t \cdot A \cdot f^{-2} \cdot d_{LOS}^{-2} \cdot e^{-k(f)\cdot d_{LOS}}}{P_N + P_I}, \tag{5.1}$$

where P_t is the transmit power, A is a constant from the path-loss excluding the frequency part and the distance part. It is described in Equation (5.2), f represents the frequency, d_{LOS} is the distance between desired receiver and desired transmitter and $e^{-k(f)\cdot d_{LOS}}$ determines the molecular absorption phenomenon, P_N is the noise power Equation (5.3) and P_I is the interference power Equation (5.4).

$$A = \left(\frac{c}{4\cdot\pi}\right)^2 \tag{5.2}$$

$$P_N = 2 \cdot K_b \cdot T_K \cdot BW \tag{5.3}$$

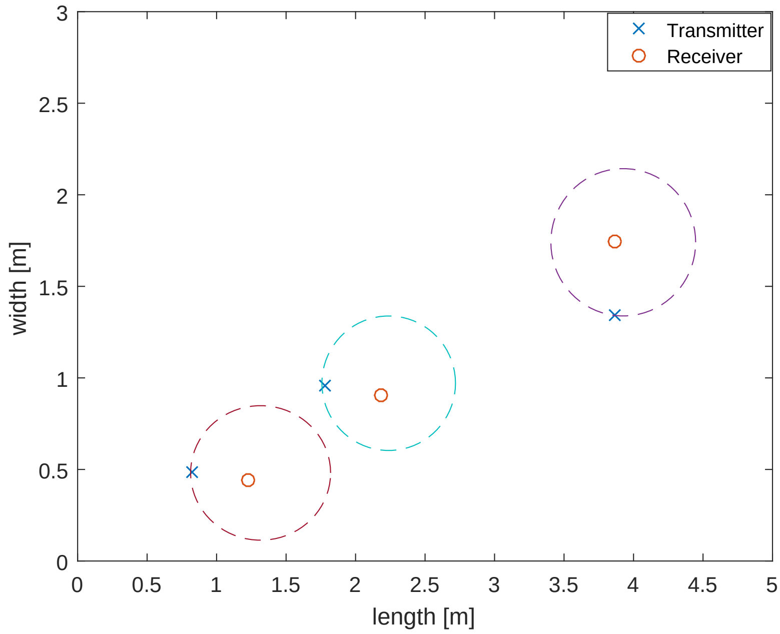


Figure 5.1: 3 users located in a room 5 m x 3 m

In Equation (5.3) the noise power is represented where K_b is the Boltzmann's constant, T_K defines the reference temperature, BW determines the bandwidth and the 2 is because it is assumed that the molecular absorption affects all the frequencies. The interference power P_I is defined by

$$P_I = \frac{2\pi A}{K} \cdot P_t \cdot f^{-2} \cdot D \int_{xmin}^{xmax} \frac{e^{-k(f)\cdot x}}{x} dx, \tag{5.4}$$

where K is the number of channels, the integral is used to calculate all the interferences in the room where xmax represents the largest radius possible in the room. The integral is only an approximation. However, this is expected to be useful in finding the best channels. Finally, D represents the average density in the room and can be calculated by:

$$D = \frac{N}{l \cdot w} \tag{5.5}$$

where N is the number of users, l and w are the length and width of the room, respectively.

5.2 Low Density

As a first step, a low density scenario will be considered and the best channels to fulfill the requirements of the WWDs will be found out. Using Equation (5.1), it can be observed that the best channels is 1.73 THz, if only one channel is wanted (See also Table 5.1). If the number of users is increased a little in the case of two channels ,the best channels are

N	1	3	5
channel	1.73 THz	1.73 THz	1.73 THz

Table 5.1: One channel for N users.

N	4	5	8	10
Channel 1	1.73 THz	1.73 THz	1.73 THz	1.73 THz
Channel 2	2.31 THz	2.31 THz	2.31 THz	2.31 THz

Table 5.2: Two channels for N users.

1.73 THz and 2.31 THz. When the number of users increase the best channel changes. For instance, for N=10 users the best channel is 3.4 THz. The peformance of the SINR using the Equation (5.1) can be observed in Figure 5.2. A zoom of this figure is shown in 5.2 and it can be seen better that, for example, for N=50 the best channel is between [3-4] THz.

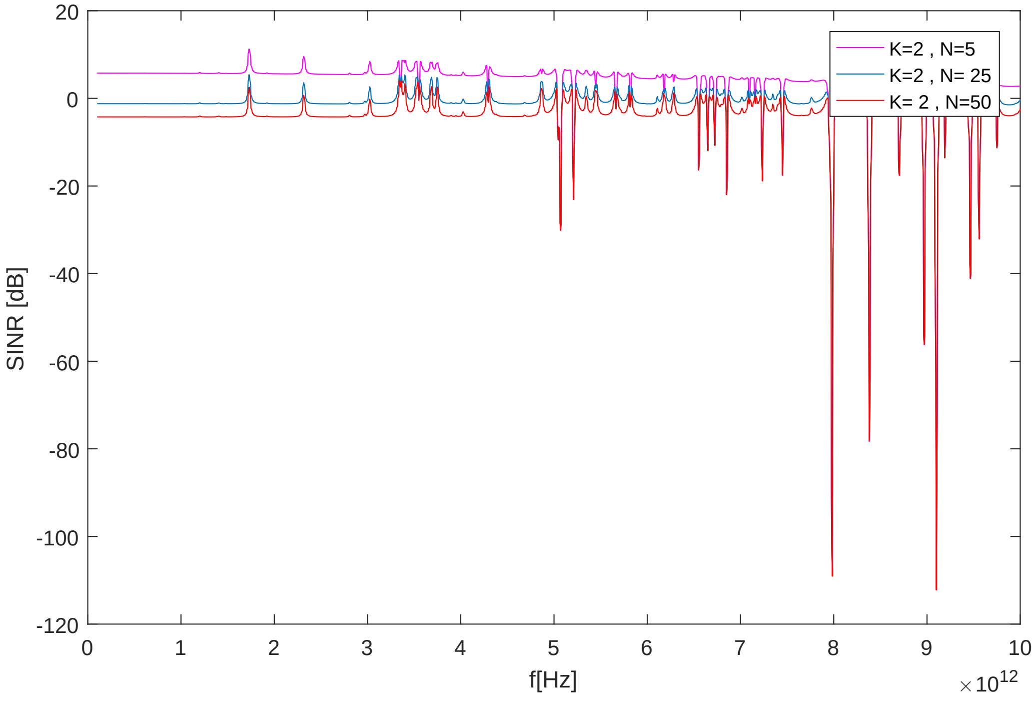


Figure 5.2: SINR for different N users and K=2 channels.

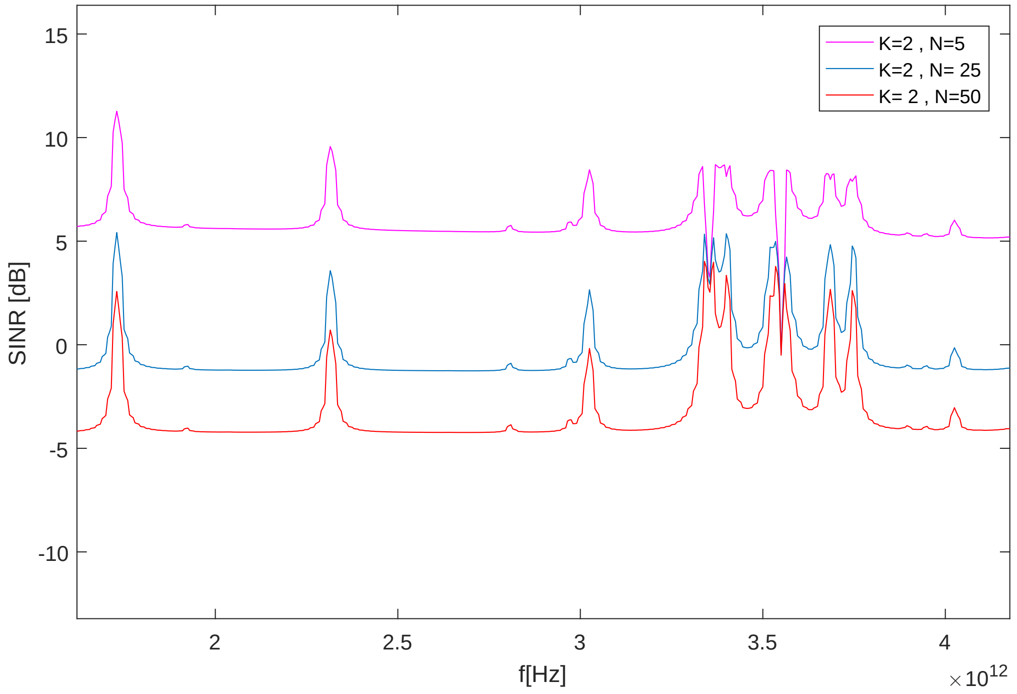


Figure 5.3: Zoom of SINR for N users and K=2channel.

Then, it can be concluded that when the density changes the best frequencies change.

5.3 High Density

Now, the number of users considered will be 10, 15 and 20. The number of channels to find will be 5, 7 and 10. The best channels are written in Tables 5.3, 5.4, 5.5.

N	channel 1	channel 2	channel 3	channel 4	channel 5
10	1.73 THz	2.315 THz	3.37 THz	4.27 THz	5.12 THz
15	1.73 THz	2.315 THz	3.39 THz	4.27 THz	5.11 THz
20	1.73 THz	2.315 THz	3.34 THz	4.3 THz	5.18 THz

Table 5.3: Five channels for N users.

N	channel 1	channel 2	channel 3	channel 4	channel 5	channel 6	channel 7
10	1.73 THz	2.315 THz	3.33 THz	4.27 THz	5.125 THz	6.11 THz	7.06 THz
15	1.73 THz	2.315 THz	3.37 THz	4.27 THz	5.12 THz	6.16 THz	7.12 THz
20	1.73 THz	2.315 THz	3.39 THz	4.27 THz	5.111 THz	6.17 THz	7.07 THz

Table 5.4: Seven channels for N users.

N	channel 1	channel 2	channel 3	channel 4	channel 5
10	1.73 THz	2.315 THz	3.02 THz	3.51 THz	4.315 THz
15	1.73 THz	2.315 THz	3.37 THz	4.27 THz	5.12 THz
20	1.73 THz	2.315 THz	3.02 THz	3.51 THz	4.27 THz
N	channel 6	channel 7	channel 8	channel 9	channel 10
10	4.85 THz	5.42 THz	6.10 THz	6.77 THz	7.36 THz
15	4.85 THz	5.42 THz	6.11 THz	6.77 THz	7.36 THz
20	5 THz	5.43 THz	6.16 THz	6.765 THz	7.39 THz

Table 5.5: Ten channels for N users.

As was mentioned before, the best channel changes when the density changes. Then, the best channels are not fixed. An important aspect to mention is that all the channels are orthogonal, then there is no interference between them.

Chapter 6

Conclusions

This research has made a contribution to know what are the benefits of the THz band when this band is used for the communication between WWDs. The line-of-sight and the non-line-of-sight propagation of waves for indoor scenarios have been analyzed, where the molecular absorption and the free-space propagation play an important role because they limit the area coverage of the transmitted signals. Overall, it is considered that the NLOS components at the receiver are almost negligible compared with the power of the LOS components. According to the analysis in this thesis and with previous researches, the molecular absorption plays the most important role in the THz band. The reasons are:

- It helps to attenuate the interference.
- It increases the SINR for certain frequencies.
- For short distances it is almost negligible.

A negative aspect with this phenomenon is that it does not have a fixed value, small changes in the temperature, distance, RH, etc affect the MA severely. The distance is another factor to consider, the closer interferer users are to the desired user, the higher are the interfenrences but the molecular absorption helps to mitigate them. It has been observed that for low frequencies the SINR is higher than for high frequencies. Thus, it is expected that the best channels are located in the low frequencies. Making use of this phenomenon along with path-loss, it was analyzed how the communication can be in the THz band what channels are the best for different user densities. Then, it is observed that if the number of users changes the best channels change.

The communication over the THz band is an interesting topic to continue developing. Furthermore, it can be the most suitable choice for the telecommunications in the next years. Although,there are still many things to develop to make the THz band successful in communications.

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