Outdoor to Indoor Wireless Propagation Simulation Model for 5G Band Frequencies

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Abstract. This paper analyses the signals propagation characteristics and the most important obstacles that encountered these signals when transmitted from outdoor to indoor (O2I) antennas for the college buildings. These buildings consists of several floors and built in the 3D form according to the real dimensions. In this study, we used measurement analysis and a ray-tracing simulation model approach based on the use of the Wireless InSite (WI) software. The use of different frequencies related to the fifth generation (5G) which are 10, 17, 30 and 60 GHz. According to the results that appeared, it is observed the increase in frequency will lead to an increase in path loss, decrease the received signal strength (RSS). There is an inverse relationship between frequency increase and delay spread and an inverse relationship between frequency increase and received power. In addition, we noticed that there is a direct correlation between frequency increase and path loss, where increasing frequency will increase the path loss, decrease delay spread and received power. Finally, the building's barriers work on obstructing the direction of the signals path and dispersion of the received signal strength (RSS).

Keywords—5G, received power, indoor waves, O2I, RSS, path loss, delay spread.

1. Introduction
The correct design for both outdoor and indoor wireless networks and the coordination of connection requirements with higher resolution make the network work reliably and able to transmit information for users in more speed through it which the network will take the right path [1]. The transmitting of the waves with high speed, resolution within the right path can be obtained by reducing the interferences among signals particularly when the selected design of the communication network is corrected regarding locations of the transmitters and the receivers [2]. Modern strategies in designing a wireless network must be tracked approach from top to down. This approach is represented in two stages, the first one is determining the requirements of the network and the main objectives of these requirements are scalability, availability, security, and manageability. The second stage is determining the applications of the network. To design a network, several factors must be considered are obstacles that play a large role in deteriorating wireless signals such as walls, furniture, buildings, high-voltage power cables, and other barriers. After design of the network, the work must validate this network or a preliminary test to determine the readiness of the performance for this network [3]. In recent years, there have been rapid developments in the field of wireless communications technology and became all the devices need for wireless communications in an unexpected manner and any working
environment. For this, become wireless network designs widely available and data transfer speeds are very high, more complex and secure in design to get a wireless network capable of operating without any penetration from certain destinations. With the growing demand for broadband wireless communications services, begun each of different the academic and industrial aspects in researches and forecasts for 5G wireless communications system, which promotes many developments, and improvements in various measurements that improve system performance when implementing any the indoor and outdoor wireless network [4]. It is expected to use very high-frequency waves in this generation from 30 to 300 GHz and the range of these frequencies is known as the millimeter-wave (mm-wave). These waves attracted many researchers to design a wireless network at high speeds and it was used in military systems, satellites, and others. The studies have confirmed that the spread of these waves in certain environments accompanied by many losses that lead to multi-paths [5, 6]. For this, the use of multiple-input multiple-output (MIMO) antenna solve this problem. These antennas are considered to reduce interference that occurs between signals when propagating in simulation environments by giving each user a special channel [7].

This paper is looking to design and implementation of O2I network capable of working well with follow-up of modern implementations. Then to study the propagation of the signals and their impact when they penetrate through the various barriers and measurement of the received power for each received point within all buildings, as well as study delay channel propagation for all paths that reach the receiving points. The scenarios of this work were implemented using the WI program at different frequencies, which are 10, 17, 30, and 60 GHz.

The rest of this paper is organized as follows. In Section 2, presents the related works. In Section 3, presents a detailed explanation about the fundamentals of the propagation of the signals in the outdoor and indoor environments. In Section 4, presents a detailed explanation for the characteristics of channel parameters to determine the performance of wireless channels. In Section 5, presents the designed and implemented a simulation scene. The results has been discuss in Section 6. Finally, conclusion of this paper has been summaries in Section 7 with proposing suggestions for future works.

2. Related works
The researchers focused on the micrometer waves in O2I scenarios at 3, 10, 17 and 60 GHz bands. According to the results which appeared that these waves accompanied by high attenuation, and this attenuation depends on the thickness of materials used in construction and frequency used [8].

The propagation of signals through O2I scenarios at 0.85 and 1.9 GHz bands by using the WI program were studied. The researchers noted that the signals are exposed to many obstructions through propagation in a simulation environment, due to a large number of barriers. In addition, they note that the frequency of 1.9 GHz generates higher losses and attenuation in signals than 0.85 GHz [9].

The internal coverage was study through the installation of external devices at 900 and 1800 MHz bands. The researchers discovered that the signals reach weakly to the receiving points exist inside the buildings. The reason for this weakness that the signals encountered several from barriers and these barriers worked to dispersion the signal strength unexpectedly. In addition, they observed that coverage gradually decreases when frequency increases [10].

In this paper, the O2I network will be designed and implemented for the College of Electrical Engineering and Electronics Technical in Baghdad according to the real engineering dimensions. This work was carried out using the WI program. The propagation of signals and their effect when transmitted from the transmitting antennas to receiving antennas have been study, measuring the received power of all receiving points in all buildings, and studying the effect of delayed signal propagation. The mm-waves were used at different frequencies related to the 5G, which are 10, 17, 30 and 60 GHz.
3. Wireless Signals Propagation
The reliability in the propagation of the outdoor wireless signals is an important part when the signals are transmitted from the transmitting antennas to the receiving antennas. Ideally, the signals or the radio waves are transmitted from the transmitting stations to the receivers without loss of the signal strength. Unfortunately, this is not possible in the real world, when the signals pass from the transmitting antennas to the receiving antennas, the signals will begin to degenerate as anything will be reflected, refracted or absorbed the signal power unexpectedly [11]. For this, the outdoor radio frequency (RF) will often behave like an electromagnetic phenomenon. Many factors impede the propagation of the wireless signals when transmitted from the transmitting antennas to the receiving antennas and most important these factors are [12]:

3.1. Absorption
The absorption is one of the factors that affect the propagation of the signals in different environments and that work on absorbing some of the signal power unexpectedly as shown in figure 1. The signal path when falls on a liquid material, this material will alleviate the beam strength in partial or total form and depending on the depth of this liquid [12].

![Figure 1. The signal absorption.](image1)

3.2. Refraction
It represents the change in the direction of the signal passing from a certain media into another as shown in figure 2, where the amount of the refraction signal is determined by the change in the speed and the initial direction for the propagation of this signal relative to the direction of the change in this speed [12].

![Figure 2. Refraction of the signal path.](image2)
3.3. Reflection
It is the change in the direction of the signals when transferred between two different media, where the signals return to the media from which the signals originated as shown in figure 3. The reflected media works to prevent the signals and not properly reach the receivers correctly, so the receiving power for the signals will decrease [12].

![Figure 3. Reflection of the signal path.](image)

3.4. Scattering
The scattering occurs when the wavelengths of the signals are much larger than the media parts. When the signals pass through smog, uneven surface, sandstorms, tree foliage, rocky terrain and other will occur the scattering as shown in figure 4 [12].

![Figure 4. Scattering of the signal path.](image)
3.5. Diffraction
The diffraction is the curvature and propagation around the signals when faced with different impediments when transmitted from the transmitting stations to the receiving antennas. The signals colliding with an object will bend around this object with long and different paths as shown in figure 5. The signals which do not face obstacles when spread through the media will not curvature and maintain on the original path and shortest reached to the receivers [12].

![Figure 5. Diffraction of the signal path.](image)

3.6. Multipath
In wireless communication networks, multipath is the propagation phenomenon produced from the radio signals that reach to the receiving antennas in two or more paths. The reasons for the multiplicity of these paths are the refractions, reflections of the buildings and others. The path of the signal wireless when colliding with objects, these objects reflect some of these wireless waves. This is called multipath as shown in figure 6. As each one of these reflected signals takes a different path because it has a capacity and a different stage [13].

![Figure 6. The multipath propagation.](image)
When the signals path collides with a particular barrier, it will create several parameters and the most important which are [14, 15]:

3.6.1. Direction of Arrival (DOA)
In wireless networks communications, DOA is the direction of the propagation wave propagation that reaches to all received points. The direction in Cartesian coordinates is given by the unit vector [14]:

\[
\hat{a} = \sin(\theta_A) \cos(\phi_A) \hat{x} + \sin(\theta_A) \sin(\phi_A) \hat{y} + \cos(\theta_A) \hat{z}
\]

where \( \theta_A \) and \( \phi_A \) with reference to the spherical coordinate system, which gives direction from any path that reaches the received point.

\[
\theta_A = \tan^{-1} \left( \frac{A_x^2 + A_y^2}{A_z} \right)
\]

\[
\phi_A = \tan^{-1} \left( \frac{A_y}{A_x} \right)
\]

The mean direction of arrival (MDOA) from which power arrives at the received point in the direction [15]:

\[
A = \sum_{i=1}^{N_p} P_i \hat{a}_i
\]

where \( \hat{a}_i \) is a unit vector in a direction for each \( i^{th} \) path arrives at the received point, \( N_p \) is the total number of the paths and \( P_i \) is the time average power in watts for each \( i^{th} \) path can be calculated by:

\[
P_i = \frac{\lambda^2 \beta}{8 \pi \eta_0} \left| E_{\theta,i} g_{\theta}(\theta_i, \phi_i) + E_{\phi,i} g_{\phi}(\theta_i, \phi_i) \right|^2
\]

where \( \eta_0 \) is the impedance of free space at 377 \( \Omega \), \( E_{\theta,i} \) and \( E_{\phi,i} \) are components of the electric field for each \( i^{th} \) path at the received point, \( \theta_i \) and \( \phi_i \) give the DOA, \( \beta \) is an overlap of the frequency spectrum in the transmitted waves and \( g_{\theta}(\theta_i, \phi_i) \) is the DOA that can be calculated by:

\[
g_{\theta}(\theta, \phi) = \sqrt{\left| G_{\theta}(\theta, \phi) \right|} e^{j\phi_{\theta}}
\]

where \( G_{\theta} \) is a component of receiving antennas gain and \( \phi_{\theta} \) is a relative phase of \( \theta \) component for far region electric fields.

3.6.2. Direction of Departure (DOD)
In wireless communication, the DOD is the direction of radiated power from the transmitter to a certain direction in the simulation scene. The direction in Cartesian coordinates is given by the unit vector [14]:

\[
\hat{d} = \sin(\theta_D) \cos(\phi_D) \hat{x} + \sin(\theta_D) \sin(\phi_D) \hat{y} + \cos(\theta_D) \hat{z}
\]

where \( \theta_D \) and \( \phi_D \) with reference to the spherical coordinate system, which gives the direction of any path that leaves the transmitter.

\[
\theta_D = \tan^{-1} \left( \frac{D_x^2 + D_y^2}{D_z} \right)
\]
The mean direction of departure (MDOD) from which power leaves the transmitter is given by the angles [14]:

\[ D = \sum_{i=1}^{N_p} P_l \mathbf{d}_i \]  

where \( \mathbf{d}_i \) is a unit vector in a direction for each \( i^{th} \) path leaves the transmitter.

### 4. Wireless Communication and Channel Model

The characteristics of the wireless communication signals change radically when transmission from transmitter antenna to received points. These characteristics depend largely on distances between transmitter and receiver. This distance between the two antennas is called a channel model. There are many different methods to measure the performance of any wireless communication channel, in which this performance differs from network to another, due to the design nature of this network as well as the devices used in this network. There are parameters for measuring the performance of the wireless communications networks to respond to any channel as explained in detail below [16]:

#### 4.1. Path Loss (PL)

It is a decrease in the received power of the signals when propagated in the simulation environment. Many factors play a big role in the low of the path, which are the far distances between the transmitting and receiving antennas because the path will go through several obstacles that lead to successive losses in this path, as well as the multipath that cause the reflections and collisions between the paths. PL can calculate by [14]:

\[ PL(d)dB = 20 \log \left( \frac{4\pi d_0}{\lambda} \right) + 10\alpha \log \left( \frac{d}{d_0} \right) \]

Where \( \lambda \) is the wavelength of the carrier frequency, \( d_0 \) is distance reference in the free space, \( \alpha \) is exponent of the path loss and \( d \) is the distance between transmitter station and receiving points.

#### 4.2. Delay Spread (\( \sigma_t \))

The spread delay is the difference between the arrival time of the shortest path to the longest path. It considered one of the important measurements to find out the time delay of the paths and as well as the effects that affect the performance of the various wireless communication systems, \( \sigma_t \) is calculated by [14]:

\[ \sigma_t = \sqrt{\frac{\sum_{i=1}^{N_p} (t_i - \bar{t})^2 P_l}{P_R}} \]

where \( P_l \) is time average of the power in watts, \( N_p \) is the total number of paths, \( P_R \) is the received power, \( t_i \) is the time of arrival during each path \( i^{th} \) and \( \bar{t} \) is the mean time of arrival.

The time of arrival for each propagation path during the wireless communications is given by [17]:

\[ t_i = \frac{L_i}{c} \]

Where \( L_i \) is the path length of total geometrical and \( c \) is the speed of light in free space.
The mean time of arrival for each propagation path during the wireless communications is given by [15]:

$$
\bar{t} = \frac{\sum_{i=1}^{Np} P_i t_i}{P_R}
$$

(14)

4.3. Received Power ($P_R$)

It is influenced by many factors that lead to the decrease this power and the most important of which are multiple paths that cause collisions, refractions, and reflections with other paths and others. $P_R$ is calculated by [14]:

$$
P_R(dBm) = 10 \log \left( \frac{P_T \lambda^2 \beta}{16\pi^2 d^2} \right) + 30(dB) - L_s(dB)
$$

(15)

where $P_T$ is the time averaged of the power, $L_s$ is any additional losses that pass through the network system and $\beta$ is an overlap of the frequency spectrum in the transmitted waves.

5. Simulation Scene Scenario

We have been designed and implemented a simulation scene that is similar to the rectangle campus of the Electrical Engineering Technical College in Baghdad according to the real dimensions. The campus consists of six buildings, which are the deanship, the internal student dormitory, department of graduate studies, the student club, engineering laboratories, and the scientific departments. These buildings are distributed for two and three floors, where the building of the college deanship, the scientific departments, the graduate studies department, and the student club consist of two floors, and the height of each floor 3.5 m. For this, the height of the buildings becomes 7 m. While the building of the internal student dormitory and engineering laboratories consists of three floors and each floor with a height of 3.5 m, for this, the overall heights of those buildings are 12 m. The rest of the small structures are information and store rooms with a height of 3.5 m for each room, while heights of the surrounding outer walls in each aspect of the college will be 2.8 m. Using AutoCAD package, a simulation model for a case study campus is designed in order to show the real dimensions of the college as shown in figure 7.

![Figure 7. The college structure designed using AutoCAD program.](image_url)
The final design of this college using the WI program as shown in figure 8.

Figure 8. Case study structure designed by using the WI program.

The types of materials used in the construction of this scene are the concrete used to build ceilings, bricks used to build walls, dense foliage used to represent the gardens, glass used to build windows while metal and wood used in doors. The materials used to construct this scene in the WI program rely heavily on the representative electrical parameters properties. Such the International Telecommunication Union (ITU) organization suggests that each material has the conductivity ($\sigma$) and the permittivity ($\varepsilon$) that depends on the type of material and suggests that ($\sigma$) and ($\varepsilon$) depend radically on the frequency used in the simulation environment. The $\sigma$ and $\varepsilon$ with thickness for all materials used in the construction are listed in table 1 [18].

Table 1. The thickness with conductivity and permittivity for all materials used in building the simulation scene [18].

| Types of materials | Thickness | 10 GHz | 17 GHz | 30 GHz | 60 GHz |
|--------------------|-----------|--------|--------|--------|--------|
|                    | $\sigma$  | $\varepsilon$ | $\sigma$  | $\varepsilon$ | $\sigma$  | $\varepsilon$ | $\sigma$  | $\varepsilon$ |
| Concrete           | 0.30 m    | 0.210  | 5.31   | 0.323  | 5.31   | 0.512  | 5.310  | 0.8966  | 5.310  |
| Brick              | 0.28 m    | 0.038  | 3.75   | 0.038  | 3.75   | 0.038  | 3.750  | 0.0380  | 3.750  |
| Glass              | 0.003 m   | 0.066  | 6.27   | 0.126  | 6.27   | 0.248  | 6.27   | 0.567   | 6.27   |
| Wood               | 0.045 m   | 0.055  | 1.99   | 0.097  | 1.99   | 0.180  | 1.990  | 0.378   | 1.990  |
| Foliage            | 0.00035 m | 0.1    | 1.0    | 0.1    | 1.0    | 0.1    | 1.0    | 0.1     | 1.0    |
| Metal              | 0.0625 m  | $1.0 \times 10^8$ | 1      | $1.0 \times 10^8$ | 1      | $1.0 \times 10^8$ | 1      | $1.0 \times 10^8$ | 1      |
The types of antennas used in both the transmitter and receivers are directional and omnidirectional respectively as shown in figure 9(a) and figure 9(b).

![Radiation Pattern](image)

Figure 9. The Radiation Pattern for (a) Directional and (b) Omnidirectional.

The properties of the transmitting and receiving antennas are listed in table 2. While the bandwidth selected for a case study is 1 GHz for 10, 17, 30 and 60 GHz bands.

Table 2. Properties of the Directional and Omnidirectional Antennas.

| Properties (Antenna)                  | (Transmitter Antenna) | (Receiver Antenna) |
|---------------------------------------|------------------------|--------------------|
|                                       | Directional            | Omnidirectional    |
| Waveform                              | Sinusoid               | Sinusoid           |
| Polarization                          | Vertical               | Vertical           |
| Voltage Standing Wave Ratio (VSWR)    | 1                      | 1                  |
| Transmit Power (dBm)                  | 30                     | --                 |
| Temperatures (K)                      | 293                    | 293                |
| Receiver Threshold (dBm)              | -250                   | -250               |
| Electric Field Plane Beam Width (EFPBW)| 120°                   | 360°               |
| Antenna gain (dBi)                    | 19                     | 2                  |

In this scenario, the transmitter was placed at a height of 3 m above the surface of the earth and located at the starting of the college entrance. The choice of this location for the transmitter is due to a detailed study in the previous research [18], where an algorithm was built to find the best location of the transmitter in college. According to the results of which appeared from the algorithm, it was noted that this place is the best location of the transmitter to coverage the college well. The received points were deployed inside all the buildings on both floors. 50 received points were deployed in the various buildings of the first floor at a height of 1.2 m and 50 received points were deployed in different buildings of the second floor at a height of 4.2 m as shown in figure 10.
The transmitter antenna and receiving points that deployed in both two floors.

6. Results and Discussion
The signal path pass in several barriers as they are transferred from the transmitter antenna to the receiving antennas and especially in NLOS regions. These barriers are built of several materials and play a major role in obstructing the direction of the beam path. It is noticed that some of the barriers materials reflect the signal, some others have absorbed the received power strength unexpectedly and others do all the cases above as shown in figure 11. It is clear that the transmitted beam from the transmitter to several various positions of the received points above a field of scenario. In addition, we noticed that the receiving points existing on the first floor are exposed to more losses and reflections than the receiving points existing on the second floor. The main reason for this is high these points as well as the presence of more barriers than the second floor that disperses beam strength.

Figure 10. The transmitter antenna and receiving points that deployed in both two floors.

Figure 11. The beam transmitted from the transmitter antenna to the receiving points at 10 GHz (a) First floor (b) Second floor.
6.1. Delay Spread
The relation between delay spread and distance for the first and second floors are shown in figure 12 (a-b). It is clear that the delay spread in all of the frequencies decreased whenever increased distances between the transmitter and all distribution of the receivers in the campus. The received signal will be mostly the resulting of reflections and especially in the NLOS regions suffer from many barriers that cause deterioration of received signals unexpectedly. As noted in figure 12(b) there is a fast decrease in the delay spread. While in the LOS scenario, the delay spread will decrease with distance increasing but it is noticed a lower decrease than NLOS regions as shown in figure 12(a) because the signal passes through fewer the barriers.

Figure 12. Delay spread versus distance (a) First Floor and (b) Second Floor.

6.2. Path Loss
The relation between path loss and distance for the first and second floors for various frequencies are shown in figure 13(a-b). Notice that the path loss will increase with increasing the distance and frequency in both LOS and NLOS regions. However, there is a rapid increase for the path losses in the NLOS regions as shown in figure 13(b), because of the far distance between the transmitter and the receiving points, as the paths reach the receiving points have encountered several obstacles that lead to dissipate the strength of the paths. While in the LOS regions less in path loss from NLOS regions as shown in figure 13(a) due to the short distances between the transmitter and the receiving points, as the paths reach the receiving points without encountering severe obstacles.

Figure 13. Path loss versus distance (a) First Floor and (b) Second Floor.
6.3. Received Power

The relation between received power and distance for the first and second floors are shown in figure 14(a-b). The obtained data in this figure include studying the effect of changing frequency upon the outcomes. Generally, it has found that increasing the distance and frequency leads to decrease the received power. This perhaps indicates the received polygon can get the highest power than received points, because of the received polygon is located in a place which does not contain barriers that lead to decrease received power. While in the NLOS regions there is a rapid decrease in the received power, because of reflections of the building surface and the far distance between the transmitter and the receiving points, as the paths that reach the receiving points have encountered several obstacles, which will dissipate these paths.

Figure 14. Received power versus distance (a) First Floor and (b) Second Floor.

Finally, it is noted that all resulting figures indicate that 10 GHz frequency produces the best outcome regarding delay spread, path loss, and received power on both two floors as compared to other frequencies. The increase in frequency will lead to an increase in path loss, decrease RSS and increase the propagation of paths resulting from reflections in the college and network performance will decrease gradually.

7. Conclusion

In this paper, the barriers and materials used to build these barriers and their thickness play a major role in obstructed the direction of the signals transmitted from the transmitting antenna to the receiving points. It is noted that these signals cannot penetrate barriers made of concrete and these signals will be fully reflected. In addition, the signals can penetrate the walls made of bricks, but it is difficult with high dispersion. Furthermore, the signals can easily penetrate dense foliage used to represent the gardens, glass, and metal. Increasing in the frequency negatively affects the performance of the designed network, because the high frequencies cannot penetrate a large number of barriers for this will increase reflections and refractions, which causes interference between signals and the reduced received power which receive by each user. In addition, observed that there was an inverse relationship between the increasing frequency and delay spread and as well as the received power and also observed a direct relationship between frequency increase and path losses in both two floors. In future work, we aim to use devices that can apply real measurements for the 5G band frequencies and compare this work with simulation works.
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