A Comparison between Different C-band and mmWave band Frequencies for Indoor Communication

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***Abstract* —**A comparison between the performance of C-band and mmWave band with different range of frequencies has been presented in this paper. These frequencies are included 3.5 and 5.2 GHz for C-band, whereas they involved 38 and 42 GHz for mmWave band. This comparison has been accomplished with two different scenarios including Line-of-Sight (LOS) and non-Line-of-Sight (NLOS). Statistical parameters of channel propagation characteristic including delay spread, path loss and received power are inspected in this paper. Furthermore, the impact of building material on the signal penetration has been considered as function of frequency. A Comparative Study of Wireless Propagation Simulation has been carried out using Wireless InSite software-based Ray tracing model. Using this software, the simulated results have been analyzed. Of particular note is the inverse relation between delay spread and separation distances with values in mmWave are much smaller than that in C-band. In contrast, there is a direct correlation between the path loss and the separation distance has been found, where the path loss value in mmWave is much higher than C-band. A substantial contribution has been proposed to enhance the coverage area of mmWave band as an attempt to make it closer to the C-band performance. This study would be considered for designing and implementation of smart modern buildings. In particular, when technology trends to move toward the next Fifth Generation (5G) communication system with increasing the coverage area of signals particularly for indoor communication aspects.

Index Terms—Wireless InSite, C-band, millimeter wave, indoor communication, 5G, propagation.

I. Introduction

Smart mobile communication systems being one of the successful communication techniques as results of people demands with continuing advent of new mobile devices with new technologies [1]. Currently, the fourth generation (4G) Long Term Evolution (LTE) wireless network is widely developed for indoor applications with frequency around sub-6 GHz spectrum. In particular, this technique provides narrowness bandwidth, highest attenuation and poor multipath propagation characteristics. However, mobile data traffic is suffering from unequaled growth. For example, the study in [2] denoted that there will be a growth of 108 percent of Component Annual Growth Rate (CAGR) in data traffic. Consequently, a huge congestion problem in the sub-6 GHz spectrum has been highlighted. Even though, many advanced techniques such as Multiple-Input Multiple-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) have been utilized to achieve the highest efficiency of the current spectrum and to increase the capacity to specific limits [3]. However, these techniques are not expected to satisfy the requirement of huge traffic at least till 2020. Hence, fresh efforts have been achieved as attempt to maximize the capacity of current spectrum and to find new spectrum beyond the 4G network. This is because the overcrowding in the current spectrum and also due to the needing for a large frequency bandwidths for the next generations in the future of communication network world [4].

The mmWave band with frequency range from 30 to 300 GHz considered to be the best innovative solutions for achieving high channel bandwidth, degrading the interference, allowing high speed data communication and making propagation characteristics more homogeneous [4]. It is agreed [5] that mmWave with short wavelength (1-10mm) contribute significantly in developing antenna design. It is found that hundreds of antennas which install as array can work as transmitter and Access Point (AP) device with proportionately small physical chipset. Moreover, the 5G system is consider being solution for the problems that related to signal attenuation [4], [6].

Extensive work and investigation have been achieved to study channel and multipath propagation characteristics at different frequencies. For example, in [7], the channel characterization has been investigated for path loss and delay spread to exploit a wide range of frequency ranged from C-band to 28 GHz and with specific bandwidth around 250 MHz and input power of 16 dBm. This study [7], however, has not included the effects of building materials. In contrast, comparison between traditional method that used 6 GHz band of (0.8, 2, 3.5 and 5.2 GHz) and mmWave frequency band of (10, 18 and 28 GHz) have been performed in another study [8], where omnidirectional antennas for both transmitter and receiver has been used. At that study, the effects of different building materials and walls have also been included in the comparison. Another study [9] has been investigated for indoor model with frequency 5.2 GHz and 500 MHz bandwidth. It is concluded from this study

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[9] that the delay spread in NLOS case increases with increasing frequency, which is differ than LOS case. The propagation characteristics of mmWave band with 38 GHz in indoor corridor environment for a LOS and NLOS scenarios has been studied by many researchers like in [10], [11]. In the later study, omnidirectional with height of 1.7 m and directional horn antenna with height of 1.5 m for transmitter and receiver respectively have been fixed. The transmitted power, the gain and the bandwidth are considered to be zero dBm, 3 dBi, and 1 GHz respectively. It is worth to mention, that 38 GHz are available with spectrum allocations above 1 GHz of bandwidth, which generally used for Local Multipoint Distribution Service (LMDS) in the past decade [12]. Moreover, this band could be utilized for mobile communication and backhaul [12]. On the other hand, signal with 42 GHz frequency has attractive more attention by researcher and communication companies than other frequencies due to the fact that this frequency being mediated between the license free (60 GHz band) and the most intensity utilized 28 GHz [13]. Such these frequencies would require a LOS case which it was very suitable for Point to Multipoint Technology (PTMP) backhaul [13]. The researchers in [14] investigate the LOS transmission performance of 42 GHz band.

In this paper, however, an extensive comparison and investigation has been performed for multipath propagation characteristics at C-band and mmWave frequency with frequencies 3.5 and 5.2 GHz and 38 and 42 GHz, respectively. For context, delay spread, path loss and received power are included in the calculations of this paper for both LOS and NLOS scenarios. Perhaps, the most significant aspect of this study is including the effects of different building materials in the case study of this paper. This study can add a significant contribution to enhance the coverage performance of mmWave band to be approached to the C-band frequency. The rest of the paper is organized as follows. The channel propagation characteristics have been described in section II. Section III discusses the case study of this work. In section IV, the result and discussion have been presented. Finally, section V outlines the conclusion of this paper.

II. Channel Propagation Characteristics

It is agreed that material of buildings has significant impacts on the characteristics of signal propagation. This effect is depending on the frequency of transmitted signal, particularly, for indoor communication [15]. Therefore, in this study, the effects of building material were considered within the comparison study between the performance of signal with C-band and mmWave band. To study the physical material properties, losing in dielectric medium is included in Wireless InSite software from REMCOM, where the real part of relative permittivity (η`) and conductivity ($\sigma$) of different materials are calculated based on frequency dependency. A dedicated software designed by Graphical user interface (GUI) using MATLAB as demonstrated in Fig. 1 to calculate the different value of $\eta$` and σ for common building materials and as a function of frequency. Results obtained from previous software are listed in Table I.

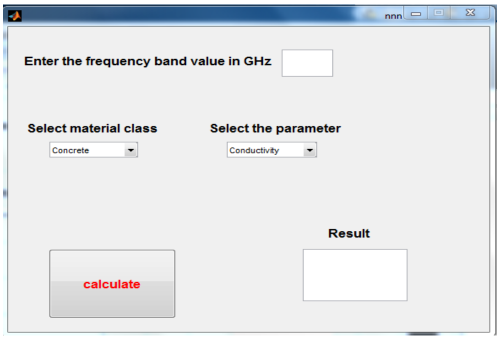


Fig. 1. GUI window for our software designed in MATLAB to calculate (η`) and (σ) values for different materials based on frequency dependency.

TABLE I: BUILDING MATERIAL THICKNESS, CONDUCTIVITY AND PREMITTIVITY VALUES THAT UTILIZED IN THIS WORK

Materials	Thickness (cm)	η`	F=3.5 GHz	F=5.2 GHz	F=38 GHz	F=42 GHz
			σ			
Concrete	30	5.31	0.089	0.123	0.619	0.671
Wood	4.5	1.99	0.017	0.027	0.231	0.258
Glass	0.3	6.27	0.019	0.030	0.329	0.370
Brick	28	3.75	0.038	0.038	0.038	0.038
Ceiling Board	0.9	3.66	0.002	0.003	0.034	0.038
Floor Board	2.2	1.5	0.023	0.040	0.600	0.687
Drywall	0.9	2.94	0.028	0.037	0.152	0.163

A. Delay Spread

Generally, signal emanating by transmitter can propagate in different paths toward receiver. In each path, delay spread (σ_τ) can be calculated as the statistical measure of the variety of multipath related effect. In general, increasing σ_τ can lead to Inter-Symbol Interference (ISI), which has considerable effect on antenna selection and limiting the coverage of transmitter [17]. The σ_τ can be calculated using equation (1) [15].

$$\sigma_\tau = \sqrt{\frac{\sum_{n=1}^{NP} Pn(tn-\bar{t})^2}{P_R}} \tag{1}$$

where P_R is the received Power, $\bar{t}$ is the mean time of arrival, NP is the number of paths and Pn time average power in watts of the n^{th} path which can be expressed in equation (2).

$$Pn = \frac{\lambda^2 \beta}{8\pi n_0} |E\theta, ng\theta(\theta n, \Phi n) + E\Phi, ng\Phi(\theta n, \Phi n)|^2 \tag{2}$$

where λ is the wavelength, β is the overlap of the frequency spectrum, n_0 is the impedance of the free space, $E\theta,n$ and $E\Phi,n$ are the theta and phi components of the electric field of the n^{th} path at the receiver point and θn and Φn give the direction of arrival. To derive the relation between frequency and delay spread. First we apply equation (2) on equation (1) to form a new equation as clarified in equation (3).

$$\sigma_\tau = \sqrt{\frac{\sum_{n=1}^{NP}(tn-\bar{t})^2 \lambda^2 \beta |E\theta,ng\theta(\theta n,\Phi n)+E\Phi,ng\Phi(\theta n,\Phi n)|^2}{P_R 8\pi n_0}} \quad (3)$$

Note that the wavelength (λ) can be expressed with respect to frequency as indicate in equation (4):

$$\lambda = \frac{c}{f} \quad (4)$$

Next step was applying equation (4) on (3) and get the equation (5).

$$\sigma_\tau = \sqrt{\frac{\sum_{n=1}^{NP}(tn-\bar{t})^2 (\frac{c}{f})^2 \beta |E\theta,ng\theta(\theta n,\Phi n)+E\Phi,ng\Phi(\theta n,\Phi n)|^2}{P_R 8\pi n_0}} \quad (5)$$

The later equation can be re-write in the following formula as seen in equation (6).

$$\sigma_\tau = \sqrt{\frac{\sum_{n=1}^{NP}(tn-\bar{t})^2 c^2 \beta |E\theta,ng\theta(\theta n,\Phi n)+E\Phi,ng\Phi(\theta n,\Phi n)|^2}{f^2 P_R 8\pi n_0}} \quad (6)$$

From equation (6) it can be concluded that there is a reversal relationship between the delay spread and the frequency.

B. *Path Loss*

Another important characteristic of channel propagation is path loss. It demonstrates the signal power loss in indoor propagation medium to determine the radio wave coverage [18]. In addition, it has substantial to specify the location of transmitter, as well as to determine the transmit power and sensitivity of receiver [19]. The most commonly used definition of path loss can express in equation (7) [15].

$$L_{path}(dB) = P_T(dBm) - P_R(dBm) + G_{T,Max}(dBi) + G_{R,Max}(dBi) - L_s(dB) \quad (7)$$

where P_T is the time average radiated power, $G_{T,Max}$ and $G_{R,Max}$ are the maximum gains of the transmitting and receiving antennas, respectively and LS is the sum of all other losses in the system (in dB), including the bandwidth overlap factor. In order to derive the serious relation of path loss versus frequencies, Free Space Path Loss (FSPL) equation used to clarify the previous relation which in turn has derived from Friis transmission equation that expressed in (8).

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \quad (8)$$

where G_T and G_R is the antenna gain for transmitter and receiver, respectively and R is the distance between transmitter and receiver. Dividing the last equation by $(1/P_T)$ and neglecting the G_T and G_R. Since, Friss transmission equation considered using isotropic antennas. FSPL can be derived as seen below and expressed in equation (9).

$$\frac{P_R}{P_T} = \frac{\lambda^2}{(4\pi R)^2}$$

$$FSPL = \frac{P_T}{P_R} = \frac{(4\pi R)^2}{\lambda^2}$$

$$FSPL = (\frac{4\pi R}{\lambda})^2 \quad (9)$$

In addition, equation (9) can be expressed in term of fre-quency as seen in equation (10)

$$FSPL = (\frac{4\pi R f}{c})^2 \quad (10)$$

A convenient way to express FSPL is in terms of dB can be derived from equation (10) as seen below:

$$FSPL = 10\log_{10}(\frac{4\pi R f}{c})^2$$

$$= 20\log_{10}(\frac{4\pi}{c}) + 20\log_{10}(R) + 20\log_{10}(f)$$

$$= -147.56 + 20\log_{10}(R) + 20\log_{10}(f) \quad (11)$$

From equation (11) it can clearly indicate that there are a direct relation between frequency and path loss.

C. *Received Power*

Received power can be calculated with or without antenna pattern and with specific equation formula as expressed in equation (12) and equation (13), respectively [15].

$$P_R = \frac{\lambda\beta P_T}{(4\pi)^2 R^2} |g^T,\theta(\theta A,\Phi A) + g^T,\Phi(\theta D,\Phi D) g^R,\Phi(\theta A,\Phi A)|^2 \quad (12)$$

$$P_R = \frac{\lambda\beta P_T}{(4\pi)^2 R^2} \quad (13)$$

where θD and ΦD are the direction in which ray leaves the transmitter, θA and ΦA are the direction in which ray arrives at the receiver. Finally, g^T and g^R represent the direction of arrival for both transmitter and receiver. It is worth to mention, that in this paper, we used equation (13) to determine the received power without the effect of antenna parameter. A convenient way to express the relation of received power and frequency by modifying equation (13) in term of frequency as seen in equation (14). From the later equation, it can deduce a reversal relationship between received power and frequency.

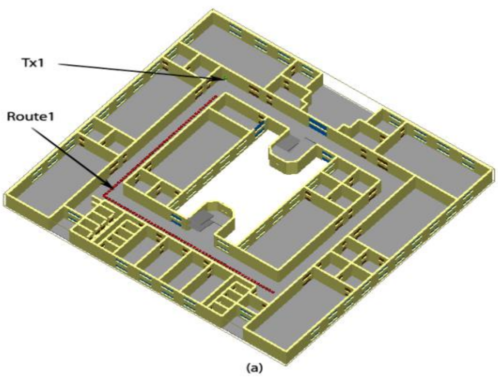
$$P_R = \frac{c\beta P_T}{(4\pi)^2 R^2 f} \tag{14}$$

III. Case Study

The case study that used in this paper is focused on the corridor area of the first and second floor in the laboratory building of the electrical engineering technical college. The building was designed and simulated using Wireless InSite software [15]. The thickness of different building materials used is listed in Table I. The layout of building design is shown in Fig. 2, where two transmitters Tx1 and Tx2 are located in the same corner of the corridor in the first and second floor respectively and with same height of 2.5 m above the ground. On the other hand, for the receivers, we proposed two routes. Route1 and Route2 are located in the corridor of the first and second floor of the building respectively. The distance of these routes are ranged from (1-50) m. The total numbers of received points that have been studied in this work are 104 points with 0.5 m separation distance between each point. The characteristics of used transmitters and receivers antenna are highlighted in Table II. In this study, both LOS and NLOS scenarios were included, where Tx1 and Tx2 with Route1 and Route2 respectively for first scenario; whereas in the second scenario, would be formed by considering Tx1 with Route2 and vice versa. The serious effects of different building materials have been taken into consideration for the entire investigations and based on International Telecommun-ication Union (ITU) recommendations [16]. In this paper, the selected bandwidth for the case study is 500 MHz for both 3.5, 5.2 GHz and 1 GHz for both 38 and 42 GHz.

TABLE II: Transmitter and Receiver Antenna Properties

Antenna properties	Tx Antenna	Rx Antenna
Antenna type	Omni-Directional	Omni-Directional
Input Power (dBm)	20	-
Gain (dBi)	20	10
E-Plane HPBW	10°	90°
Waveform	Sinusoid	Sinusoid
Polarization	V	V



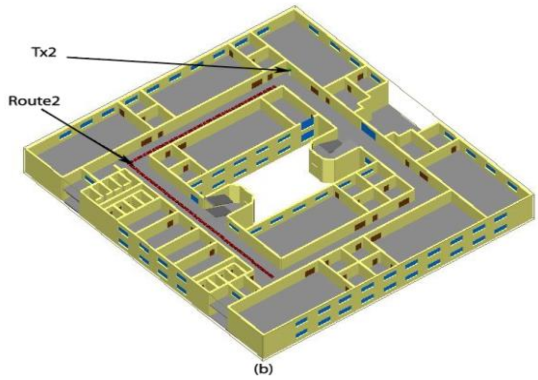


Fig. 2. Building 3D design with simulation case study (a) first floor, (b) second floor.

IV. Results and Discussion

The case study that has been clarified previously was simulated using wireless InSite software, channel characterization was incorporated based on delay spread, path loss and received power, for both C-band and mmWave band. It is found from [20], that C-band ranging from (3.4-8) GHz, noted that using the band from (3.4-4) GHz will cause somewhat an overlapping into the IEEE S-band for radars [20]. Fig. 3 shows the multipath propagation for 3.5 GHz from Tx2 to several received points along Route2 within the corridor of second floor. It is noticed, that the highest power path is penetrated through glass without considerable power loss. In brick penetration degree, however, an inversely proportional is noticed with the wall thickness. On the other hand, the present of concrete in the area can prevent the signal from penetration.

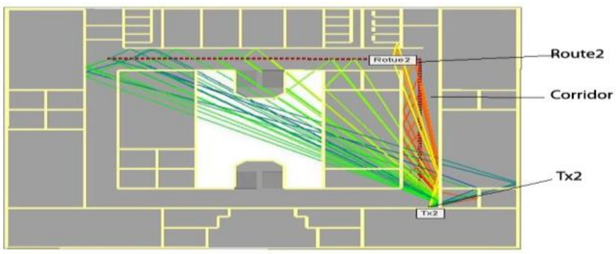


Fig. 3. Different multipath propagation from Tx2 to Route2 with highest power path and for different received points

To show the relation between the delay spread and separation distance for both LOS and NLOS scenarios, Fig. 4(a-b) present the LOS scenario. The mean value of delay spread for Route1-Tx1 and Route2-Tx2 are calculated and presented in Table III. It can be noticed, that in the LOS case, the delay spread of mmWave band is smaller than the C-band. In NLOS scenario shown in Fig. 4(c-d), the mean value of delay spread is calculated for the Route1-Tx2 and Rotue2-tx1 respectively and clarified at the same previous table. The serious effect of building materials have been noticed on the delay spread values for the two covered floors. From the comparison of mean values between LOS and NLOS scenarios, it is concluded that delay spread for LOS and NLOS scenarios in mmWave band is relatively smaller than that in C-band.

It is also found that the separation distance between transmitter and receiver has no clearly proportional effect on delay spread values.

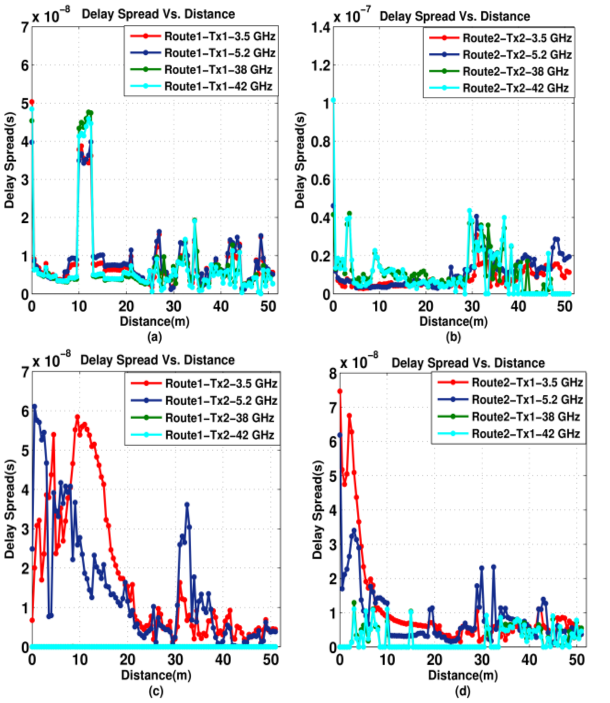


Fig. 4. Delay spread Vs. separation distance for (a, b) LOS scenario and (c, d) NLOS scenario.

TABLE III: THE CALCULATION OF DELAY SPREAD MEAN VALUES PER EACH SELECTED FREQUENCY

Routes		Delay spread mean values in (ns) based each selected frequency			
		3.5 GHz	5.2 GHz	38 GHz	42 GHz
LOS	Route1-Tx1	9.022	8.54	7.689	7.291
	Route2-Tx2	8.083	0.112	0.111	0.105
NLOS	Route1-Tx2	0.175	0.148	0.004	0
	Route2-Tx1	8.75	2.39	2.28	0.110

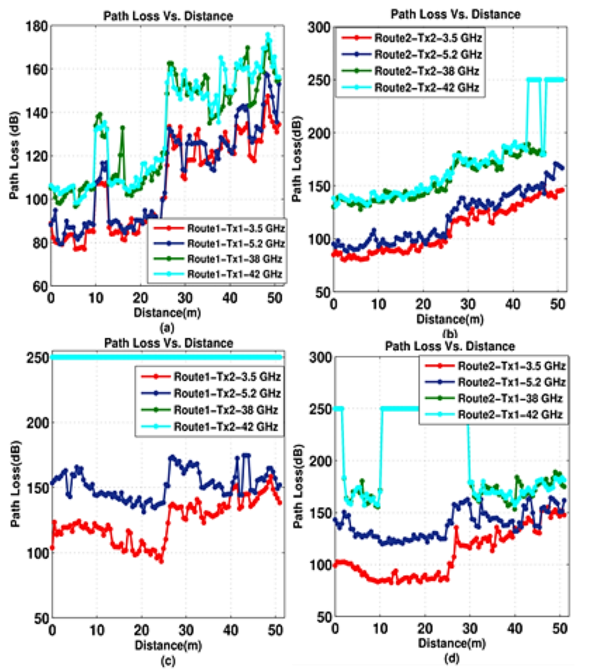


Fig. 5. Path loss Vs. separation distance for (a, b) LOS scenario and (c, d) NLOS scenario.

TABLE IV: THE CALCULATION OF PATH LOSS MEAN VALUES PER EACH SELECTED FREQUENCY

Routes		Path loss mean values in (dB) based each selected frequency			
		3.5 GHz	5.2 GHz	38 GHz	42 GHz
LOS	Route1-Tx1	106	110	131	132
	Route2-Tx2	109	119	162	169
NLOS	Route1-Tx2	124	152	250	250
	Route2-Tx1	110	138	203	203

To illustrate the effect of the separation distance on the path loss for both LOS and NLOS scenarios, Fig. 5(a-b) illustrates the first scenario, in which the mean value of path loss for Route1-Tx1 and Route2-Tx2 are calculated and presented in Table IV. For NLOS case, Fig. 5(c-d) shows the relation between path loss and distance. In contrast, the mean value of path loss Route1-Tx2 and vice versa has been recorded in the same previous table. It's obvious that mmWave can produce higher loss values compared to C-band. This is because the fact that dealing with increasing frequency that yield decreasing in the related signal wavelengths, resulting an increasing in the signal attenuation. Moreover, it can be seen in Fig. 5 that the overall trend of path loss increases with increasing the separation distance. The path loss in LOS is relatively smaller than the case in NLOS. This is due to the direct path of the propagation, which can create considerable effect on the collected received power.

The performance of received power versus separation distance for LOS scenario was illustrates in Fig. 6(a-b) where the mean values of received power were calculated for LOS and NLOS routes respectively. For LOS represented by Route1-Tx1 and Route2-Tx2, The calculations have been presented in Table V. It can be observed the reverse relationship between received power value and frequency, which make C-band have higher values compared to mmWave band. Moreover, the same relation was clarified between the received power and separation distance. The relation between received power and distance for NLOS case was clarified in Fig. 6(c-d). The mean values of received power per each frequency has been calculated and inserted in Table V. It is worth to mention that, NLOS suffers from same relationship for both frequency and separation distance but with much lower values especially for mmWave band, because of the being strongly attenuated by different building materials in the first and second floor which may result in frequency reuse and user privacy.

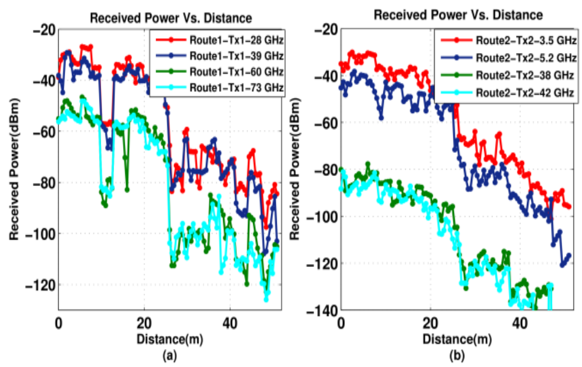
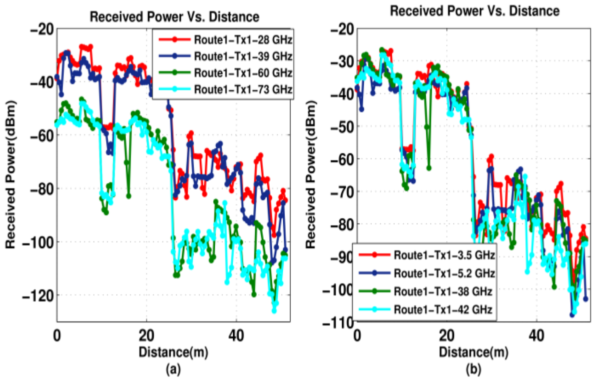


Fig. 6. Received power Vs. separation distance for (a, b) LOS scenario and (c, d) NLOS scenario.

TABLE V: THE CALCULATION OF DELAY SPREAD MEAN VALUES PER EACH SELECTED FREQUENCY

Routes		Received power mean values in (dBm) based each selected frequency			
		3.5 GHz	5.2 GHz	38 GHz	42 GHz
LOS	Route1-Tx1	-56	-60	-81	-82
	Route2-Tx2	-59	-69	-116	-126
NLOS	Route1-Tx2	-74	-102	-250	-250
	Route2-Tx1	-60	-88	-174	-174

Finally, in order to reach with mmWave band to cover the comparatively longest link lengths and an overall performance asymptotic to the performance of C-band in coverage of indoor environment, one solution was increasing the input power to its double value selected for the C-band in order to achieve the relatively same coverage within LOS scenario as it can be seen in Fig. 7, Where Fig. 7(a, c) represent the relation of received power vs. distance and for (Route1-Tx1) and (Route2-Tx2) respectively with input power of 20 dBm, while in Fig. 7 (b, d) represent the same relation for the same routes but with doubling value of input power for mmWave band to be equal to 40 dBm. The overall calculation of mean for received power values listed in Table VI. It can be deduced that, the slight effect for the NLOS scenario would not make a tangible result in practical scenario this is because of the effect of complex permittivity of different materials consisting the building, its thickness and surface roughness. On the other hand, LOS scenario shows an encourage results where received power level increased by 20 dBm for the case of (Route1-Tx1) and more than 25 dBm for (Route2-Tx2).



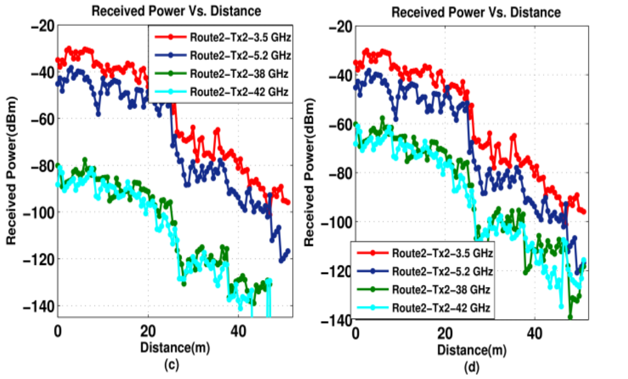


Fig. 7. Received power Vs. separation distance for different input power showing the LOS route with input power of: (a, c) 20 dBm, (b, d) 40 dBm.

TABLE VI: OVERALL MEAN RECEIVED POWER (MRP) CALCULATION OF RECEIVED POWER MEAN FOR MMWAVE BAND AT DIFFERENT INPUT POWER

Input power		20 dBm		40 dBm	
Frequency		38 GHz	42 GHz	38 GHz	42 GHz
LOS	Route1-Tx1	-81	-82	-61	-62
	Route2-Tx2	-116	-126	-89	-91
NLOS	Route1-Tx2	-250	-250	-213	-234
	Route2-Tx1	-174	-174	-125	-134

V. CONCLUSION

In this paper, the propagation characteristics of C-band frequency for (3.5 and 5.2) GHz and mmWave band of (38 and 42) GHz have been investigated and compared in delay spread, path loss and received power and for indoor environment. It has been concluded that mmWave band has smaller delay spread as compared to C-band which will result in preferable ability to enhance the quality of indoor communication by increasing the ISI. In addition, the comparison showed that mmWave recorded much higher values of path loss as compared to C-band, which means that the coverage of mmWave band is smaller than C-band due to its high attenuation. As a result, a contribution to enhancing the coverage area for LOS case is investigated and reported by increasing the input power to its double original value, which should be keep in consideration when dealing with the problem of coverage in mmWave, another important parameter was the effect of different building materials on the penetration degree of signal which should be considered for the selection of modern building, smart cities and appropriate building materials. These conclusions can provide the Theoretical basis for the coverage of indoor communication system for fifth generation (5G) networks. Furthermore, providing the optimal balance between coverage and capacity for cost effectiveness implementation. For the future studies, many methods and investigations could be done to improve the emerging of C-band as a primary frequency band for 5G communication and for uplink coverage assistance issues.

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