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Performance Analysis of Millimeter Wave Communication Link for Next Generation Mobile Networks

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Abstract: Higher data rate and increased capacity are the primary challenges of the next Generation mobile network infrastructure. In order to address such issues, Millimeter wave (mmWave) communication technology can play a vital role and enable the seamless connectivity among the devices in such a network infrastructure. However unlike the low frequency signals, millimeter waves cannot propagate to long distances and are very sensitive to blockage. Hence such a communication link needs a rigorous analysis prior to its successful practical implementation in next generation networks (5G and beyond) especially in highly dense environmental scenarios. This paper presents the mathematical analysis of the mmWave communication link for various propagation scenarios in a next generation network infrastructure. A simulation study is also carried out to investigate the effect of blocking and other factors such as operating frequency, transmitter and receiver antenna gain and the use of MIMO antenna systems on the performance of mmWave communication link.

Keywords: Millimeter Wave Link, Blocking, Attenuation; Next Generation Network, MIMO, 5G

1. Introduction

From the past few years there has been an unprecedented growth in the wireless traffic especially the mobile data traffic. This trend will continue and to deal with the situation the essential features of the next generation mobile communication networks (5G and beyond) are "to provide increased capacity, high speed data transfer rates and better quality of service" [1-3] as shown in figure 1. In order to meet such requirements of next generation networks (including 5G), Millimeter wave communication is considered as the key technology for both indoor and outdoor application operational scenarios. This is due to the availability of huge unexploited bandwidth in the mmWave spectrum (30 GHz to 300 GHz) which can in turn lead to the multiple Gigabit data transfer rates [4-8].

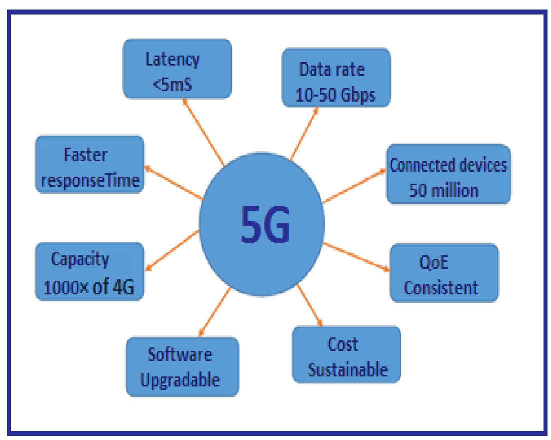

Figure 1. Characteristic features of 5G mobile network

However despite of the theoretical potentials of mmWave communication, there are certain natural constraints associated with the implementation of this technology like severe attenuation of mmWaves due to the free space, atmospheric and foliage losses [9-10], easy signal blocking by obstacles such as buildings, trees, furniture, and human movement due to the poor diffraction ability of millimeter waves [11-12]. These factors affect the transmission range/coverage of the

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mmWave communication link and may even bring the status of the link to the disconnected state which can affect the performance of the communication network. In order to overcome this problem of mmWaves, different approaches have been proposed so far which include relaying, beam switching, multipath routing, use of high gain antenna arrays and Multi Input Multi Output (MIMO) systems [13-16]. However every approach has certain limitations and should be efficiently used to achieve the optimum network performance. This can be done by rigorously investigating the mmWave link for various possible operational scenarios in the next generation communication network.

In this paper, we perform the mathematical analysis of the mmWave communication link for Line of Sight (LOS) and Non Line of Sight (NLOS) case scenarios in a next generation network infrastructure and also investigate the effect of using high gain transceiver antennas and MIMO systems on improving the performance of the mmWave channel in terms of capacity and coverage. In addition a simulation study is carried out to evaluate the effect of blocking and other factors such as operating frequency, transmitter and receiver antenna gain, use of MIMO antenna systems on the channel performance. The simulations have been performed in MATLAB software. The rest of the paper is organised as: Section II gives the mathematical analysis of the mmWave communication link. The simulation study to evaluate the link performance is given in Section III. Finally section IV concludes the paper.

2. Mathematical analysis

Consider a mmWave communication scenario as shown in figure 2.

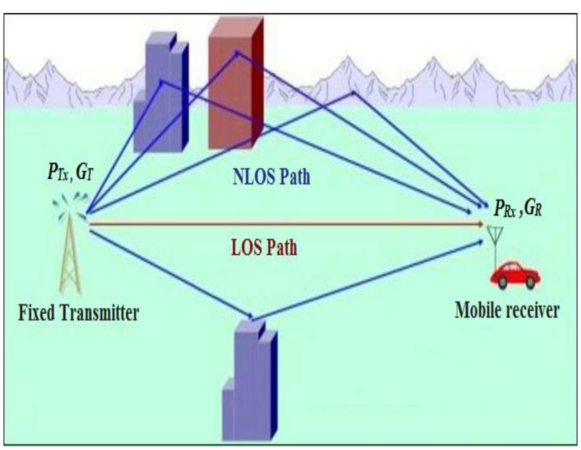

Figure 2. A typical mmWave communication Scenario.

If "f" is the frequency of operation of mmWave link and "R" be the distance between transmitter and receiver, then according to the Friis transmission equation for general transmission scenario [17]:

$$\frac{P_{Rx}}{P_{Tx}} = \left(\frac{c}{4\pi f R}\right)^n \cdot G_T \cdot G_R \tag{1}$$

Where P_{Rx}= Received Signal Power

P_{Tx}= Transmitted Signal Power

G_T= Transmitter antenna Gain

G_R= Receiver antenna Gain

n=path loss exponent which varies with the propagation environment. The typical values of n for different scenarios are given as [18-19]:

$$n = \begin{cases} 1.8 & \text{LoS Indoor} \\ 2.0 & \text{LoS Outdoor} \\ 2.5 & \text{NLoS (Urban area)} \\ 3-5 & \text{NLoS (Suburban area)} \end{cases}$$

From (1), Range of the link can be calculated as:

$$Ro^n = \left(\frac{c}{4\pi f}\right)^n \cdot \frac{P_{Tx} \cdot G_T \cdot G_R}{P_{Rx}} \tag{2}$$

If "P_n" is the receiver noise power and "SNR_{in}" be the Signal to noise ratio at receiver input then we have [20]:

$$SNR_{in} = \frac{P_{Rx}}{P_n} \tag{3}$$

In terms of the band width "B" and power spectral density "N_0" of Additive White Gaussian Noise (AWGN) of the channel, above equation can be written as:

$$SNR_{in} = \frac{P_{rx}}{B N_o} \tag{4}$$

Or,
$$SNR_{in} = \frac{P_{rx}}{\alpha f N_o} \tag{5}$$

Using, $B = \alpha f$; where α is fractional bandwidth and 'f' is the center frequency.

However the range of any communication link is managed by minimum Signal to Noise ratio ("SNR_{min}") at the receiver and hence the corresponding received power will be given by:

$$P_{Rxo} = \alpha f N_o SNR_{min} \quad (6)$$

Using above equation in (2), we can write range of the link as:

$$R_o{}^n = \left(\frac{c}{4\pi f}\right)^n \cdot \frac{P_{Tx} \cdot G_T \cdot G_R}{SNR_{min} \cdot \alpha f No}$$

Or $R_o = \left(\frac{c}{4\pi f}\right) \cdot \left(\frac{P_{Tx} \cdot G_T \cdot G_R}{SNR_{min} \cdot \alpha f No}\right)^{\frac{1}{n}}$

Or, $R_o = \beta_o \cdot \frac{1}{f^{\frac{n+1}{n}}}$ (7)

where, β_o is equal to $\left(\frac{c}{4\pi}\right) \cdot \left(\frac{P_{Tx} \cdot G_T \cdot G_R}{SNR_{min} \cdot \alpha No}\right)^{\frac{1}{n}}$

The equation 7 depicts three things in general: (i) Range or the coverage distance of the communication link is the inverse function of operating frequency i.e. At mmWave frequencies, the transmission range will be lesser as compared to the low frequency counterparts (ii) Range of the communication link depends on the propagation environment i.e. NLOS transmission range will be less compared to indoor as well as outdoor LOS case. (iii) Range of the transmission link is direct function of combined transmitter and receiver antenna gain. This is also illustrated in figure 3(a and b) which has been plotted using equation 7.

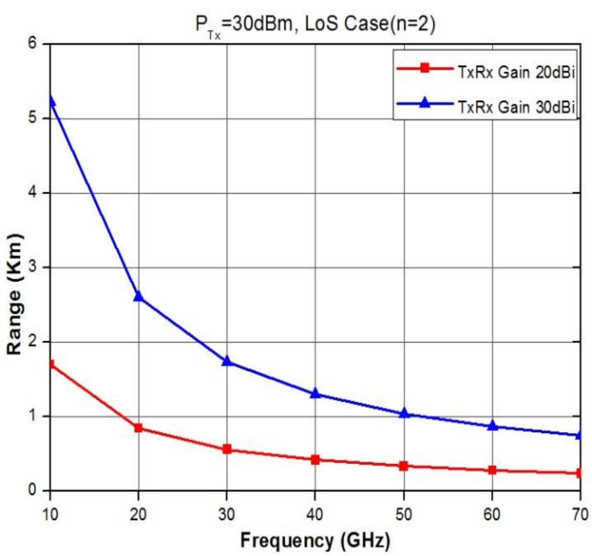

Figure 3(a). Range as function of frequency (LOS Case)

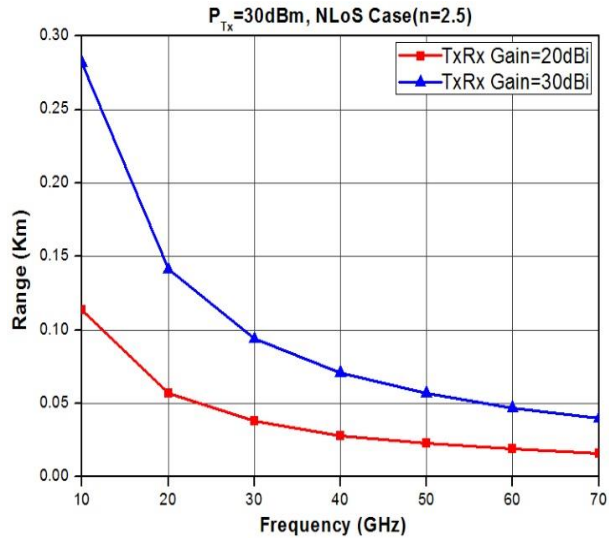

Figure 3(b). Range as function of frequency (NLOS Case)

Similarly the data carrying capacity 'C' of the mmWave link will be given by the Shannon's capacity formulae as:

$$C = B \log_2 (1 + SNR)$$

Or, $C = \alpha f \log_2 (1 + SNR) bps.$ (8)

It means the data carrying capacity of the link will increase linearly as function of frequency. But there is a limitation in increasing the operating frequency as it results in the decrease in transmission range of the communication link as mentioned earlier. However, with same operating frequency, the data carrying capacity can be further improved by using an "M×N" MIMO system so that by capacity formulae [21]:

$$C = MB \log_2 \left(1 + \frac{N}{M} SNR\right) \quad (9)$$

Where, M and N are the number of antenna elements at the transmitter and receiver end respectively and N >=M to ensure all transmitted signals decoded at the receiving end. This is also illustrated in figure 4. The figure depicts that: (i) the Capacity of the link for NLOS signal transmission is comparatively less than LOS case. This is also supported by the fact that SNR for LOS transmission is more as compared to NLOS transmission (ii) Capacity of the link increases as the function of frequency for both LOS and NLOS scenario as also evident from equation 8 that capacity(C) is direct function of operating frequency. (iii) For both LOS and NLOS scenarios, the capacity is highly improved by employing a "2×2" MIMO system which can be further enhanced by "4×4", "8×8", "16×16" MIMO systems as per application requirements as evident from equation 9 that capacity (C) of the link is directly proportional to the number of antenna elements at the transmitter end (M). However this can increase the overall system complexity and cost.

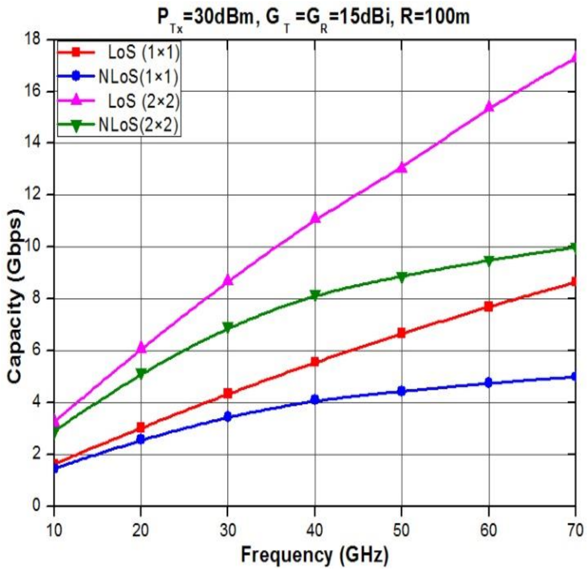

Figure 4. Data carrying Capacity as function of frequency

3. SIMULATION STUDY

Consider a mmWave link transmission in a highly dense network scenario of next generation mobile network infrastructure as shown in figure 5. The mmWave link is subjected to the different propagation environments such as free space LOS, NLOS, blocking due to buildings, trees and human shadowing in addition of the free space and atmospheric losses.

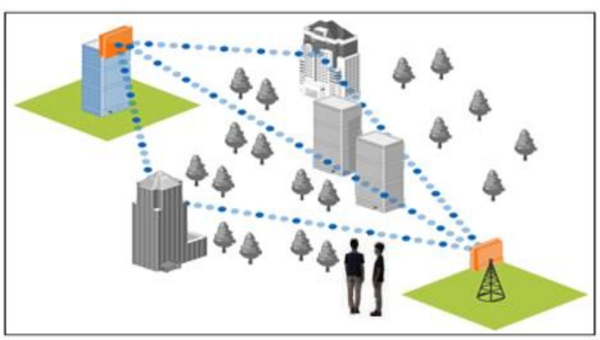

Figure 5. mmWave link transmission scenario

The mmWave link in the presented scenario (figure 5) is simulated in the MATLAB Software and its performance is investigated for different parameters such as: transmission distance (d), frequency of operation (f), transceiver antenna gain (dBi) and Capacity of the link (Gbps). Also the effect of using the MIMO technology with mmWave systems to improve the mmWave link performance for both LOS and NLOS case scenarios is examined. The various system parameters taken into account during the simulations for performance evaluation of mmWave link given in figure 5 are listed in table I [22].

Table.I. Parameters for Mmwave Link Simulation

Parameter	Value
Transmitted power	30 dBm
Amplifier at receiver	30 dB
LNA at receiver	20 dB
Tx Feeding Network	-5 dB
Rx Feeding Network	-5 dB
Channel Selector Filter	-5 dB
Shadowing (LOS)	-1 dB
Shadowing (NLOS)	-5 dB

The various results obtained through the simulations have been plotted and are given in figure 6 to 8. Figure 6 shows the data carrying capacity of the mmWave communication link as the function of the combined transceiver antenna gain for operating frequencies of 33.5 and 60 GHz for a transmitting distance of 100 m. It is observed that in order to achieve the Gbps data rates in a next generation network, high gain antennas are required at both transmitter and receiver end of the mmWave communication link. For a NLOS link at 33.5 GHz, a data rate of 1 Gbps is not possible with the transmitter and receiver gain of below 19 dBi approximately. The situation gets worse at higher frequency like in the scenario for 60 GHz, a combined transceiver antenna gain of above 25 dBi is required to achieve the data rates of Gbps. Figure 7 shows the capacity as a function of transmission distance at 33.5 GHz and 60 GHz in different propagation scenarios (LOS and NLOS scenarios). It is clear from the figure that higher the operating frequency, higher is the data carrying capacity of the link but lower will be the transmission range.

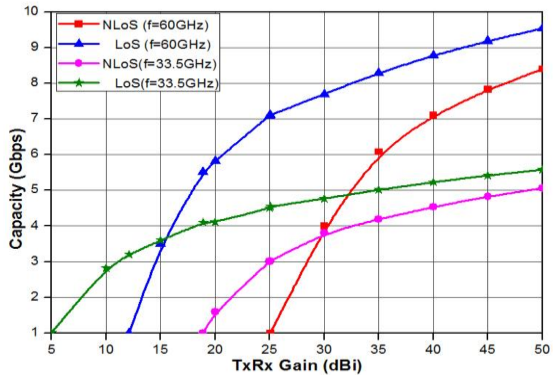

Figure 6. Capacity as function of combined transceiver gain

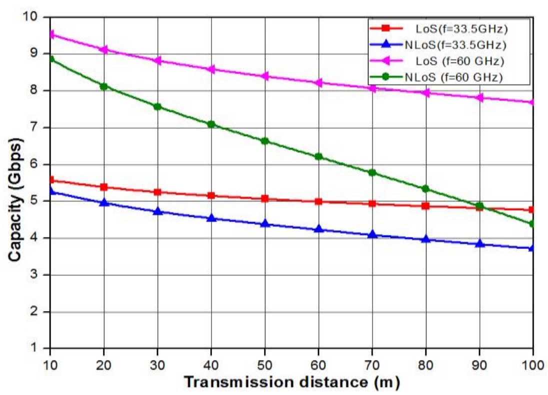

Figure 7. Capacity at 33.5 and 60 GHz for LOS and NLOS cases.

Similarly Figure 8 shows the capacity of the mmWave link for different propagation scenarios using a MIMO system. It is observed that there is a considerable increase in the capacity of the mmWave link by employing a 2×2 MIMO system which can be further enhanced by a 4×4 or 8×8 MIMO system as per application requirements but this may increase the system complexity.

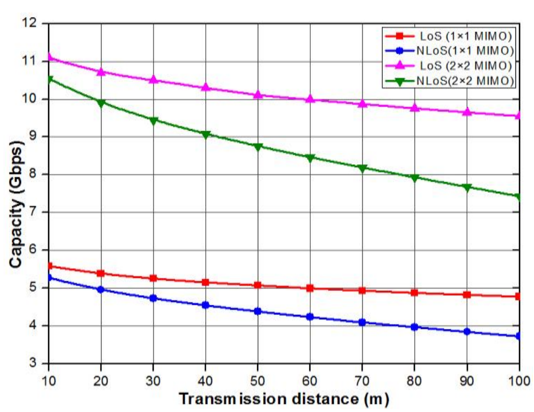

Figure 8. Capacity of mmWave link using MIMO system

4. CONCLUSION

Millimeter wave (mmWave) communication technology is a promising solution to support the high data rate and capacity requirements of next generation networks especially 5G networks. However, mmWaves have a very limited range and are very sensitive to blockage due to the huge propagation losses and weak diffraction capability. The paper gives the mathematical analysis of the mmWave communication link in a next generation network scenario. A simulation study has also been done to study and examine the effect of operating frequency, transmission distance, blocking, transceiver antenna gain and the advantage of MIMO systems on the performance of the mmWave communication link in different propagation environments. It is observed from both mathematical analysis as well as simulation study that although data carrying capacity of the mmWave link increases with the increase in operating frequency, but at the same time, the range of the link decreases severely for both LOS and NLOS scenarios. Also in order to achieve the Gbps data rates for larger transmission range, high gain antennas are necessarily required at transceiver of the mmWave communication system. The further improvement in the capacity and range of the mmWave link can be achieved with the help of MIMO systems.

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