Evaluation and Analysis of Bit Error Rate due to propagation mechanisms of millimetre waves in a QAM system

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Abstract: - The waves falling in the 40GHz to the 100GHz band in the electromagnetic spectrum are referred to as millimetre waves. Due to the large bandwidth availability, these high data-rate signals find a wide range of applications in modern communication technology such as broadband multimedia wireless systems and 4G cellular communications. Achieving a reduced Bit Error Rate (BER) of around 10^{-7} for high quality audio and video streaming, is a challenging task in this band of frequencies. In this paper, we have reviewed and studied the mathematical models for various propagation mechanisms that lead to an increase in the Bit Error Rate. We have then presented a formulation for the calculation of Bit Error Rate of a system employing Quadrature Amplitude Modulation.

Key-words Bit Error Rate, Millimetre waves, Frequency, Attenuation, path loss, loss due to atmosphere, water vapour dispersion, scattering due to buildings, vegetative loss, QAM

1 Introduction

Millimeter waves have frequencies above 40GHz and very small wavelengths. These account for the numerous advantages they pose, such as, reduced component size, increased bandwidth, LOS communication and so on. Such advantages in turn emphasise the need for mm waves in new generation wireless communication technologies. Mm waves have potential applications in radar systems, remote sensing and medical systems which are described in table-1. With the advent of mm wave technology, wireless connectivity is advancing so much so that high speed, high quality data access to "everyone, anywhere, at any time" is now being achieved. Varied applications of the mm waves have resulted in extensive research on their characteristics. The major hurdle in implementing mm wave technology in a fully fledged manner lies in the difficulty and cost of manufacturing components and worst case propagation characteristics encountered during its transmission.

The design of a communication system starts with the knowledge of the required Bit Error Rate (BER). Bearing this in mind, we have connected the BER to the losses caused due to various propagation mechanisms at radio frequencies. This will prove helpful in taking into account the co-channel interferences. In this paper, we have reviewed and analysed the BER characteristics under various physical conditions such as free space path loss, attenuation due to atmosphere, attenuation due to moist atmosphere, diffraction loss due to buildings, attenuation due to vegetation and have analysed the performance of a QAM system in the mm wave frequency band.

Table 1: Application of different portions of the mm-wave spectrum [1]

Frequency (GHz)	Applications
30 – 50 Q-Band	1. Radio astronomy studies (QUIET telescope). 2. Automotive radars 3. Radars used to investigate the Earth's surface. – write in sentence
46 – 56 V- band	1. mm wave radar research 2. High capacity high data rate terrestrial communication systems. 3. Unlicensed band from 57 to 64GHz for high capacity, short distance, secure wireless systems. 4. 70 to 90GHz band can offer long range multi gigabyte communication systems.
56 – 100 W – Band	1. Passive mm wave cameras for concealed weapon detection. 2. Automotive cruise control radar 3. Less-than-lethal weapons to heat outer skin of human body in order to cause uneasiness (Active Denial System).

	4. Due to overcrowding of the lower spectra, the W band is posing an increasingly viable option for commercial satellite operations.

2 Propagation Mechanism

Consider a practical communication system transmitting and receiving a millimetre wave. A number of propagation mechanisms exist between the transmitter and the receiver. The channel between the transmitter and the receiver consists of atmospheric gases, dry air, water vapour, buildings and vegetation, each of which act as an attenuation factor, thus increasing the BER of the communication system.

The main cause of dispersion of energy of a transmitted millimetre wave is the free space path loss modelled by the Friis formula [1]. In addition, atmospheric attenuation occurs due to absorption caused by different gases present in the atmosphere [2]. The so caused attenuation does not follow a monotonic pattern. It has peak attenuation at frequencies corresponding to the absorption frequency of specific gases present in the atmosphere. For example, oxygen absorption occurs at 60GHz as shown in figure.1. Thus, the BER is extremely high at this frequency. However, the BER at 70GHz is much lower since no absorption spectra is present at that frequency. The loss due to atmosphere is further increased by the presence of water vapour, which cause refractive dispersion losses [3]. Another major factor causing the attenuation of mm waves is the scattering and reflection due to buildings [4, 5], which has been modelled as functions of their geometry and the material out of which they are constructed. Another natural cause of attenuation is vegetation. The height of the vegetation is the major parameter that decides the loss [4].

3 Modelling the Received Signal and BER

Let the transmitted signal have a power P_t. Let the received power be P_r. . The distance between the transmitter and receiver is D. Let c be the speed of light and f is the frequency of the signal. Let G_t and G_r represent the transmitter and receiver antenna gains respectively.

The upper limit of the power received when power P_t is transmitted is given by the Friis formula, which accounts for the free space path loss [1]:

$$P_r = P_t G_t G_r \left(\frac{c}{4\pi D f}\right)^2 \quad (1)$$

Loss due to atmospheric gases has been measured accurately and its variation with frequency is according to the following graph. We will sample the values loss present in this graph at the frequencies we need, in order to calculate the BER.

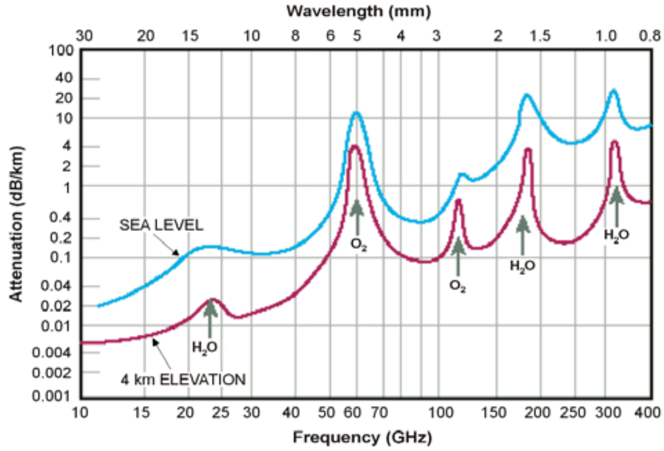

Figure 1: Attenuation of electromagnetic wave above 10GHz Source: [2]

Let the values of loss obtained from this graph be denoted by L_{atm}.

Apart from atmospheric gases a typical component present in the atmosphere is water vapour. The attenuation due to water vapour is due to refractive dispersion denoted by $R'(f)$ and refractive absorption denoted by $R''(f)$ [3]. The frequency independent refractivity is denoted by R_0. All three refractions are in ppm. The following empirical results are stated for refraction due to water vapour:

$$R''_e(f) = [b_f p + b_e e\theta^3] f e\theta^{2.5} \quad (2)$$

$$R'_e(f) = b_0 e\theta^{2.4} f^{2.05} \quad (3)$$

Where, $b_0 = 6.47 \times 10^{-6}, b_f = 1.40 \times 10^{-6}$, $b_e = 5.4 \times 10^{-5}$

The attenuation is given by:

$$L_{wv} = \int_0^d \alpha(x) dx \quad (4)$$

$$\alpha(x) = 0.1820 f R''(f) \quad (5)$$

Based on their physical geometry and the characteristics of materials out of which they are constructed. The expression for loss is given as [4]:

$$L_b = S_G S_R \mu_P \quad (6)$$

Where S_G: Scattering coefficient based on the geometry of the building, S_R: Reflection coefficient based on the material of the building and μ_P is the polarisation coefficient.

The reflection coefficient S_R is material specific and is calculated as a function of the surface roughness which in turn is defined by the Rayleigh roughness criterion. The polarisation coefficient μ_P is defined in terms of incident and reflected azimuthal and elevation angles.

The expression for loss due to vegetation has been empirically derived as [4]

$L_{veg} = 0.39 f^{0.39} d^{0.25}$-Trees with leaves (7)

$L_{veg} = 0.37 f^{0.18} d^{0.59}$-Trees without leaves (8)

Where, L: Loss in dB, f: Frequency in MHz, d: Height of the vegetation in metres.

For a channel consisting of buildings made of wood and having trees with leaves of height of 2.5m, we define the received power P_r as:

$$P_r = 10\log P_t + 20\log c - 20\log 4\pi D - 20\log f - 10\log L_{atm} - 10\log L_{wv} - 10\log L_b - 1$$

The Bit Error Rate of any communication system [6, 7, 8] with an Additive White Gaussian Noise (AWGN) channel is defined in terms of the probability of symbol error P_e as:

$$BER = \frac{P(e)}{\log_2 M} \qquad (10)$$

Where, M denotes the number of signals needed to represent the bits. Thus, $\log_2 M$ represents the number of bits represented by each signal.

3.1 Quadrature Amplitude Modulation

In a communication system, if the in-phase and Quadrature components vary in phase and in amplitude, with respect to variation in the digital information bits, then the resulting modulation scheme is known as Quadrature Amplitude Modulation [6]. A QAM signal is represented as

A. $$s(t) = \sqrt{\frac{2E_0}{T}}a_i\cos(2\pi f_c t) + \sqrt{\frac{2E_0}{T}}b_i\sin(2\pi f_c t)$$

$$0 \leq t \leq T \qquad (11)$$

Where E_0 represents the energy of the signal with the lowest amplitude, a_i and b_i are independent integers that decide the position of a particular message in the signal constellation and T is the symbol duration. The constants a_i and b_i are chosen from an $L-by-L$ matrix

$$\{a_i, b_i\} = \begin{bmatrix} (-L+1, L-1) & (-L+3, L-1) & \dots & (L-1, L-1) \\ (-L+1, L-3) & (-L+3, L-3) & \dots & (L-1, L-3) \\ \vdots & \vdots & \vdots & \vdots \\ (-L+1, -L+1) & (-L+3, -L+1) & \dots & (L-1, -L+1) \end{bmatrix}$$

Where $L = \sqrt{M}$ and M is the number of signals needed to represent the message signal.

The signal constellation of a 16-QAM is shown in the figure 2.

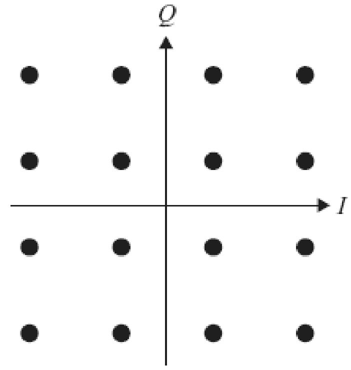

Figure 2: Signal constellation for M-ary QAM with M = 16

The symbol error of an M-ary QAM signal is given by

$$P_e \cong 2\left(1 - \frac{1}{\sqrt{M}}\right)erfc\left(\sqrt{\frac{E_0}{N_0}}\right) \qquad (12)$$

Since the amplitude of the transmitted signal is time variant in QAM, we define the average energy of the transmitted signal as

$$E_{avg} = \frac{2(M-1)E_0}{3} \qquad (13)$$

Hence we write the probability of error as

$$P_e \cong 2\left(1 - \frac{1}{\sqrt{M}}\right)erfc\left(\sqrt{\frac{3E_{avg}}{2(M-1)N_0}}\right) \qquad (14)$$

We will calculate the Bit Error Rate of 4-QAM in which case we observe that the E_{avg} is equal to the E_0. For a 4-QAM, the BER is given by

$$BER = \frac{P_e}{2} = \frac{1}{2}erfc\left(\sqrt{\frac{E_0}{N_0}}\right) \qquad (15)$$

4 Evaluation of BER

In order to evaluate the Bit Error Rate of a practical communication system employing QAM, we substitute the values of received power P_r into the BER formulation. We assume the following standard specifications

Distance between transmitter and receiver: 100m
Gain of the transmitter and receiver antennas: 20dB
Temperature: 300K
Pressure: 1KPa
Relative humidity: 0.70
Effective Isotropic Radiated Power at 40GH: 78dB
Effective Isotropic Radiated Power at 60GHz: 88dB
Effective Isotropic Radiated Power at 90GHz: 98dB

The simulated values of BER for a QAM system in three different frequency ranges are shown in figures 3, 4, 5 and 6. Figure 5 shows the reduction of extremely high BER at 60GHz by means of increasing the EIRP.

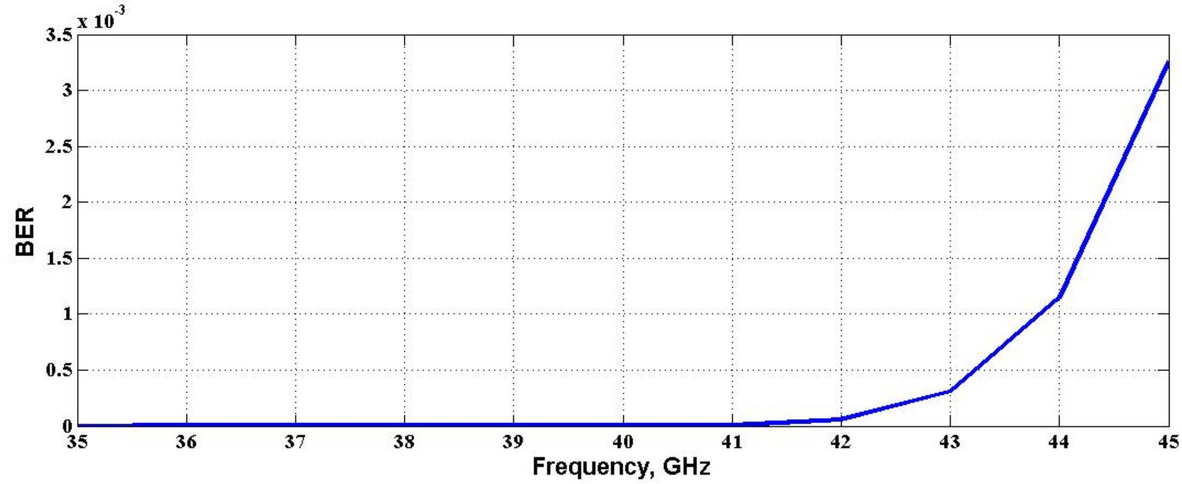

Figure 3: BER Vs Frequency of a QAM system in the 40GHz range

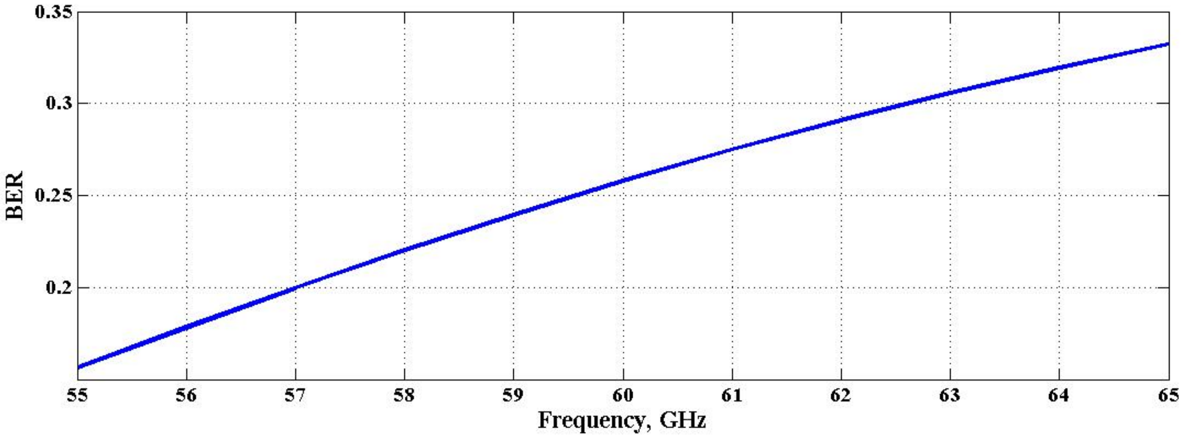

Figure 4: BER Vs Frequency of a QAM system in the 60GHz range

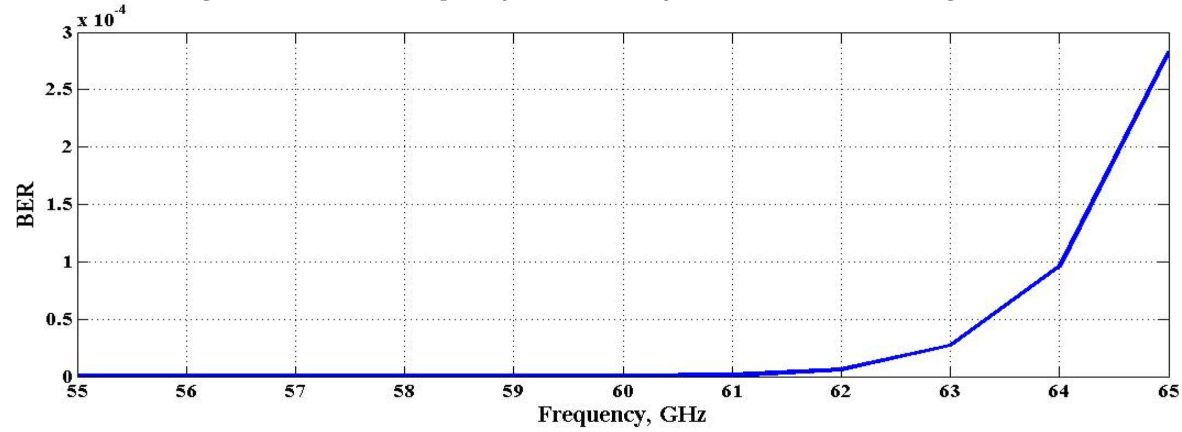

Figure 5: Compensation in BER at 60GHz by increasing the EIRP

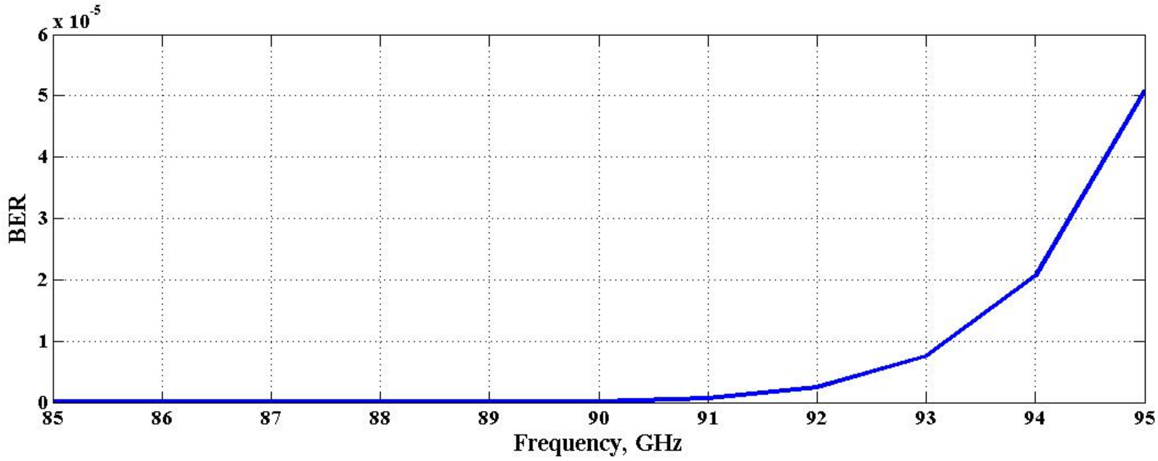

Figure 6: BER Vs Frequency of a QAM system in the 90GHz range

5 Results and Discussions

We have presented above, the simulated values of BER for a 4-QAM system employing mm-waves that undergo propagation mechanisms such as free space path loss, loss due to atmosphere and water vapour, scattering and reflection due to buildings and loss due vegetation. Figure 3, shows that the BER at 40GHz is 10^{-7} at an EIRP of 78dB. This BER is sufficiently low for high quality audio and video signal transmission. However, in the 60GHz range, we see that the BER increases to an extremely high value of 0.1 (figure 4), which is intolerable. This is due to the oxygen absorption spectrum that occurs at 60GHz. Due to this phenomenon; the loss due to atmosphere is extremely high (higher than at 50GHz and at 70GHz) at 60GHz. Thus, we see that the 60GHz band is unusable for long range communication or broadcasting. This property of the 60GHz band is used for shielding [9] microwave systems from one another. It is ideal for indoor communications where it can be used for wirelessly transmitting and receiving live video signals in short ranges with very high signal to noise ratio. Figure 5 shows the compensation in BER that can be achieved by increasing the EIRP, that is, either the transmitted power or the gain of the antenna. An increase of about 38dB is required to achieve a BER of 10^{-7} at 60GHz. That is, an EIRP of about 106dB is required. From figure 6, we see that a BER of 10^{-7} can be achieved at 90GHz by supplying an EIRP of 114dB, which is very high.

6 Conclusion

We have estimated the losses caused due to various natural and man-made obstacles present in the channel of a practical communication system, employing QAM modulation with mm waves. The BER of such a system is evaluated at 40GHz, 60GHz and 90GHz range. We find that the BER at 60GHz is unusually high due to the atmospheric loss caused by oxygen absorption. This increase in BER can be compensated by increasing either the gain of the transmitter antenna or the transmitted power. After analyzing QAM signals in three frequency bands, we conclude that the 40GHz band is ideal for high-speed, live audio and video transmission. The 60GHz band is used best for shielding one system from another thereby making it ideal for indoor wireless multimedia applications [10]. The 90GHz band offers a much higher data rate than the 40GHz band. However, the EIRP required for providing a sufficiently low BER is very high, which makes the system very expensive to develop.

References:

[1] X1. David M. Pozar, *Microwave Engineering, Third Edition*, Wiley & Sons Publications.

[2] X2. Technology report - A Growing Number of Applications boosts mm-Wave Technology, *High Frequency Electronics Copyright Summit Technical Media*, May 2006

[3] X3. H.J. Liebe, K.C. Allen, G.R. Hand, R.H. Espeland, E.J. Violette, *"Millimeter-Wave Propagation in moist air: Model Versus Path Data*, US department of commerce, March 1985

[4] X4. M O AI-Nuaimi *A generalised site shielding procedure for radio system planning at microwave frequencies*, Fifteenth National Radio Science Conference, Feb. 24-26,1998, Helwan, Cairo, Egypt.

[5] X5. Ana Vázquez Alejos, Manuel García Sánchez, *Member, IEEE*, and Iñigo Cuiñas, *Measurement and Analysis of Propagation Mechanisms at 40 GHz: Viability of Site Shielding Forced by Obstacles.* IEEE transactions on vehicular technology, Vol 57, No: 6, November 2008

[6] X6. Simon Haykin, *Digital Communications*, Wiley & sons publications.

[7] X7. William C. Lee, *Wireless & Cellular Telecommunication, Third Edition*, McGraw Hill publications.

[8] X8. Fehler, *Wireless Digital Communications*, Prentice Hall Publications

[9] X9. G. A. J. van Dooren and M. H. A. J. Herben, *Site-shielding factor of block-shped obstacle*, Electronic Letters, 7th January 1993 Vol. 29 No. 1

[10] X10. Peter Smulders, *Exploiting the 60 GHz Band for Local Wireless Multimedia Access: Prospects and Future Directions*, Eindhoven University of Technology