CHAPTER 4

PROPAGATION MODEL
4.1 INTRODUCTION.

CMCS of the future will require a many order increase in the user density and this can be achieved by employing much higher propagation frequencies with proportionately wider bandwidths. Such frequencies are available in 35-70 GHz range. The atmospheric effects in this range greatly influence the propagation characteristics. Major components like OXYGEN and WATER VAPOUR in the atmosphere contribute to the attenuation of signal in a greater measure as compared to the other components. (figure 1.1)

Propagation modelling for conventional cellular networks in an urban/suburban area has traditionally relied on empirical models derived from a large measurement database. This approach might be valid in the situation where base station is positioned on a tall building or high above the majority of buildings, its applicability in the case of microcells is questionable. With the antenna located below the roof height and the operating frequency in GHz, the coverage characteristics will be strongly influenced by the position, orientation and composition of buildings.

4.2 HYPOTHESES.

4.2.1 Diffraction.

In case of conventional mobile communication system the cell dimensions are such that one has to consider knife edge diffraction caused due to hills, trees and buildings, since the base station is located well above. In case of microcellular mobile communication system the cell dimensions are very small and height of the antenna is below the height of buildings and is almost at the level of lamp-posts. Due to this position of the base station antenna, diffraction due to top edges of the buildings will not have influence on the propagation [79]. The effect of undulating terrain in urban and suburban area should be considered separately.
4.2.2 Refraction and Effect of Earth’s Radius.

In case of micro-cellular structure the maximum radius of cell is 1000 m and the height of base station antenna is 10 m or less. Hence the effect of earth’s radius is negligibly small. In such a case the signal received is due to LOS and the reflected rays that are not travelling very large distance the height of the antenna is also not too high. Hence the variation of refractive index of earth’s atmosphere on propagation will not be taken into account.

4.2.3 Rayleigh criterion.

At the higher microwave frequencies the assumptions of a plane earth may no longer be valid due to surface irregularities. A measure of surface roughness that provides an indication of the range of Bullington model is given by the Rayleigh criterion.

\[
C = \frac{4\pi \sigma \theta}{\lambda}
\]

Where,

- \(C\) -- Surface roughness factor.
- \(\theta\) -- Angle of incidence of the electromagnetic wave.
- \(\sigma\) -- Standard deviation of the surface irregularities relative to the mean height of the surface.
- \(\lambda\) -- Wavelength in metres.

Experimental evidence shows that for \(C < 0.1\) specular reflection results and the surface may be considered smooth and surfaces are considered rough for values of \(C\) exceeding 10. [280] For the analysis under consideration surface is considered to be smooth on account of cell dimension and urban location.
4.2.4 Effect of walls.

In an urban environment, balconies, windows, bus-stops, which are few tens of wavelength large, play a significant role in propagation. They contribute very little to the received power. Nevertheless they take part in the impulse response spreading. In our case it is assumed that walls of buildings are almost smooth.

4.2.5 Equatorial radius.

Ray theory can be applied to radio wave propagation if and only if the equatorial radius ($\rho$) of the Fresnel zone ellipsoid is less than the dimension of the reflecting medium.

The equatorial radius is given by the formula

$$\rho = \frac{1}{2} \sqrt{\lambda d}$$

(4.2)

Where,

$\rho$ - Equatorial radius in metres.

$\lambda$ - Wavelength in metres.

$d$ - Distance between transmitter and receiver in metres.

For the 35-70 GHz frequency range the reflecting medium is much larger than the equatorial radius $\rho$ will range from 32.70 to 46.29 cm. for a cell radius of 100 m.

4.3 THEORY.

4.3.1 Background.

In the light of the above mentioned hypotheses, propagation in the 35-70 GHz range can be studied using ray theory. This theory was initiated by
Keller[80] with the well-known geometrical theory of diffraction (GTD) and extended by Kouyoumjan and Pathak[81].

A propagation model based upon GTD [82] provides estimates of received signal strength by calculating the contributions of various rays and ray combinations. These rays are

i) direct
ii) singly reflected
iii) doubly reflected
iv) triply reflected.

The direct ray is assumed to exist if there is no terrain blocking the path between transmitting and receiving antennas. If the direct ray is determined to exist, its contribution is calculated according to free-space loss.

Reflected rays are assumed to exist if there are points on the terrain profile or building walls where the angle of incidence is equal to the angle of reflection and the path is not blocked by intervening terrain. The amplitude and phase of the reflected ray are determined by the frequency, angle of incidence and electrical constants of the ground plane and the walls. Many researchers have used the GTD model for the estimation of signal in the frequency range of 800-900 MHz and PCS band 1700-2200 MHz [76,81 to 97]. The results obtained by these researchers confirm that the use of GTD for development of propagation model will result in more accurate estimation of pathloss.

The GTD gives quite accurate prediction of propagation considering direct and reflected rays from ground and surrounding buildings. The large scale variations of average signal over flat ground are predicted to follow the two ray model [p2,83], whereas the effects of buildings can be predicted using N ray model where N will vary from 4 - 8 depending on the accuracy required.

4.3.2 GTD Model.

To predict the signal received, the model suggested by Bullington is used as basic model. The received power ($P_r$) is given by the equation,
\[ P_r = P_t \left( \frac{\lambda}{4\pi d} \right)^2 G_b G_m \left| 1 + Re^{j\Delta} + (1-R)Ae^{j\Delta} \right|^2 \]  \hspace{1cm} (4.3)

Where,

- \( P_t \) - Transmitter power in watts.
- \( \lambda \) - Wavelength in metres.
- \( G_b \) - Base station antenna gain.
- \( G_m \) - Mobile station antenna gain.
- \( R \) - Reflection coefficient.
- \( \Delta \) - Phase difference between reflected and direct path.

Within the absolute value symbols, the first term represents the direct ray, the second term represents the reflected wave, the third term represents the surface wave and the remaining terms represent the induction field and secondary effects of ground. According to Norton [280] the effects of surface wave, induction field and its secondary effects are significant only to a few wavelengths above the ground. As the frequency range of interest is 35-70 GHz this effect can very-well be neglected.

The reflection coefficient \( R \) depends on the angle of incidence \( \theta \), the polarization of the wave and the reflecting medium characteristics and is given by

\[ R = \frac{\sin\theta - z}{\sin\theta + z} \]  \hspace{1cm} (4.4)

where \( z = \frac{\varepsilon_0 - \cos^2\theta}{\varepsilon_0} \) for vertical polarization \hspace{1cm} (4.5)

\[ z = \varepsilon_0 - \cos^2\theta \]  \hspace{1cm} (4.6)

and \( \varepsilon_0 = \varepsilon - j\varepsilon_0 \sigma \lambda \) \hspace{1cm} (4.7)

where \( \varepsilon_0 \) -- Absolute permittivity.

\( \varepsilon \) -- The dielectric constant of the ground relative to unity in free space.

The estimation of propagation loss of radio waves through the atmosphere above 10 GHz involves not only the use of equation (4.3) but also of several other important factors. These include the gaseous contribution of the
homogeneous atmosphere due to resonant and non resonant polarization mechanisms, the contribution of inhomogeneities in the atmosphere and the particulate contribution due to rain, fog, mist and haze. Since nitrogen has no absorption in the radio frequency range, molecular absorption is due almost entirely to oxygen and water vapour.

4.3.3 Specific attenuation due to oxygen and water vapour. [283]

Using the Van Vleck and Weisskopf line pattern and taking account of available observation results the specific attenuation in dB per Km due to oxygen in the lower part of the atmosphere can be represented by the following approximate equations

\[
\gamma_o = \left( \frac{6.6}{f^2 + 0.33} + \frac{9.8}{(f - 57.5)^2 + 22} \right) \times f^2 \times 10^{-3}
\]
for \( f < 57.5 \) GHz

\[
\gamma_o = 14.7 \text{ dB}
\]
for \( 57.5 < f < 62.5 \) GHz

\[
\gamma_o = \left( \frac{4.13}{(f - 62.5)^2 + 1.1} + \frac{0.19}{(f - 118.7)^2 + 2} \right) f^2 \times 10^{-3}
\]
for \( 62.5 < f < 350 \) GHz

The specific attenuation in dB per Km due to water vapour in the lower part of the atmosphere can be represented by the following approximate expression.

\[
\gamma_{\text{H}_2\text{O}} = \left( \frac{0.067 + 2.4}{(f - 22.3)^2 + 6.6} + \frac{7.33}{(f - 183.5)^2 + 5} + \frac{4.4}{(f - 323.8)^2 + 10} \right) \times f^2 \times \rho \times 10^{-4}
\]

(4.11)
Where ‘f’ is expressed in GHz and ρ in grams of water vapour per m³ of air. For frequencies lower than about 100 GHz only the first two terms need be taken into account.

**4.3.4 Calculation of path attenuation due to oxygen and water vapour.**

Figure 1.1 shows the attenuation values obtained using equations (4.8) to (4.11). For water vapour, a value of ρ equal to 7.5 g per m³ was chosen, which corresponds to 1% water vapour molecules mixed with 99% molecules of dry air. This value corresponds, at ground level, to 50% relative humidity for temperature of 16.5°C or 75% at 10°C.

Along a terrestrial path it can generally be assumed that the atmosphere is homogeneous and total attenuation can be calculated by multiplying the length of the path by the sum of specific attenuation due to oxygen and water vapour.

**4.3.5 Influence of temperature.**

For many applications the effect of temperature can be completely neglected. If we want to take temperature into account, we can treat equations (4.8) to (4.11) as valid for a temperature of 15°C and then subtract 0.7% per degree to correct for other temperatures. For the estimation of propagation loss the effect of temperature is neglected.

**4.3.6 Path attenuation due to rainfall.**

One of the most accepted methods of dealing with excess path attenuation A due to rain fall is an empirical procedure based on the approximate relation between A and the rain rate R.
$A = a R^b$ \hspace{1cm} (4.12)

Where $a$ and $b$ are functions of frequency $f$, rain temperature $T$ and polarization. Table 4.1 gives the regression coefficient for estimating specific attenuation from equation (4.12).

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$a_h$</th>
<th>$a_v$</th>
<th>$b_h$</th>
<th>$b_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.187</td>
<td>0.167</td>
<td>1.021</td>
<td>1.000</td>
</tr>
<tr>
<td>35</td>
<td>0.263</td>
<td>0.233</td>
<td>0.979</td>
<td>0.963</td>
</tr>
<tr>
<td>40</td>
<td>0.350</td>
<td>0.310</td>
<td>0.939</td>
<td>0.929</td>
</tr>
<tr>
<td>45</td>
<td>0.442</td>
<td>0.393</td>
<td>0.903</td>
<td>0.897</td>
</tr>
<tr>
<td>50</td>
<td>0.536</td>
<td>0.479</td>
<td>0.873</td>
<td>0.868</td>
</tr>
<tr>
<td>60</td>
<td>0.707</td>
<td>0.642</td>
<td>0.826</td>
<td>0.824</td>
</tr>
<tr>
<td>70</td>
<td>0.851</td>
<td>0.784</td>
<td>0.793</td>
<td>0.793</td>
</tr>
<tr>
<td>80</td>
<td>0.9750</td>
<td>0.906</td>
<td>0.769</td>
<td>0.769</td>
</tr>
</tbody>
</table>

$h$- Horizontal polarization. $v$- Vertical polarization.

The rain rate can be obtained by identifying the region of interest from the maps appearing in figures 6.4, 6.5, 6.6 of [284], then selecting the appropriate rainfall intensity for the specified time percentage from Table 6.3 of [284].

To estimate the path loss it is necessary to consider the effective path length. This is obtained by multiplying the actual path length $L$ by a reduction factor $r$.

$$r = \frac{90}{90 + L} \hspace{1cm} (4.13)$$

Hence attenuation due to rain is given by

$$A_{eff} = A L r \hspace{1cm} (4.14)$$
4.4 TWO RAY MODEL
4.4.1 The Model.

Two ray (LOS and road reflected rays) model adequately describes the propagation in rural areas.

![Diagram of propagation in a rural environment](image)

Figure 4.1. Direct and ground reflected rays geometry.

Figure 4.1 depicts propagation in a rural environment where only the direct ray LM of length $r$, road reflected ray of length $r_1 = LC + CM$ play a significant role. The base and mobile antenna heights are $h_b$ and $h_m$ respectively. The transversal separation between one side of the road and the base station antenna is $y_1$, and mobile antenna is $y_2$. The width of the road is $w$. The reflection coefficient $R$ of the ground reflected ray depends on the dielectric constant of the ground $\varepsilon_r$, and conductivity of the ground $\sigma$, the angle $\theta$, and polarization. For the
estimation of pathloss we use equation (4.1) as the basic equation. In this model the
direct ray and ground reflected ray contribute to the signal received and hence the
first two terms of equation (4.1) are considered for estimation.

Hence the modified equation is

\[ P_r = P_t \left( \frac{\lambda}{4\pi} \right)^2 \left( \frac{G_d}{r} \right)^2 + \left( \left( \frac{G_r}{r_1} \right) R_1 e^{j\Delta} \right)^2 \]  

(4.15)

where \( \Delta = \left( \frac{2\pi d}{\lambda} \right) \sqrt{\left( \frac{H_b - H_m}{d} \right)^2 + 1} - \sqrt{\left( \frac{H_b + H_m}{d} \right)^2 + 1} \)  

(4.16)

\( G_d \) and \( G_r \) are the products of base and mobile antenna field
radiation patterns corresponding to the paths of the direct and reflected rays. \( d \) is
the radial distance between base station antenna and mobile antenna, \( r \) is the direct
ray length and \( r_1 \) is the ground reflected ray length. The reflection coefficient of the
ground reflected ray, \( R \) is given by equation (4.5).

**4.4.2 Specifications for Field Strength Estimation.**

To study the effect of propagation in a rural area a two ray model is
developed in the section 4.3.1. For simulation following are the parameters

i) Frequency range - 35-70 GHz.
ii) Cell radius - 10,000 m.
iii) Base station antenna height (dipole) - 10 m.
   (The position of the base station antenna from side of the road - 1m.)
iv) Mobile antenna height (monopole) - 1.5 m.
   (The position of the MS at the center of the road - 15 m.)
v) Width of the road - 30 m.
vi) Water vapour concentration - 7.5 gm per m³.
   (Corresponding to 50% relative humidity.)
vii) Rain rate - 35 mm per hr.
   (Average rain rate for peninsular India.)
viii) Transmitter power - 1 Watt.

ix) For the estimation of reflection coefficient various values of the dielectric constant and surface conductivity are referred from CCIR study report Vol. V Rep. No. 229.

4.4.3 Simulation Results.

The simulation results for the 2-ray model using equation (4.15) at frequencies of 35, 40, 45, 50, 60 and 70 GHz are shown in figures 4.2 to 4.7 respectively.

We observe that for the 2-ray model the interference between the two rays creates peaks and dips. The separation between successive peaks or dips as well as the width of these dips increases with frequency and distance. After a certain distance no dips occur and the decay of RSS approaches the asymptotic law.

Table 4.2 shows the distance at which a threshold value below -135 dBm corresponding to receiver sensitivity of 0.2 μv/m² occurs with respect to the distance.

**Table 4.2: Distance of threshold value at various frequencies.**

<table>
<thead>
<tr>
<th>Frequency in GHz</th>
<th>Distance of threshold (-135 dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>870 m</td>
</tr>
<tr>
<td>40</td>
<td>800 m</td>
</tr>
<tr>
<td>45</td>
<td>750 m</td>
</tr>
<tr>
<td>50</td>
<td>625 m</td>
</tr>
<tr>
<td>60</td>
<td>600 m</td>
</tr>
<tr>
<td>70</td>
<td>635 m</td>
</tr>
</tbody>
</table>

Table 4.3 shows the position of last dip in the graph at different frequencies with its associated loss.
Fig. 4.2. Power received by MS.

\[ \text{RSS (dBm)} \]

2-ray Model.
\[ f = 35 \text{ GHz}. \]

Distance (m)

Fig. 4.3. Power received by MS.

\[ \text{RSS (dBm)} \]

2-ray Model.
\[ f = 40 \text{ GHz}. \]

Distance (m)
Fig. 4.4. Power received by MS.

2-ray Model.

f = 45 GHz.

Fig. 4.5. Power received by MS.

2-ray Model.

f = 50 GHz.
Fig. 4.6 Power received by MS.

2-ray Model.
f = 60 GHz.

Fig. 4.7 Power received by MS.

2-ray Model.
f = 70 GHz.
Table 4.3: Distance of last dip.

<table>
<thead>
<tr>
<th>Frequency in GHz</th>
<th>Distance of last dip in m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>1750 (-160.3 dBm)</td>
</tr>
<tr>
<td>40</td>
<td>4000 (-197.3 dBm)</td>
</tr>
<tr>
<td>45</td>
<td>4500 (-202.5 dBm)</td>
</tr>
<tr>
<td>50</td>
<td>5000 (-206.5 dBm)</td>
</tr>
<tr>
<td>60</td>
<td>6000 (-214.3 dBm)</td>
</tr>
<tr>
<td>70</td>
<td>7000 (-216.4 dBm)</td>
</tr>
</tbody>
</table>

Table 4.4 shows the loss at different distances at various frequencies.

Table 4.4: Loss in dBm at different Distances.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>35 GHz</th>
<th>40 GHz</th>
<th>45 GHz</th>
<th>50 GHz</th>
<th>60 GHz</th>
<th>70 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-89.12</td>
<td>-91.07</td>
<td>-93.09</td>
<td>-95.27</td>
<td>-100.4</td>
<td>-104.2</td>
</tr>
<tr>
<td>200</td>
<td>-95.17</td>
<td>-107.1</td>
<td>-98.44</td>
<td>-108.5</td>
<td>-109.5</td>
<td>-110.0</td>
</tr>
<tr>
<td>300</td>
<td>-100.2</td>
<td>-102.4</td>
<td>-117.8</td>
<td>-104.2</td>
<td>-120.1</td>
<td>-108.3</td>
</tr>
<tr>
<td>500</td>
<td>-103.7</td>
<td>-127.5</td>
<td>-128.7</td>
<td>-129.7</td>
<td>-131.3</td>
<td>-132.2</td>
</tr>
<tr>
<td>1000</td>
<td>-116.3</td>
<td>144.2</td>
<td>-118.3</td>
<td>-145.6</td>
<td>-146.8</td>
<td>-147.2</td>
</tr>
</tbody>
</table>

4.5 4-RAY MODEL.

There can be an infinite number of rays reflected between the building fronts on the two sides of the street. Each reflection is accompanied by a loss due to the fractional transmission of power into the wall or road. Strictly speaking, if building walls were truly flat and continuous, the RSS would be due to infinite wall reflections. In practice, however, scattering from building irregularities and absorption into gaps between the buildings are expected to be significant attenuation mechanisms, particularly for rays that are reflected many times. A simple modification towards allowing for these effects is to truncate the sum of just a few rays, ignoring all rays which are reflected from wall more than 4 times. This
value of number of reflections is determined empirically by many researchers. [82 to 97 ] Therefore, the basic features of the propagation characteristics will be determined by a finite number of rays with a relatively small number of reflections.

4.5.1 The Model.

A 4-ray model is used for urban area that fits those cities in which row houses and/or wide buildings line both sides of the street. This topography is prevalent in many cities. The propagation model for such a case is depicted in figure 4.8.

Figure 4.8 Wall reflected rays geometry. (Single reflection.)

Figure 4.8 depicts the singly wall reflected ray LDM, associated reflection angle $\theta_2$ and pertinent parameters, $h_b$, $h_m$, etc. For this model it is
assumed that one city building wall is located at \( y = 0 \) while the other is at \( y = w \).

The transversal location of the base antenna is \( y_t \).

In a 4-ray model following signal paths are assumed:

1) Direct path (LOS)
2) Ground reflected
3) Single wall reflection (twice)

Taking into account above mentioned paths the received power can be estimated with the help of equation (4.3).

That is,

\[
P_r = P_t \left( \frac{\lambda}{4\pi} \right)^2 \left[ G_d + \sum_{i=2}^{N} \frac{G_{ri} R_i e^{j\Delta_i}}{r_i} \right]^2
\]  

(4.17)

Where,

- \( R_i \) - Reflection coefficient for \( i \)th ray.
- \( G_{ri} \) - Product of \( R_x \) and \( T_x \) antenna gain for the \( i \)th ray.
- \( r \) - Ray length of the direct ray.
- \( r_i \) - Ray length of \( i \)th ray.
- \( \Delta_i \) - Phase difference between \( i \)th ray and direct ray.
- \( N \) - Number of rays = 4.

### 4.5.2 Specifications for Field Strength Estimation.

To study the effect of propagation in an urban area a four ray model is developed in the section 4.4.1. For simulation the parameters used are as mentioned in section 4.3.2. The finite conductivity of walls is taken into account through heuristic coefficients of Luebbers[82] or through the reflection and scattering model developed by O. Landron et al.[99].
4.5.3 Simulation Results.

The simulation results for the 4-ray model using equation (4.17) are shown in figures 4.9 to 4.14 for frequencies of 35, 40, 45, 50, 60 and 70 GHz respectively.

From these figures we observe that the estimated signal strength using 4-ray model creates peaks and dips of very random nature before it assumes an asymptotic law. This is due to the interference between the multiple rays that contribute to the RSS. As observed in the case of 2-ray model the separation between successive dips as well as the width of these dips increases with distance.

Table 4.6 the shows the distances at which a threshold value below -135 dBm occurs.

<table>
<thead>
<tr>
<th>Frequency in GHz</th>
<th>Distance of threshold (&lt; -135 dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>758 m</td>
</tr>
<tr>
<td>40</td>
<td>865 m</td>
</tr>
<tr>
<td>45</td>
<td>469 m</td>
</tr>
<tr>
<td>50</td>
<td>520 m</td>
</tr>
<tr>
<td>60</td>
<td>420 m</td>
</tr>
<tr>
<td>70</td>
<td>480 m</td>
</tr>
</tbody>
</table>

Table 4.7 shows the loss at different distances at various frequencies.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>35 GHz</th>
<th>40 GHz</th>
<th>45 GHz</th>
<th>50 GHz</th>
<th>60 GHz</th>
<th>70 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-96.2</td>
<td>-99.1</td>
<td>-102.6</td>
<td>-107.3</td>
<td>-94.8</td>
<td>-104.2</td>
</tr>
<tr>
<td>200</td>
<td>-89.9</td>
<td>-99.8</td>
<td>-93.2</td>
<td>-101.7</td>
<td>-108.5</td>
<td>-110.0</td>
</tr>
<tr>
<td>300</td>
<td>-94.3</td>
<td>-97.0</td>
<td>-104.4</td>
<td>-98.3</td>
<td>-111.9</td>
<td>-108.3</td>
</tr>
<tr>
<td>500</td>
<td>-105.1</td>
<td>-106.9</td>
<td>-109.9</td>
<td>-110.4</td>
<td>-104.7</td>
<td>-132.2</td>
</tr>
<tr>
<td>1000</td>
<td>-112.6</td>
<td>-117.9</td>
<td>-124.4</td>
<td>-119.6</td>
<td>-117.8</td>
<td>-147.2</td>
</tr>
</tbody>
</table>
Fig. 4.9 Power received by MS.

4-ray Model.
f = 35 GHz.

Fig. 4.10 Power received by MS.

4-ray Model.
f = 40 GHz.
Fig. 4.11 Power received by MS.

4-ray Model.
\( f = 45 \text{ GHz} \).

Fig. 4.12 Power received by MS.

4-ray Model.
\( f = 50 \text{ GHz} \).
Fig. 4.13 Power received by MS.

4-ray Model.

$\text{f} = 60 \text{ GHz}.$

Fig. 4.14 Power received by MS.

4-ray Model.

$\text{f} = 70 \text{ GHz}.$
In case of 4 ray model the position of the last dip is not well defined and hence the Table corresponding to Table 4.3 for 2 ray model, has not been included.

4.6 8-RAY MODEL.

4.6.1 The Model.

A 8-ray model is used for urban area that fits those cities in which row houses and/or wide tall buildings line both sides of the streets. This topography is prevalent in many metropolitan cities. The propagation model for these cities is developed by adding multiple reflection due to wide and tall buildings lined along the road.

Figure 4.15(a) Wall reflected rays geometry. (Double reflection.)

Figure 4.15(a) depicts the doubly, wall reflected ray LEFM and its
associated reflection angle $\theta_4$ are shown along with the corresponding geometry and pertinent parameters. Figure 4.15(b) depicts the triply, wall reflected ray LG1HM and its associated reflection angle $\theta_6$ are shown along with the corresponding geometry and pertinent parameters.

**Figure 4.15(b) Wall reflected rays geometry. (Triple reflection.)**

For this model it is assumed that one city building wall is located at $y = 0$ while the other is at $y = w$. The transversal location of the base antenna is $y_v$.

In a 8-ray model following signal paths are assumed

1) Direct path (LOS)
2) Ground reflected
3) Single wall reflection (twice)
4) Double wall reflection (twice)
5) Triple wall reflection (twice)
Taking into account above mentioned paths the received power can be estimated with the help of equation (4.3) and equation (4.17) where number of rays $N = 8$.

### 4.6.2 Specifications for Field Strength Estimation.

To enhance capacity of a CMCS the designers are forced to use the micro/pico cellular system. In such systems the cell dimensions are of the order of few hundred metres only. Therefore for 8-ray model the simulation is carried out upto a distance of 2000 m.

As discussed in chapter 1 and as suggested by Prof. R. Steel [1] it is appropriate that the study of hand-off algorithms in the band of 35-70 GHz be carried out at 35 GHz near the band $W_1$, at 50 GHz where the attenuation due to oxygen and water vapour is moderate and at 60 GHz where the oxygen absorption is maximum [2]. Therefore it is proposed to analyse and simulate the model for 35, 50 and 60 GHz.

To study the effect of propagation following simulation parameters are redefined.

i) Frequencies - 35, 50, 60 GHz.

ii) Cell radius - 2000 m.

Other parameters are as given in 4.3.2.

### 4.6.3 Simulation Results.

The simulation results for the 8-ray model using equation (4.17) are shown in figures 4.16 to 4.18 at frequencies of 35, 50 and 60 GHz respectively.

It is observed that in 8-ray model the interference between the multiple rays creates peaks and dips of very random nature. In case of 8-ray model well-defined peaks and dips of 2-ray model are superimposed by a noise-like curve. These sharp peaks and dips are due to multiple rays that contribute to the RSS at different distances at different phase angle.
Fig. 4.16. Power received by MS.
Fig. 4.17. Power received by MS.

Distance (m)

RSS (dBm)

F = 50 GHz
B-ray Model
Fig. 4.18. Power received by MS.
Table 4.9 shows the distance at which a threshold value below -135 dBm occurs.

**Table 4.9: Distance of threshold value at various frequencies.**

<table>
<thead>
<tr>
<th>Frequency in GHz</th>
<th>Distance of threshold (&lt; -135 dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>941 m (-148.8940)</td>
</tr>
<tr>
<td>50</td>
<td>923 m (-155.4680)</td>
</tr>
<tr>
<td>60</td>
<td>643 m (-141.8663)</td>
</tr>
</tbody>
</table>

Table 4.10 shows the loss at different distances at various frequencies.

**Table 4.10: Loss in dBm at different Distances.**

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>35 GHz</th>
<th>50 GHz</th>
<th>60 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-96.3772</td>
<td>-106.9360</td>
<td>-94.6679</td>
</tr>
<tr>
<td>200</td>
<td>-89.7150</td>
<td>-102.2060</td>
<td>-109.4820</td>
</tr>
<tr>
<td>300</td>
<td>-93.7888</td>
<td>-97.9093</td>
<td>-110.7440</td>
</tr>
<tr>
<td>500</td>
<td>-102.5230</td>
<td>-111.0630</td>
<td>-105.8740</td>
</tr>
<tr>
<td>1000</td>
<td>-113.7230</td>
<td>-122.3840</td>
<td>-119.0880</td>
</tr>
</tbody>
</table>

**4.6.4 Regression Analysis.**

The primary tool in study of radio signal variations over distance is regression analysis, in which a linear fit is made to the signal in dBm versus distance from BS to MS on a logarithmic scale. Typically, a single straight line is fitted to all the data over the given range. However it can be seen from the figures 4.16-4.18 that a single line fit may not describe the data in true manner, that is the pathloss slope can not be described with single line slope. Hence a two-line regression analysis approach is used to describe the signal.

Figures 4.19 to 4.21 shows the two-line regression analysis at 35, 50 and 60 GHz.

The values of the path loss exponent ($n_1$ and $n_2$) at various frequencies are listed in Table 4.11.
Fig. 4.19. Multiple slope regression fit to the 8-ray model.
Fig. 4.20. Multiple slope regression fit to the 8-ray model.
Fig. 4.21. Multiple slope regression fit to the 8-ray model.

Pr in dBm

Distance (m)

f = 60 GHz

n1 = -1.6308

n2 = 3.4847
Fig. 4.22 Location variability of received power by MS.

8-ray Model.
f = 36 GHz

RSS (dBm)

Width of Road (m) (scale 1:1)

Length of Road (m) (scale 1:10)
Fig. 4.23 Location variability of received power by MS.

- Rayleigh Model, $f = 50$ GHz.

Width of Road (m) [scale 1:1]

Length of Road (m) [scale 1:10]

RSS (dBm)
Fig. 4.24 Location variability of received power by MS.
Table 4.11: Path Loss Exponent using Dual Slope Regression Analysis.

<table>
<thead>
<tr>
<th>Frequency in GHz</th>
<th>n₁</th>
<th>n₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>-1.5846</td>
<td>-3.5767</td>
</tr>
<tr>
<td>50</td>
<td>-1.7119</td>
<td>-3.3119</td>
</tr>
<tr>
<td>60</td>
<td>-1.6308</td>
<td>-3.4847</td>
</tr>
</tbody>
</table>

The values for n₁ are just lower than the free-space law, whereas the values of n₂ are much higher than that of free-space law.

The location variability of the received signal using 8-ray model along the width of the road for a distance of 1000 m is shown in figures 4.22 to 4.24.

4.7 SIGNAL STRENGTH AVERAGING.

4.7.1 Theory.

Traditional hand-off algorithms calculate signal strength time averages \( \langle r_i(t) \rangle \) from N neighbouring BSs \( i = 1, \ldots, N \) and recommend the MS to alternative BS whenever the signal strength of the alternative BS exceeds that of the serving BS by at least a hysteresis level of \( H \) dB. In a CMCS, the received signal envelope is characterised by short term fading, long-term fading and path loss attenuation. In microcellular structures the received signal \( \langle r_i(t) \rangle \) is affected by Rician fading, log-normal shadowing, and path loss attenuation.

For estimation of the averaging period of the received signal let

\[
y(t) = X_i(t)\cos \omega_c t - X_q(t)\sin \omega_c t
\]

(4.18)

\[
X_i(t) = x_i(t) + m_i
\]

(4.19)

\[
X_q(t) = x_q(t) + m_q
\]

(4.20)

be Gaussian random processes with variance \( \sigma^2 \), mean \( m_i \) and \( m_q \) respectively. The envelope of \( y(t) \) is Rician distributed with Rice factor \( K \) given by.
\[
K = \frac{s^2}{2\sigma^2}
\]  
\[(4.21)\]

where,
\[
s^2 = m_l + m_q
\]

In the propagation model for CMCS multi-ray model has been used to estimate the received signal. The analysis carried out by Austin [56] suggest that the multi-ray model can be represented by
\[
X_r(t) = x_r(t) + s \cos(\omega_o t + \theta_o)  
\]  
\[(4.22)\]
\[
X_q(t) = x_q(t) + s \sin(\omega_o t + \theta_o)  
\]  
\[(4.23)\]

where \(s \cos(\omega_o t + \theta_o)\) and \(s \sin(\omega_o t + \theta_o)\) are inphase and quadrature components of the LOS signal and \(\omega_0\) and \(\theta_0\) are the Doppler shift and phase offsets respectively.

From the original work of W. C. Y. Lee and Y. Yeh [100] and the extended work of Austin and Stuber [56] we can write, the received signal strength at any point \(y\) can be written as
\[
r^2(y) = r_p(y) \cdot m_p(y)
\]  
\[(4.24)\]

where \(r^2(y)\) is the squared envelope, \(r_p(y)\) is a non-central chi-square random variable and \(m_p(y)\) is a lognormal random variable. If the local mean is constant then \(m_p(y) = m_p\). Assuming ergodicity, an integral spatial average of \(r^2(y)\) can be used to estimate the local mean \(m_p\)

\[
\text{i.e. } m_p = \frac{1}{2L} \int_{x-L}^{x+L} r^2(y) dy
\]  
\[(4.25)\]
\[
= \frac{m_p}{2L} \int_{x-L}^{x+L} r^2(y) dy
\]  
\[(4.26)\]

The accuracy of the estimate can be determined from the variance of \(4.26\). That is, the 1\(\sigma\) spread can be calculated to measure the accuracy of the estimation. Therefore,
\[
1\sigma \text{ spread} = 10 \log_{10} \frac{m_p + \sigma_{m_p}}{m_p - \sigma_{m_p}}
\]  
\[(4.27)\]
It was shown that for $\theta = 60^0$ $1\sigma$ spread is 0.68 and for $\theta = 90^0$ $1\sigma$ spread is 0.475.

The effect of the spatial window length on hand-offs is well documented in the literature [42, 101, 102, 103]. In most practical cases of signal strength estimation, averaging of samples is used rather than analog averaging. It is shown that for $K = 1$ and a spatial window length of $40\lambda$ the $1\sigma$ spread is well below 2 dB [100]. On this basis and as suggested by W. C. Y. Lee, we use sample space less than $0.5\lambda$ metres over length '$L$' of $20\lambda$ to $40\lambda$ metres for signal strength averaging.[279]

4.7.2 Specifications for field strength estimation.

From Table 4.10 it is observed that the RSS reaches a value less than $-110$ dBm and the signal averaging is required in the current or adjacent cell of the MS only. Hence for the signal strength averaging the radius of the cell is assumed to be 1000 m. All other parameters are as mentioned in section 4.6.2.

4.7.3 Simulation results.

Simulation results for the signal strength averaging (i.e. local mean) at 35, 50 and 60 GHz are carried out. Figures 4.25 - 4.27 shows the local mean RSS, the standard deviation of this local mean shown in figures 4.28-4.30. The maximum value of the standard deviation observed is 9.899 dB. This signal strength averaging will be used for the hand-off analysis of a CMCS operating at 35, 50 and 60 Ghz.

4.8 CONCLUDING REMARKS.

In this chapter we have described the model and implementation principles governing a LOS microcell wave propagation simulator. Multi-ray propagation above a plane earth constitutes our basic model.
Fig. 4.25 Local mean of RSS.
Fig. 4.26 Standard deviation of Local mean of RSS.
Fig. 4.27 Local mean of RSS.
Fig. 4.28 Standard deviation of Local mean of RSS.
Fig. 4.29 Local mean of RSS.
Fig. 4.30 Standard deviation of Local mean of RSS.
Results of the 2-ray model show that, before the propagation assumes an asymptotic law the radio signal oscillates severely due to additive and subtractive combination of two rays, while after the last dip it decreases more rapidly with distance. This particular behavior of the RSS can be described with the help of Fresnel zone clearance. When the propagation path has first Fresnel zone clearance the signal attenuation, as MS moves away from the BS, is essentially due to the spreading of the wave-front. However, when the first Fresnel zone starts to become blocked (that is the **turning point**), attenuation in addition to the free space wave-front spreading results from the obstructing of the first Fresnel zone. Consequently, a steeper path loss slope is found. From Table 4.3 we observe that the 2-ray model agrees with the Fresnel zone theory, which shows the point where the first Fresnel zone cuts the earth.

From the results of simulation of 2-ray model it is concluded that this model is useful for predicting the RSS in rural environment only. The results are similar in nature with the work carried out by many researchers for the frequency band of 800-900 MHz or 1700-2200 MHz. [280,76, 80-98]

Considering the shortcomings of the 2-ray model for urban area the propagation model should take into account multiple reflections due to the buildings that are lined along the road along which the MS is moving. Therefore, the simulation program was extended to include four/eight rays. For 4-ray model the number of rays considered are the direct, road reflected ray and two of each single wall reflected rays. For 8-ray model two of each double wall reflected and two of each triple wall reflected rays are considered along with four rays considered for 4-ray model.

The result of simulation of 4-ray model shows that the effect of wall reflected rays adds/subtracts from the power received by the 2-ray model. This is because the phase of the received ray varies with distance and frequency. This change in the phase difference results in the sharp peaks and dips in the received signal strength. In case of 4-ray model the wall reflected rays do have a significant effect on the RSS. Therefore the pathloss estimation is required to be carried out in more details by increasing the number of rays to 8.
Table 4.2, Table 4.6 and Table 4.9 give the values of distances at which the RSS reaches the pathloss equal to the value of receiver sensitivity level of -135 dBm. The distances obtained give a rough estimate of the cell radius that can be serviced by a BS with the parameters specified in section 4.4.2. The distance for 35 GHz using 2-ray model is 870 m and 865 m for 40 GHz. For other frequencies the distance, at which a threshold value of RSS corresponding to receiver sensitivity, is less than 870 m. In case of 4-ray model the distance at which the RSS value attains the receiver sensitivity is maximum of 865 m at 40 GHz. The detailed analysis of the RSS using 8-ray model shows that the maximum distance at which the RSS attains receiver sensitivity is 941 m at 35 GHz. Hence we conclude that with these specifications the cell radius will always be less than 1000 m for the CMCS operating in the 35-70 GHz band.

The regression analysis is carried out. It is found that the propagation characteristics cannot be described by the single line curve fitting for the logarithmic plot. Hence two line regression analysis is used. The path loss exponent values $n_1$ and $n_2$ so obtained can in turn be used to contain the coverage of cell. The cell boundaries are determined on the basis of the regression analysis. From Table 4.11 it is observed that the pathloss slope value is such that within the cell boundary the MS is not experiencing significant pathloss. Outside the cell boundary the radio signal decreases rapidly with distance according to a high inverse power law.

From above discussion it is evident that for hand-off analysis 8-ray model is the best fit to generate the data of RSS. The averaging of the signal strength is to be carried out as given in section 4.7. From this signal strength averaging analysis it is evident that the RSS estimated at every $20\lambda$ to $40\lambda$ metres depending on the frequency describes the RSS in a refined way for the hand-off analysis.