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Radio Propagation

Week 7

I have no picture of this electromagnetic field that is in any sense accurate...I see some kind of vague, shadowy, wiggling, lines...so if you have some difficulty in making such a picture, you should not be worried that your difficulty is unusual. -Richard Feyman Nobel Prize laureate in Physics

CSCD609: Lecture Outline

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- Introduction to radio wave propagation
- Types of Radio waves
- Propagation mechanisms
- Free space propagation Model
- Land propagation

CSCD609: Types of Radio Waves

Type	Frequency Range	Key Uses
VLF 10 – 100 km	3–30 kHz	Submarine communication
LF 1 – 10km	30–300 kHz	Maritime navigation
MF 100 – 1000m	300 kHz–3 MHz	AM radio broadcasting
HF 10 – 100m	3–30 MHz	Shortwave radio, global communication
VHF 1 – 10m	30–300 MHz	FM radio, TV broadcasting
UHF 10cm – 10m	300 MHz–3 GHz	Mobile phones, Wi-Fi
SHF 1 – 10cm	3–30 GHz	Satellite communication, radar
EHF	30–300 GHz	Space communication, scientific research

CSCD609: **Propagation of Waves**

The basic modes by which radio waves are transmitted to a receiving antenna are:

- Free Space Propagation
- Ground (Surface) Waves
- Space Waves
- Sky Waves
- Satellite Communication

- **Key Characteristics:**

1. **Straight-Line Path**:
   1. Radio waves travel in a straight line from the transmitter to the receiver (line-of-sight propagation).
2. **No Obstacles**:
   1. There are no physical barriers such as buildings, mountains, or trees to obstruct or alter the wave.
3. **Ideal Conditions**:
   1. No atmospheric effects like refraction, scattering, or absorption that would degrade the signal.

- **Inverse Square Law**:
- The strength of the signal decreases with the square of the distance from the source.

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- **Applications:**

1. **Satellite Communication**:
   1. Signals travel through space between ground stations and satellites.
2. **Space Exploration**:
   1. Used for communication with spacecraft and interplanetary missions.
3. **Point-to-Point Wireless Communication**:
   1. Microwave links or laser-based communication systems in ideal conditions.

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- **Advantages:**
- Predictable and consistent signal behavior.
- No multipath fading or distortion caused by obstacles.
- Maximum efficiency in transmitting high-frequency signals.
- **Limitations:**

1. **Attenuation with Distance**:
    1. Signal strength decreases rapidly over long distances due to the inverse square law.
2. **Limited to Line-of-Sight**:
    1. Requires a clear, unobstructed path between transmitter and receiver.
3. **Environmental Sensitivity**:
    1. Not practical in environments with obstacles or atmospheric interference.

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Ground Wave Propagation:

1. Radio waves travel along the Earth's surface.
2. Best for low-frequency waves (e.g., AM radio).
3. Limited by terrain and obstacles.

CSCD609: Ground Waves

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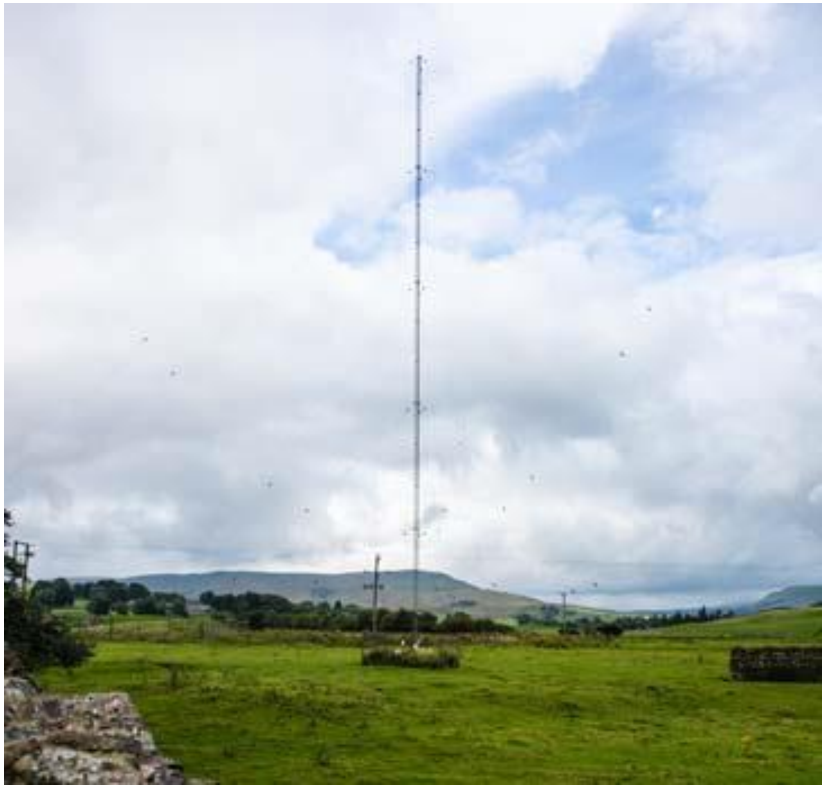
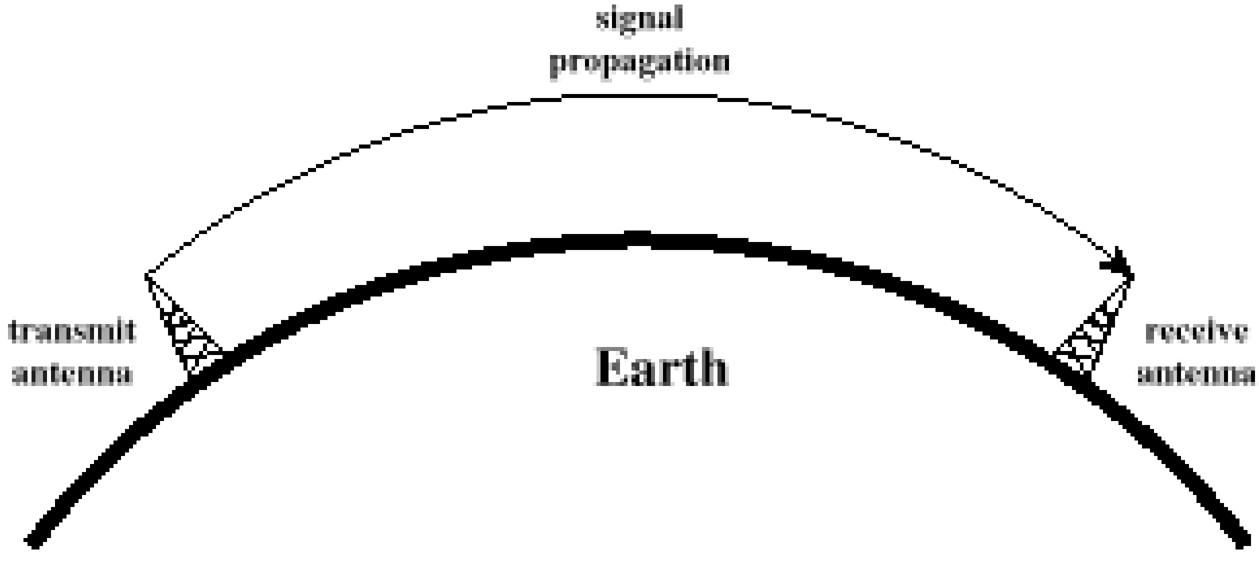
- Important on the LF and MF portion of the radio spectrum.
- Used to provide relatively local radio communications coverage, especially by radio broadcast stations that require to cover a particular locality.
- Ground wave radio signal propagation is ideal for relatively short distance propagation on these frequencies during the daytime.



CSCD609: Ground (Surface) Waves

These travel along the surface of the earth (more or less following the contour of the earth) and must be vertically polarized to prevent short-circuiting.



CSCD609: Ground Waves

They can travel considerable distances, well over the visual horizon.

As the wave propagates over the earth, it tilts over more and more. (A current is induced in the earth's surface by the electromagnetic wave, the result is the wavefront near the surface slows down).

This causes the wave to short circuit completely at some distance (in wavelengths) from its source.

CSCD609: Ground Waves

- Follows contour of the earth
- Can Propagate considerable distances
- Frequencies up to 2 MHz
- Example
  - AM radio

CSCD609: Surface Waves

- Disadvantages
  - Requires relatively high transmission power
  - They are limited to very low, low and medium frequencies which require large antennas
  - Losses on the ground vary considerably with surface material
- Advantages
  - Given enough power they can be used to communicate between any two points in the world
  - They are relatively unaffected by changing atmospheric conditions

CSCD609: Space wave propagation

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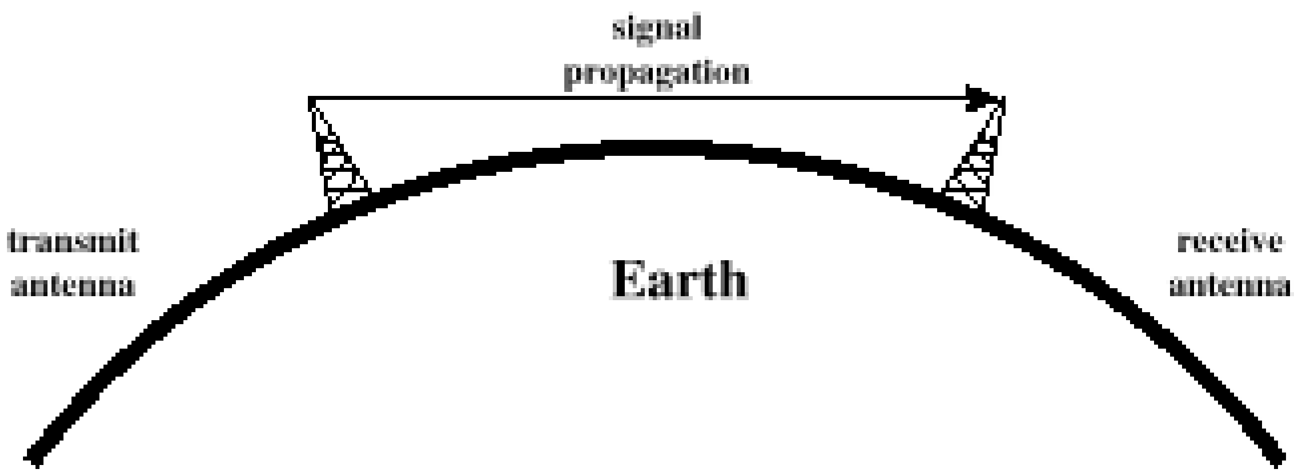
- This includes radiated energy that travels in the lower few miles of the earth's atmosphere. They include both direct and ground reflected waves.

- Direct waves travel in essentially a straight line between the transmitting and receiving antennas. The most common name is line of sight propagation.

- The field intensity at the receiving antenna depends on the distance between the two antennas and whether the direct and ground reflected waves are in phase.

CSCD609: Line-of-Sight Propagation



CSCD609: Line-of-Sight Propagation

- Optical line of sight

$$d = 3.57\sqrt{h}$$

- Effective, or radio, line of sight

$$d = 3.57\sqrt{\mathrm{K}h}$$

  - d = distance between antenna and horizon (km)
  - h = antenna height (m)
  - K = adjustment factor to account for refraction, rule of thumb K = 4/3

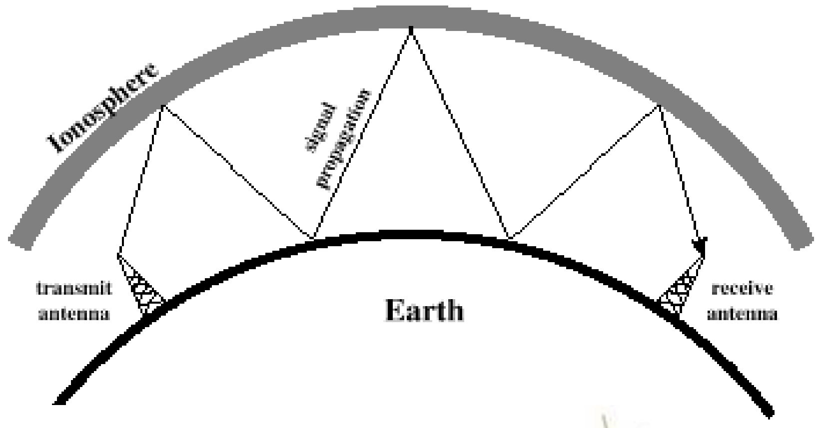
CSCD609: Line-of-Sight Propagation

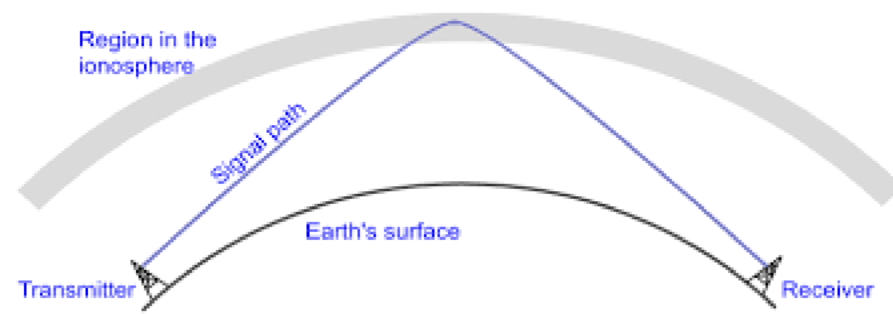
- Maximum distance between two antennas for LOS propagation:

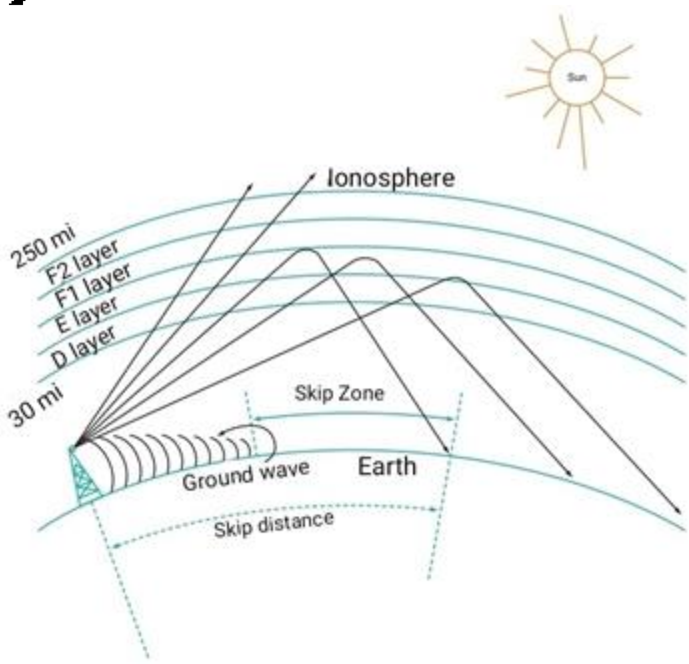
$$3.57\left(\sqrt{\mathrm{K}h_1} + \sqrt{\mathrm{K}h_2}\right)$$

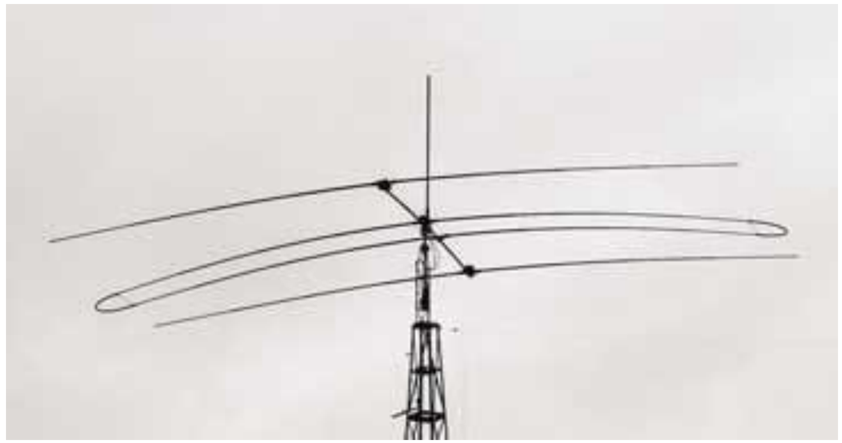
  - h_1 = height of antenna one
  - h_2 = height of antenna two

CSCD609: Sky Wave Propagation









CSCD609: Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth's surface
- Reflection effect caused by refraction
- Examples
  - Amateur radio
  - CB radio

- ***D region:***
  - This region attenuates the signals as they pass through. The level of attenuation depends on the frequency. Low frequencies are attenuated more than higher ones.
- ***E region:***
  - little attenuation of the signals, this region reflects, or more correctly refracts signals
  - The level of refraction reduces with frequency, higher frequency signals may pass through this region and on to the next region.
  - The E region is of great importance for HF propagation at the lower end of the HF spectrum and even the MF spectrum.
-

- ***F region:***
  - Enables HF for worldwide communications.
  - During the day this region often splits into F1 and F2 regions.
-

CSCD609: **Effects of the Ionosphere on the Sky wave**

If we consider a wave of frequency , f incident on an ionospheric layer whose maximum density is N then the refractive index of the layer is given by

$$n = \sqrt{1 - \frac{81N}{f^2}}$$

CSCD609: **Critical Frequency**

If the frequency of a wave transmitted vertically is increased, a point will be reached where the wave will not be refracted sufficiently to curve back to earth and if this frequency is high enough then the wave will penetrate the ionosphere and continue on to outer space. The highest frequency that will be returned to earth when transmitted vertically under given atmospheric conditions is called the *critical frequency*.

$$f_c = 9\sqrt{N}$$

CSCD609: **Maximum Usable Frequency**

There is a best frequency for communication between any two points under specific ionospheric conditions. The highest frequency that is returned to earth at a given distance is called the Maximum Usable Frequency (MUF).

$$f_{muf} = 9\sqrt{N}\sec\theta$$

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CSCD609: **Optimum Working Frequency**

This is the frequency which provides the most consistent communication and is therefore the best to use. For transmission using the F2 layer it is defined as

$$f_{owf} = 0.85 \times 9\sqrt{N}\sec\theta$$

CSCD609: **Lowest Usable Frequency**

This is set by the attenuation in the ionosphere. A practical value of this is usually taken as 3 MHz.

Propagation characteristics of wireless channels

Contents

Introduction

- Nature of radio channels makes them complicated
  - Wired medium provides reliable guided link
  - Wireless medium is unreliable
  - Has low bandwidth
  - Inherently a broadcast type
  - Different signals on a wired medium are physically conducted through different wires
  - All wireless transmission share the same medium
    - Cellular 1GHz
    - PCS and WLAN 2GHz
    - WLAN 5GHz
    - Local multipoint distribution service 28-60 GHz
    - Optical communication IR

Introduction

- It is heavily site dependent accurate characterization is thus important in predicting signal coverage.
  - Terrain
  - Frequency of operation
  - Speed of mobile terminal
  - Interference sources
  - Other dynamic factors

Introduction

- Attenuation is a major limitation on performance of mobile systems
- If path is line of sight then signal loss may not be severe
- In urban surroundings the path may be indirect and signal would reach final destination after reflection, diffraction, refraction and scattering
  - Signal strength depends on
    - distance travelled
    - Obstacles they have reflected from or passed through
    - Architecture of the environment
    - Location of objects from receiver and transmitter

Introduction

- Frequency of operation affects propagation characteristics
  - <500 MHz signal strength loss is small at first the metre
    - Less bandwidth, prohibitive antenna size, difficult to use diversity schemes to improve signal quality
  - > GHz,
    - Low power transmitters can be use (1 W), antenna sizes are much smaller order of a couple of cm, diversity schemes can be employed
    - Signal strength loss at first metre is high, greater loss when passing through obstacles eg walls
  - >10 GHz,
    - Signals confined within walls of a room
  - >60 GHz
    - Atmospheric gases such as oxygen absorb the signals.

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Introduction

- Three most important radio propagation characteristics
  - Achievable signal coverage
    - This determines the size of the cell in a cellular topology as well as range of operation of the BS – path loss models
  - Maximum data rate that can be supported by the channel
    - This is influenced by multipath structure and fading characteristics
  - The rate of fluctuation in the channel
    - Caused by movement of transmitter, receiver or objects in between
    - Characterized by the doppler spread of the channel

Wireless Transmission Impairments

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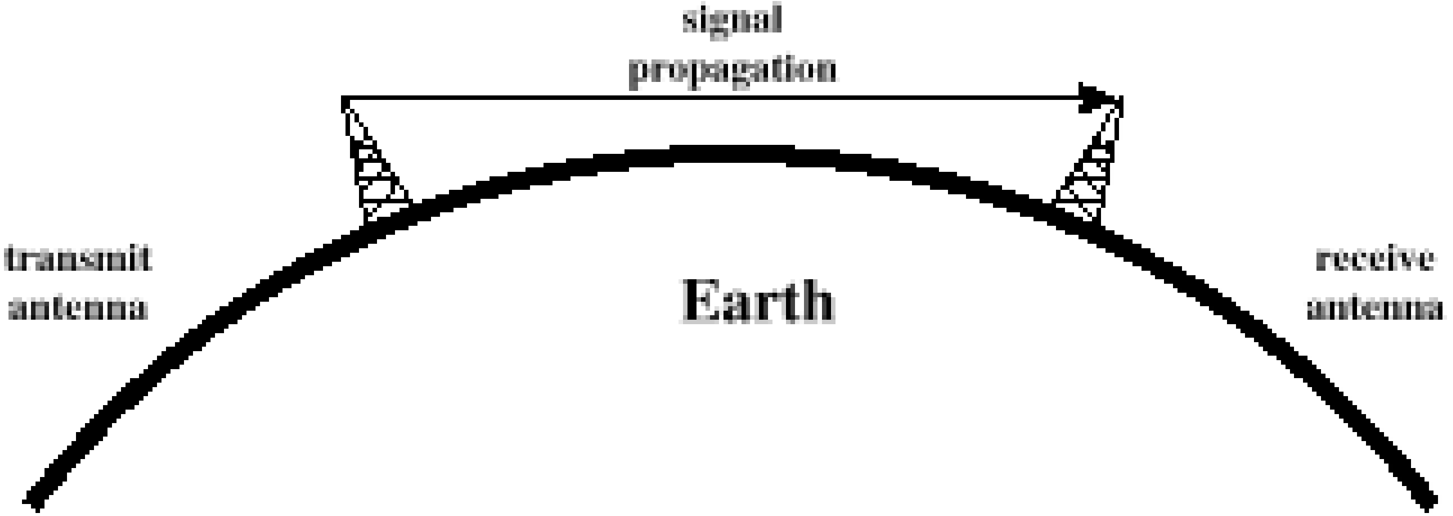
- Attenuation and attenuation distortion
- Free space loss
- Noise
- Atmospheric absorption
  - water vapor and oxygen contribute to attenuation

Wireless Transmission Impairments

- Multipath
  - obstacles reflect signals so that multiple copies with varying delays are received
- Refraction
  - bending of radio waves as they propagate through the atmosphere

Line of sight propagation



Radio propagation mechanisms

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- Most mobile communication systems are characterized by these N-LOS conditions:
  - Reflection
  - Diffraction
  - Scattering

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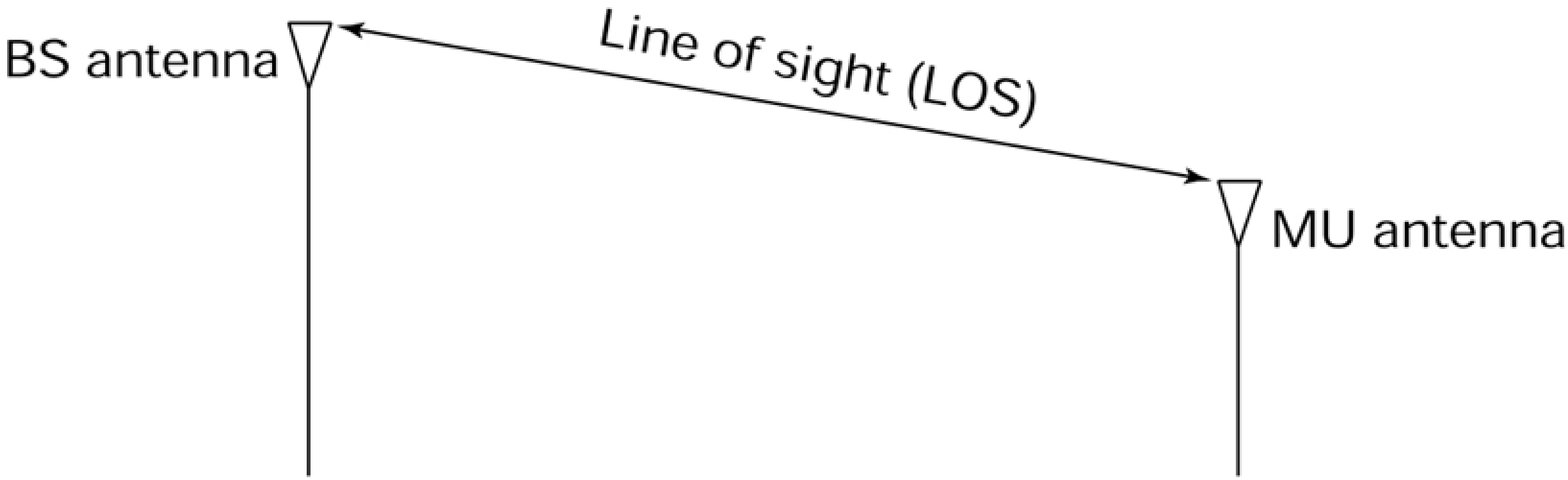
A direct (line of sight) between two antennae.



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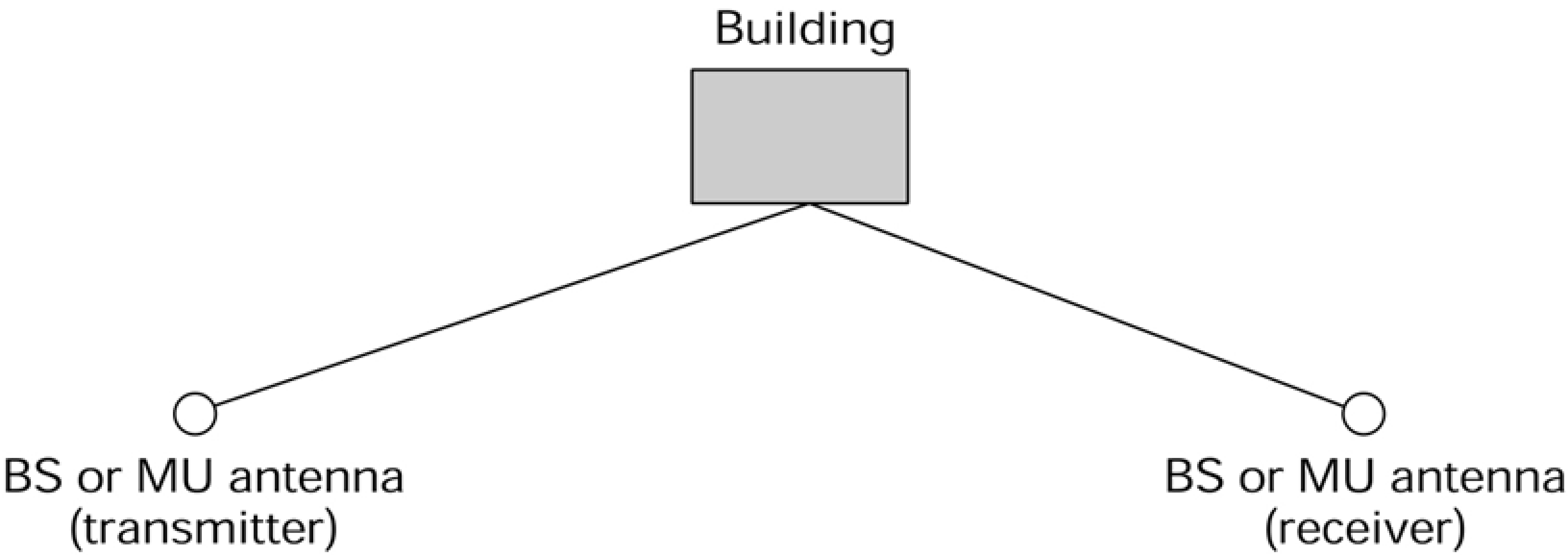
Reflection of the electromagnetic wave at a boundary.



Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal

Diffraction of the electromagnetic wave at the edge of a building.

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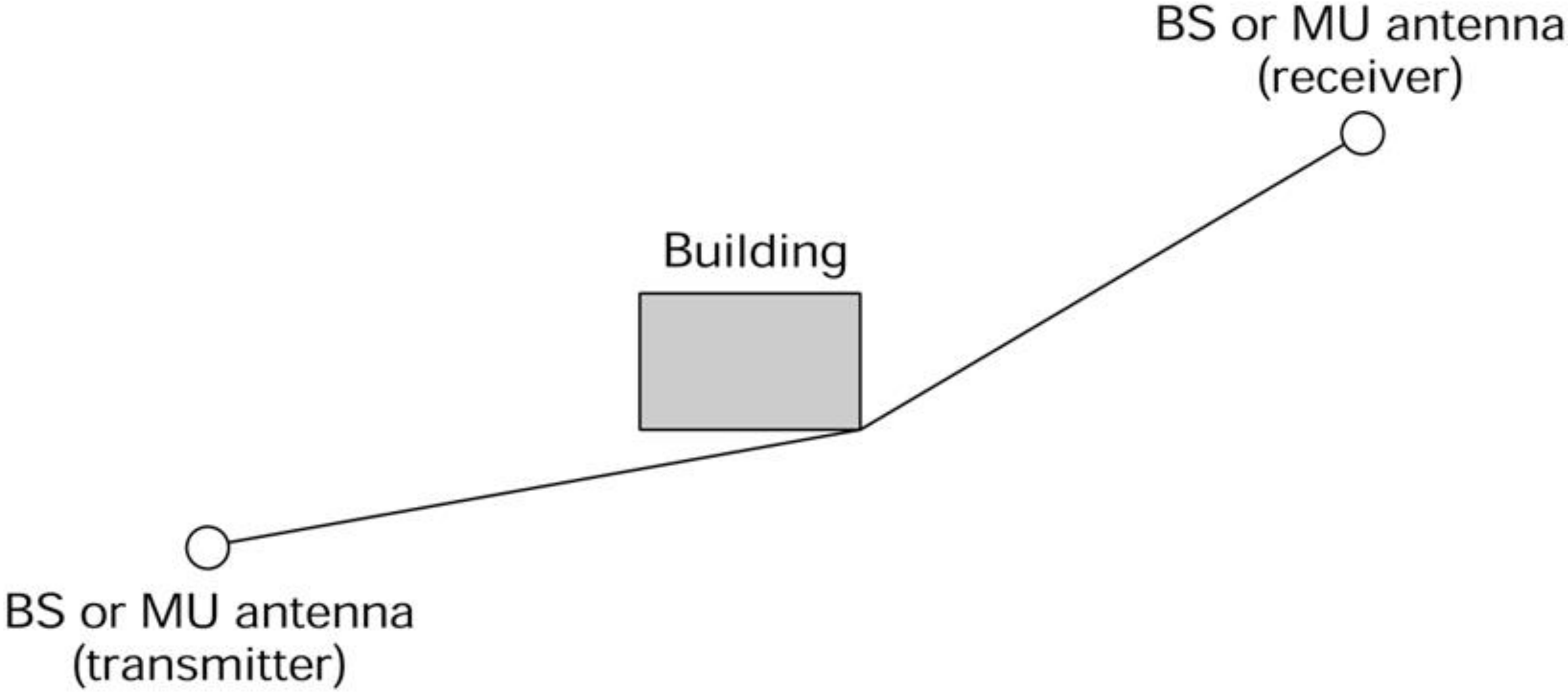
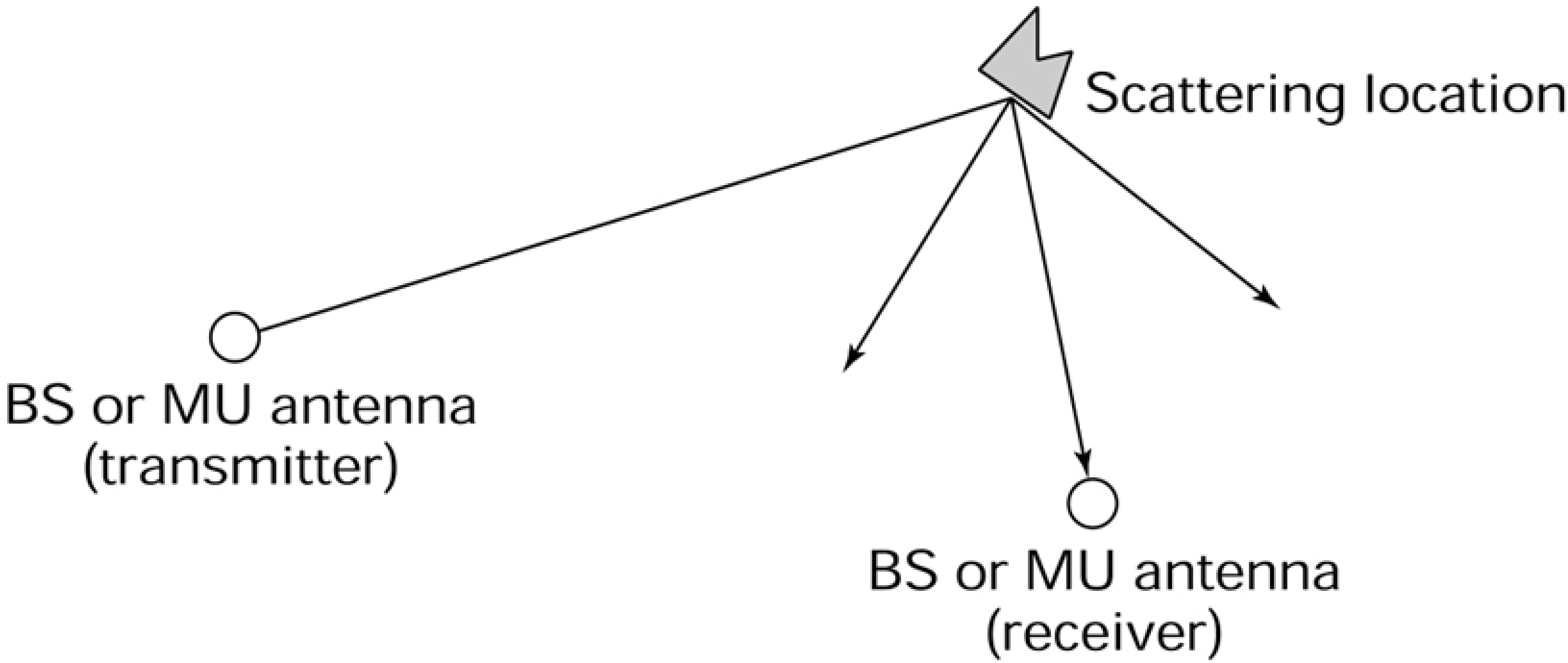


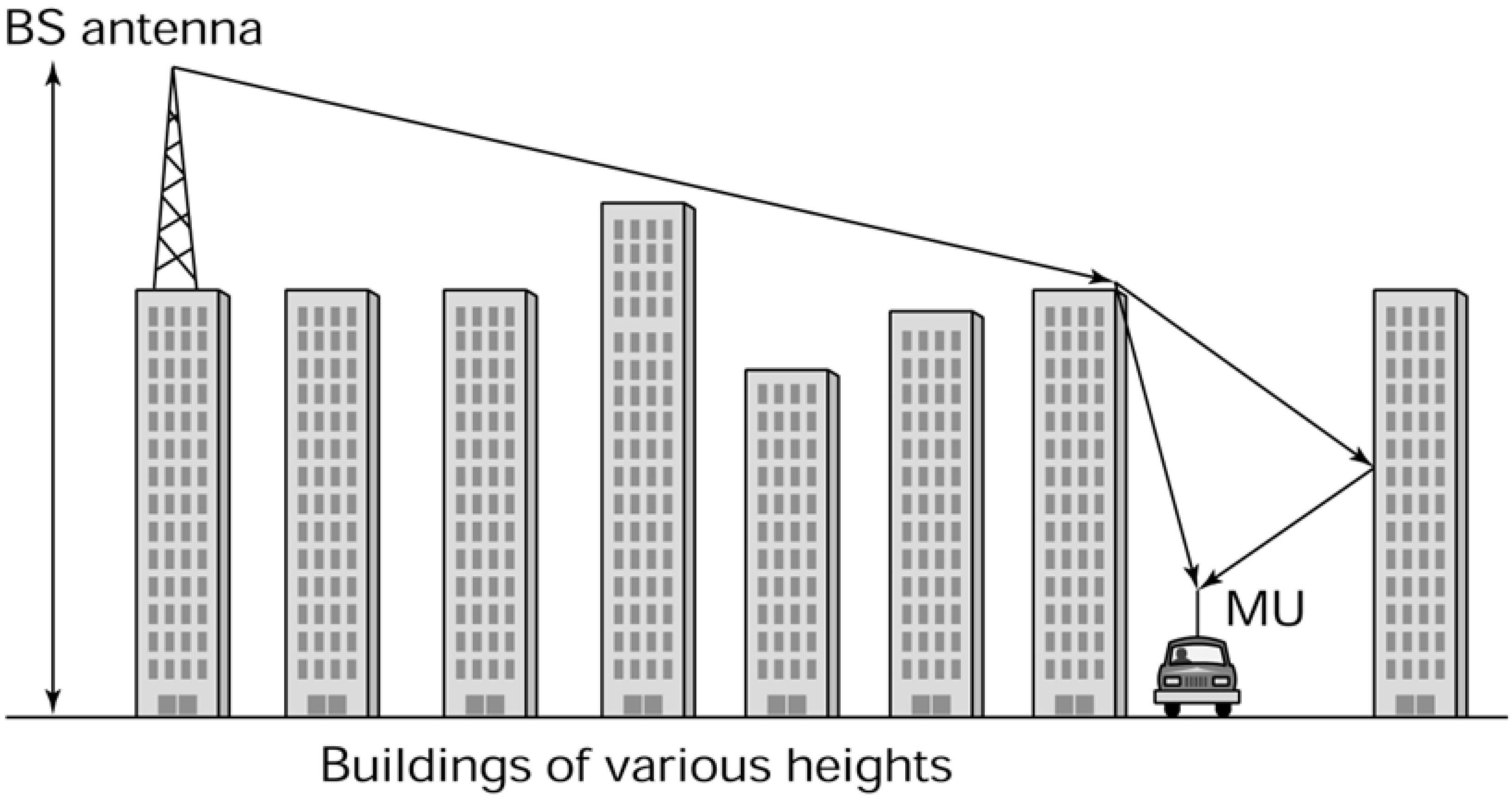
Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave

Scattering of the electromagnetic wave.

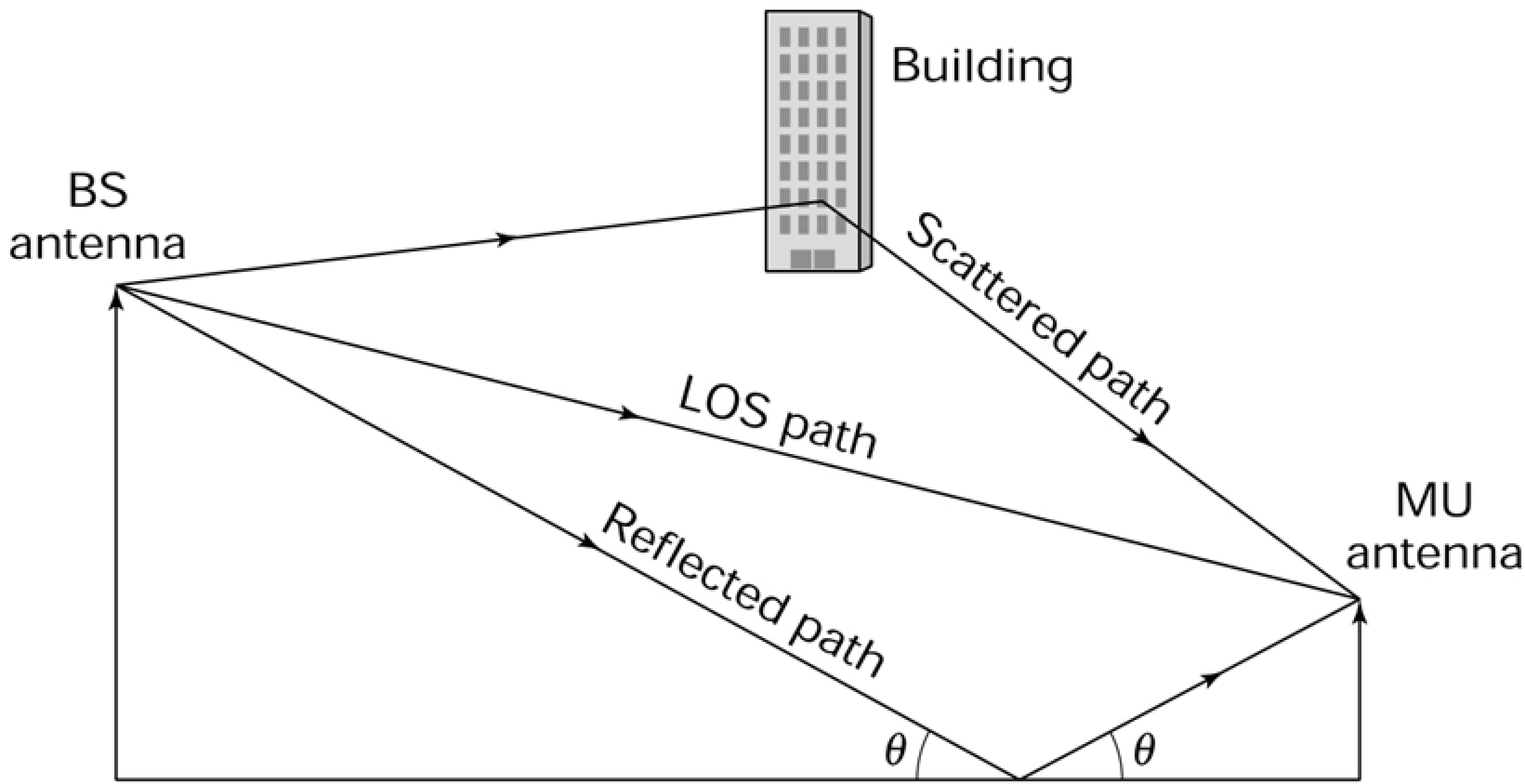


Scattering – occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less

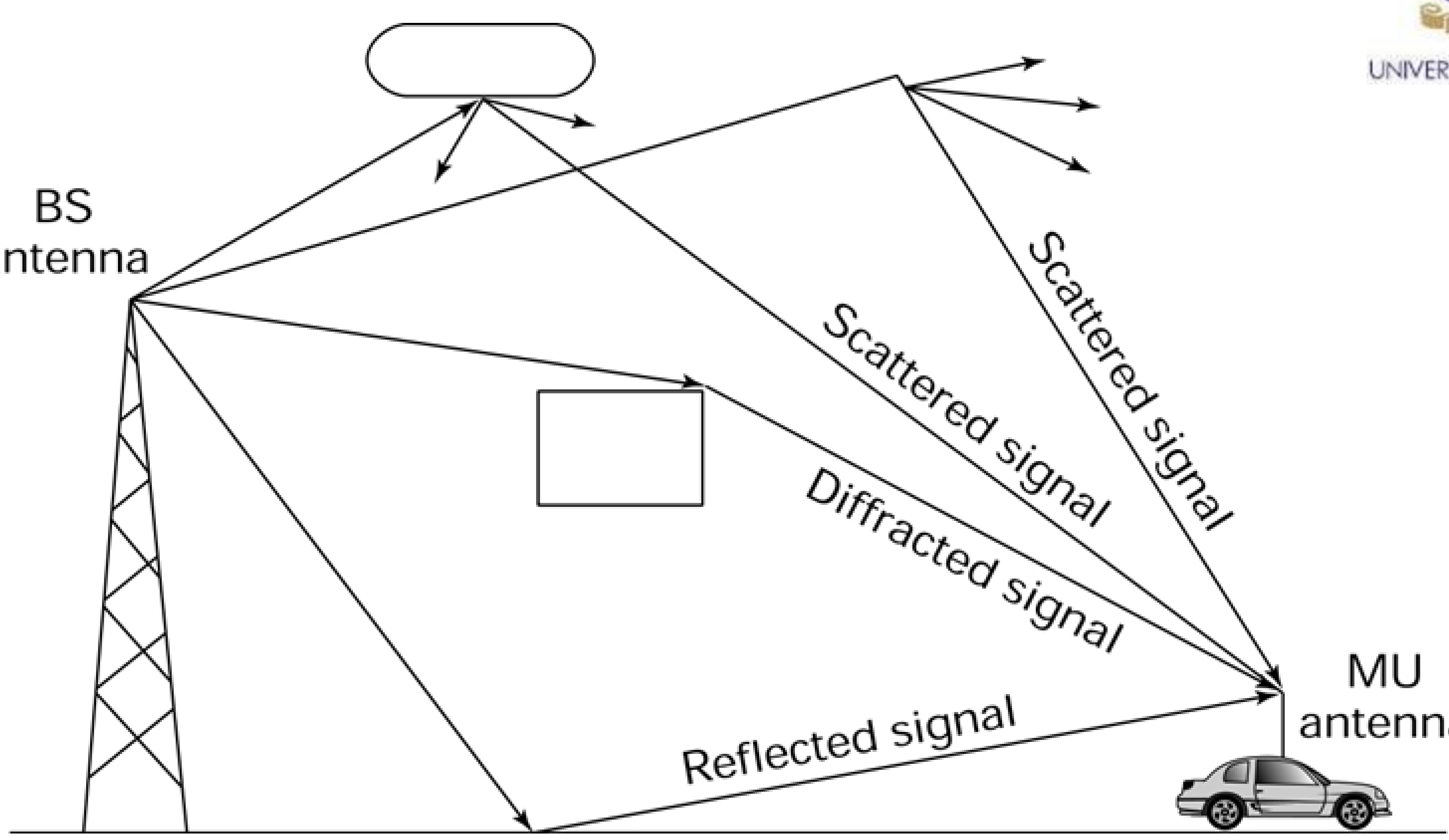
The signal reaches the receiver through reflection ar diffraction.



The signal reaches the receiver through reflectio scattering, as well as via a direct path.



The most general case of signal reception, consisting of a direct path, a reflected path, a scattered path, and a diffracted path.



Path loss

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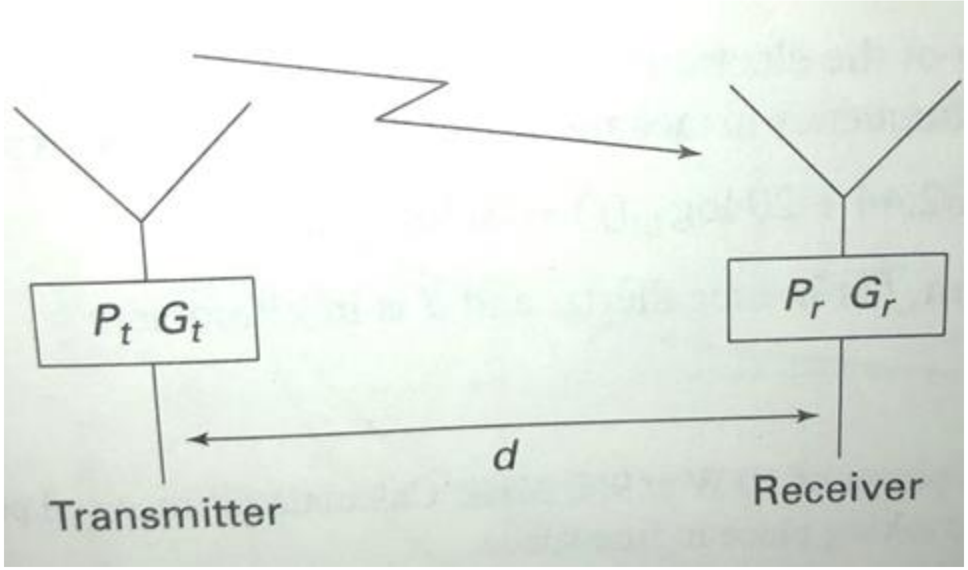
- *Path loss* is the average propagation loss in signal strength over an area.

- It is the ratio of the transmitted power to the received power and includes all possible loss factors associated with the propagation wave between the transmit and receive antennas.

Path loss

- $P_r \propto P_t d^{-\alpha}$
- $P_r \propto \frac{P_t}{d^{\alpha}}$
- For the most simple case $\alpha = 2$
- $P_r \propto \frac{P_t}{d^2}$
- $P_r = G_r G_t P_t \left(\frac{\lambda}{4\pi d^2}\right)^2$
- $\lambda = \frac{c}{f}$
- $c = 3\times10^8 m/s$



Path loss

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- Assuming that the power received at distance d=1m is P_o
- Then
- $P_o = P_t G_r G_t \left(\frac{\lambda}{4\pi}\right)^2$
- The power received at some distance d is therefore
- $P_r = \frac{P_o}{d^2}$
- $10\log(P_r) = 10\log(P_o) - 20\log(d)$ (dB)
- The transmission delay is given by
  - $\tau = \frac{d}{c} = \frac{d}{3\times10^8} = 3\text{d ns}$

Free Space Propagation

- What is the received power in dBm in free space of a signal whose transmit power is 1 W and carrier frequency 2.4GHz if the receiver is at a distance of 1 mile from the transmitter? Assume the gains of both the receiver and transmitter are 1.6.
- What is the path loss in dB
- What is the transmission delay in ns

Free Space Propagation

- Recall that 1 watt in dBm is
- 10 log (1W/1mW)= 30dBm
- The transmit power is thus 30dBm
- From $P_r = G_r G_t P_t \left(\frac{\lambda}{4\pi d^2}\right)^2$
- $\lambda = \frac{3\times10^8}{2.4\times10^9} = 0.125$
- $G_r G_t = 1.6\times1.6 = 2.56$

Free Space Propagation

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- Power received at distance 1m will be
- $P_o = P_t G_r G_t \left(\frac{\lambda}{4\pi}\right)^2$; $G_r \times G_t = 2.56$
- $P_o = 10\log P_t + 10\log G_r + 10\log G_t + 20\log\lambda - 20\log 4\pi$
- $P_r = P_0 - 20\log(1600)$
- Path loss = $P_t - P_r$
- Transmission delay $= \frac{1600}{c}$

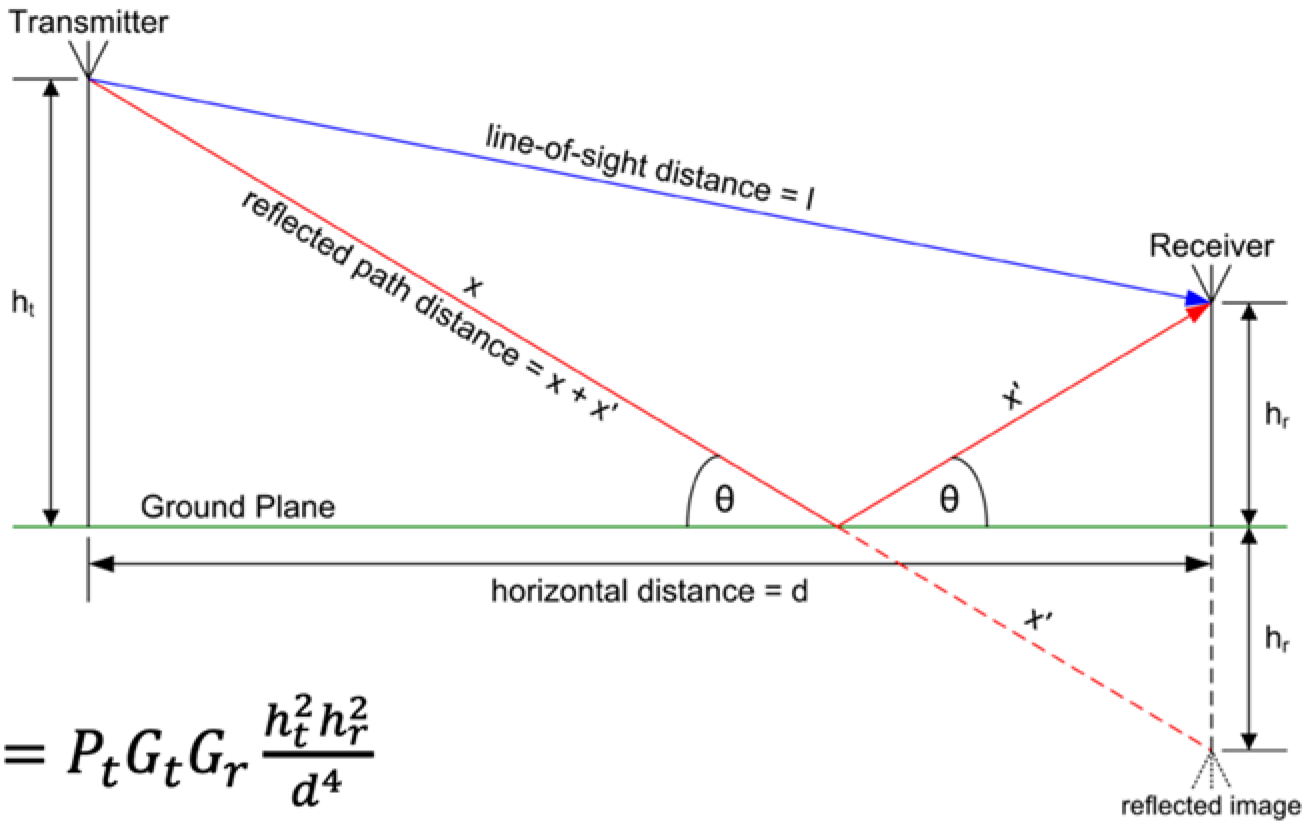
Free Space Propagation

Develop an interactive implementation of the solution in Matlab.

Your program must allow the user to specify all variables

Show a plot of the received signal over distance

Two Ray Model



- $P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$

Distance Power Relation

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- The received signal power is proportional to the distance between transmitter and receiver raised to some exponent alpha, the distance power gradient;

$$P_r = \frac{P_o}{d^{\alpha}} = P_o d^{-\alpha}$$

$$10\log(P_r) = 10\log(P_0) - 10\alpha\log(d)$$

- If path loss in dB at a distance of 1m is:

$$L_o = 10\log(P_t) - 10\log(P_o)$$

- Total path loss is then:

$$L_p = L_o + 10\alpha\log(d)$$

For direct path

$$P_r \propto d^{-2}$$

so that power received at a distance *d*

$$P_r(d) = \frac{P_t G_r G_t \lambda^2}{(4\pi)^2 d^2 L}$$

Free space loss is given as

$$L_{free} = -20\log_{10}\left(\frac{\lambda}{4\pi d}\right) dB$$

This can be rewritten as

$$L_{free} = 32.44 + 20\log_{10}(f) + 20\log_{10}(d)$$

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This is an ideal case. The attenuation is much faster than predicted by inverse square law.

$$P_r \propto d^{-v}$$

Given the power at a reference point then the received power

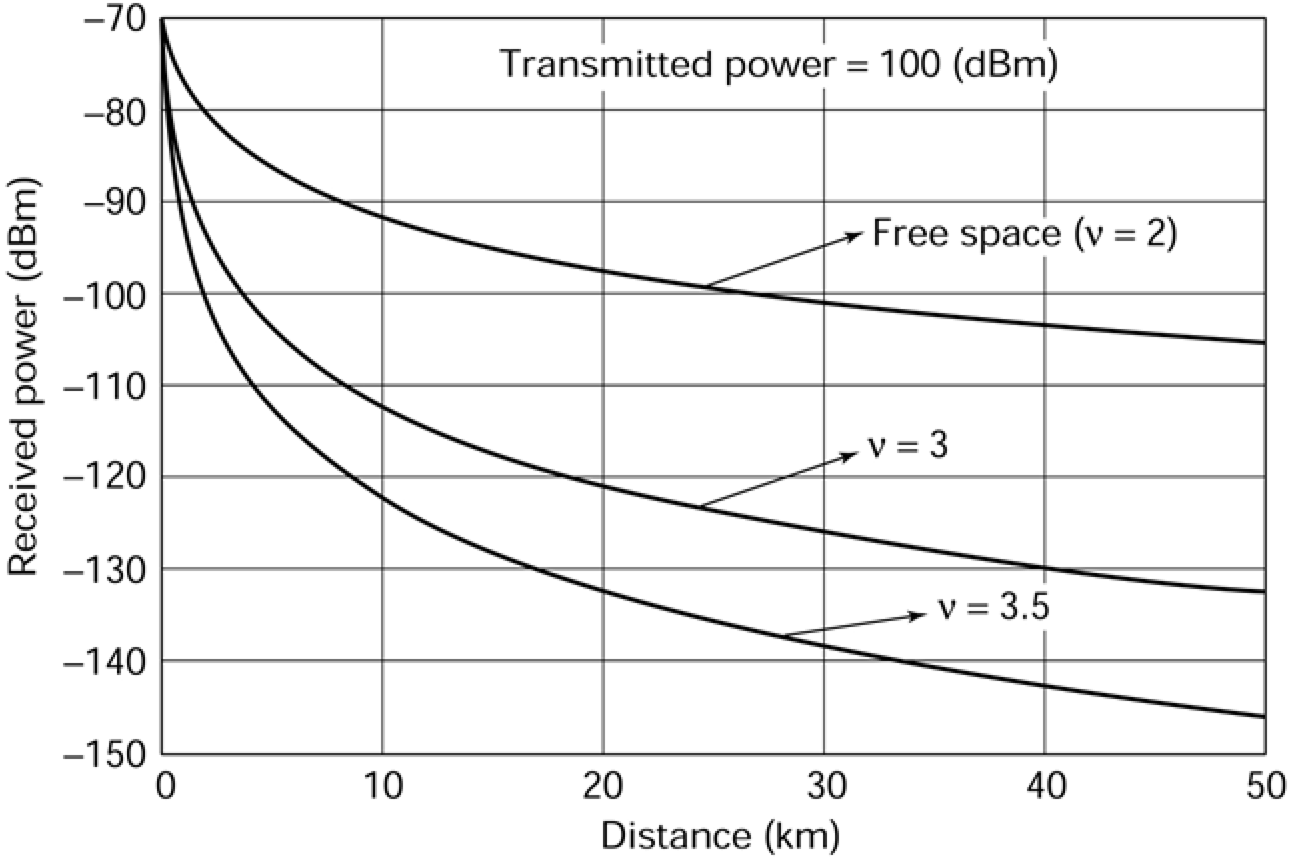
$$P_r(d) = P_r(d_{ref})\left(\frac{d_{ref}}{d}\right)^2$$

If we combine this with the previous equation we obtain

$$P_r(d)dBm = 10\log_{10}\left[P_r(d_{ref})\right] + v\log_{10}\left(\frac{d_{ref}}{d}\right)$$

d_{ref} **this is the reference distance (100m)**

Received power for different values of loss parameter v (v=2 corresponds to free space). Increased loss is seen as v goes up.



Path loss modeling

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Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion

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- Fading
- This is a process that describes the fluctuation of the received signal as it travels to the receiving antenna.
- It can be described in terms of
  - primary cause
    - multi-path or doppler
  - statistical distribution of the received envelop
    - Rican, lognormal or Rayleigh
  - duration of fading
    - long-term/short term, fast/slow □ multipath/shadow

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- Multi-path
- this results from the existence of multiple paths between the transmitter and receiver.
  - The signals arriving will have different phases. The phase of the arriving signals will change rapidly and hence the received signal amplitude will fluctuate. The Rayleigh distribution is used to characterize this type of fading.

$$f(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad r \geq 0$$

  - Random signal amplitude, r

- Rician Distribution
- If with the signals arriving there is a strong LOS component then the Rician distribution is used to described it.

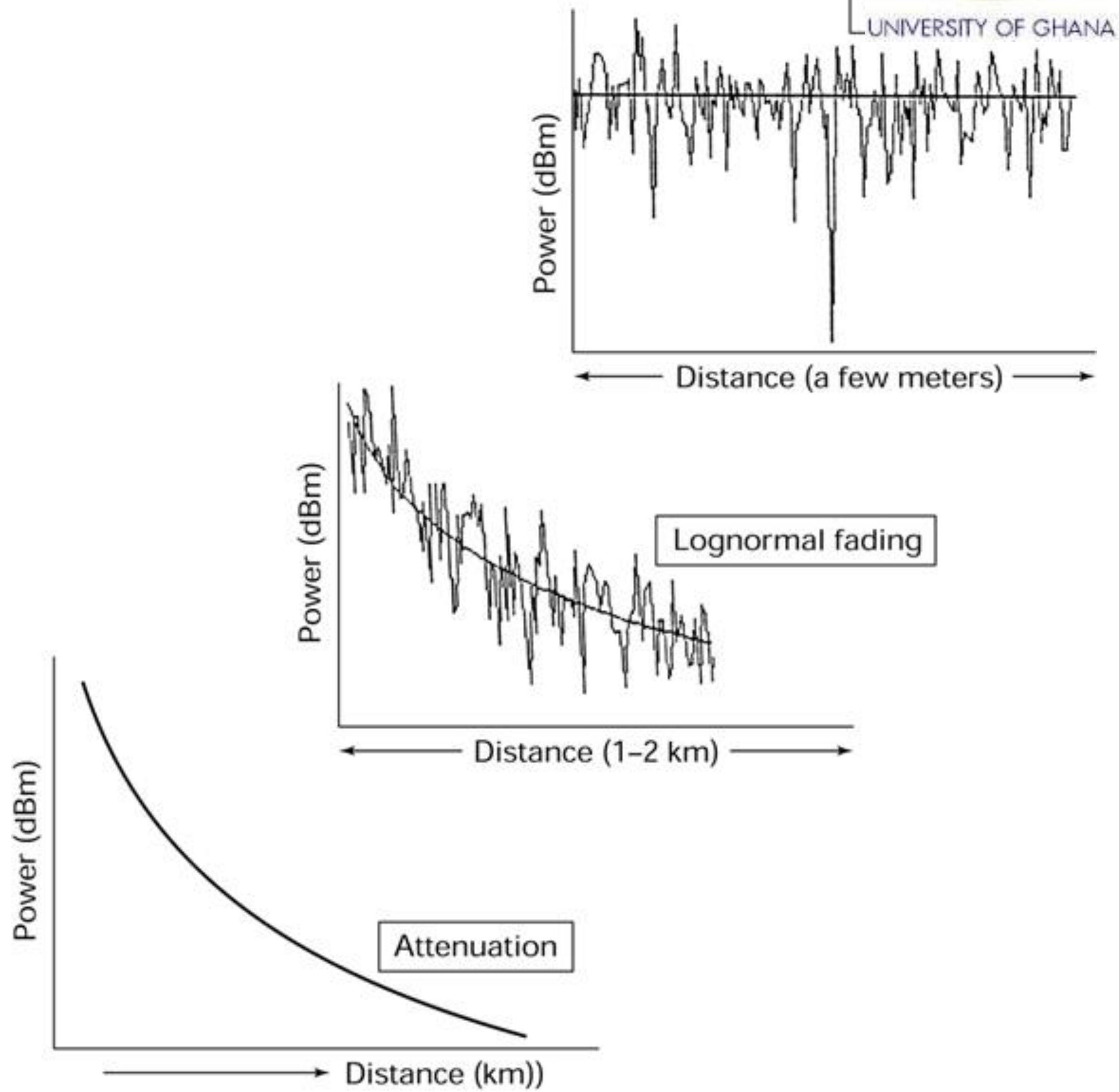
$$f_{rician}(r) = \frac{r}{\sigma^2}\exp\left(-\frac{(r^2+K^2)}{2\sigma^2}\right)I_o\left(\frac{Kr}{\sigma^2}\right) \quad r \geq 0 \; K \geq 0$$

- K is a factor that determines how strong the LOS component is.

- Lognormal Distribution
- This is the random shadowing effects that occur over a large number of measurement locations. It is also known as shadow fading or slow fading. Shadow because the fluctuation is caused by blockage of signal by buildings.
- Slow because the fluctuations are much slower with distance than that caused by another phenomenon also multi-path.

$$f_{LN}(r) = \frac{r}{\sqrt{2\pi}\sigma x} \exp\left(- \frac{(\ln x - \mu^{2}}{2\sigma^{2}} \right)$$

Power loss showing the three major effects: attenuation, long-term fading, and short-term fading.



- It is important to know for how long a signal will be below a specified value (duration of fade)
- how often it crosses a threshold value (fading rate).
- These factors are important for the design of efficient coding schemes.

Doppler shift

- For a mobile user, motion will result in frequency shift of signal being received. This is called Doppler shift, f_d

$$f_d = f_o \frac{v}{c} \cos\theta$$

Pulse duration

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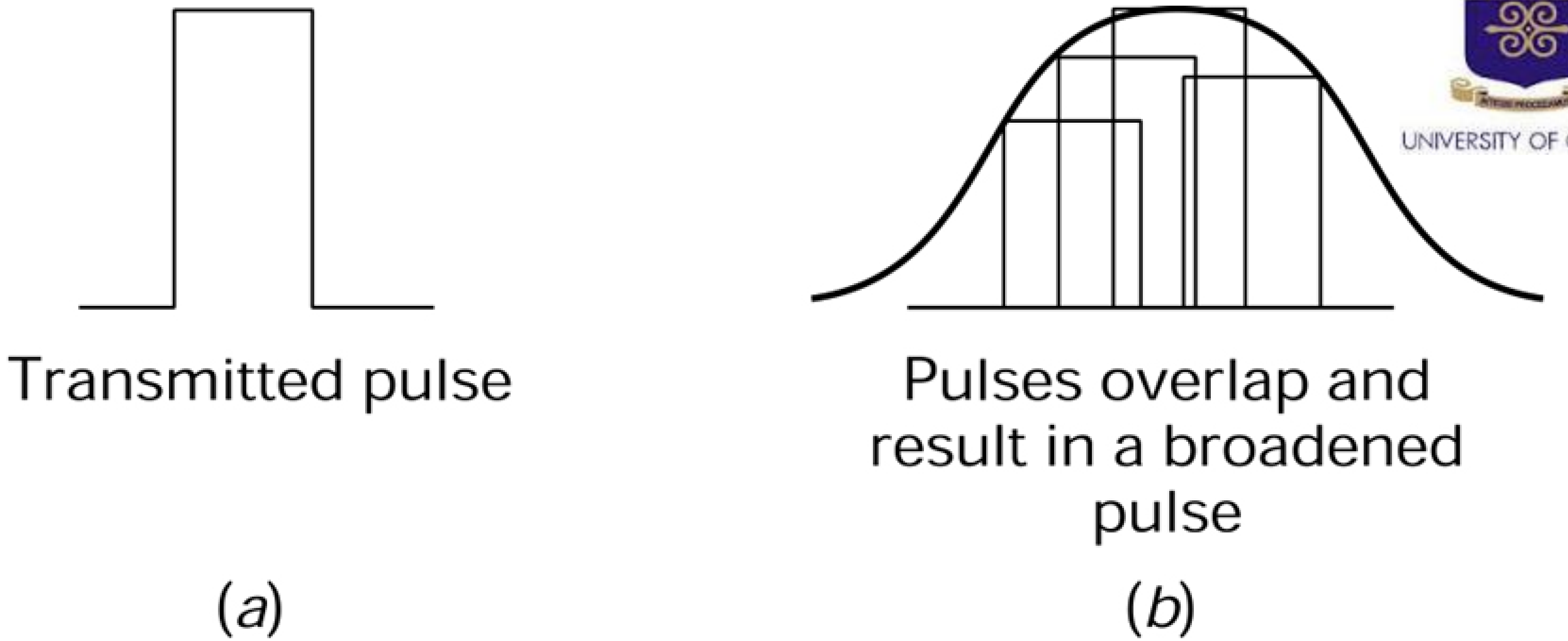
- The duration of the pulse is an important factor.
  - If the duration of the pulse is very short, then changes introduced by motion will be slow and have no impact on the received signal
  - for large duration pulse, fast changes will be introduced as a result of motion and will thus affect transmission.
- Slow versus fast fading can be expressed in terms of the coherence time

$$T_c = \frac{9}{16\pi f_d}$$



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(a) A transmitted pulse. (b) The multiple pulses produced due to the multipath arriving at different times and with different powers, leading to a broadened envelope of the pulse.

The Effects of Multipath Propagati

- Multiple copies of a signal may arrive at different phases
  - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit.
  - The most common methods in reducing it are use of guard time, pulse shaping, signal coding and equalisation

Example:

- BS has a 900 MHz transmitter and a receiver is moving at the speed of 30 mph. Calculate the frequency of the received carrier and the coherence time if the vehicle is moving
  - i) directly toward the BS.
  - Ii) directly away from the BS

Loss Prediction Models

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A number of models have been proposed to predict the median loss. These models take into account the different ways in which the signal can reach the receiver. Two widely used models are:

Okumura-Hata Model

COST 231 Model

Loss Prediction Models

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Okumura-Hata Model : It is possible to calculate the

free space loss between any two points based on empirical formula derived from experimental data for an urban area with correction factors then added for

Antenna height

- suburban, quasi-open or open space or hilly terrain
- Diffraction loss due to mountains
- Sea or lake areas
- Road slope

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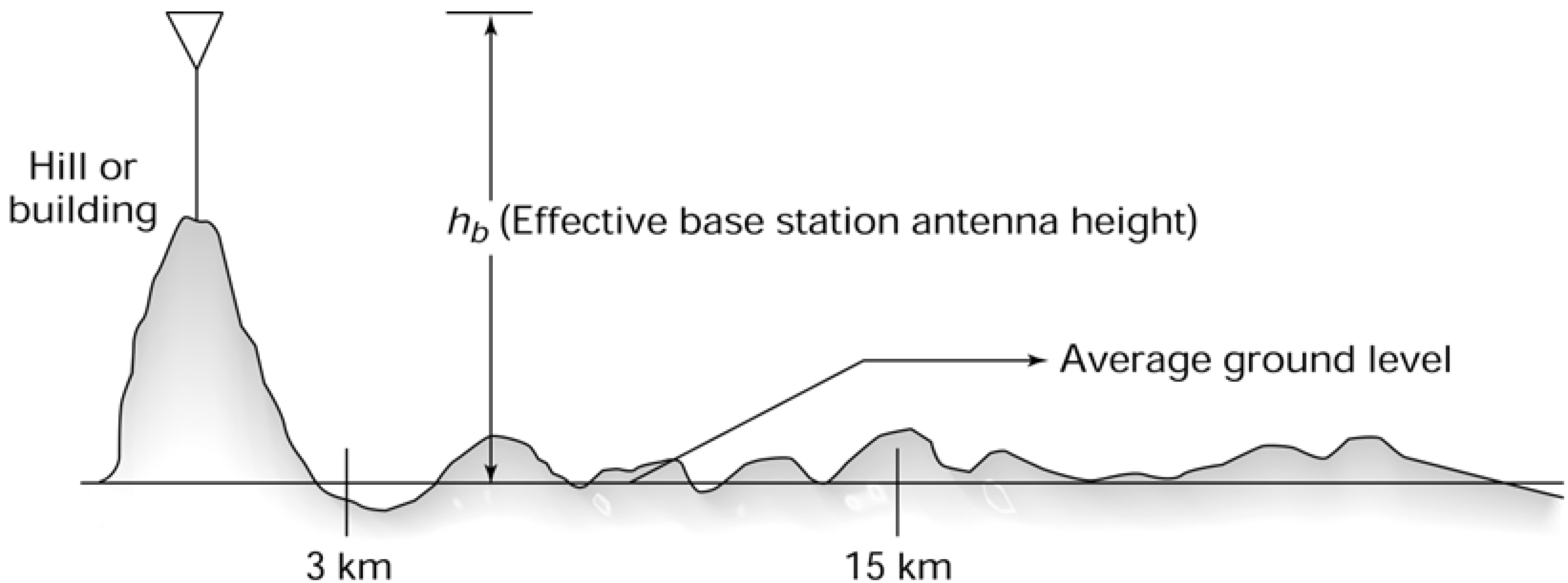
The effective height of the BS antenna.



The loss is given in terms of effective heights

The median path loss in urban areas for the Okumura-Hata Model is

$$L_p(dB) = 69.55 + 26.16\log_{10}(f_o) + (44.9 - 6.55\log_{10} h_b)\log_{10} d$$
$$-13.82\log_{10} h_b - a(h_{mu})$$

Correction Factors are as follows

Large cities

$$a(h_{mu}) = 3.2[\log_{10}(11.75h_{mu})]^2 - 4.97 \quad (f_o \geq 400\text{MHz})$$

Small and Medium Cities

$$a(h_{mu}) = [1.1\log_{10}(f_o) - 0.7]h_{mu} - [1.56\log_{10}(f_o) - 0.8]$$

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Median Loss in Suburban areas

$$L_{sub}(dB) = L_p - 2\left[\log_{10}(f_o/28)\right]^2 - 5.4$$

where Lp is the loss in small to medium cities

Median loss in Rural areas

$$L_{sub}(dB) = L_p - 4.78\left[\log_{10}(f_o)\right]^2 + 18.33 - 5.4\log_{10}(f_o) - 40.94$$

- Where f_o
  - carrier frequency
  - d distance between base station and mobile (km)
  - h_b base station antenna height
  - h_{mu} mobile unit antenna height
- the model is valid for the ff parameter range

$$150 \le f_o \le 1500 MHz$$

$$30 \le h_b \le 200m$$

$$1 \le h_{mu} \le 10m$$

$$1 \le d \le 20km$$

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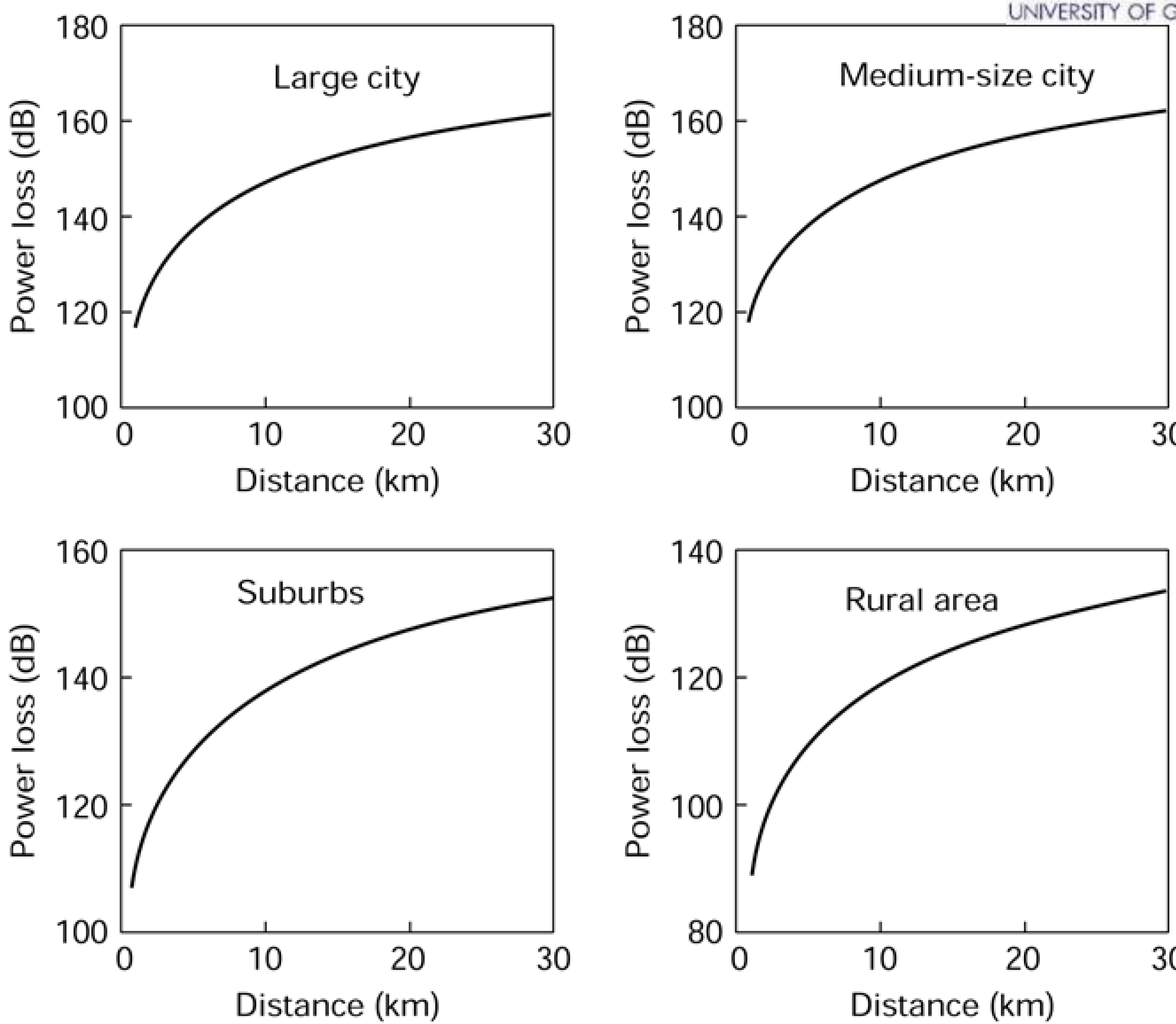
Loss calculations based on the Hata model for four different environments. Carrier frequency = 900 MHz, base station antenna height = 150 m, MU antenna height = 1.5m.



COST 231 Model

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- It is a combination of empirical and deterministic models for estimating path loss in urban area over frequency range of 800-2000MHz. The model is used in Europe for the GSM1800 system

$$L_p = L_f + L_{rts} + L_{ms}$$

or

$$L_p = L_f \quad \text{when} \quad L_{rts} + L_{ms} \leq 0$$

where

L_f free space loss

L_{rts} rooftop - street diffraction and scatter loss

L_{ms} multiscreen loss

COST 231 Model

- The rooftop-to-street loss is given as

$$L_{rts} = \text{-}16.9\text{-}10\log W + 10\log f_o + 20\log \Delta h_m + L_o$$

$where\, W$ is the street width (m)

$$\Delta h_m = h_r \text{ - } h_m (m)$$

$$L_o = -9.646 dB \quad 0 \le \phi \le 35^{\circ}$$

$$L_o = 2.5 + 0.075(\phi - 35) dB \quad 35 \le \phi \le 55^{\circ}$$

$$L_o = 4 + 0.114(\phi - 55) dB \quad 55 \le \phi \le 90^{\circ}$$

ϕ is the incident angle relative to the street

COST 231 Model

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- The multiscreen (multiscatter) loss is given as

$$L_{ms} = L_{bsh} + k_a + k_d \log d + k_f \log f_o - 9\log b$$

$$where\ b \text{ is the distance between buildings along radio path (m)}$$

$$L_{bsh} = -18\log 11 + \Delta h_b \quad h_b > h_r$$

$$L_{bsh} = 0 \quad h_b < h_r$$

$$k_a = 54 \quad h_b > h_r$$

$$k_a = 54 - 0.8h_b \quad \text{d} \geq 500\text{m}; h_b \leq h_r$$

$$k_a = 54 - 1.6\Delta h_b \text{d} \quad \text{d} < 500\text{m}; h_b \leq h_r$$

COST 231 Model

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$$k_d = 18 \quad h_b < h_r$$

$$k_a = 18 - \frac{15\Delta h_b}{\Delta h_m} \quad h_b \geq h_r$$

$$k_f = 4 + 0.7\left(\frac{f_c}{925} - 1\right) \text{ for midsize cities and suburban}$$

$$k_f = 4 + 1.5\left(\frac{f_c}{925} - 1\right) \text{ for metropolitan areas}$$

Indoor Models

- Extra Large Zone
  - There is a single base station outside the building which handles all traffic. Ideal for a region with a number of small offices and shops
- Large Zone
  - Ideal for large building with low population density. A single base station housed with the building is used.
- Middle Zone
  - The building is large and heavily populated eg shopping mall. A number of base stations housed within the building are used.
- Small Zone and Microzone
  - Building with many partitions material properties of wall will determine signal penetration. Each room should have its own base station

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The Finite Element Method

$$\nabla^2 \mathbf{E} + \omega^2 \mu\varepsilon \mathbf{E} = 0$$

$$\nabla^2 \mathbf{H} + \omega^2 \mu\varepsilon \mathbf{H} = 0$$

The Finite Element Method

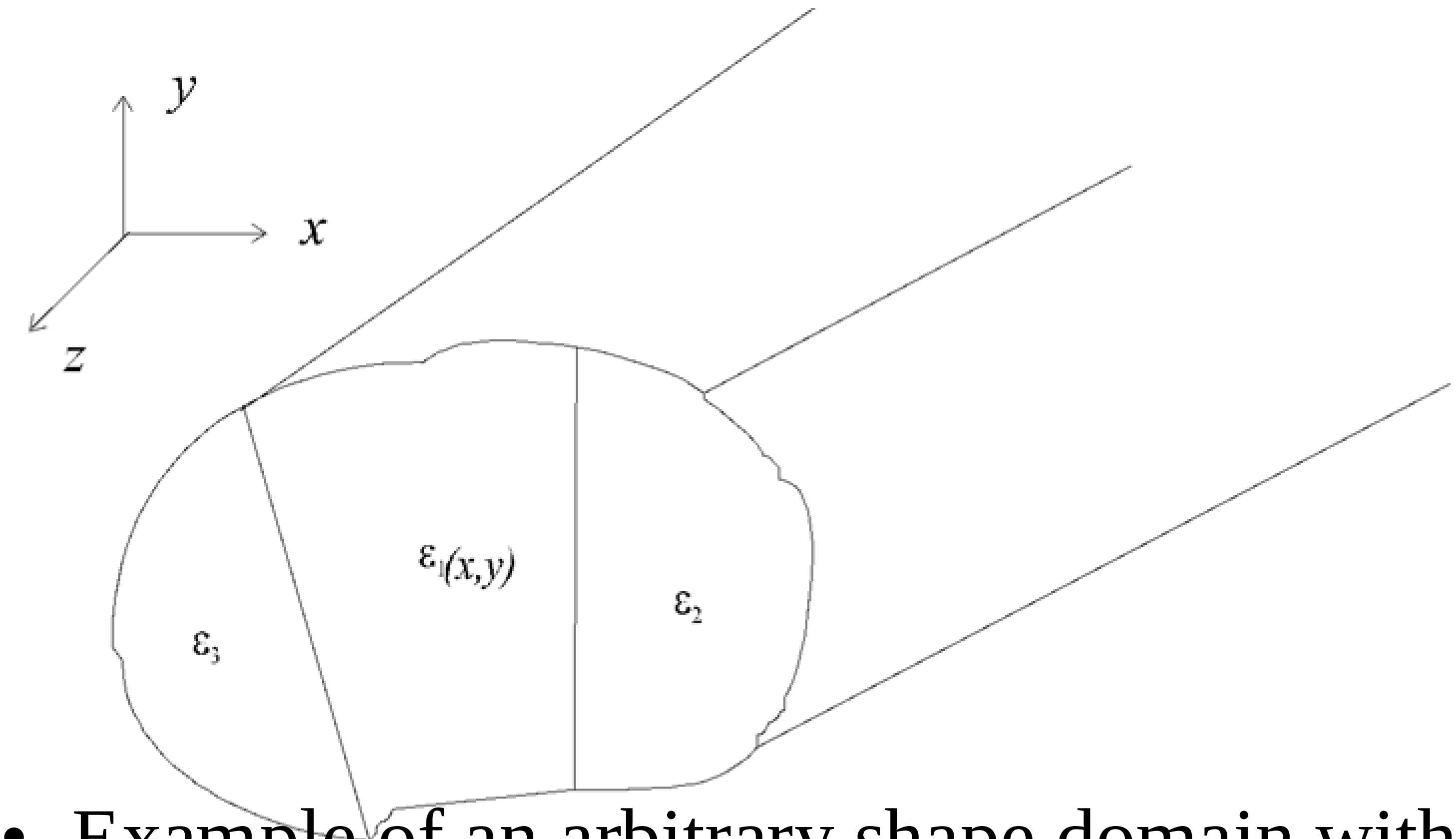
- Find the variational integral whose first variation is zero for the given boundary conditions.
- Choose an appropriate trial function and expand the field components as a sum of the trial functions.
- Substitute the trial fields in the variational integral and find the first variation and equate it to zero
- The resulting simultaneous equations from the weak formulation of the boundary value problem are equivalent to a standard eigenvalue matrix equation of the form $Ax - \lambda x = 0$

The Finite Element Method

- **Basic Concepts in the finite element method**
- In the finite element method, the key ideas are the

  discretization of the region of interest into elements
- and
- using interpolating polynomials to describe the variation of the field within each of the elements

The Finite Element Method

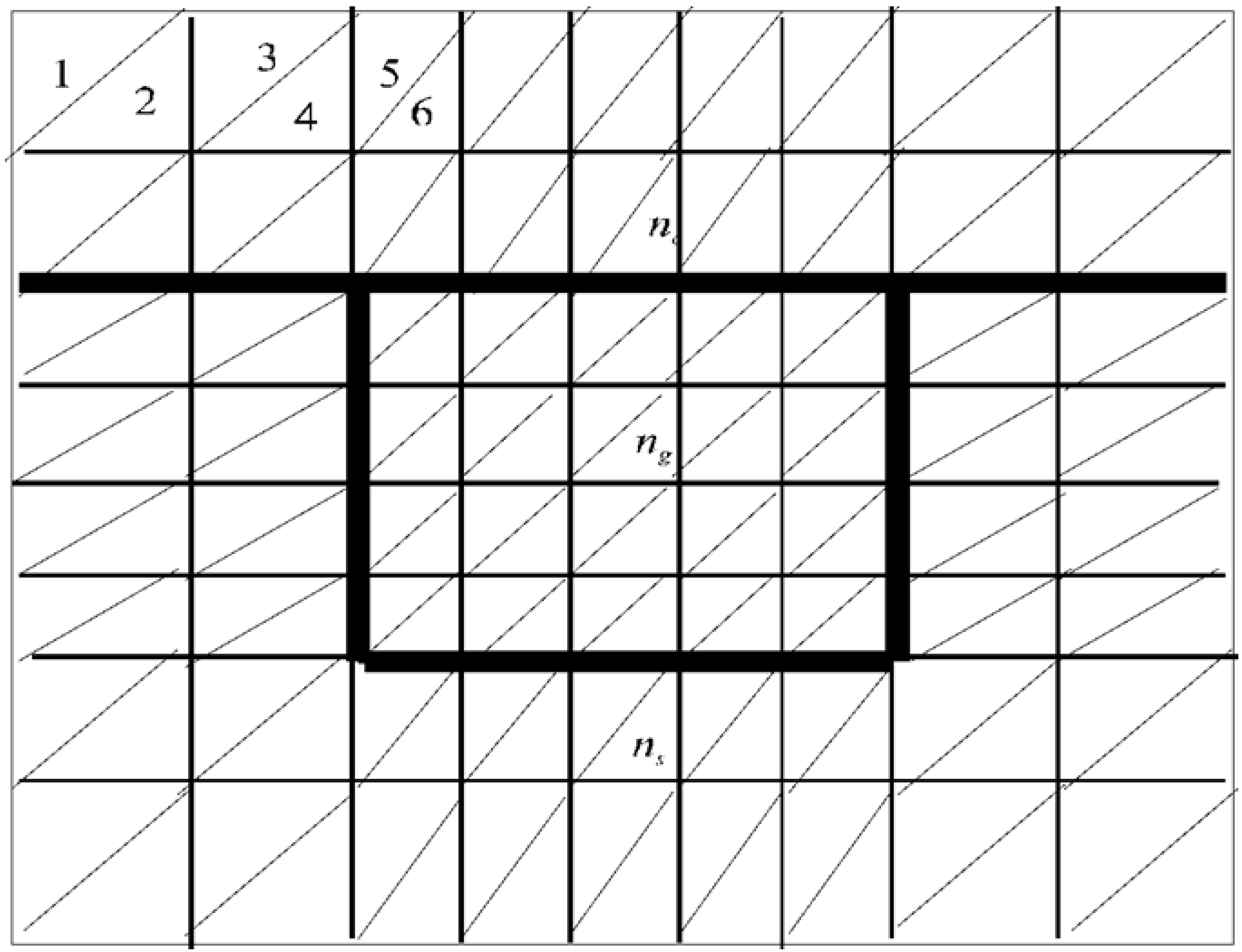


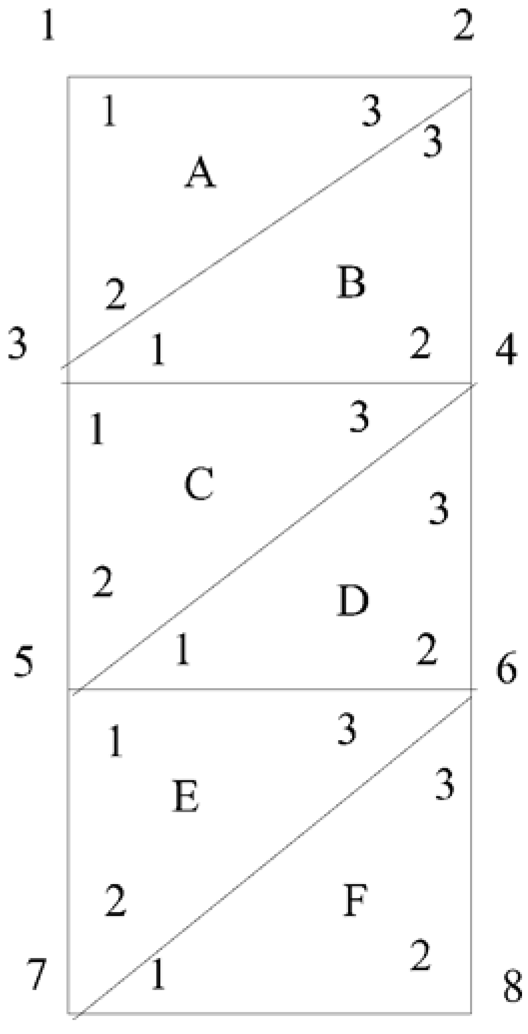
- Example of an arbitrary shape domain with several regions of different material types

The Finite Element Method

- **Steps involved in the finite element analysis**
- discretize the domain under investigation into sub-domains or elements.
- The functionals for which the variational principle should be applied for the elements are then derived
- assemble all the element contributions to form a global matrix.
- solve the system of equations that is obtained, in this case a matrix equation

The Finite Element Method





The Finite Element Method

The Finite Element Method

$$\mathrm{A}x - \lambda \mathrm{B}x = 0$$

$$B_e = \int_{\Delta} [N]^* \cdot [N] \, d\Omega$$

$$\varepsilon = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$

$$A_e = \int [Q]^* \hat{\varepsilon}^{-1} \cdot [Q] \, d\Omega$$

FEM in Wireless Propagation

$$j2k_o n_o \frac{\partial \phi}{\partial z} = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + k_o^2 \left(n^2 - n_o^2\right)\phi$$

$$-\mathrm{j}2\beta[\mathrm{B}]\frac{\partial\{\phi\}}{\partial \mathrm{z}} + \left([\mathrm{A}] - \beta^2[\mathrm{B}]\right)\{\phi\} = 0$$

$$[\mathrm{A}] = \sum_e \iint \left[k_o^2 n^2 \{N\}\{N\}^T - \{N_x\}\{N_x\}^T\right] dxdy$$

$$[\mathrm{B}] = \sum_e \iint \left[k_o^2 n^2 \{N\}\{N\}^T\right] dxdy$$

FEM in Wireless Propagation

- Solution Methods
- **Forward Difference Scheme**

$$\frac{\partial \phi}{\partial z} = \frac{\phi^{k+1} - \phi^{k}}{\Delta z}$$

$$\frac{j2k_o n_o}{\Delta z}\left(\phi^{k+1} - \phi^{k}\right) = \frac{\partial^2 \phi^k}{\partial x^2} + \frac{\partial^2 \phi^k}{\partial y^2} + k_o^2\left(n^2 - n_o^2\right)\phi^k$$

$$\phi^{k+1} = \mathrm{A}\phi^{k}$$

FEM in Wireless Propagation

- **The Crank-Nicolson Method**

$$\frac{\partial \phi}{\partial z} = \frac{\phi^{k+1} - \phi^{k-1}}{2\Delta z}$$

FEM in Wireless Propagation

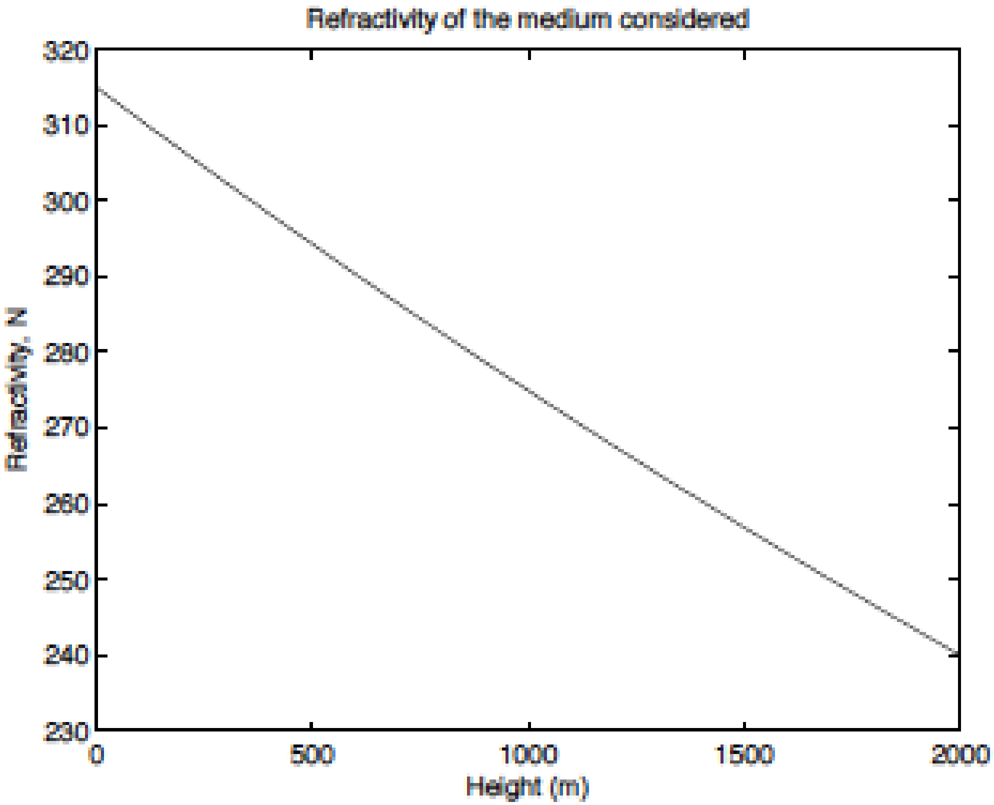
- **The Crank-Nicolson Method**

$$\frac{j2k_o n_o}{\Delta z}\left(\phi^{k+1}-\phi^{k}\right)=\left(\frac{\partial^2\phi^k}{\partial x^2}+\frac{\partial^2\phi^k}{\partial y^2}+k_o^2\left(n^2-n_o^2\right)\phi^k\right)\Bigg|_{z=(k+0.5)\Delta z}$$

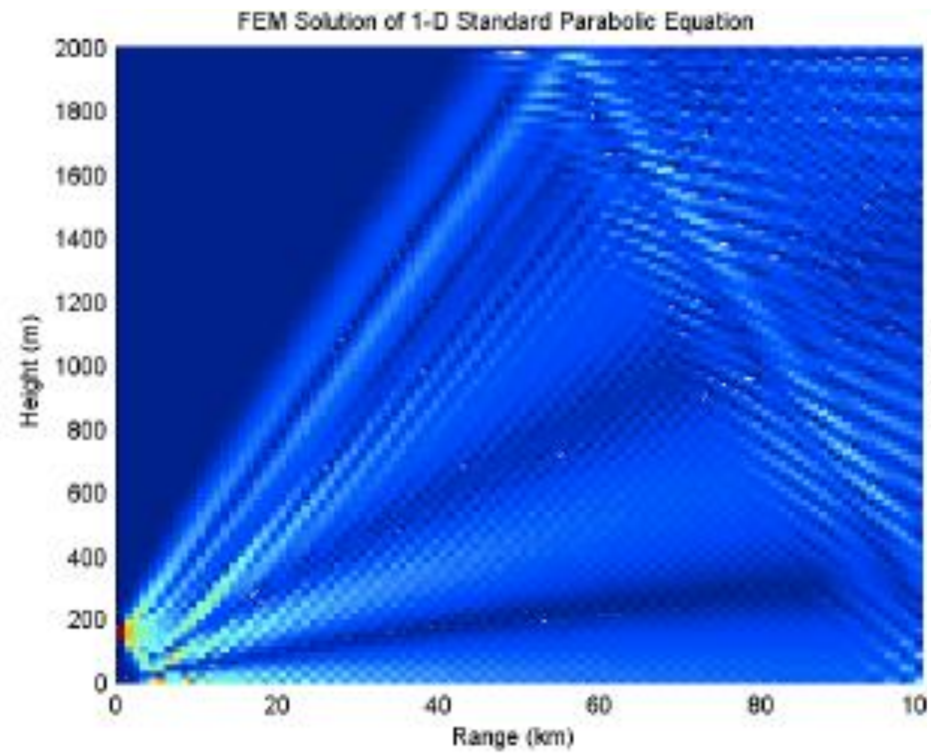
$$\phi^{(k+0.5)}=\frac{\phi^{k+1}+\phi^{k}}{2}$$

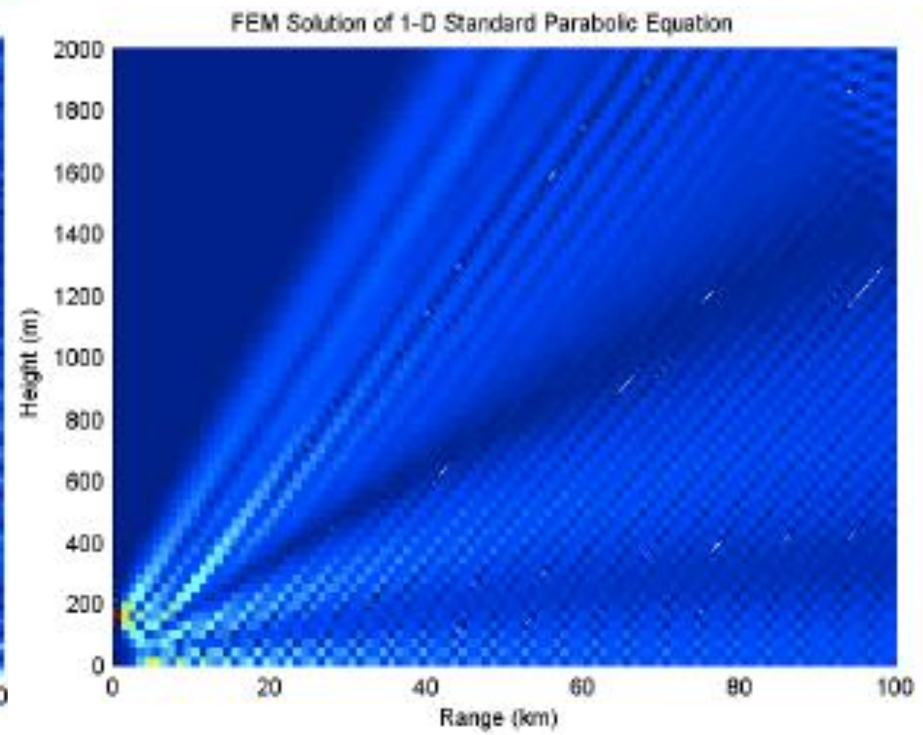
FEM in Tropospheric Propagation

- Antenna height 150m
- Beamwidth k_f=11
- Vertically polarized wave
- Simple boundary condition at upper level

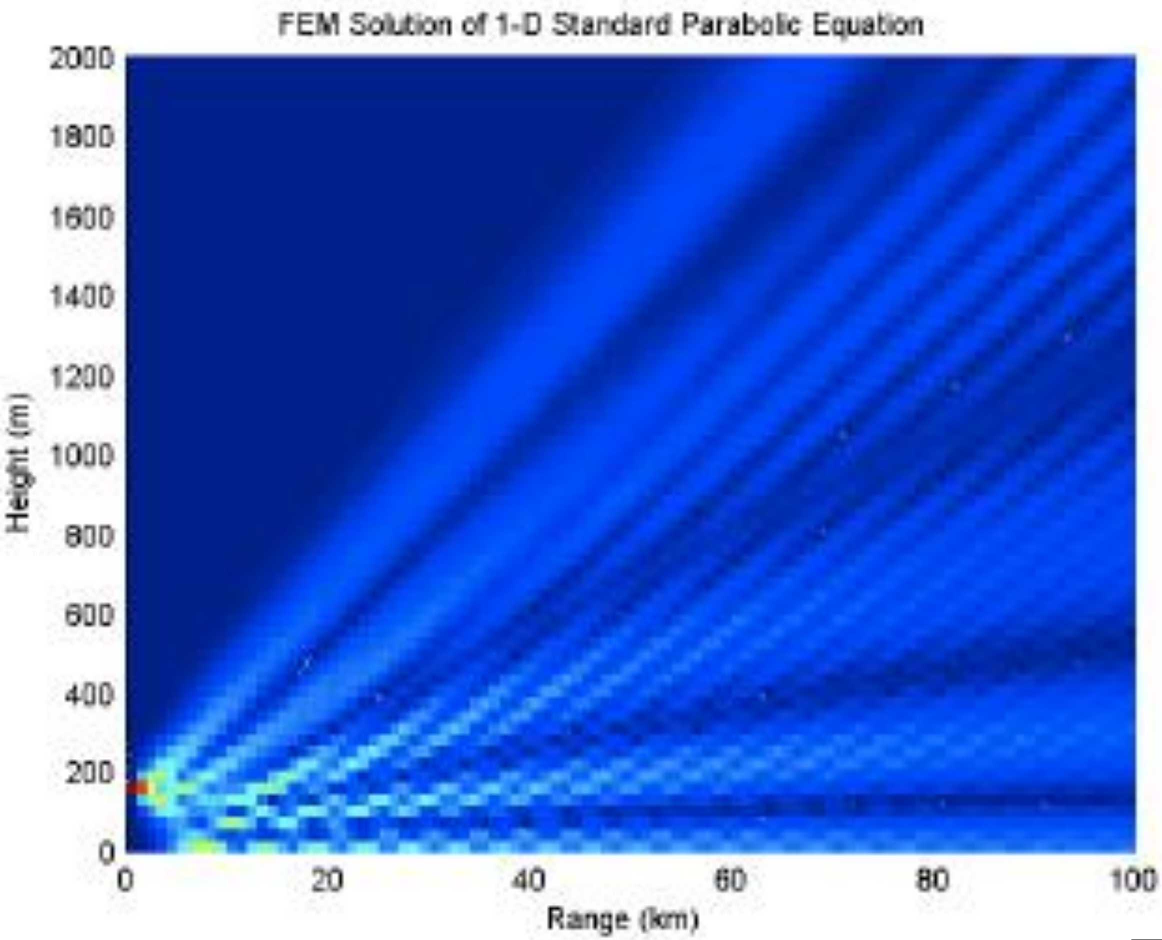


FEM in Tropospheric Propagation



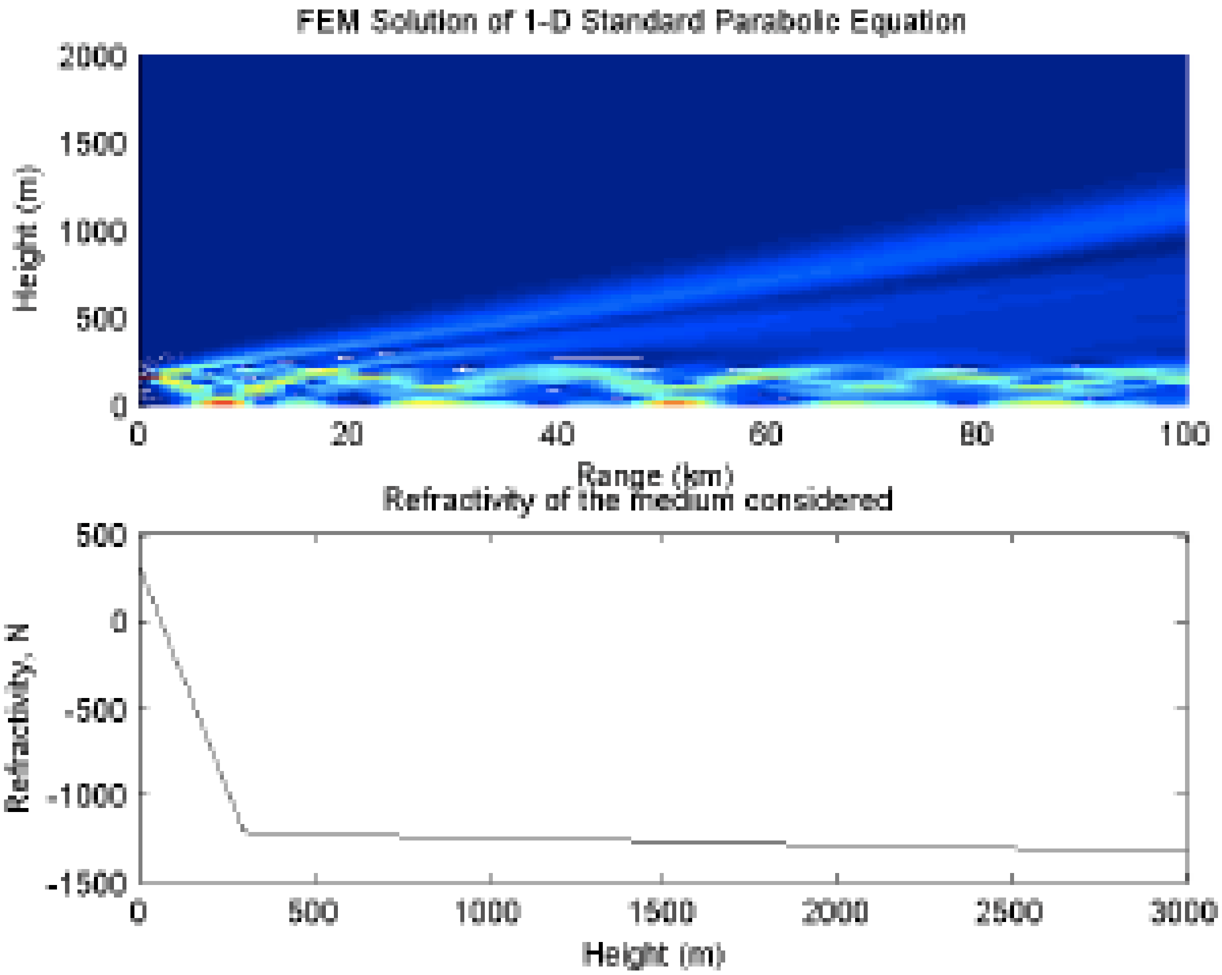


- Without Boundary Condition With Boundary Condition

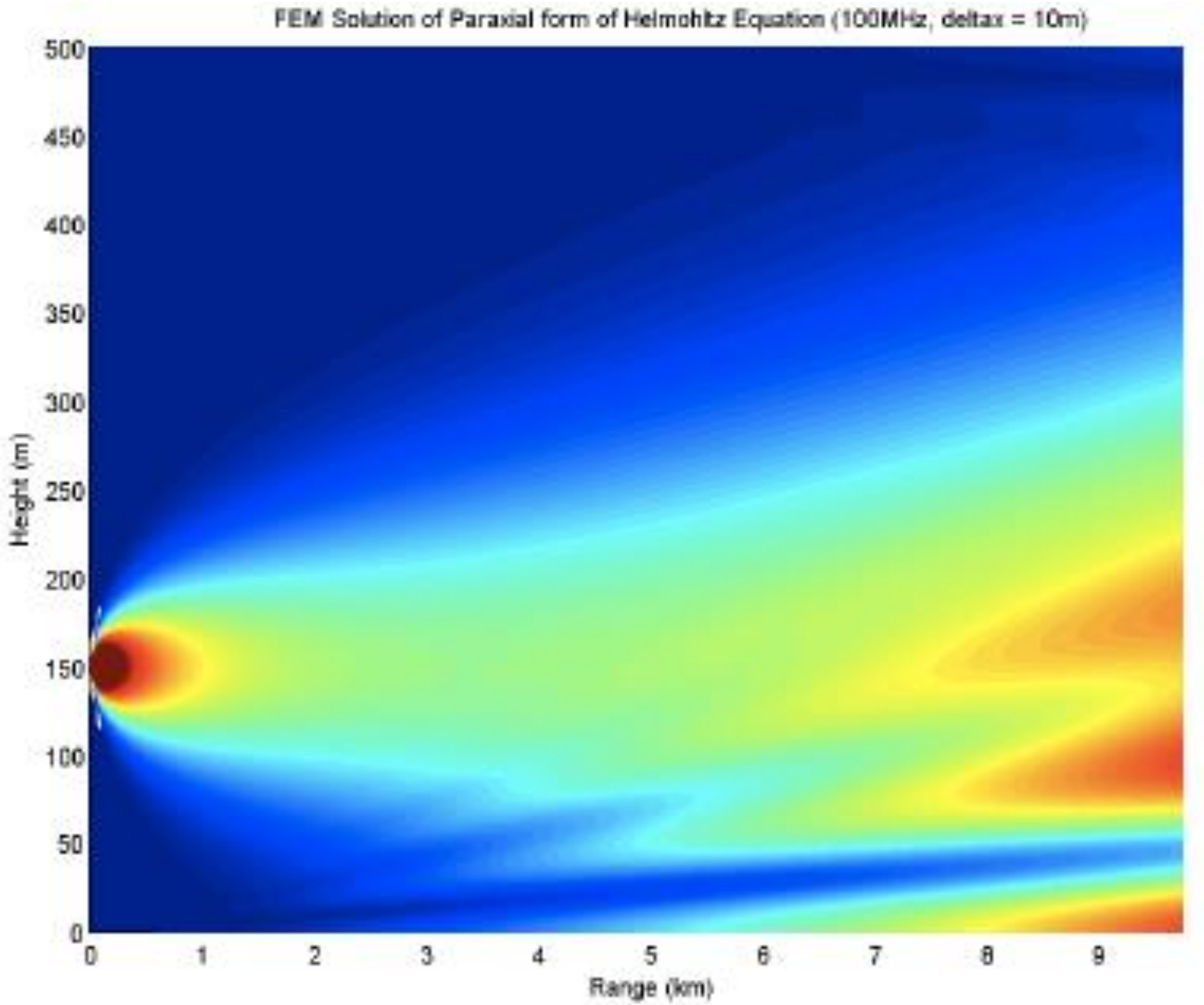


- Frequency of 200MHz

FEM in Tropospheric Propagation

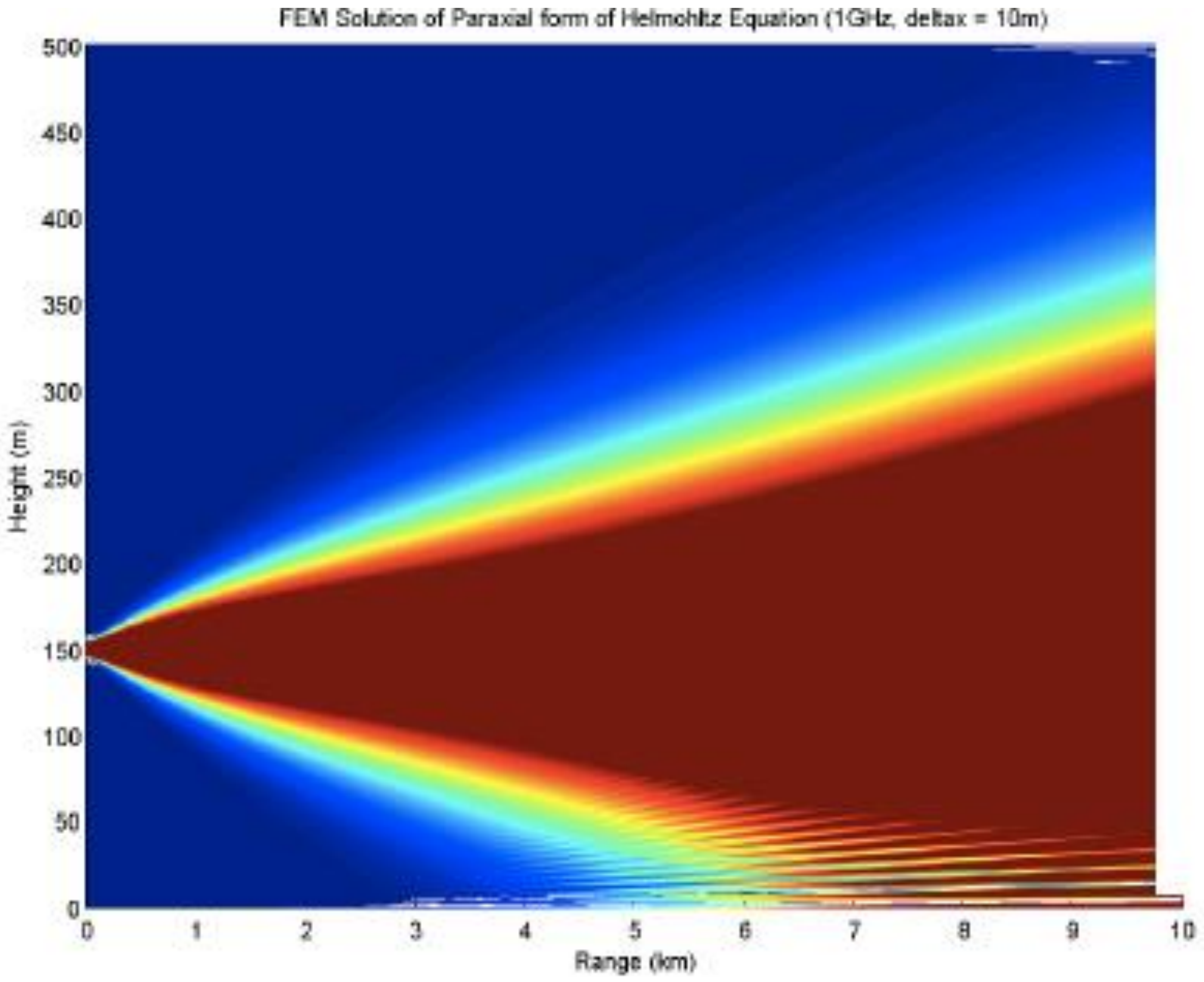


FEM in Tropospheric Propagation



100MHz

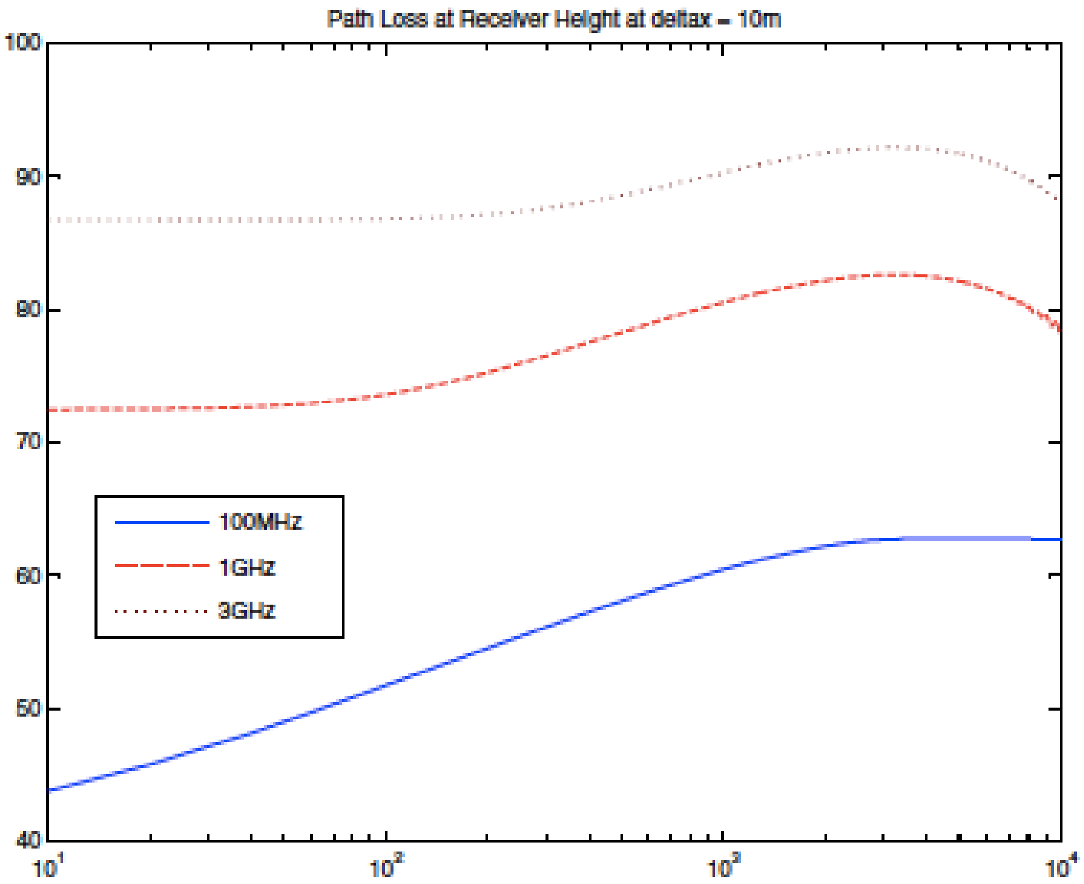
Paraxial form of
Helmholtz Equation

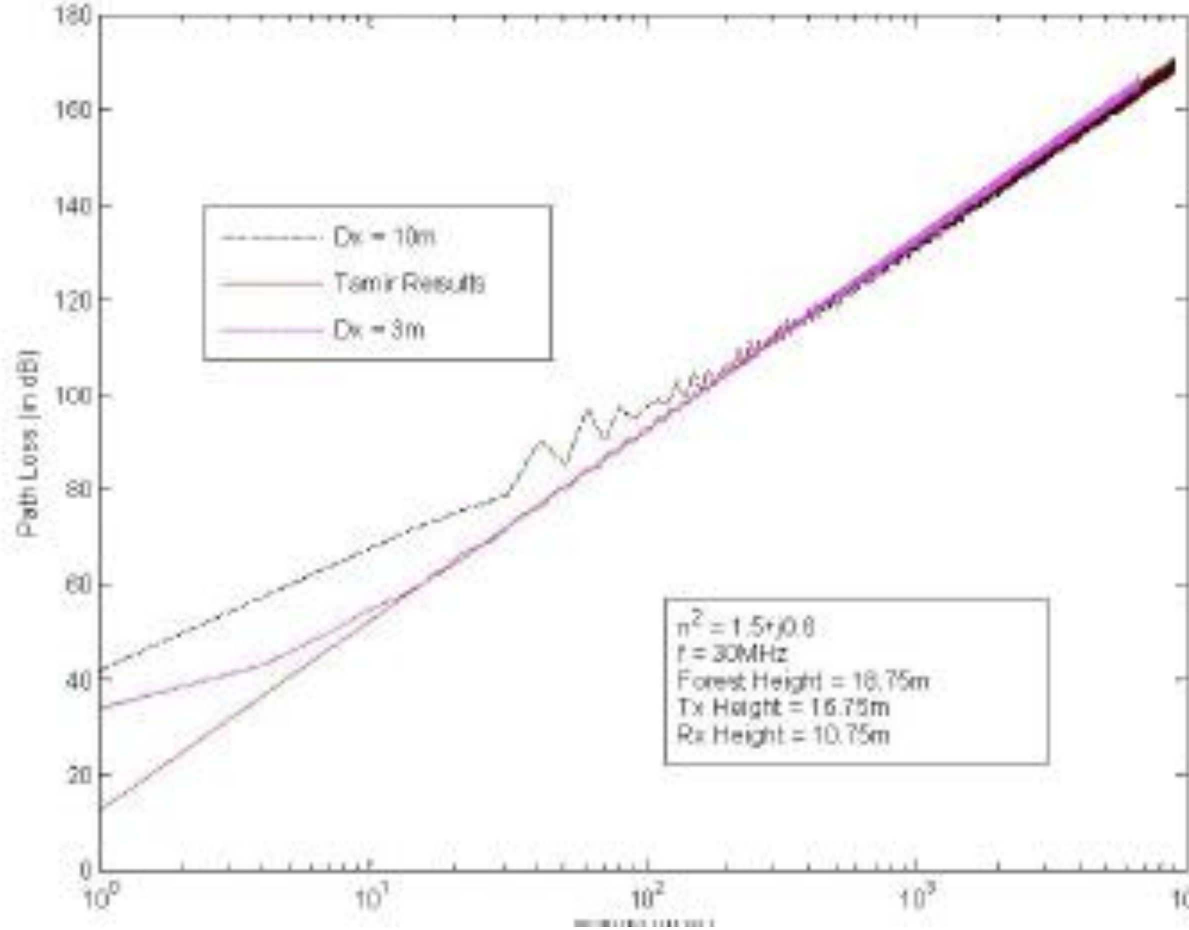


1GHz

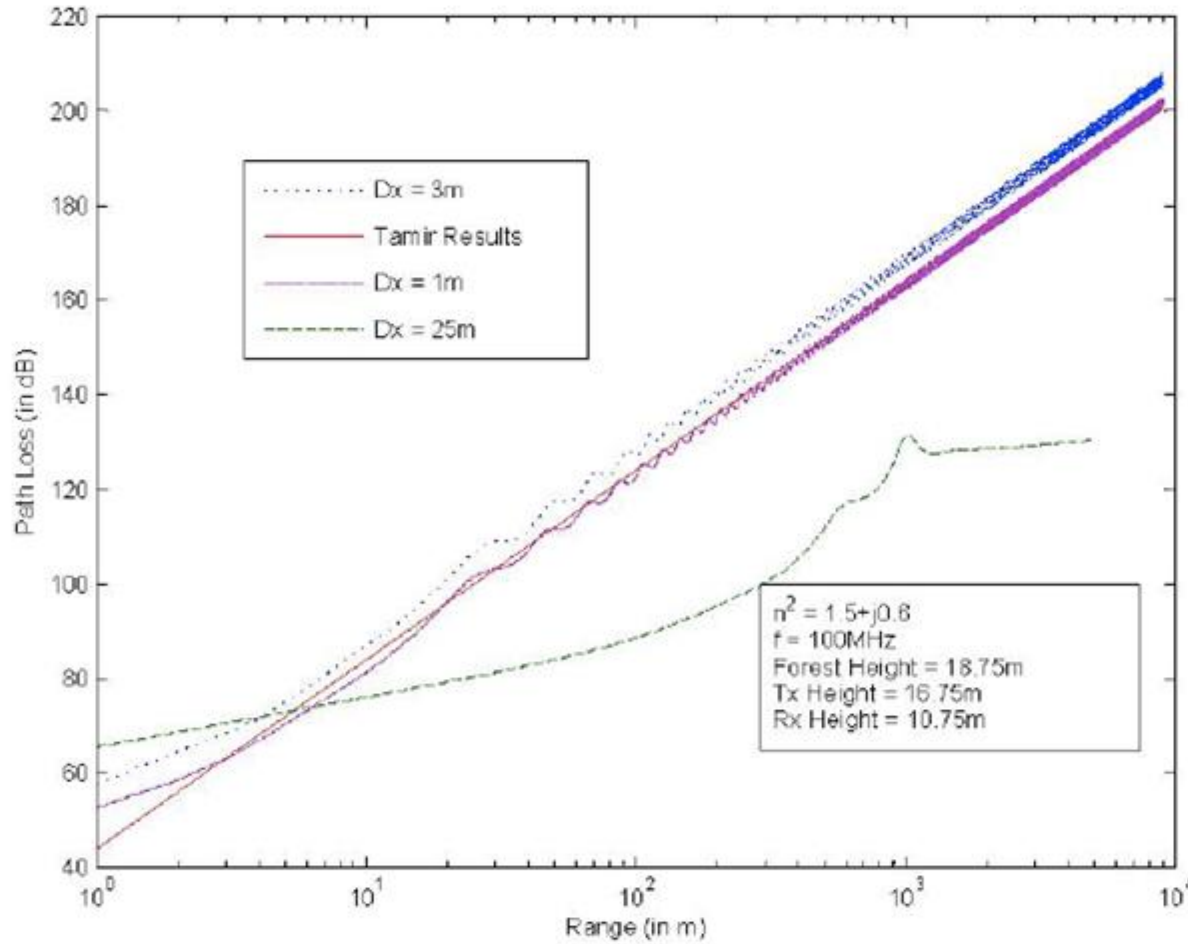
Paraxial form of
Helmholtz Equation

Path Loss at different frequencies

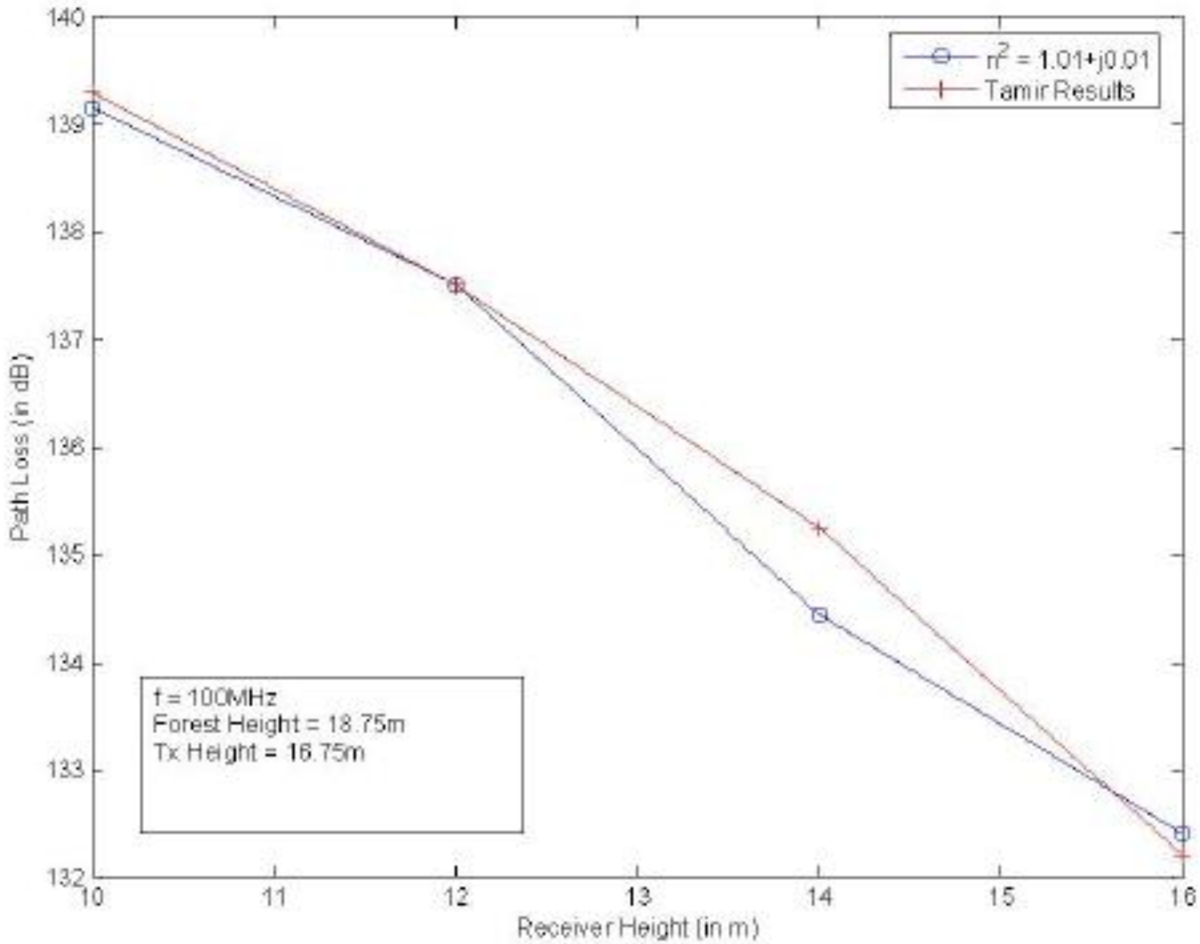




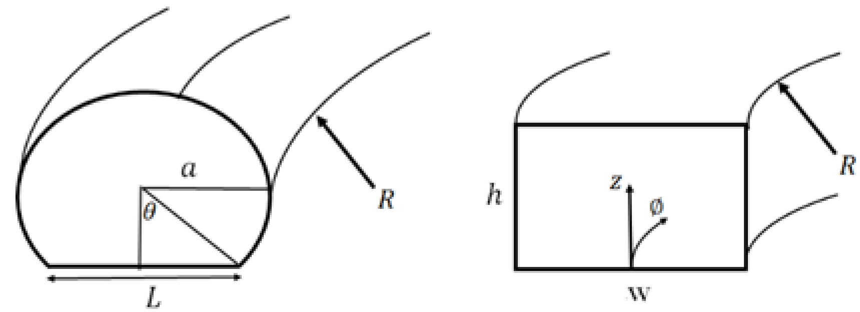
Path Loss (in dB)
Dx = 10m
Tamir Results
Dx = 3m
n^2 = 1.5+j0.8
f = 30MHz
Forest Height = 16.75m
Tx Height = 16.75m
Rx Height = 10.75m
180
160
140
120
100
80
60
40
20
0
10^0
10^1
10^2
10^3
10^4



220
200
180
160
140
120
100
80
60
40
Path Loss (in dB)
10^0
10^1
10^2
10^3
10^4
Range (in m)
Dx = 3m
Tamir Results
Dx = 1m
Dx = 25m
n^2 = 1.5+j0.6
f = 100MHz
Forest Height = 18.75m
Tx Height = 16.75m
Rx Height = 10.75m



140
139
138
137
136
135
134
133
132
10
11
12
13
14
15
16
Path Loss (in dB)
Receiver Height (in m)
n2 = 1.01+j0.01
Tamir Results
f = 100MHz
Forest Height = 18.75m
Tx Height = 16.75m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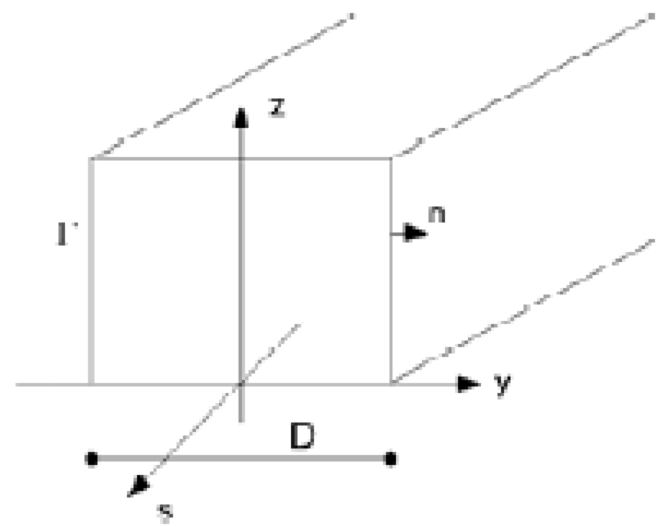
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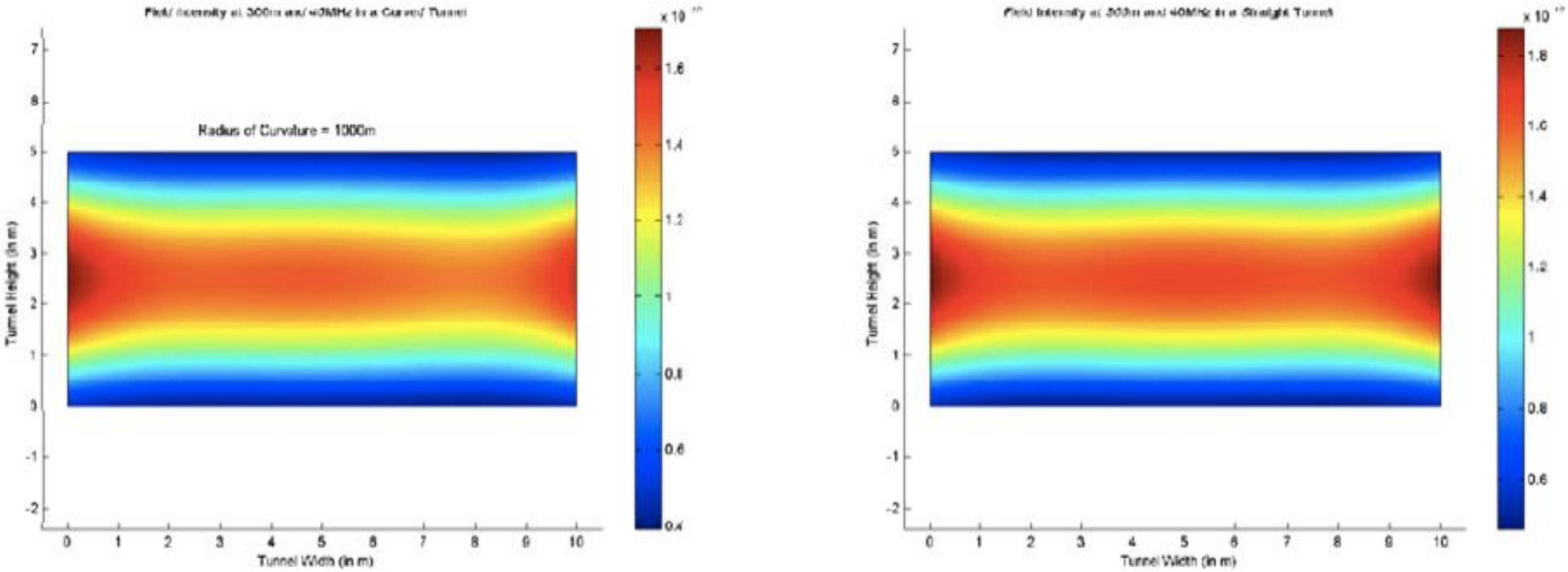
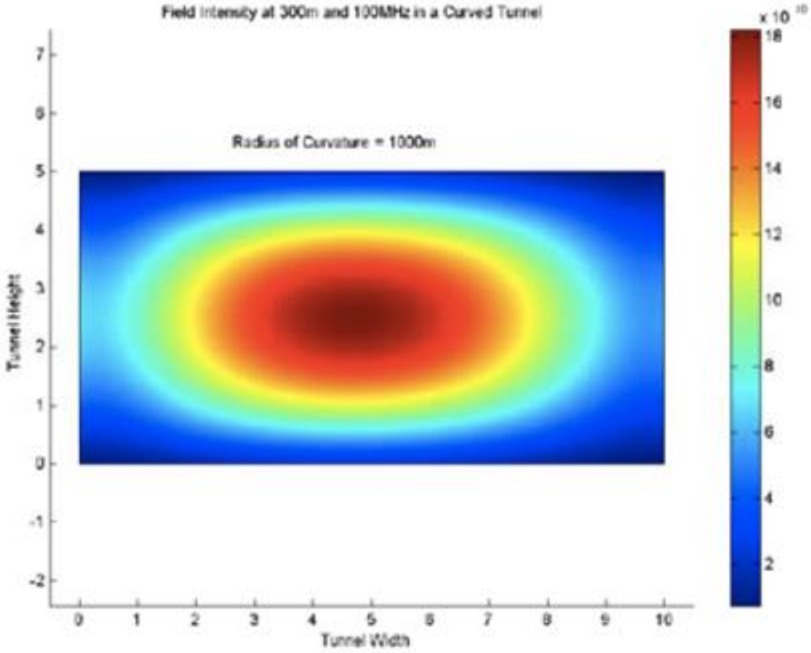


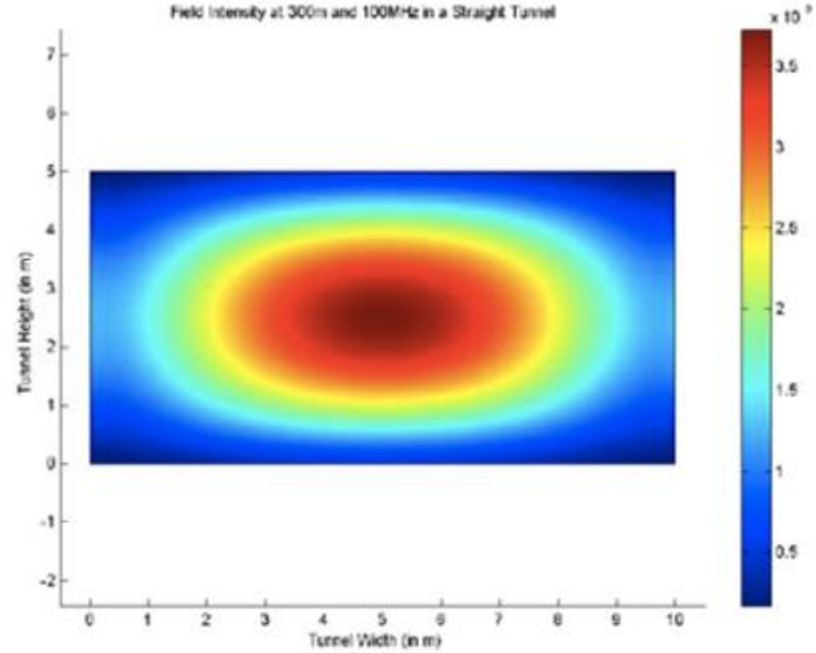
(a) Curved Tunnel

(b) Straight Tunnel

Signal Intensity at Tunnel end 40MHz

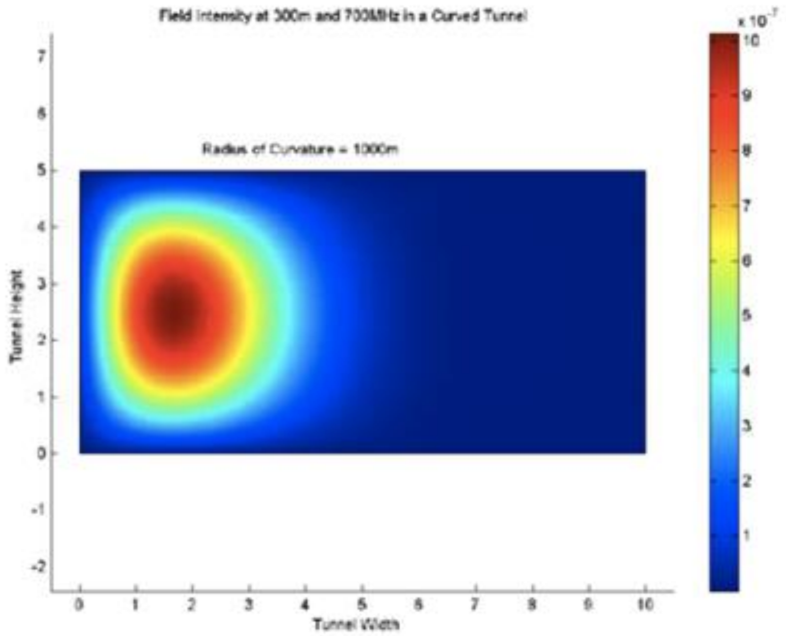


(a) Curved Tunnel

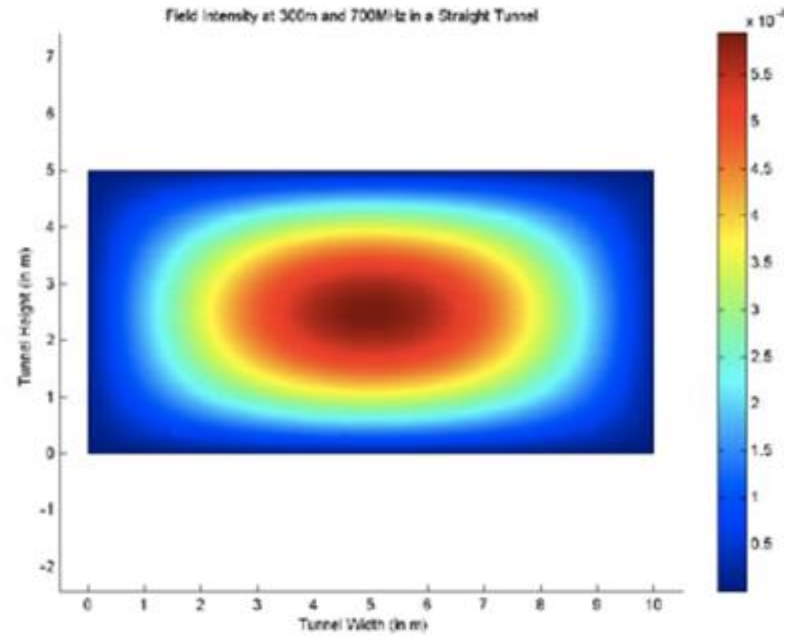


(b) Straight Tunnel

Signal Intensity at Tunnel end 100MHz

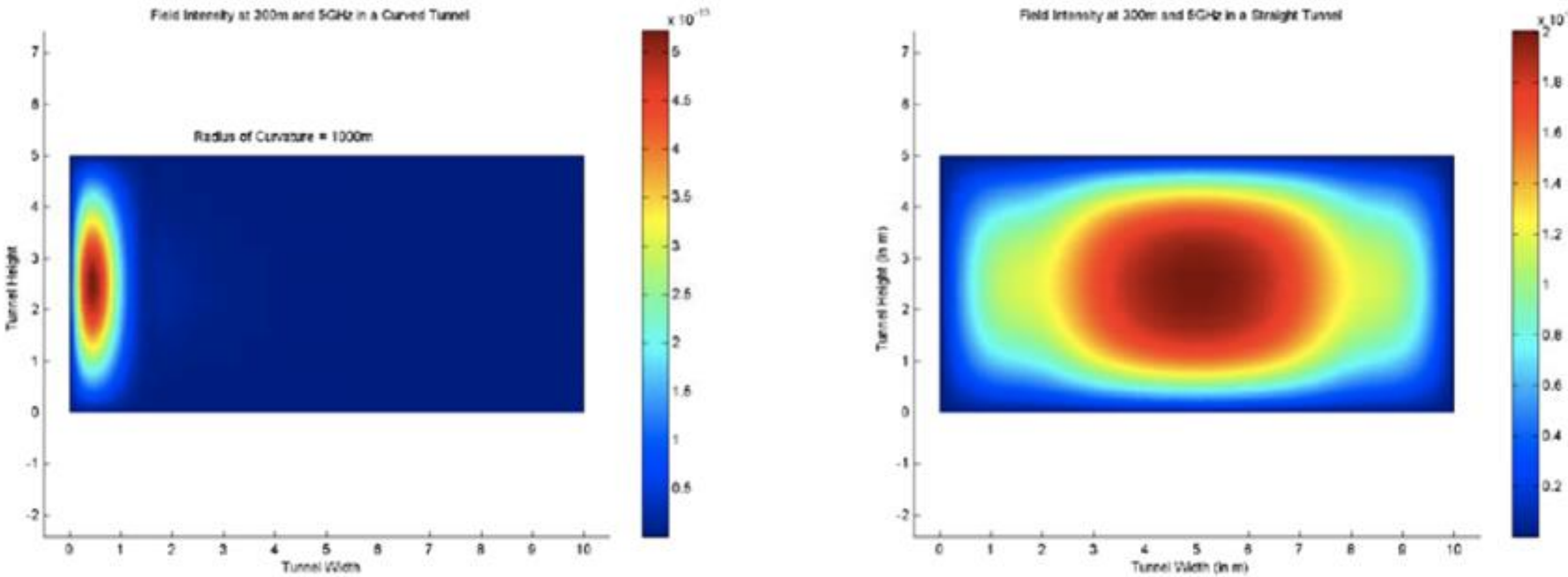


(a) Curved Tunnel



(b) Straight Tunnel

Signal Intensity at Tunnel end 700MHz



(a) Curved Tunnel

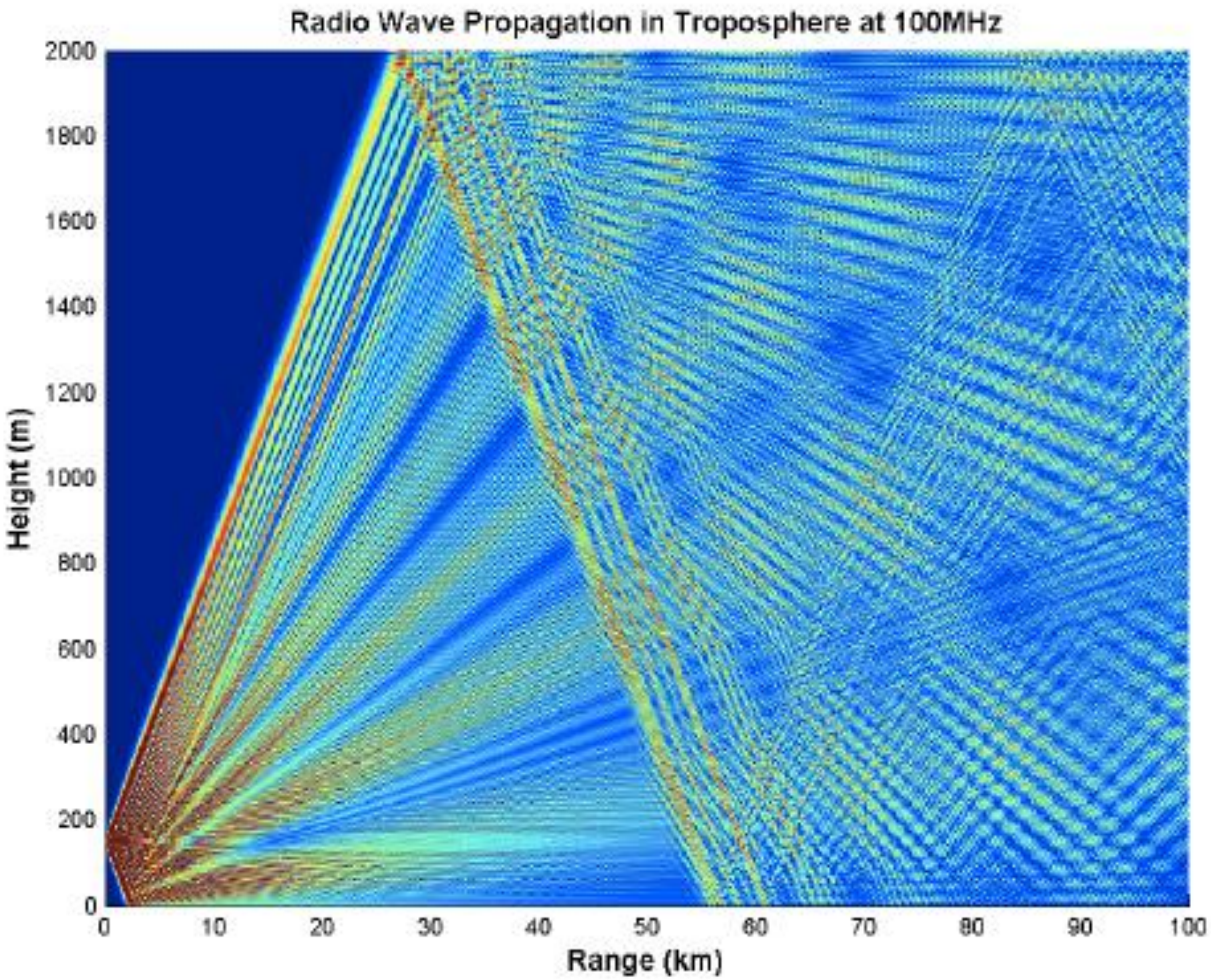
(b) Straight Tunnel

Signal Intensity at Tunnel end 5GHz

Urban Streets

Parameter	Value(s)
Tx Antenna Height	150m
Tx Antenna Gain	43.5dB
Rx Antenna Height	150m
Antenna 3dB bandwidth	10°
Ground Conductivity	0.01mho/m
Ground Permittivity	15
PML zone	300m
Tropospheric Duct Height	300
Antenna Polarization	HPOL or VPOL
Frequency of Waves	100MHz, 1GHz

Urban Streets



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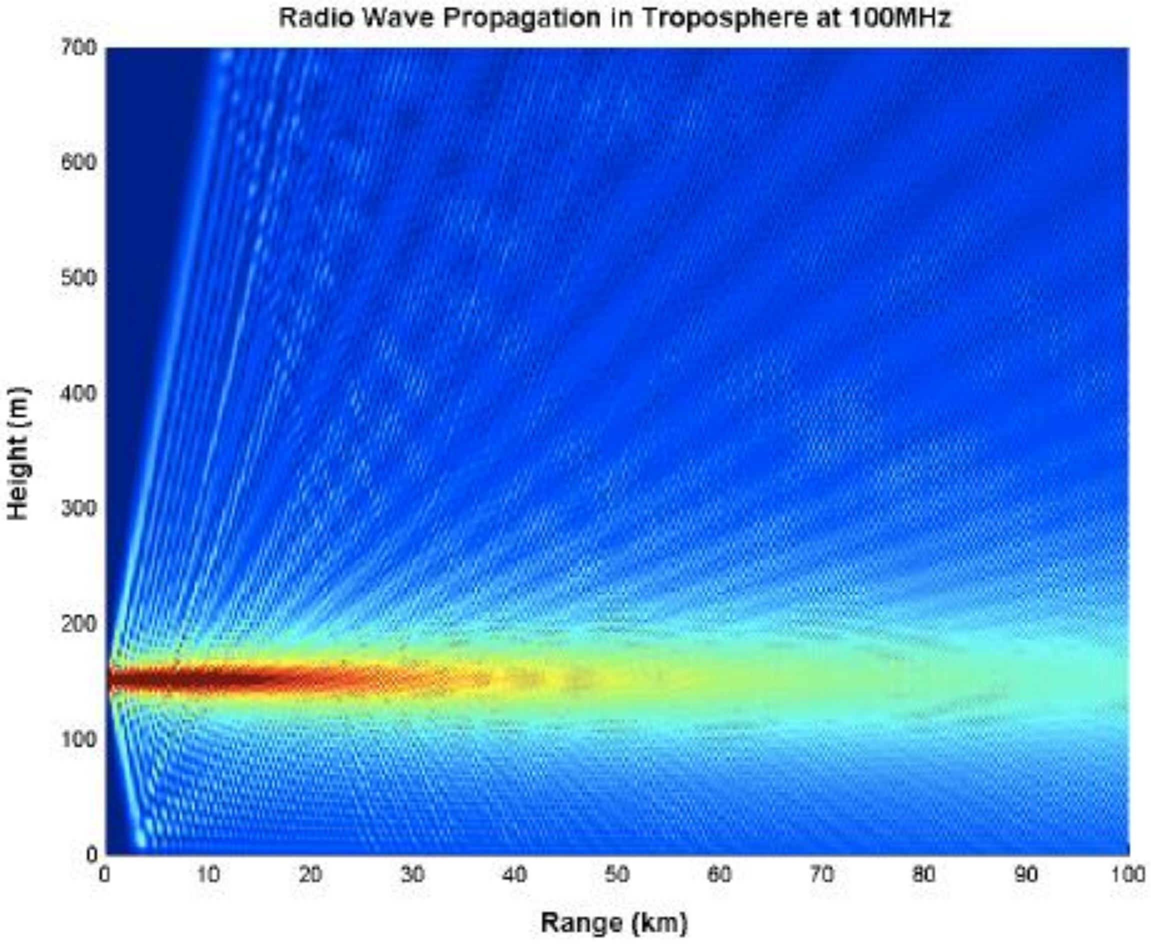
Urban Streets



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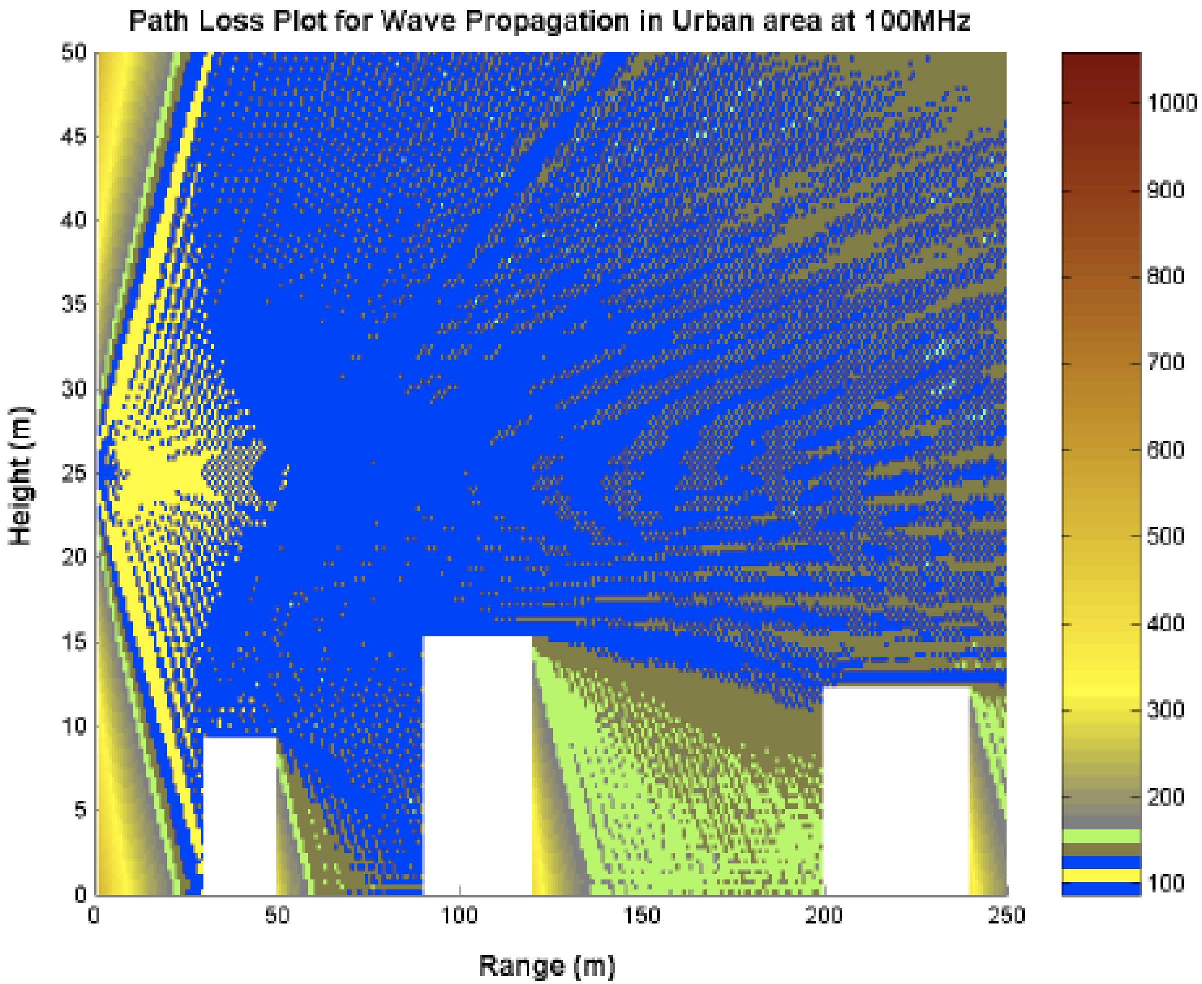
Urban Streets



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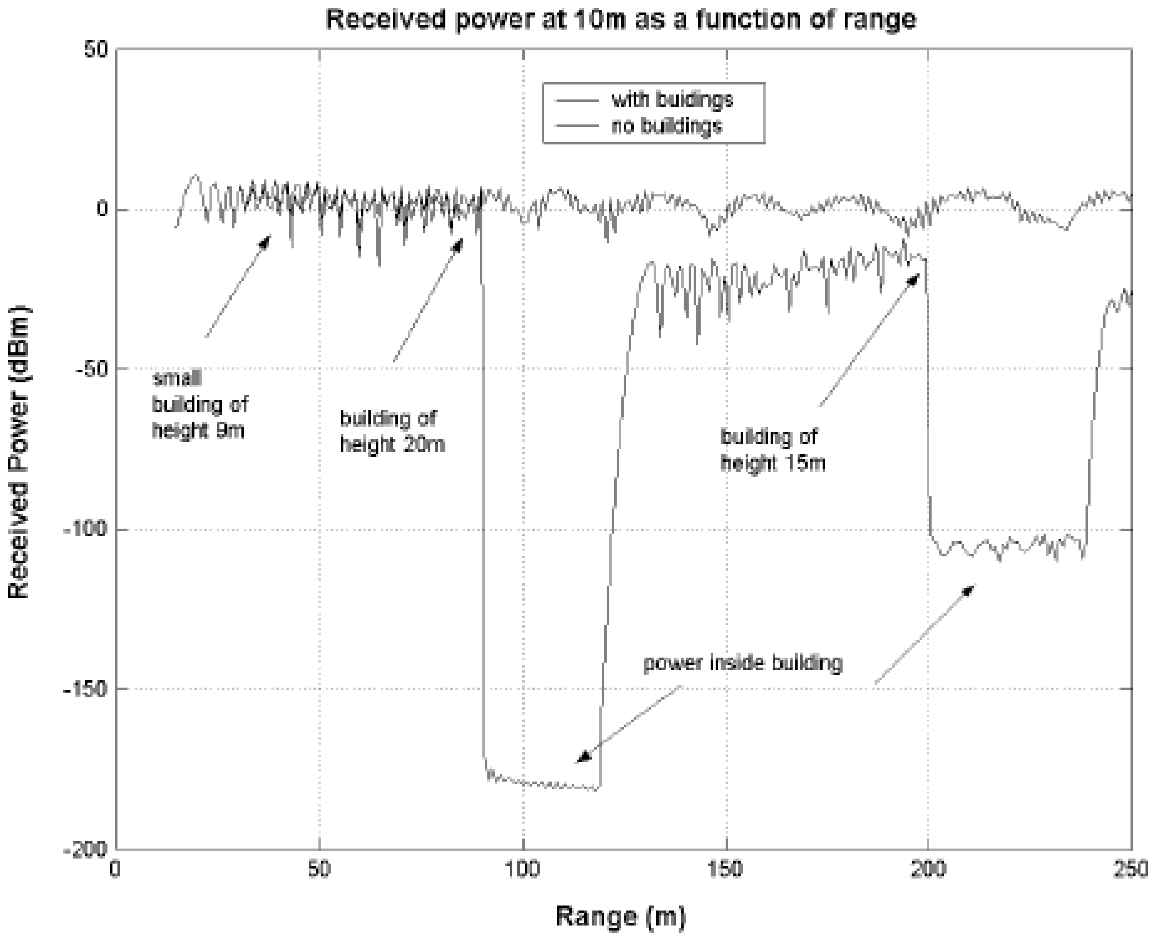
Successful IT projects

Received Power at 100MHz



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on the book by D. Dalcher and L. Brodie

Next Steps

- Characterisation of EM wave propagation in soil?
  - Determine accurately the permittivity of soil
  - Solve propagation equation using improved value of epsilon