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MIMO Signal Modeling in various Tunnels

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***Abstract*— Wireless communication draws the attention a lot and that is because, it increases data throughput and also the link range without the increased transmit power or additional bandwidth. MIMO techniques are based on multiple antennas in receiving and transmitting signals and also used in multipath propagation for the transformation of entire channel into many independent virtual channels. When the link will be made in long tunnel, then the number of reflecting objects near or between the receiver and transmitter will be quite low. In this situation, spatial diversity concept must be replaced with the concept of modal diversity. Primary objective of the study is to understand and model propagation of MIMO channel through a tunnel. Secondary objective is to analyze the applications of modal theory. To explore how modal theory can be applied in identifying wave propagation through tunnels and to simulate it using MATLAB. This work discusses about the application of Rayleigh's and Modal theory of electromagnetic propagation in circular or rectangular tunnels and also investigated by some experimental results. It describes about the propagation of MIMO through tunnels by many algorithms, ray approaches, various applications and functions of MIMO technology.**

***Index Terms*—Beamforming , CSI-Channel State Information, H- channel matrix, MIMO- multiple input multiple output, Rx-receiver, SBR- Shoot, Bounce and Reflect, VNA -Vectorial network analyzer.**

I. INTRODUCTION

Basic idea of Multiple-Input-Multiple-Output systems is to improve data rate (bits/sec) and/or data quality (BER) by using the multiple TX/RX antennas. Multiple-input multiple-output wireless system uses the spatial dimension of channel to provide capacity and increased resilience to fading.

MIMO achieves goal by spreading the overall transmit power through the antennas to obtain array gain and improves the spectral efficiency. This technology is primarily used to increase their data rate instead of improving the robustness and also more attracted in the area of wireless communication.

Multiple Antennas are used in many ways:

- Transmit Diversity
- Beamforming
- Receive Diversity

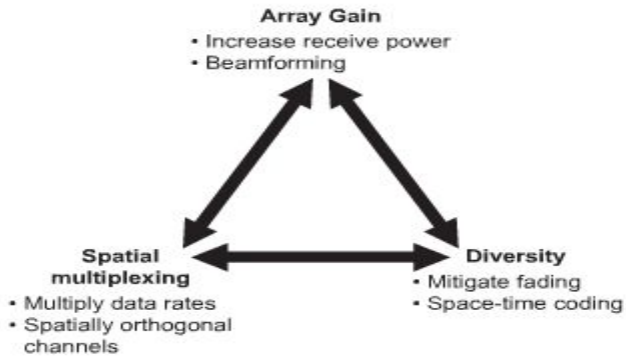

Fig.1: Benefits that MIMO offers

Spatial multiplexing (SM) techniques make receivers very complex and so it is combined with OFDMA (Orthogonal Frequency Division Multiple Access) the OFDM (orthogonal frequency-division multiplexing) modulation and these makes some problems because of multi-path channel and this must be handled efficiently and effectively. The IEEE 802.16e standard incorporates Multiple-Input Multiple-Output - Orthogonal Frequency Division Multiple Access (MIMO-OFDMA).

WiMAX implementations are also using the Multiple-Input Multiple-Output technology. The use of Multiple-Input Multiple-Output improves reception and also allows for the better rate of transmission and better reach. The implementation of Multiple-Input Multiple-Output provides WiMAX significant increase in the spectral efficiency. 3G Multiple-Input Multiple-Output describes that Multiple-Input Multiple-Output techniques are considered as the 3G standard techniques. Generally, MIMO improves the radio systems performance by providing the electronics intelligence to the spatial processing unit .

Multiple-Input Multiple-Output is also using in the Mobile radio telephone standards such as 3GPP2 and 3GPP standards. In 3GPP, LTE (Long Term Evolution) and HSPA+ (High-Speed Packet Access plus) standards take Multiple-Input Multiple-Output into the account. It is to fully support the cellular environments Multiple-Input Multiple-Output research consortia including the IST-MASCOT to develop the advanced Multiple-Input Multiple-Output techniques, such as MU-MIMO (Multi-User Multiple-Input Multiple-Output)

II. MIMO MULTIPATH COMMUNICATION

The idea of using the spatial processing is to enhance the communication performance. For example, assume the wireless communication node that equipped with N element antenna array which sends data to N distinct users. Using

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null-steering (traditional beamforming), the system may synthesize the array which response to transmit the data to single user by placing the nulls on the remaining N-1 users . By encoding the unique data stream on every pattern and synthesizing the unique pattern for every user, the system can have possibilities to simultaneously communicate with all users and also with spectral occupancy which is equal to single data stream. This principle is also can be used in point-to-point multipath channel.

For example: Consider the following figure which shows the two propagation paths between the receiver and the transmitter.

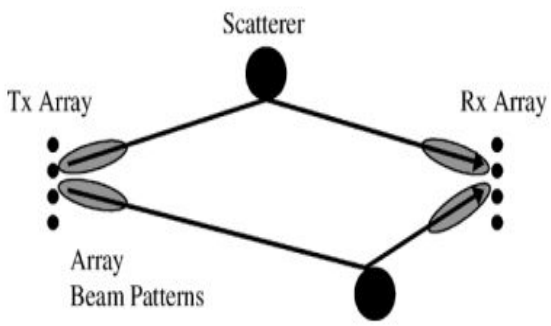


Fig 2: Simple Multipath Propagation Environment

If the arrays in antenna can resolve two multi-paths, then the system will encode the unique data stream on each and every propagation path and it results in the increase in the communication capacity and without the increase in required bandwidth. The typical wireless channels may contain several different closely spaced paths and the resolution of the individual multi-paths is not possible. So, Multiple-Input Multiple-Output implementations should use advanced array signal processing and this is to exploit the resources of spatial channel.

III. MIMO COMMUNICATION SYSTEM MODEL

A general model of Multiple-Input Multiple-Output communication system is represented in the following figure:

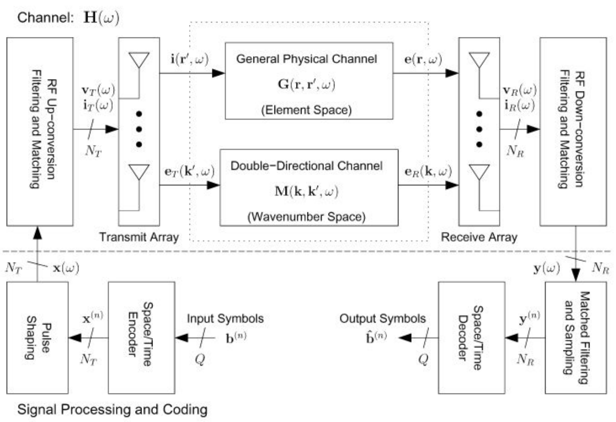


Fig 3: Block diagram of a generic Multiple-Input Multiple-Output wireless system

For simplicity, in the above figure, channel is assumed as time invariant over interval of the transmission block.

The figure, generic Multiple-Input Multiple-Output wireless system is divided into

- The channel (top)
- Signal processing and coding (bottom)

The RF (radio frequency) components are included in channel and they influence the function of end-to-end transfer.

In this system, the set of Q independent data streams are denoted by symbol vector $b^{(n)}$, where n is the time index and these are encoded into the N_T discrete-time complex baseband streams $x^{(n)}$ at transmitter. The coding may distribute the input symbols over the samples (time) and over the N_T outputs. The pulse-shaping block will convert the discrete-time samples to the continuous-time baseband waveforms $x(\omega)$ where, ω is the frequency and feeds them to N_T channel inputs (antennas and RF chains). Then the channel H(ω) will combine the input signals to get N_R element output waveform vector Y(ω). Then the matched filter will produce discrete-time baseband sample stream$y^{(n)}$ and then the space/time decoder will generate the estimates of Q transmitted streams .

For the linear channel elements, the Multiple-Input Multiple-Output channels, input–output relationship can be written as

$$Y(\omega) = H(\omega)\, x(\omega) + \eta\, (\omega) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(I)$$

Where η (ω) is the additive noise that is produced by the channel (noise plus interference from RF front end) and matrix dimensions are specified. Then the element H_{ij} (ω) denotes the transfer function between ith receives and jth transmit antenna. Then the transmit vector will be projected onto H(ω) in signal processing and coding, then number of the independent data streams (Q) which is to be supported should be equal to the rank of H(ω).

Generally, properties of H(ω), such as distribution of singular values will determine the performance of the Multiple-Input Multiple-Output system. Factors such as mutual coupling, array size and configuration, antenna impedance matching, multipath propagation characteristics, element pattern and polarization properties will influence these properties. So, incorrect assumptions about channel and poor design of system components will lead to the drastic reduction in the system performance

IV. MIMO CHANNEL MODELS

Multiple-Input Multiple-Output (MIMO) channel modeling has two main approaches and they are:

- Physically based modeling
- Non- physically based modeling

The physical models of Multiple-Input Multiple-Output describes about the Multiple-Input Multiple-Output channel or its distribution with some physical parameters. The non-physical models basically rely on statistical characteristics of Multiple-Input Multiple-Output channels that are obtained from measured data [10].

The following figure illustrates the classification of MIMO channel models.

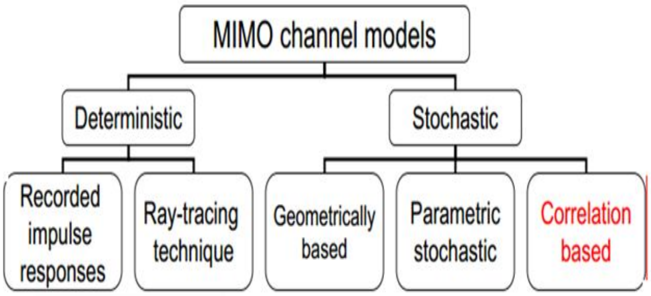


Fig 4: Classification of MIMO channel models

Physically based modeling of Multiple-Input Multiple-Output is called deterministic model. The deterministic model is further divided in two categories and they are:

- Recorded impulse responses
- Ray tracing technique

Non-physically based modeling of Multiple-Input Multiple-Output is called stochastic model. The stochastic model is further divided in three categories and they are

- Geometrically based stochastic model
- Parametric based stochastic model
- Correlation based stochastic model

Stochastic channel models have capacity to provide the statistics of received power and this is by predicting the PDF (probability density function) of the parameters such as path loss, Doppler shift, delay, etc. The stochastic channel models has special category of model called geometry-based stochastic channel models [8]. The geometry-based stochastic channel models will assign properties and positions to the scatterers stochastically and also perform the ray tracing before the contributions at the receiver. The geometry-based stochastic channel models are useful for the non-stationary environments and it can easily model motion of receiver, transmitter, or scatterers [4].

Deterministic methods are used for deployment of cellular systems. So, in this method, the coverage will be tested for the specific deployment option. One of the common deterministic methods is called ray tracing method and here rays are launched from transmitter and finds their paths to receiver which was determined from the geometric optics with all propagation mechanisms . Ray-tracing methods have ability to produce accurate results.

Non-physical models are also called as the analytical models. Analytical models characterize the channel by capturing certain effects on the wave propagation. Analytical models use narrow band models and this is to neglect the delay spreads. In addition to these, in analytical models, the numbers of antennas that used in the system is predetermined. In the analytical models, modeling is possible only to the spatial structure. Analytical models are well suited for the testing signal processing algorithms. Analytical models can be used with the combination of propagation based algorithms. The following figure illustrates the basic characteristics of the analytical model.

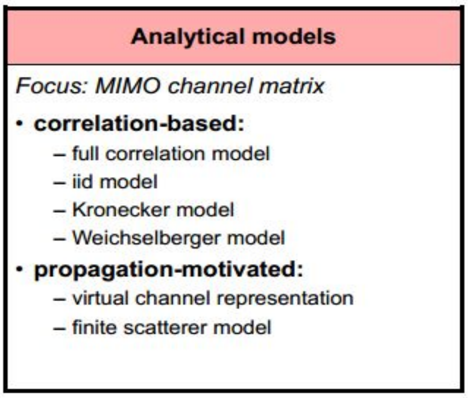


Fig 5: Analytical models

Models that use the realistic and geometric scattering environment are called as the physical models. The following figure illustrates the basic characteristics of the propagation based model.

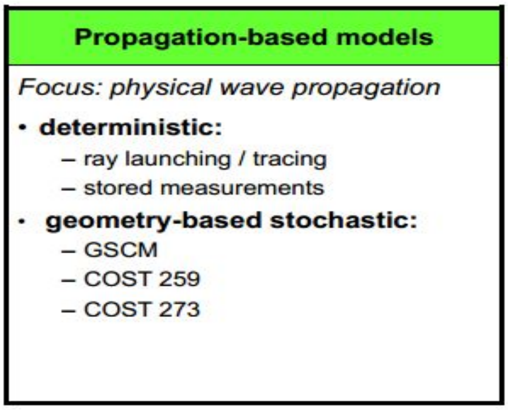


Fig 6: Propagation Based Model

In Propagation Based Model, modeling of all system parameters is possible with the help of spatial structure, frequency selectivity and time variance (moving Rx/Tx/scatterers).

V. WORKING STRUCTURE OF MIMO

Multiple-Input Multiple-Output can be sub-divided into 3 main categories:
Precoding, Spatial multiplexing or SM, and Diversity coding.

Multiple-Input Multiple-Output takes the advantage of using multi-path while working. Multiple-Input Multiple-Output uses multiple antennas to send the multiple parallel signals from the transmitter to receiver [7]. Multi-path occurs will occur when different signals arrive at the receiver and also at various time.

The following figure illustrates the how MIMO sends multiple parallel signals.

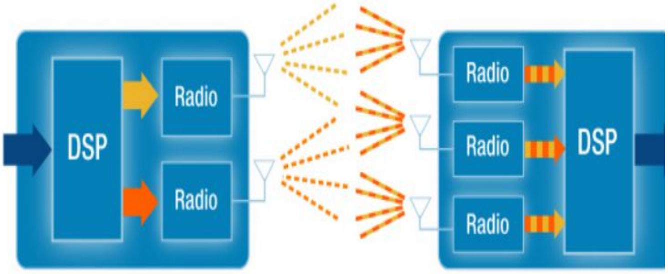


Fig 7: MIMO Signals from Transmitters to Receiver

The above figure shows that:

- Multiple data streams that transmitted in the single channel and also at same time
- Multiple radios can collect the multipath signals
- Multipath can delivers simultaneous coverage, speed, and reliability improvement.

In an ideal multipath channel the Multiple input multiple output capacity is approximately N times in the capacity of a single antenna system, here N is the smallest number to receive or transmit antenna elements. The correlated signals at the antenna elements will lead to decrease in the capacity[2][3].

It has been predicted that the Multiple input multiple output (MIMO) channel capacity is very low when compared to the Single input single output (SISO) channel capacity even though the signals at the antenna elements are being uncorrelated. This kind of effect has been named as a pinhole or keyhole. This is related to the receiver will lead to low correlation signal level while other propagation effects like wave guiding or the diffraction that leads to the rank reduction of the matrix function which transfers[17].

When the Multiple input multiple output maximum capacity techniques are implemented in the tunnels especially in the subway tunnels. There is an increasing demand in improving the effective transmission bit rate between a track and train. Most of the new command and control systems of automatic subways mainly based on an exchange of an amount of data which must be conformed even in the underground part of the subway line. It is proved recently that the multiple input and multiple output techniques has improved the channel capacity but only under the condition of a small correlation paths between each transmitting and the receiving antenna[8].

It is not possible to implement the antennas on the tunnel ceiling practically and they have to put on a platform near the track. To increase of the mean signal to the noise ratio by using the directive antennas or to get profit of a spread of the direction of arrival. The preliminary experiments have been shown that the average direction of arrival spread angle is smaller or in the angle 90 degree. For this type of trails horn antennas, the platform 12dBi gain is used. In order to check the validity of this trails , additional trails have been made with the bertical half wave dipoles.The channel capacity deduced the configuration, assuming the same signal to the noise ratio.It was not possible for the security reasons in the train to place the quarter wavelength monopolies on the roof and for this the only solution have to put the antennas behind the windscreen. These antennas were placed in order to maximize the decorrelation at each corner. The Channel sounder is mainly based on a technique of correlation and has a bandwidth of 35 MHz and has a centre frequency of 900 MHz. This bandwidth is very much greater than the necessary bandwidth of the final system[14].

VI. MIMO ANTENNA AND BEAMFORMING DEVELOPMENT

For several years antenna technology was used to increase the MIMO performance in a better way. Directive antennas have used to enhance the levels of signal and to decrease interference. At the same time, it is also used to improve the capability of cellular telecommunication systems. For instance, by portioning a cell site into sector if each antenna has 60/120 degree of capacity could be highly improved and it's tripled while using 120 degree antennas [4].

The rapid development of adaptive systems has high levels of processing power; it is more possible to use antenna beam forming technology with their MIMO systems.

MIMO beamforming smart antennas

The beam forming techniques are freely used with any other antenna system not only on MIMO systems. Because, it is utilized to make a specific antenna directive pattern to provide the better performance based on some conditions. Generally, smart antennas are used and it is automatically controlled due to required performance and its existing conditions.

Smart antennas can be classified into two different systems [4]. They are:

Phased array systems: It is switched and includes a number of predefined patterns; the required one is switched depends on the required direction.

Adaptive array systems: This kind of antenna utilizes an adaptive beam forming and contains infinite number of patterns should be adjusted with such requirements in real time.

MIMO beam forming use phased array systems needs the whole system to differentiate the direction of an arrival of incoming signal and after that switch in its suitable beam. An adaptive array system is able to direct the beam in appropriate direction and also move towards the beam in real time. This is a good advantage for moving systems, involves a factor which happens along with cellular telecommunications. Hence, the cost is feasible but also provides effective performance of MIMO systems.

MIMO spatial multiplexing

The key benefits of Multiple Input Multiple Output (MIMO) spatial multiplexing are able to produce additional capacity of data. This achieves by using multiple paths and efficiently utilizing features as additional "channels" to transmit data. Based on Shannon's law, the large amount of data which could be transmitted by a radio channel but it's limited through physical boundaries

Shannon's law and MIMO spatial multiplexing

The theoretical boundaries aren't possible to continue depending on various fields of science. It is a fact because the amount of data which travelled by a particular channel in presence of noise. The law which governs, it is known as Shannon's Law; this is named after the man who formulated it. It is more significant because MIMO wireless technology promotes a method not to breaking this law as well as improving the rate of data in one channel [8].

This law defines the highest rate of error free data is able to transmit on a given bandwidth in the occurrence of noise. It can be written in the form of:

$$C = W \log_2(1 + \frac{S}{N}) \quad \text{.................................(2)}$$

Where,
C – Channel capacity in bits/sec
W – Bandwidth in Hz
S/N – Signal to Noise Ratio (SNR).

It can be observed that the limitations over the channel capacity along the given bandwidth. But its point is reached, the capacity being limited by SNR of received signal. This kind of limits involve various decisions require to made about their transmission and its modulation scheme acts as major role in spatial multiplexing. The capacity of channel is enhanced with the help of high order modulation schemes. However, it needs a good SNR than the low order of modulation schemes. Therefore balance occurs among the error rate and data rate, signal to noise ratio (SNR) and its power could be passed in the channel. It is required to looking forward at many ways of increase the data rate based on single channel. MIMO is a way such that wireless communications should be increased and it receiving a substantial degree of interest [9].

VII. IMPLEMENTATION

MIMO (Multiple Input Multiple Output) techniques is the best method to enhance the communication performance in a tunnel environment and highly useful for urban, sub-urban and indoor environments. Thus, the characteristics of propagation through tunnel are quite different and their rays impose to the walls of tunnel with grazing angle of incidence without endure a heavy attenuation for the entire field. The departure of ray is relatively small and the techniques of MIMO produce many interesting results. Theoretical and Experimental research shows that the capacity of channel is nevertheless improved with the help of Multiple Input Multiple Output techniques. For more better results are obtained from transmitting (Tx) and receiving (Rx) array elements are associated with perpendicular to the axis of the tunnel.Spatial fluctuations of Rx signal because of the interference between two modes, fading distribution that leads to a Rayleigh distribution.

How can MIMO be propagated through tunnels

New technologies of information and communication are key components for the transit systems with applications such as embedded surveillance, video on demand, maintenance reporting and control and command [5]. These wireless systems are deployed using the antennas, wave guides or radiating cables using free propagation in tunnels. It is essential for the wireless systems to maximize data rate or robustness and it is essential to avoid the increase of transmission bandwidth or transmitting power.

Multiple-Input Multiple-Output (MIMO) systems introduced to answer the needs for high data rate communications and robust without the additional bandwidth or power consumption [3]. In the multipath environment, use of the multiple antenna arrays at both the receiving and transmitting sides leads to identification of many independent propagation channels that are linked to rank of channel matrix . The capacity of Multiple-Input Multiple-Output channel depends on the rank. With the key hole or spatial correlation effect in channel, the H matrix will be degenerated [17]. This will be the efficiency and interest of such system is suitable for the transport environments The performance of Multiple Input Multiple Output (MIMO) systems depends on the condition number of H matrix as denoted in the ratio of the highest Eigen values. However, two MIMO algorithms are measured to estimate the condition number and those algorithms are regarded as OSTBC, VBLAST or QSTBC codes.

Applying MATLAB for ray tracing

The ray tracing propagation model depends upon their frequency-time and frequency-domain techniques are briefly explained in this section. The complicated portion of propagation simulation of ray predicts the path of the rays between the transmitter and receiver. The two ray paths such as reflected and refracted rays are produced by using two alternative methods namely Eigen ray search and Brute force. Eigen ray search is used to identify properties of rays between the transmitter and receiver through the propagation path. Brute force is useful for the purpose of bouncing and shooting rays. It is shortly called as SBR. This force determines a bundle of transmitted rays that can or cannot reach the receiver's end. Hence, it is taken as a challenge for ray-tracing techniques and calculated rapidly to specifying dominant ray paths that helps to predict the field-strength. It also acts as a research tool for the prediction of ducting and non-ducting conditions in many refractive profiles.

A simple MATLAB package was prepared for the purpose of visualization by using this ray-shooting technique [9]. The *Snell_gui* package shoots for more number of rays, the angles of arrival which is pointed by user along the medium of propagation characterized by different linear vertical refractivity profiles i.e. it is regarded as straight forward and refractivity is range-dependent. When a user chooses the range of *(zlast)*, the actual height denotes *(xlast)*, the source height *(xsource)*, the horizontal layer thickness Δx , and refractivity parameters and may select to place 1 or 2 PEC obstacles in the propagation path. GUI (graphical user interface) package has *Snell_gui. Fig* was made in Mat lab 6.5 along its design command guide. The functional part is described in *Snell _gui. m*. In this figure illustrates a picture representation about the core of package that depends upon direct application of Snell's law among adjacent horizontal layers and its refractive indexes are assumed as constant rate. The angle of ray can be measured in the vertical axis x [13].

As longer, the co-ordinates of ray is lesser than the actual range and height, since the package shooting rays produce from the source, one by one and it store co-ordinate points over the ray path as (x, z) pairs. The five various procedures may involve in this package. The first step of procedure based on consecutive application of Snell's law by a multi-horizontally layered propagation medium [14]. The height of the layer Δx representing user specified constant. The top most layer which equivalent to user supplied source of height. The first ray exits from the source of first angle and depending on Snell's law [15]:

$n_i \sin \varphi_i = n_{i+1} \sin \varphi_{i+1}$……………………(3)

It produces the angle of refracted ray in the next layer then 'i' is an index of source layer. The horizontal distance Δz and Δs the ray segment, its adjacent layer (i + 1) should be calculated by using trigonometric relations and based on its formulas as shown below:

$$\Delta z_{i+1} = |\Delta x| \sin \varphi_{i+1}$$

$$\Delta s_{i+1} = \sqrt{\Delta x^2} + \sqrt{(\Delta z_{i+1})^2} \quad \text{…………(4)}$$

The ray is propagated by the adjacent layer in a similar way until it reaches their maximum range of height. The ray segment co-ordination is given by:

$z(i+1) = z(i) + \Delta z_{i+1}$………………..(5)

$x(i+1) = x(i) \pm \Delta z_{i+1}$…………….....(6)

The above equation denotes upward and downward propagating rays correspondingly. The ray of loci is stored and plotted . The ray fields are measured and the total ray path is followed as:

$$R_i = \sum_{n=1}^{M} \Delta s_n \quad \text{………………………………(7)}$$

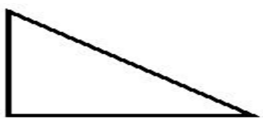
Where, i and M represents an index of ray and the number of ray segments respectively.
The second step of procedure based on total reflection from PEC's bottom of the surface and it is realized by bending upward ray along the same angle which hits the bottom surface. In Mat lab this condition is satisfied by replacing instead of Δx as -Δx. The third procedure follows the same second one excluding the reflection produced on top of user specified obstacles. In fourth procedure, a ray hits the left walls of obstacles. In this method, the ray terminates there and the package initiates shooting next ray [9].
Another significant procedure for ray reaches at a level of 90° , this angle is known as *ray caustics.* In programming, they followed the similar second procedure. When a ray reach the angle 90° it is propagating upward and bending downward through replacing once again Δx and -Δx.

VIII. RESULTS

Tunnel 1

The following are the configurations for various coordinates of the triangular tunnel

Z1= 300
Z2= 500
Z3= 1000
Z4=1200



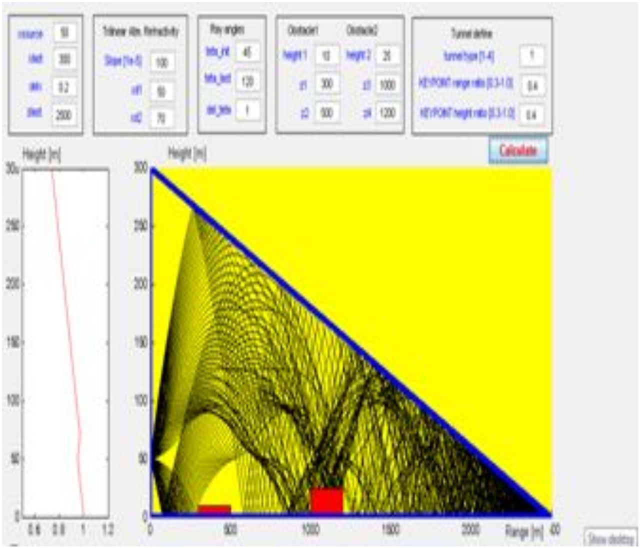
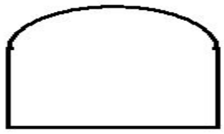


Fig 8 : Ray diagram of tunnel 1

Tunnel 2
The following are the configurations for various coordinates of the arch shaped tunnel
Z1= 300
Z2= 500
Z3= 1000
Z4=1200



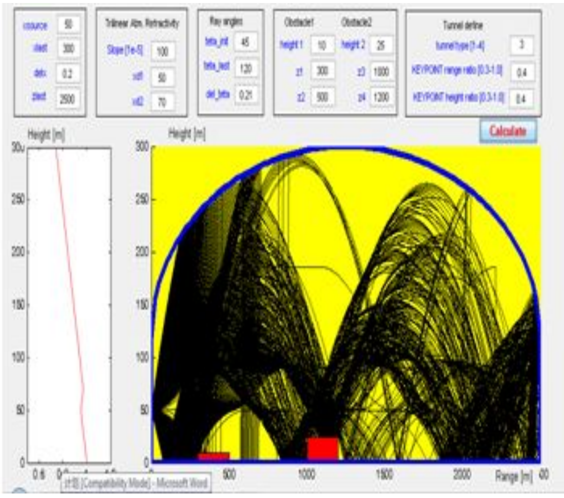


Fig 9 :

Ray diagram of tunnel 2

The above is the ray diagram shot for the second tunnel.

Tunnel 3
The following are the configurations for various coordinates of the curve shaped tunnel
Z1= 300
Z2= 500
Z3= 1000
Z4=1200

The following is the ray diagram shot for the third tunnel box, making the layout look confusing.

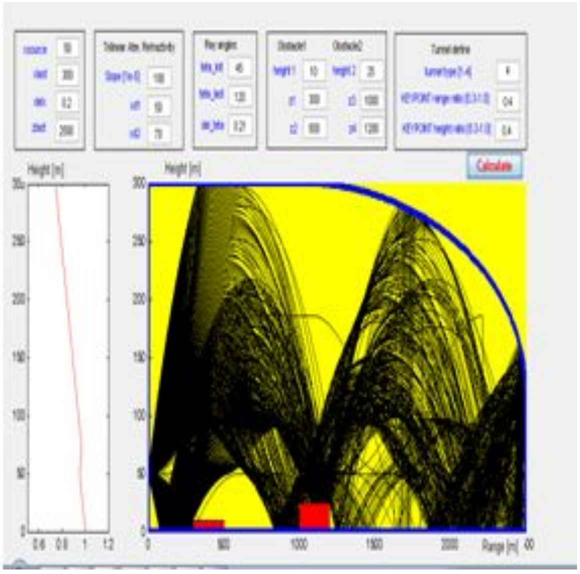


Fig 10 : Ray diag ram of tunnel 3

IX. Conclusion

The implementation of MIMO in wireless communication greatly facilitates for spectral efficiency, link reliability, better performance and high rate of transmission. This work discusses about how the signals propagate through the tunnels. Application of Rayleigh's and Modal theory of electromagnetic propagation in circular or rectangular tunnels and also investigated by some experimental results. On the other hand, MATLAB package are more helpful for beginning the ray-shooting techniques. These main packages should be used as an educational tool in various components by using antennas and propagation, wireless propagation and Electromagnetic Wave theory. MIMO techniques are often used in many wireless technologies such as Wi-Fi and LTE (Long Term Evaluation) standards. The Wi-Fi devices make use of multiple antennas to transmitting and receiving signals at the same point of time. Although, it is used to reduce the bit error rate and provides an outstanding performance of MIMO configuration .

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