NIST Quasi-Deterministic (Q-D) Channel Realization Software Documentation

by

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Abbreviations

5G	Fifth Generation
AMF	Additive Manufacturing File format
AoA	Angle of Arrival
AoD	Angle of Departure
DoA	Direction of Arrival
DoD	Direction of Departure
GIS	Geographic Information System
LOS	Line Of Sight
NIST	National Institute of Standards and Technology
Q-D	Quasi-Deterministic
STL	STereoLithography
Rx	Receiver
Tx	Transmitter
XML	eXtensible Markup Language

Notation

τ	delay
d	path length
c	velocity of light
λ_0	wavelength
f_0	frequency
Δf	change in frequency due to Doppler effect
$\Delta\phi$	phase shift due to Doppler effect
Δv	relative velocity
K factor	the ratio of specular power to the sum of diffuse power
γ	rate of decrease of power of diffuse components with respect to specular components
λ	delay spread parameter
Θ	Angular spread parameter
θ	AoA/AoD elevation angle
ϕ	AoA/AoD azimuth angle

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1 Introduction

A wireless channel propagation model can be expressed as a collection of rays – each representing a separate electromagnetic wave front – propagating through a physical medium between two communicating devices or nodes. Stochastic propagation models, that describe the properties of the rays, are generally being used to characterize the wireless channel for both outdoor as well as indoor environments [1]. As the wireless communication protocols become increasingly complex, these stochastic models are now insufficient for modeling channels, in particular for the IEEE 802.11ay standard for next-generation 60-GHz Wireless-Fidelity (Wi-Fi) systems [2]. With the advent of these standards, channel models that provide the space, time, and phase characteristics of all rays deterministically has become necessary for modeling these complex systems.

Geometrical raytracing is one of the possible techniques to capture the deterministic components of all the rays. However, few physical phenomena like rough surface scattering cannot be modeled in deterministic manner. In this context, the National Institute of Standards and Technology (NIST) has adopted the Quasi-Deterministic (Q-D) channel model proposed by the IEEE 802.11ay task group [3] and extracted parameters based on rigorous channel measurements [4] to stochastically model the rough surface scattering. Geometrical raytracing can be implemented by extracting the geometrical features of an environment and storing it in Computer Aided Design (CAD) or Geographic Information System (GIS) file formats. NIST Q-D channel realization software has chosen CAD files to extract geometrical features from a given environment since they can be generated easily for both indoor and outdoor environments.

The NIST Q-D channel realization software developed by the NIST has two major engines – a deterministic engine and a stochastic engine – to compute the rays between communicating nodes. Each of the rays is characterized by the path loss, the phase, the angle-of-arrival (at the receiver (Rx)), and the angle-of-departure (from the transmitter (Tx)). The deterministic engine generates deterministic rays, also referred to as specular rays[1]. Using the deterministic rays as the basis, stochastic rays are generated from them using a statistical distribution function based on the NIST rough surface scattering model.

2 Overview of NIST Q-D channel realization software

NIST Q-D channel realization software is a raytracing software developed in Matlab 2017b, which computes multipath components between communicating nodes. A sample output of NIST Q-D channel realization software for two stationary (or fixed) nodes simulated until second order reflection is shown in Fig. 1. However, it is worth noting that the NIST Q-D channel realization software not only supports stationary nodes but also supports mobile nodes.

[1]Specular rays

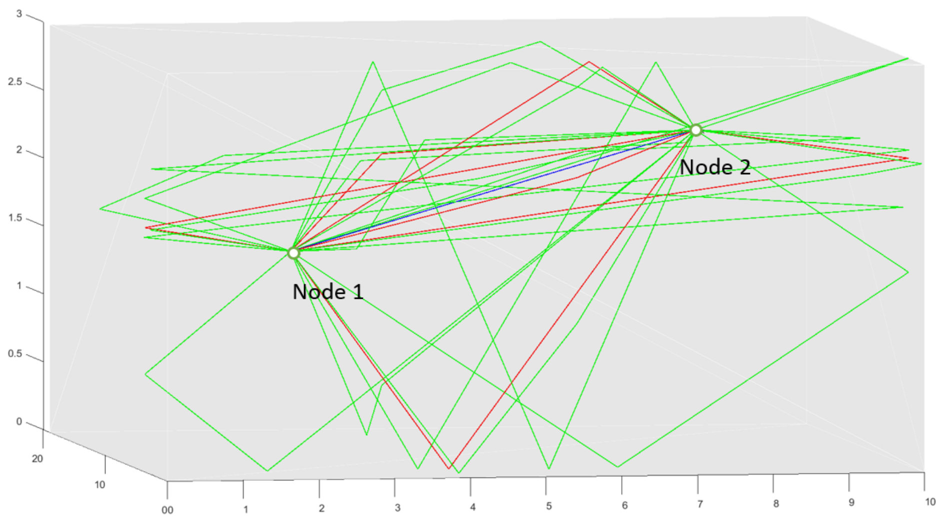


Figure 1: Scenario with two nodes simulated up to second-order reflections. Blue line is the line of sight (LOS), the red lines are first order reflections, and the green lines are second order reflections.

All the features of NIST Q-D channel realization software are described below.

1. Generates specular rays which are dependent on the CAD model of the environment under consideration;
2. Generates nodes either randomly or based on a user-specific placement;
3. Accounts for mobility of the nodes in the environment using a random waypoint model;
4. Generates diffuse rays;
5. Can deal with multiple nodes in the environment.

NIST Q-D channel realization software generates rays based on the node locations and node velocities which can be generated either randomly or based on a user-specific placement. For example, a scenario with three nodes has a total of six possible pair combinations for a fully connected network. These combinations are shown in Table

I and the simulated scenario is shown in Fig. 2 where node locations are generated randomly.

Rx / Tx	Node 1	Node 2	Node 3
Node 1	N/A	Tx1 Rx2	Tx1 Rx3
Node 2	Tx2 Rx1	N/A	Tx2 Rx3
Node 3	Tx3 Rx1	Tx3 Rx2	N/A

Table I: Different combinations of nodes as Transmitter (Tx) and Receiver (Rx).

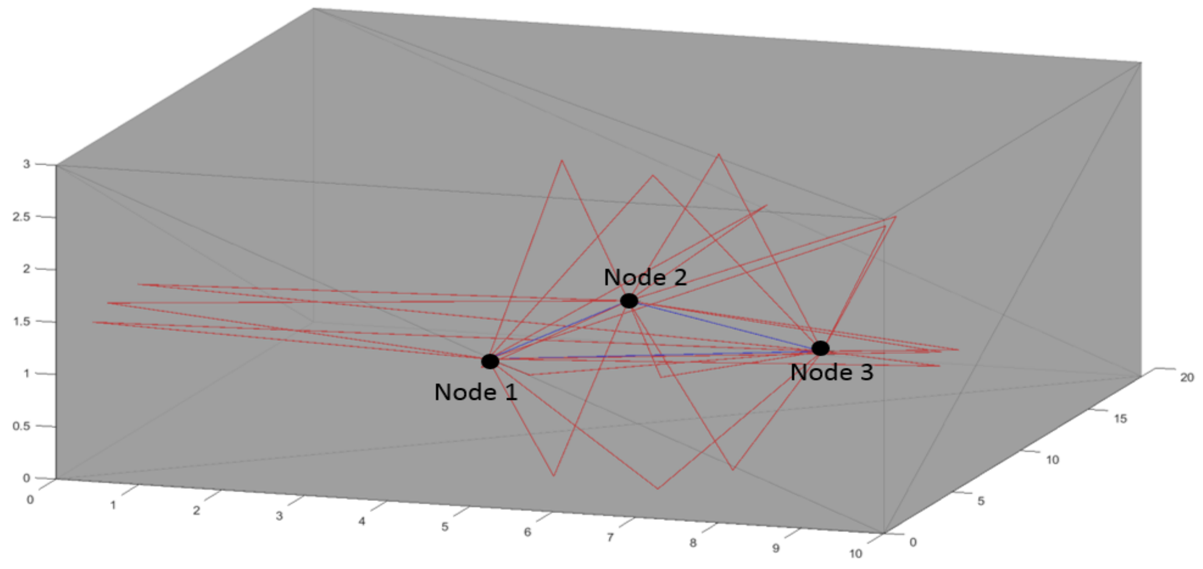


Figure 2: Scenario simulated for multiple stationary nodes which includes LOS (in blue) and first-order reflections (in red).

2.1 Mobility Model

Mobility model is defined for a fixed period of time and the number of divisions that make up this time period. Two modes of mobility are employed in the software – linear mobility and custom mobility.

Linear mobility – In linear mobility, the velocities are given by the user or can also be generated randomly. The velocities are given in vectorial form, i.e., (x, y, z) form. Based on the time period and the number of time divisions provided by the user, the node position in each time step[2] is calculated using finite difference method. The new location or position using finite difference method is given as

$$\text{newLocation} = \text{oldLocation} + (\text{velocity}\times\text{timeStep})$$

For the scenario when the node hits an object/wall, then the software automatically reverses the velocity, i.e., simply multiplies the velocity by -1.

Custom mobility – In custom mobility, the node positions of each time step are given by the user. In addition, the value of time step is also provided by the user. Using finite difference method, software calculates the velocity vector at every time step as follows.

$$\text{velocity} = \frac{\text{oldLocation}-\text{newLocation}}{\text{timeStep}}$$

2.2 Ray Properties

Geometrical properties of a single ray between Tx and Rx are characterized by

- Path length, which is defined as the length of the propagation path of the ray between Tx and Rx.
- The direction of arrival and the direction of departure in the respective coordinate systems of Rx and Tx.

These are the primary attributes of a ray and are shown in the Fig. 4. The directional vector of the ray where the ray starts from Tx is the direction of departure. The angle

[2]Time step is defined as the ratio of the time period and the number of divisions.

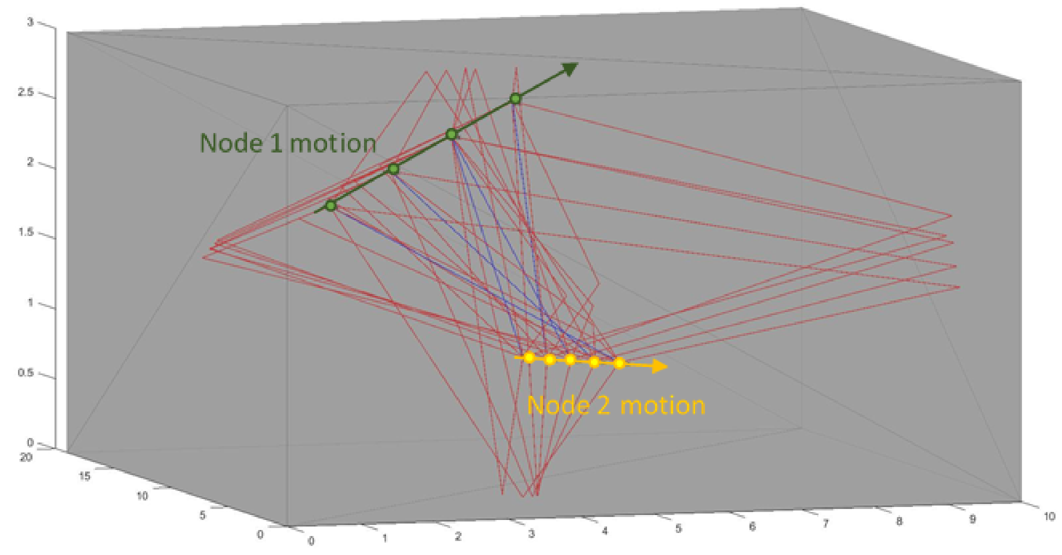


Figure 3: Scenario simulated for mobile nodes which includes LOS (in blue) and first order reflections (in red).

of this directional vector in the spherical coordinate system is defined as the angle of departure. The negative of directional vector of the ray where the ray ends is the direction of arrival. The angle of the direction of arrival in the spherical coordinate system is defined as the angle of departure. The direction of departure and arrival vectors are considered to be emanating from Tx and Rx, respectively. The angles of departure and arrival has two components – azimuth and elevation. The angle of departure in the azimuth plane is calculated by projecting the direction of departure vector onto x-y plane and computing the angle between this projected vector and x axis. The angle of departure in elevation plane is obtained by computing the angle between the direction of departure and the positive z axis. These angles are shown in the Fig. 5 for better clarity. Similarly, the angles of arrival in azimuth and elevation planes can be computed.

There are some secondary characteristics which can be determined from geometrical

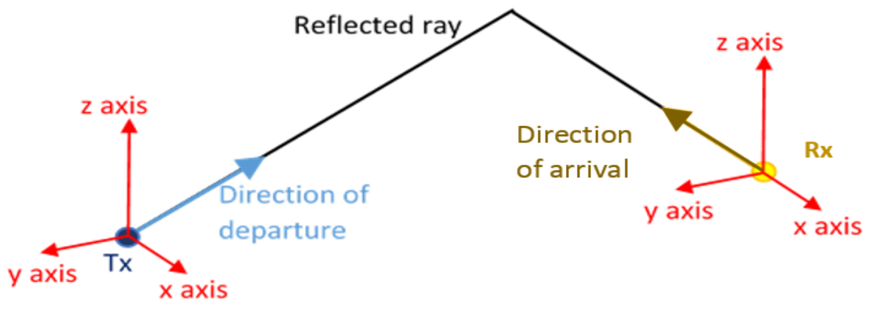


Figure 4: Reflected ray and its direction of arrival and departure vectors.

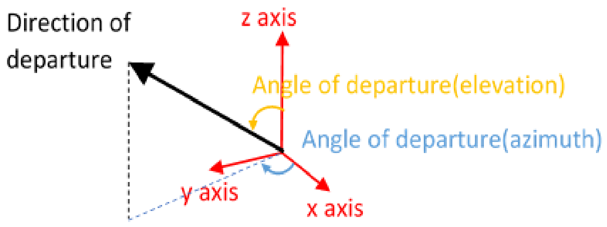


Figure 5: The angles of departure in azimuth and elevation planes.

properties of a ray and are described below.

1. **Delay**: The delay (τ) is defined as the ratio of the path length (d) and the speed of light (c).

$$\tau = \frac{d}{c}. \tag{1}$$

2. **Path loss**: The path loss is affected by the path length. This effect can be computed using Frii's transmission loss equation as given below

$$\text{Path Loss} = 20 \log_{10}\left(\frac{4\pi d}{\lambda_0}\right), \tag{2}$$

where λ_0 is the wavelength of the carrier frequency of the wireless communications system and d is the path length.

3. **Phase shift**: The phase shift of a ray is taken to be 180 degrees for every reflection. For a second order reflection, this phase shift would be 360 degrees. Phase is also affected by the Doppler effect which occurs due to mobility of communicating nodes.

4. **Doppler effect**: The Doppler effect is a change in frequency of a wave perceived by the observer when there is a relative motion between the observer and the source [5, Pages 352 - 358]. The phase of the received signal is affected by relative velocity between two nodes. Doppler effect is observed when the nodes are moving. The change in frequency, Δf is given by

   $$\Delta f = \frac{\Delta v}{c} f_0, \tag{3}$$

   where c is the velocity of light, Δv is the relative velocity between Rx and Tx, and f_0 is the frequency of operation.

   Using the change in frequency from (3), the phase shift due to the Doppler effect is given as

   $$\Delta \phi = \Delta f \times \tau, \tag{4}$$

   where $\Delta \phi$ is the phase shift and τ is the delay.

   The Doppler effect will vary for different reflections because it is dependent on relative velocities of the reflected images but not on the actual node velocities. The relative velocities of the reflected images are calculated by

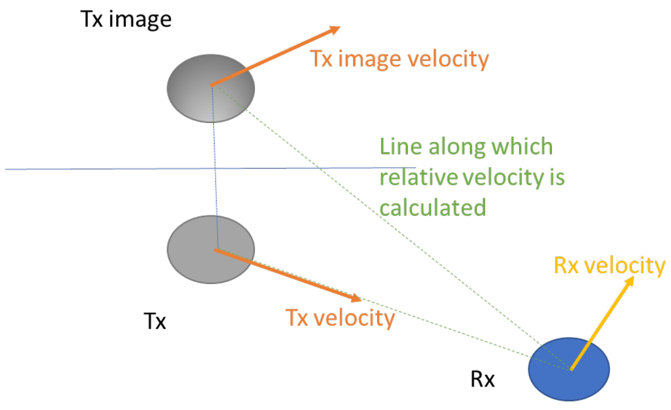


Figure 6: Schematic diagram to calculate the relative velocity of the reflected images for the scenario where two nodes are moving.

- first computing the velocities of the individual nodes
- and then finding the velocities of the reflected images recursively in the chronological order. The velocity of the node and the velocity of its image are opposite to each other about the normal vector of the reflection plane and constant along the reflection plane as shown in Fig. 6. Once the final image is obtained, then the relative velocity is calculated along the line joining the final image and the other node.

2.3 Block Diagram of NIST Q-D channel realization software

The NIST Q-D channel realization software has been developed to combine the deterministic results computed by raytracing with that of stochastic models of measurements conducted by the NIST [4]. The flow of this procedure is shown in Fig.7 where

Block 1 : Input – Input parameters such as node position, velocities, order of reflection etc are fed into the software. The detailed information regarding the inputs can be found in Section 3.

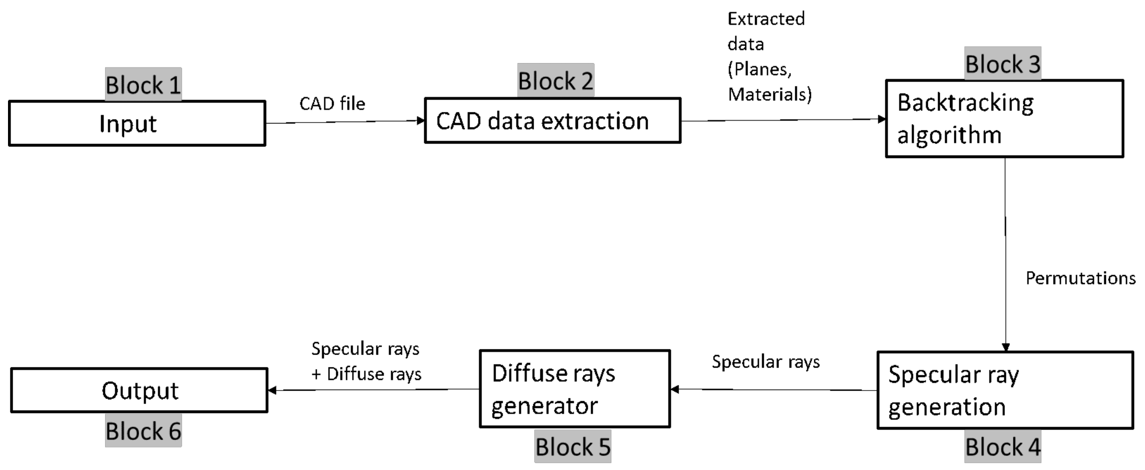


Figure 7: Step-by-step procedure of the NIST Q-D channel realization software.

Block 2 : CAD data extraction – The way to process a CAD file is to extract the convex planar polygon data and compute its plane equations. Mobility model is included in this block. The detailed information about extracting the CAD data file can be found in Section 4.

Block 3 : Backtracking algorithm - All the possible permutations of plane combinations, where there is a possibility of reflection, are generated using backtracking algorithm. The detailed algorithm is described in Section 5.

Block 4: Method of Images - Once the plane combinations are known, the Method of Images [6] is used to compute the individual rays, as described in Section 6.

Block 5 : Q-D model - The stochastic channel model can be applied on every ray generated by the method of images to create a cluster of diffuse rays surrounding the specular ray. This cluster of rays is then generated as an output by the software. The detailed information can be found in Section 7.

Block 6 : Output - The final output consists of ray's attributes namely path loss, delay, phase, AoA, AoD at every time step and node combination. Output consists of node postions at every time step. Please refer to Section 8 for detailed information.

The following subsections describe the file and code structures of the NIST Q-D channel realization software which will be used in Sections 3-8.

2.4 File structure

The file structure is shown in Fig. 8 where *QDSoftware* is the main folder. The main folder contains two sub-folders as well as a main file *main.m*, two parameter configuration function files, i.e. *parameterCfg.m* and *nodeProfileCfg.m*. Two preexisting sub-folders are *Input* and *Raytracer*. The scenario sub-folders will be created when new scenario is generated either automatically by software or manually by user. It is worth noting that the working root folder must be “QDSoftware\”.

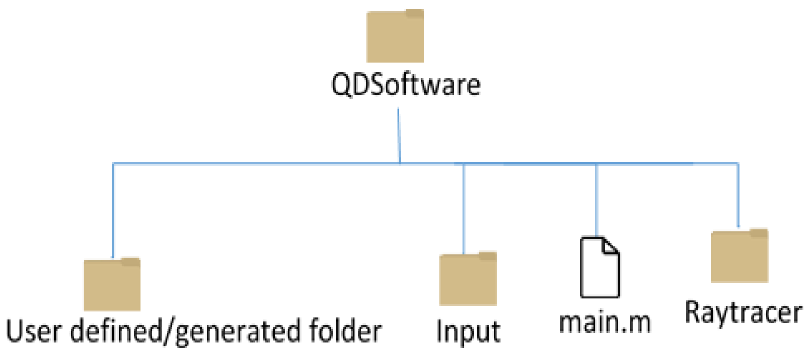


Figure 8: File structure of the NIST Q-D channel realization software

2.5 Code structure

There are four major MATLAB functions which call other functions to import the input and generate the output, namely the *main.m*, *parameterCfg.m* and *nodeProfileCfg.m* in main-folder *QDSoftware*, and the *Raytracer.m* in sub-folder *Raytracer*. The *main.m* calls the *parameterCfg* function to import the system input parameters such as the number of nodes, the number of time steps, and the order of reflection from from files present in the *Input* folder and return them to the main file. The *main.m* also calls the *nodeProfileCfg* function to import the node profile information such as the node positions and velocities from files present in the *Input* folder and return them to the main file. The main file sends all the above mentioned input parameters to *Raytracer* function for further processing.

The *Raytracer* function first extracts the CAD information as shown in Fig. 9. Next, the first loop is to iterate through all the time steps. It is important to note that the node positions are updated for every iteration.

After that, a second nested loop is called, which iterates through all the node combinations. For every iteration, LOS ray is computed and its existence is verified. A third nested loop iterates through the order of reflection. Here, the backtracking algorithm and method of images are used to compute the rays. Once all the iterations are completed, the final output is stored in the folder *Output*.

The detailed description of each block used in NIST Q-D channel realization software is given in the following Sections.

3 Input (Block 1)

The first block of the NIST Q-D channel realization software is *Input*, which operates the system parameter configuration in *parameterCfg* function and the node profile configuration in *nodeProfileCfg* function.

The *parameterCfg* function is called to import several important system parameters as listed below from customized input configuration file *paraCfgCurrent.txt* in folder *Input* and includes them in structure *paraCfg* to return to the main file. If the *paraCfgCurrent.txt* does not exist, a default input configuration file *paraCfgDefault.txt* in folder *Input* will be used.

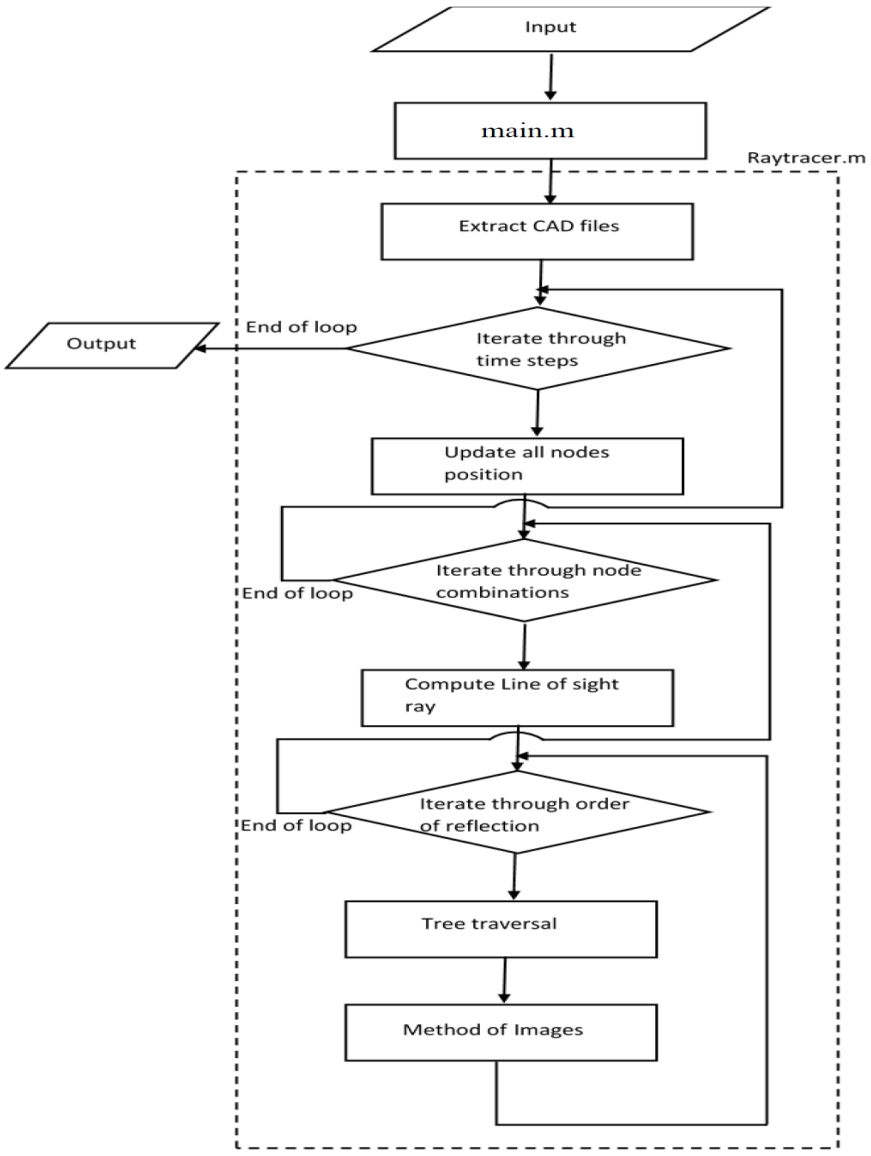

Input
main.m
Raytracer.m
Extract CAD files
End of loop
Output
Iterate through time steps
Update all nodes position
Iterate through node combinations
End of loop
Compute Line of sight ray
Iterate through order of reflection
End of loop
Tree traversal
Method of Images

Figure 9: Flowchart of raytracer.m

Specifically, the system input parameters imported through file *paraCfgCurrent.txt* are defined as members in structure *paraCfg* as described below.

1. ***environmentFileName*** - This parameter defines the file name of the environment to be setup in the system.

2. ***generalizedScenario*** - This parameter defines the generalized scenario flag

in the system. A generalized scenario is a scenario which cannot be classified as purely indorr or outdoor scenario. For instance, building where there are nodes both inside the building and outside the building. The default setting is *generalizedScenario* = 1.

3. ***indoorSwitch*** - This parameter defines indoor switch flag in the system. The default setting is *indoorSwitch* = 1.

4. ***inputScenarioName*** - This parameter defines customized input scenario name in the system. The user is required to enter this as string value when prompted via MATLAB command line.

5. ***mobilitySwitch*** - This parameter indicates whether mobility is present or not in the given scenario. If *mobilitySwitch* = 1 specifies that the nodes are mobile. On the other hand, *mobilitySwitch* = 0 specifies that the nodes are static or stationary.

6. ***mobilityType*** - This parameter defines the mobility model where *mobilityType* = 1 indicates linear mobility and *mobilityType* = 2 indicates custom mobility.

7. ***numberOfNodes*** - This parameter defines the number of nodes present in the network.

8. ***numberOfTimeDivisions*** - This parameter defines the total number of time steps. If *numberOfTimeDivisions* = 100 and *totalTimeDuration* = 10, then we have 100 time divisions for 10 seconds. Each time division is 0.1 secs in length.

9. ***referrencePoint*** - This parameter defines the referrence point of the center of limiting sphere. The default setting is *referrencePoint* = [3,3,2].

10. ***selectPlanesByDist*** - This parameter defines the selection of planes/nodes by distance. *selectPlanesByDist* = 0 means that there is no limitation (Default).

11. ***switchQDGenerator*** - This parameter indicates whether the diffuse[3] components are generated or not while generating the specular[4] components. If *switchQDGenerator* = 1 then diffuse components are generated with specular components otherwise only specular components are generated.

12. ***switchRandomization*** - This parameter indicates whether the location and velocity of each of the nodes are randomly generated or not. If *switchRandomization* = 1 then the locations and the velocities are generated randomly. On the other hand, if *switchRandomization* = 0 the locations and the velocities are imported from the files present in the *Input* folder.

13. ***switchVisuals*** - This parameter defines the switch visual flag for the system. The default setting is *switchVisuals* = 0.

14. ***totalNumberOfReflections*** - This parameter denotes the highest order of reflection considered in the model. For example, *totalNumberOfReflections* = 2 means the model considers the LOS, the first and the second order reflections. The default setting is *totalNumberOfReflections* = 2.

15. ***totalTimeDuration*** - This parameter defines the time period in seconds for which the simulation must run when the nodes are assumed to be mobile. The default setting is *totalTimeDuration* = 1.

Apart from the input system parameters mentioned above, there are three input files that are present in the *Input* folder, as shown in Fig. 10. These node profile config-

[3]The diffuse components are the secondary multipath components generated based on rough surface scattering model.

[4]The specular components are the primary multipath components which follow the law of reflection.

uration are imported via *nodeProfile* function called in *main* file, including in structure *nodeCfg* to return to the *main.m*, along with an updated *paraCfg* at meantime. It is important to note that these files are not needed when the nodes are generated randomly when *switchRandomization* = 1 in *parameterCfg* function and *main* file.

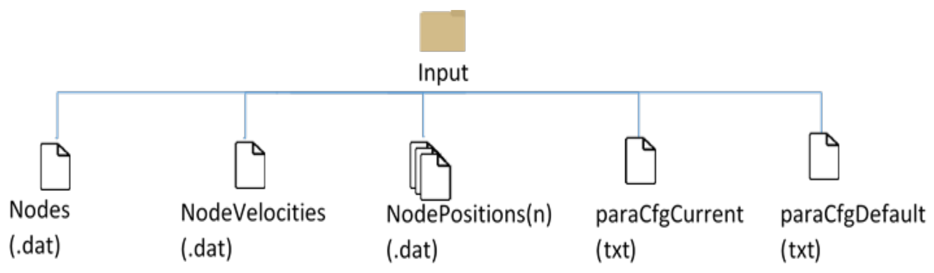


Figure 10: Files in *Input* folder.

The five input files that are present in the *Input* folder are described below.

1. ***nodes.csv*** - Each row in this file contains the (x, y, z) coordinate of the node. If the number of nodes is N, this file must have N rows.

2. ***nodeVelocities.csv*** - Each row in this file contains the node velocities in x, y and z directions. For N nodes, this file must have N rows. This file is needed only for linear mobility model when *mobilityType* = 1.

3. **NodePosition(n).csv** - In addition to *nodes.csv* and *nodeVelocities.csv*, the *Input* folder also contains the set of files named as *NodePosition1.csv*, *NodePosition2.csv*, upto *NodePositionN.csv* where N is the number of nodes. Each of the file contains the *numberOfTimeDivisions + 2* rows in the format of (x, y, z) indicating the positions of the particular node for the duration *totalTimeDuration*, where ith row indicates the position at $(i-1)$ time step. This file is needed only for custom mobility model when *mobilityType* = 2.

Regarding the *Input* block, It is important to note that:

1. Create or enter the existed scenario name to process at command line. The user can enter any scenario name without space to indicate the type;

2. Always configurate all parameters in paraCfgCurrent.txt of the customized scenario folder, i.e. *QDSoftware*\CUSTOMIZEDSCENARIO\Input\paraCfgCurrent.txt; if this *paraCfgCurrent.txt* file is not existed in this folder, the *paraCfgDefault.txt* will be load as default setting;

3. The *QDSoftware*\Input\\ folder includes the source file of input data, it should be kept in root folder as always. Unless the user create the new scenario folder manually, every new scenario created by script will copy the input data automatically to it's folder from *QDSoftware* \Input, including the *paraCfgCurrent.txt* and *paraCfgBackup.txt* as a reference.

4 CAD Data Extraction (Block 2)

4.1 CAD Format

CAD file consists of geometrical information of a given scenario. These geometrical properties can be represented as point clouds, lines, and/or polygons. In NIST Q-D channel realization software, AMF file format is used as the standard-form of input CAD file format. AMF is a file format that is like STL format i.e., geometrical structures are represented in terms of triangles only. In addition to geometrical properties, AMF file format can also store material properties of each triangle. AMF file format is an XML based format and for a detailed description, please refer to [7]. The output of the CAD data extraction block would be the set of triangles which are described by the vertices in x, y, z format and the material properties.

For example, a cube has 6 sides and it is represented as a set of 12 triangles. Once we extract the three vertices of a triangle, we can construct its plane equation.

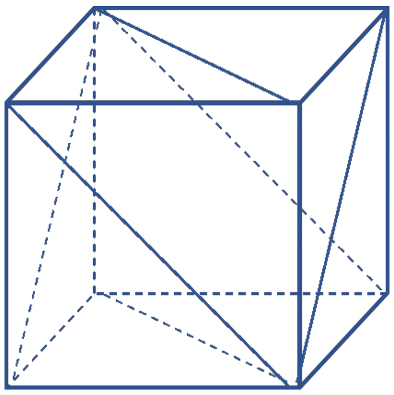


Figure 11: Cube in AMF file format described by 12 triangles.

4.2 Code Structure

Three functions *RayTracer.m*, *XmlReader.m* and *Xml2Struct.m* are used to extract the CAD information. *Raytracer.m* is the function which calls *XmlReader.m* function as shown in flow chart in Fig. 12. *XmlReader.m* takes *IndoorSwitch*, *MaterialLibrary*, r and reference point as input parameters where *IndoorSwitch* defines how the normal is oriented. Normal of a triangle either comes out of the plane (vertices defined in clockwise direction using right hand rule) or into the plane (vertices are in anti-clockwise direction using right hand rule). *MaterialLibrary* is a table which has the material properties. The quantity r and the reference point denote the radius of limiting sphere and the center of the limiting sphere, respectively. These parameters are also described in section 4.3. in detail. The MATLAB *Xml2Struct.m* function extracts the Xml data and converts it into a struct variable s. The struct variable s is arranged in such a way that the triangles and the corresponding vertices are stored in a chronological order. We iterate through all the triangles and search if the material is present in the material

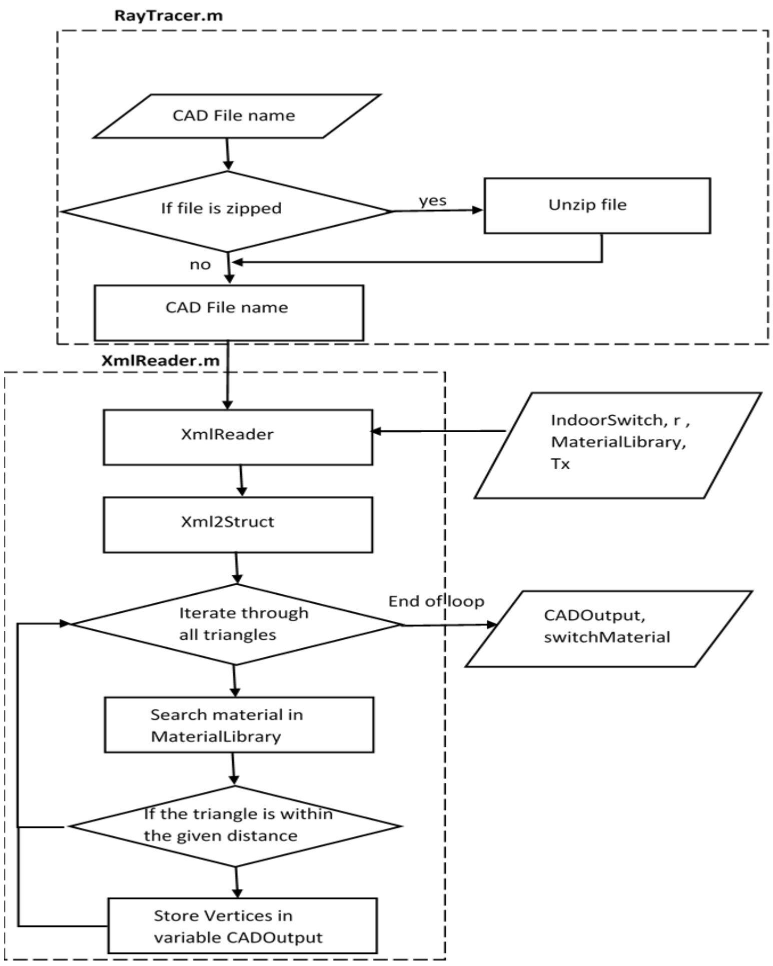
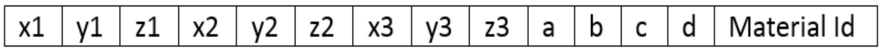

RayTracer.m
CAD File name
If file is zipped
yes
Unzip file
no
CAD File name
XmlReader.m
XmlReader
IndoorSwitch, r , MaterialLibrary, Tx
Xml2Struct
Iterate through all triangles
End of loop
CADOutput, switchMaterial
Search material in MaterialLibrary
If the triangle is within the given distance
Store Vertices in variable CADOutput

Figure 12: Flow chart of CAD extraction

library or not. If it is present, then it is associated with the triangle. The information of the triangles is finally stored in *CADOutput* variable. The *CADOutput* variable is a 2D array with 14 columns and the number of rows that is equal to the number of triangles. One row of *CADOutput* variable is shown in Fig. 13.



x1	y1	z1	x2	y2	z2	x3	y3	z3	a	b	c	d	Material Id

Figure 13: A row of *CADOutput* variable

For the first 9 columns, x1, y1, z1 are x, y, z coordinates of 1st vertex of the triangle;

x2, y2, z2 are x, y, z coordinates of 2nd vertex of the triangle, and x3, y3, z3 are x, y, z coordinates of 3rd vertex of the triangle. A plane equation is given as $ax+by+cz+d = 0$. The variables a, b, c, d in the columns 10 to 13 are x, y, z coefficients and the constant, respectively. The variable 'Material Id' in last column helps in identifying the material associated with the triangle.

4.3 Omitting Triangles based on Distance from a Reference Point

The function *distanceLimitation.m* is used to omit the triangles which are far from the defined reference point. This is because the rays associated with the triangles would have very large path loss, which does not contribute significantly in the total received power. If we consider these triangles, it would also increase the computational time significantly. The problem statement is now to find the triangles which contribute significantly in the total received power. This can be done by intersecting the triangles and the sphere[5] of radius r considering the reference point as the center of the sphere. The triangles that intersect the sphere are considered while eliminating others. There are three possible cases in which a triangle intersects the sphere and are described below.

Case 1 : Either of the three vertices are within the sphere

To know whether the triangle intersects with the sphere, we measure the distance between each vertex and the center of the sphere. If at least one distance is less than or equal to the radius of the sphere, then the triangle lies within the sphere as shown in Fig. 14.

Case 2 : A triangle whose vertices lie outside the sphere and the projection

[5]Sphere is the locus of all points whose distance (radius) from a given point (center is the reference point) is constant.

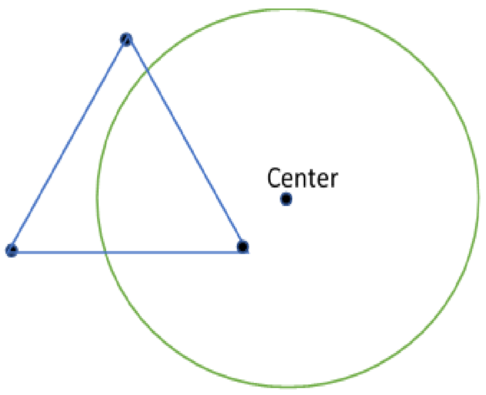


Figure 14: Case 1: Either of the three vertices are within the sphere.

of the center of the sphere onto the plane containing the triangle lies within triangle

When the distance between the center and projected point is less than or equal to radius, then the triangle lies within the sphere as shown in Fig. 15.

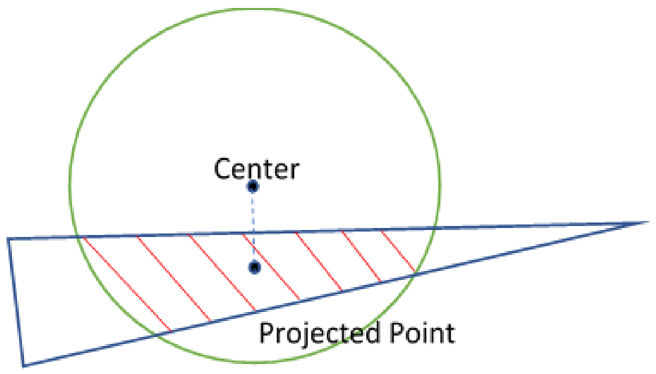


Figure 15: Case 2 : A triangle whose vertices lie outside the sphere and the projection of the center of the sphere onto the plane containing the triangle lies within triangle.

Case 3 : A triangle whose vertices lie outside the sphere and the projection of the center of the sphere onto the plane containing the triangle lies outside triangle

The perpendicular distance[6] of center of the sphere to each of the three sides is

[6]Using the Pythagoras theorem, the perpendicular distance of center of the sphere from each of the

calculated. If this perpendicular distance is less than or equal to the radius of the sphere, then the triangle lies within the sphere as shown in Fig. 16.

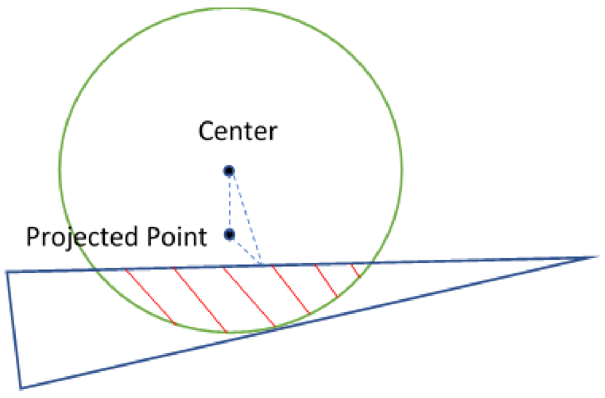


Figure 16: Case 3 : A triangle whose vertices lie outside the sphere and the projection of the center of the sphere onto the plane containing the triangle lies outside triangle.

5 Backtracking Algorithm (Block 3)

Backtracking is an algorithm for finding all possible solutions of a specific problem, such that the candidates are incrementally built while candidates without a solution are abandoned [8, Pages 272-275]. Depth first search algorithm can be used for finding all the possible permutations. This an be done by constructing a recursive tree of permutations. A set of entities form the first generation in this tree. Let this set consists of three numbers say 1,2,3. For every element in the first generation, the entire set becomes the second generation. This recursively takes place until the nth generation. Every path that traverses from the first generation to the last generation gives one combination. A recursive tree of permutations of 3 generations for a set 1,2,3 is shown in the Fig.17.

Backtracking algorithm is a slight modification this depth first search. At every

sides can be calculated as the square root of the sum of square of projected distance and perpendicular distance of projected point to the side.

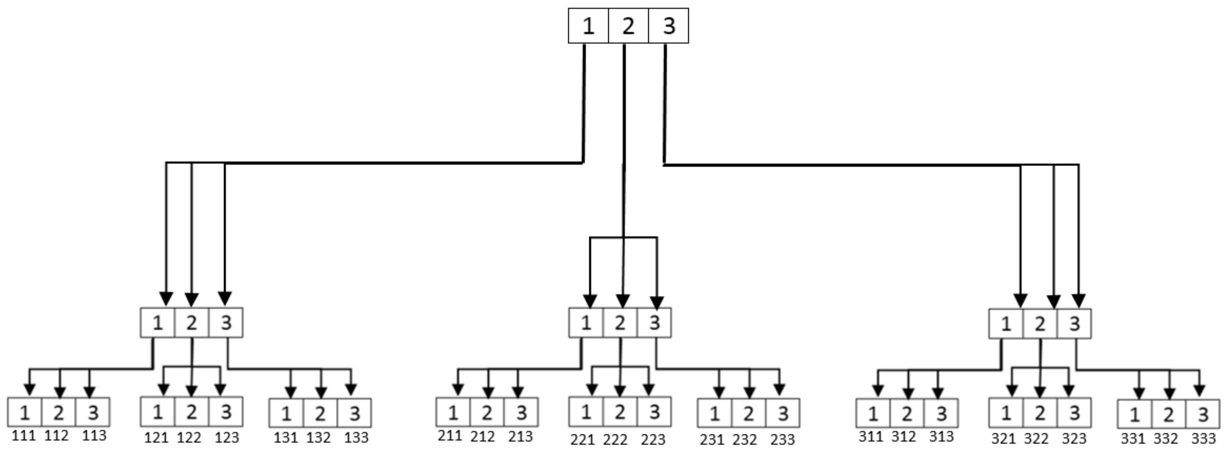


Figure 17: A recursive tree of permutations of 3 generations for a set 1,2,3. The last line is the combinations after traversing through every path.

traversal, the algorithm checks for a given condition and if it fails then the subsequent traversal through that last node is avoided.
Rather than performing raytracing on every possible combination of reflecting surfaces, it would be computationally efficient to remove the combinations where reflection is impossible. This can be done using the backtracking algorithm [8]. Once the information from CAD file is extracted, i.e. the triangles and plane equations, the information must be processed such that the reflections can be computed. For a reflection to occur, a ray must be incident on the face of the triangle. For an nth order reflection, the ray reflects n times from triangles (not necessarily distinct).

All the triangle combinations are to be computed to get reflected rays. Tx is the first node of the tree and Rx is the last node of the tree. The entire set of triangles extracted from the CAD file is the second generation while Tx is the parent node. For each element in second generation, the child nodes are again a complete set of triangles.

This carries on n number of times that is equal to the order of reflection. In the last generation all nodes end at Rx. Backtracking algorithm is the third block. Once the information is extracted from the CAD file and stored in CADOutput variable (output of block 2), backtracking is performed on this variable. All the possible permutations are generated where there could be a possible reflection. An illustrative example to explain this method is described below:

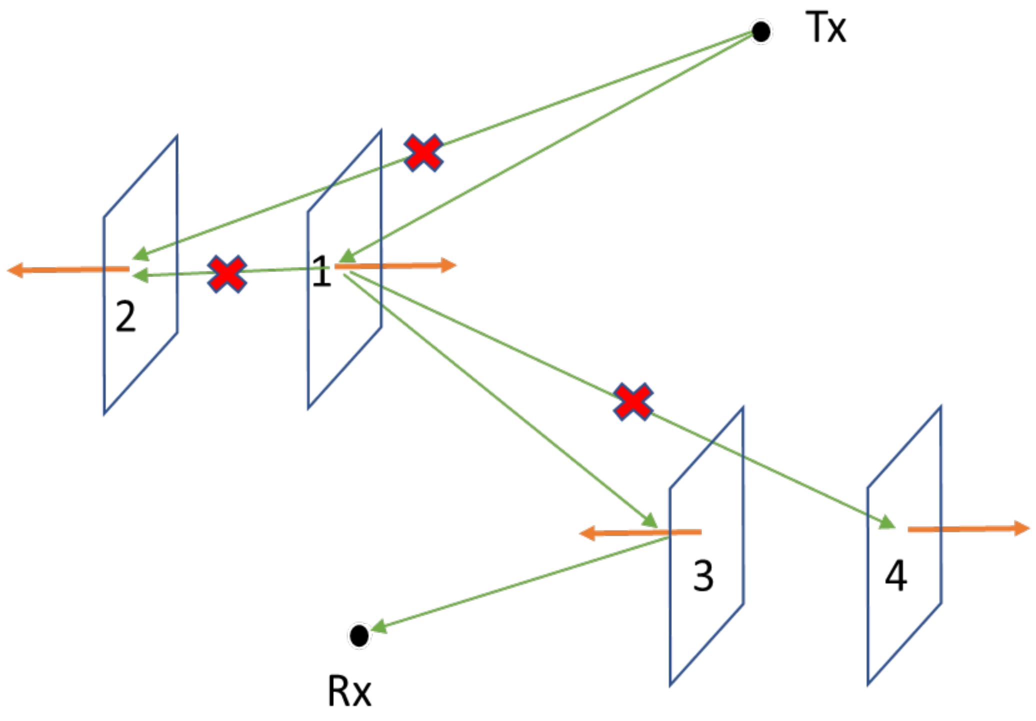


Figure 18: A scenario with 2 planes and a pair of transmitter and receiver.

An illustrative example to explain this method is described below:

Step 1: Tx is the first node or parent node of the tree as seen in Fig .18.

Step 2: Rx is the last node of the tree as seen in Fig. 18.

Step 3: The first generation of child nodes is the complete set of planes (CADop). The next generation of each child node is the complete set of planes as seen in Fig. 18.

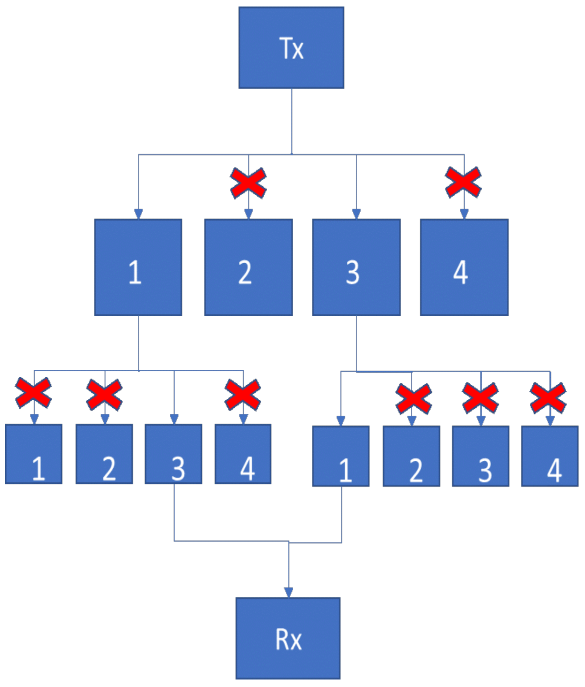


Figure 19: Tree describing the backtracking algorithm.

Step 4: A link does not exist between first generation '1' plane and second generation '1' plane, because a ray cannot exist between the same plane. Such cases are eliminated as seen in Fig. 19.

Step 5: A link does not exist two planes facing away from each other or when they have same plane equation or when dot product is negative. Such cases are eliminated. In the above example we consider that a ray cannot exist between planes 1 & 2 & 4, Tx & planes 2,4 and Rx & plane2,4.

Step 6: The final output is the set of all the possible permutations.

Complexity: the worst-case scenario is n^m where n is the number of planes and m is the highest of reflection.

5.1 Code Structure

Backtracking algorithm is implemented using two functions *Treetraversal.m* and *VerifyTreeTraversalPath.m*. *CADOutput* is a variable that is the output of previous step i.e. CAD information. A loop is run to iterate through all *CADOutput* rows. This means that we are iterating through all the triangles present in the CAD file. At every iteration, the possibility of ray is probed. If a ray cannot exist, then we move on to next iteration. If the ray can exist, then variables *ArrayOfPlanes, ArrayOfPoints* and *ArrayOfMaterials* are populated. *ArrayOfPlanes* contains the plane equations of the triangles, *ArrayOfPoints* contains the vertices of the triangles and *ArrayOfMaterials* contains the material properties of the triangle. For more information please visit the code *Treetraversal.m.* Once the variables are populated we recursively perform the same task until the recursion is performed a number of times that is equal to order of reflection.

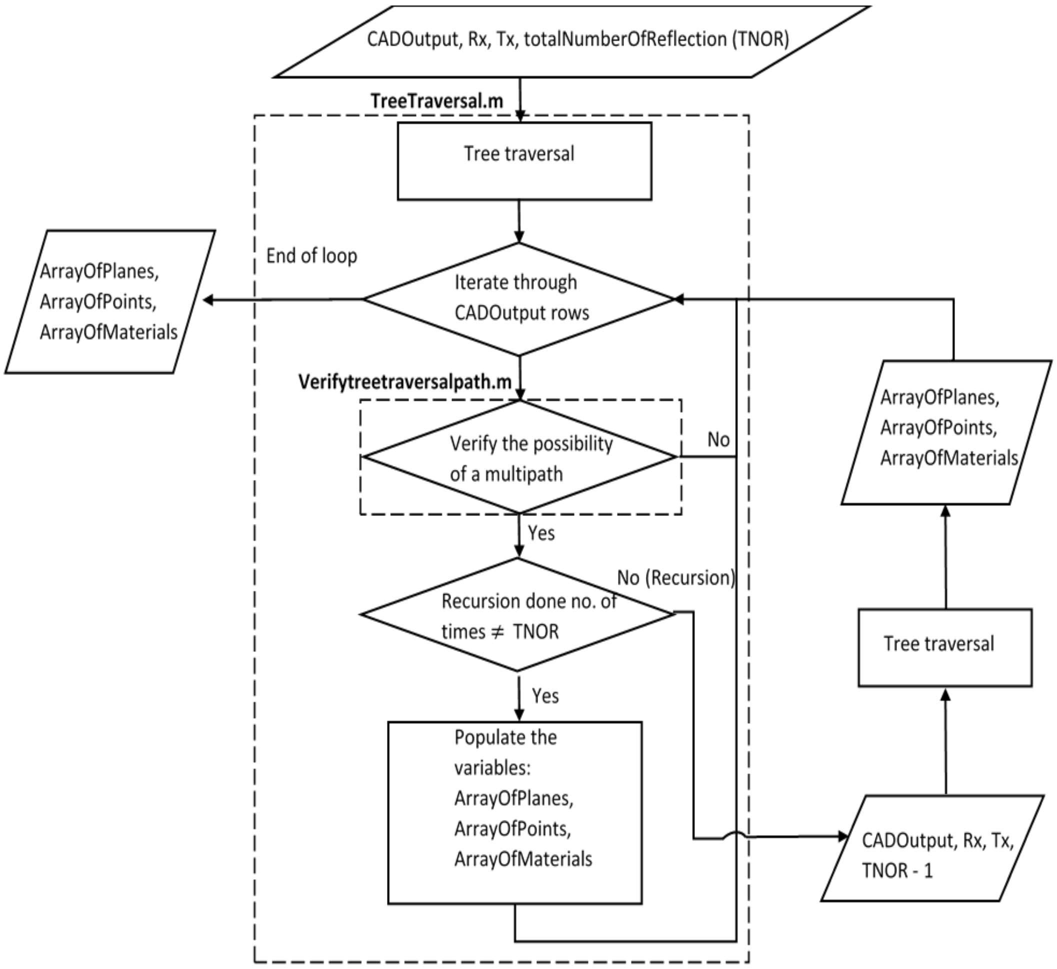

CADOutput, Rx, Tx, totalNumberOfReflection (TNOR)
TreeTraversal.m
Tree traversal
End of loop
Iterate through CADOutput rows
ArrayOfPlanes, ArrayOfPoints, ArrayOfMaterials
Verifytreetraversalpath.m
Verify the possibility of a multipath
No
Yes
No (Recursion)
Recursion done no. of times ≠ TNOR
Yes
Populate the variables: ArrayOfPlanes, ArrayOfPoints, ArrayOfMaterials
CADOutput, Rx, Tx, TNOR - 1
Tree traversal
ArrayOfPlanes, ArrayOfPoints, ArrayOfMaterials

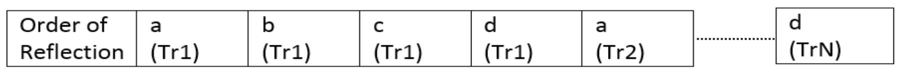
Figure 20: Flow chart of backtracking algorithm.

The variables *ArrayOfPlanes, ArrayOfPoints* and *ArrayOfMaterials* are described in the below diagrams.

Tr1 (x1)	Tr1 (y1)	Tr1 (z1)	Tr1 (x2)	Tr1 (y2)	Tr1 (z2)	Tr1 (x3)	Tr1 (y3)	Tr1 (z3)	Tr2 (x1)	....	TrN(z3)

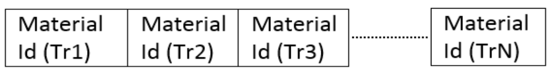
Figure 21: A row of *ArrayOfPoints* variable.

Tr1, Tr2 . . . TrN are the set of triangle combinations. *N* is equal to the order of reflection. *x1,y1,z1* are x,y,z coordinates of 1st vertex of the triangle; *x2,y2,z2* are x,y,z coordinates of 2nd vertex of the triangle and *x3,y3,z3* are x,y,z coordinates of 3rd vertex



Order of Reflection	a (Tr1)	b (Tr1)	c (Tr1)	d (Tr1)	a (Tr2)	......	d (TrN)

Figure 22: A row of *ArrayOfPlanes* variable.



Material Id (Tr1)	Material Id (Tr2)	Material Id (Tr3)	......	Material Id (TrN)

Figure 23: A row of *ArrayOfMaterials* variable.

of the triangle. A plane equation is given as ax + by + cz + d =0. *a,b,c,d* are x,y,z coefficients and the constant respectively, which describe the plane equation.*Material Id* helps in identifying the material associated with the triangle.

6 Method of Images (Block 4)

The method of images is a geometrical optics method. According to geometrical optics, a light ray travels in straight lines whose length is the least distance between two points. This is called as *Fermat's principle* [9, Pages 134 - 141]. In case of reflection, the path length of the ray should be minimum between two points while the ray is incident on a plane surface. This problem is also known as *Heron's Problem* [10]. This problem can be solved by taking the image P1' of a point P1 on to the plane surface R and connecting the other point P2 to this image via a line. The intersection point M of this line and plane is again connected to the point P1. The method of images is a raytracing

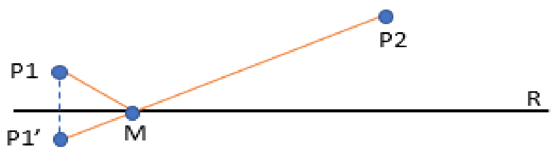


Figure 24: Reflected path between points P1, P2 and reflecting plane R.

technique that provides an exact solution as opposed an approximate solution based on trial and error , such as shoot and bounce (MOM). The method of images, however, can be used for reflections only whereas. other methods such as shoot and bounce can be used to compute diffraction and refraction as well [6]. Once the set of permutations of planes are computed, then the raytraced path for every permutation is computed using the method of images.

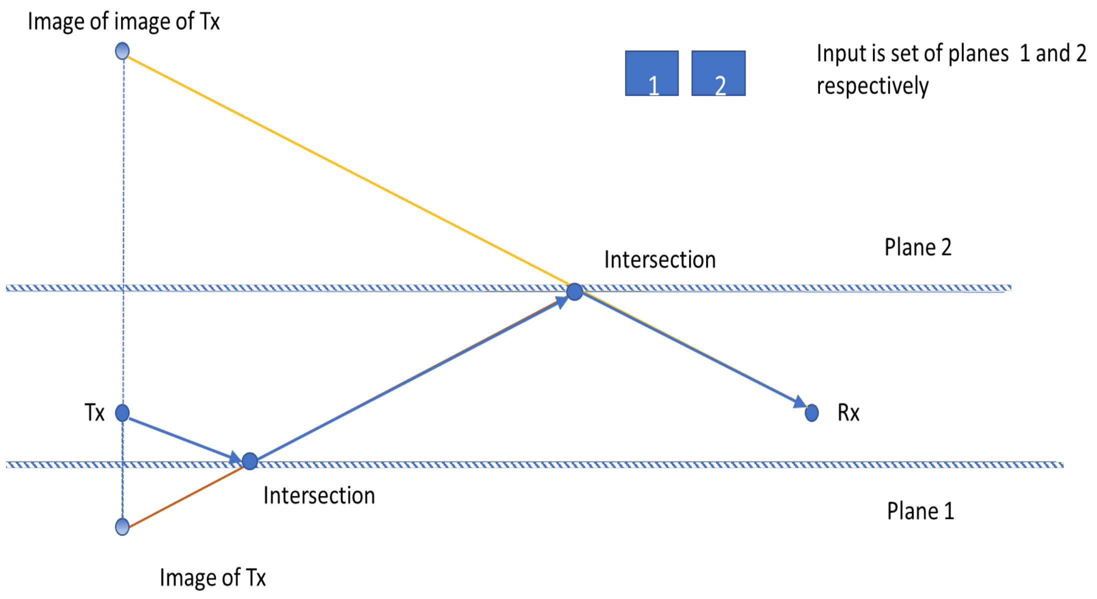


Figure 25: Scenario with an input of two planes.

Here is an illustrative example

Step 1: The input of Tx and Rx locations are imported. The input of the set of planes are also imported.

Step 2: The image of Tx in Plane 1 is computed. This is the first recursion.

Step 3: The image of image of Tx in plane 2 is computed. This is the second recursion.

Step 4: The vector joining image of image of Tx and Rx is computed. The length of this vector is path length.

Step 5: The intersection of this vector with plane 2 is the point of incidence on plane

2 for the ray. By connecting Intersection and Rx, we get DoA vector.

Step 6: The intersection and Image of Tx is connected, which gives a vector. The intersection of this vector with plane 1 is computed.

Step 7: The intersection on plane 1 is connected to intersection on plane 2, forming a vector. This vector is part of the ray.

Step 8: The Tx is connected to Intersection on plane 1. This gives DoD vector.

Complexity: n^m is the complexity to traverse through all the permutations of planes as described in tree traversal. There are $m + 1$ vectors generated and each vector is verified if it intersects a plane. It takes n^{m+1} steps. So total complexity is n^{2m+1}.

6.1 Code Structure

Method of images is implemented using *multipath.m, singlepathgenerator.m* and *LOSOutputgenerator.m.* Another function *verifyPath.m* is crucial for the functioning of Method of Images code. *LOSOutputgenerator.m* is a simple function which computes the line of sight (LOS) path. This is done by connecting *Tx* and *Rx* and checking if it doesnot pass through any of the obstacles using verifyPath.m.

multipath.m generates all the possible rays for a given *Tx, Rx* and order of reflection. It iterates through the output of tree traversal part of the code i.e., *ArrayOfPlanes* and *ArrayOfPoints.* A single row of *ArrayOfPlanes* and *ArrayOfPoints* is taken and passed through the *singleMultipathGenerator.m* to get a single ray. Once we get the ray we compute delay, gain, AoA, AoD and phase. Q-D model is applied to individual rays i.e. the output of *singleMultipathGenerator.m. singleMultipathGenerator.m* is the function where actual method of images is used. The input is received from *multipath.m.* Next step is to extract the plane equations and images of *Tx* along these extracted planes. *singleMultipathGenerator.m* is recursively called 'order of reflection' number of times.

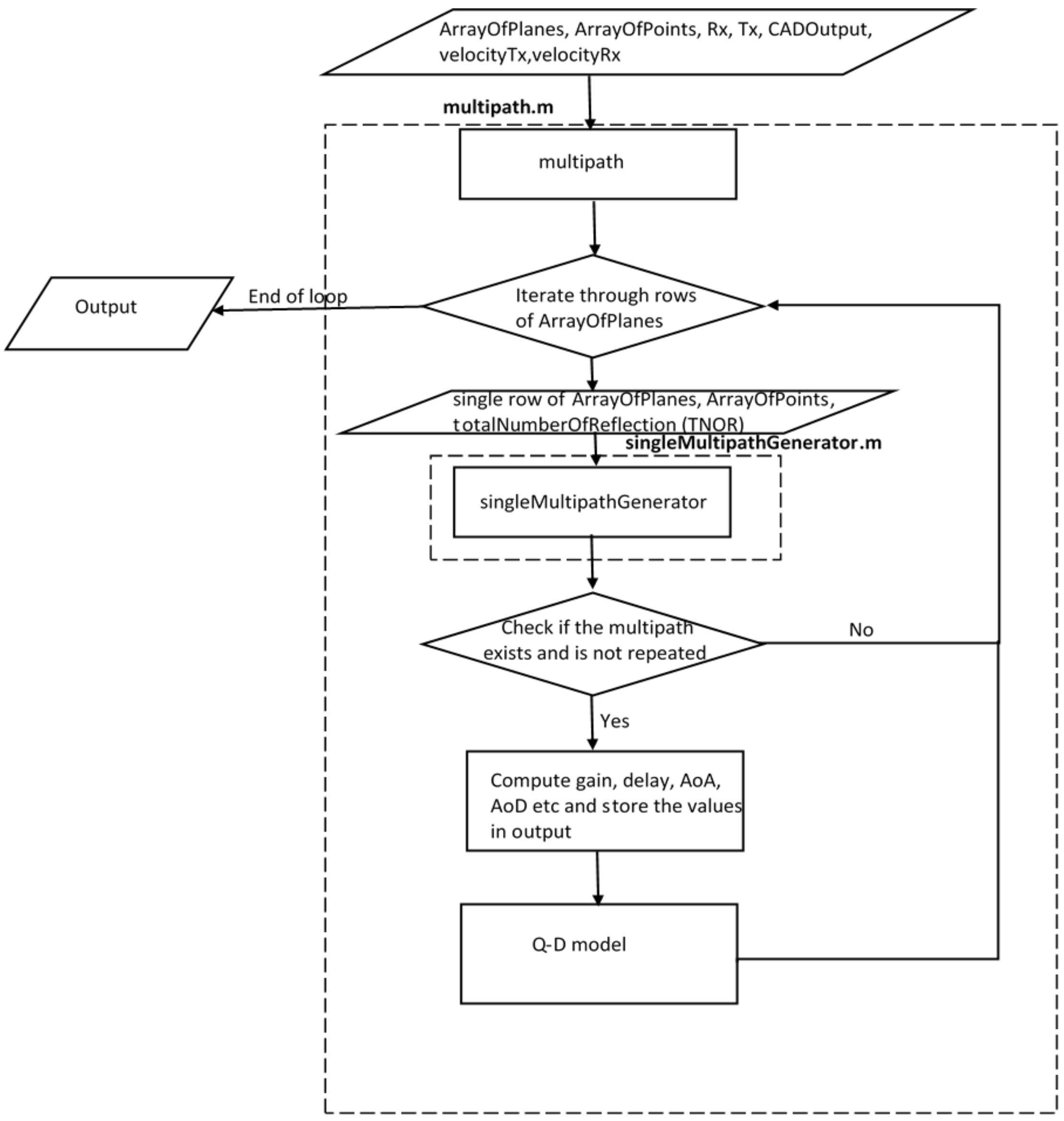

ArrayOfPlanes, ArrayOfPoints, Rx, Tx, CADOutput, velocityTx,velocityRx
multipath.m
multipath
Iterate through rows of ArrayOfPlanes
End of loop
Output
single row of ArrayOfPlanes, ArrayOfPoints, totalNumberOfReflection (TNOR)
singleMultipathGenerator.m
singleMultipathGenerator
Check if the multipath exists and is not repeated
No
Yes
Compute gain, delay, AoA, AoD etc and store the values in output
Q-D model

Figure 26: Flow chart of *multipath.m*.

The final image of *Tx* is then connected to the *Rx*. This forms the Direction of departure (DoD). We also get path length in this step. In the next step, we compute the point where this DoD intersects with the plane where reflection has happened. We dynamically allocate DoA. So, in the end recursion DoA is assigned the value of DoD. We check if DoA intersects with any other triangles in the CAD file using *verifyPath.m*. If the path exists, then we exit this recursion and we enter the function

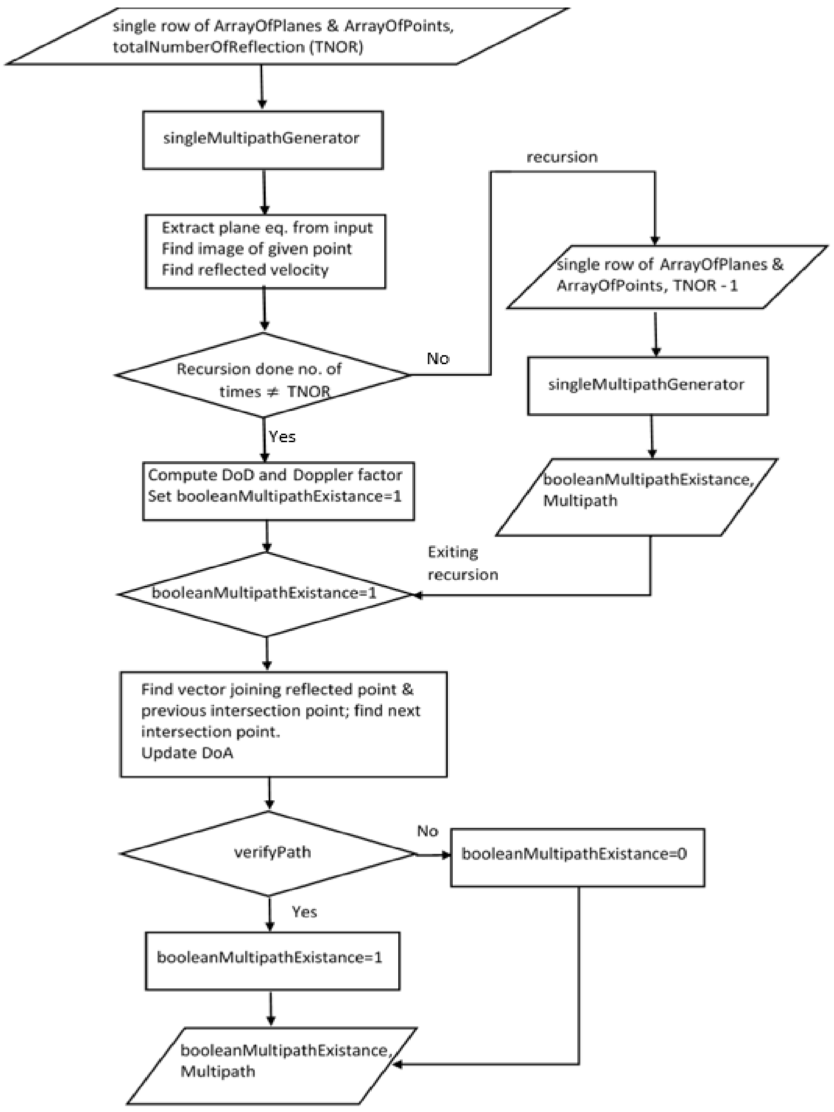

single row of ArrayOfPlanes & ArrayOfPoints, totalNumberOfReflection (TNOR)
singleMultipathGenerator
Extract plane eq. from input
Find image of given point
Find reflected velocity
Recursion done no. of times ≠ TNOR
No
recursion
single row of ArrayOfPlanes & ArrayOfPoints, TNOR - 1
singleMultipathGenerator
Yes
Compute DoD and Doppler factor
Set booleanMultipathExistance=1
booleanMultipathExistance, Multipath
Exiting recursion
booleanMultipathExistance=1
Find vector joining reflected point & previous intersection point; find next intersection point.
Update DoA
verifyPath
No
booleanMultipathExistance=0
Yes
booleanMultipathExistance=1
booleanMultipathExistance, Multipath

Figure 27: Flow chart of *singleMultipathGenerator.m*.

which recursively called the previous function. DoA is again calculated by joining the intersection point which was calculated in the previous call and the reflected image obtained in the present function. We check if this DoA does not intersect with any other triangles. Thus, these functions are recursively exited. In the end, a single ray is generated.

Based on the single ray, we can compute the gain, delay, AoA, AoD and phase.

Delay is obtained by dividing path length by speed of light. Gain is computed using Friis transmission formula and the path length. AoA and AoD are computed by knowing the coordinates of DoA and DoD vectors in spherical coordinate system. The theta and phi of DoA and DoD correspond to AoA and AoD respectively. For every reflection a phase of 180 degrees is added. These values are stored in Output variable.

7 NIST Q-D Model (Block 5)

Q-D model is a rough surface scattering model developed at NIST based on measurements. The rays computed by method of images are the specular(deterministic) rays. These rays are actual multipath between Tx and Rx. There are secondary rays which are produced due to the scattering of the deterministic reflected rays from objects. These are called as *diffuse* components. They cluster around the reflected rays and are accounted for through the stochastic properties of the clusters such as angular spread, delay spread, etc.

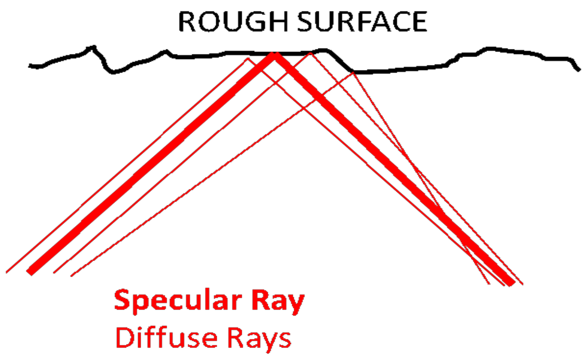


Figure 28: Rough surface scattering of specular ray (thicker red line).

Every cluster is composed of a specular component and multiple diffuse components. K factor is defined as the ratio of specular power to the sum of diffuse power. The powers of diffuse components exponential decrease from the specular component.

This rate of decrease is given by γ. K factor gives a notion of how much power is scattered. The delay spread can be characterized using Poisson distribution. This Poisson distribution's mean and variance is denoted by λ. Angular spread follows a Laplacian distribution whose mean is given by the specular component's angle and variance is given by Θ. K factor, γ, λ, Θ and reflection loss can be randomly generated using normal distribution which is characterized by a mean and standard deviation.

7.1 Code Structure

In this software, a total of 20 diffuse MPCs are generated for every deterministic ray. Th e diffuse components are further divided into precursor and postcursor components. Precursor components arrive before deterministic component and postcursor components arrive after deterministic component. There are 3 precursor components and 17 postcursor components. The rationale behind choosing 3 precursor components is that the precursor components are far lesser in number. Also, the probability of a precursor arriving earlier than the main cursor decreases rapidly as its difference from main cursor increases. The rationale behind choosing 17 post cursor components is that the power of post cursors becomes insignificant enough to be neglected.

Material library's attributes are given below:

PrimaryKey – This is the row number of the table. Throughout the code, this serves as Material Id.

Reflector – This is the name of the material.

sigma_k_Precursor – This is the standard deviation of K factor for precursors.

mu_k_Precursor – This is the mean of K factor for precursors.

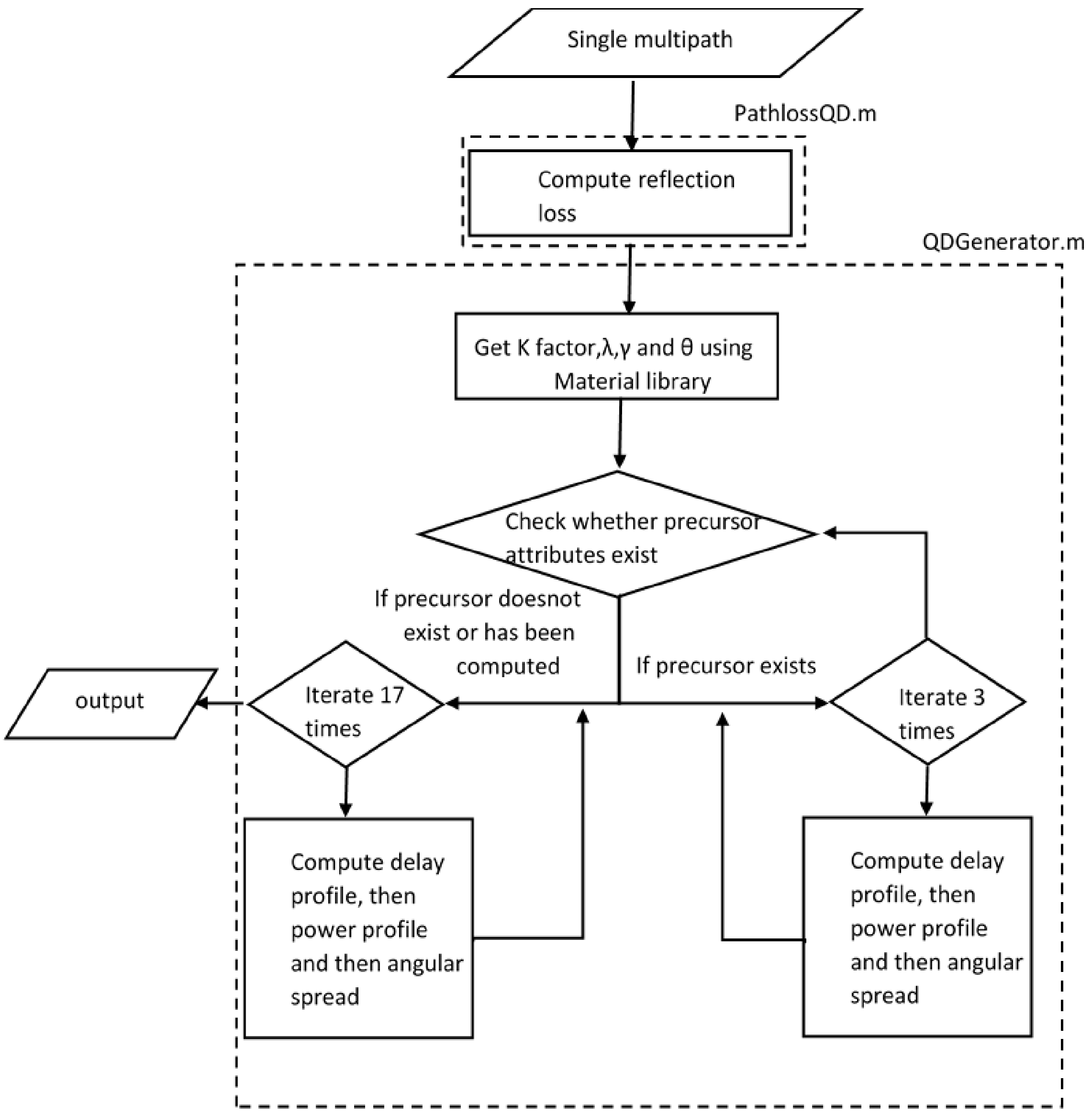

Single multipath
PathlossQD.m
Compute reflection loss
QDGenerator.m
Get K factor,λ,γ and θ using Material library
Check whether precursor attributes exist
If precursor doesnot exist or has been computed
If precursor exists
Iterate 17 times
Iterate 3 times
output
Compute delay profile, then power profile and then angular spread
Compute delay profile, then power profile and then angular spread

Figure 29: Flow chart of Q-D model.

sigma_k_Postcursor – This is the standard deviation of K factor for postcursors.

mu_Y_Postcursor – This is the mean of γ for postcursors.

sigma_Y_Precursor – This is the standard deviation of γ for precursors.

mu_Y_Precursor – This is the mean of γ for precursors.

sigma_Y_Postcursor – This is the standard deviation of γ for postcursors.

mu_lambda_Precursor – This is the mean of λ for precursors.

sigma_lambda_Precursor – This is the standard deviation of λ for precursors.

mu_lambda_Postcursor – This is the mean of λ for postcursors.

sigma_lambda_Postcursor – This is the standard deviation of λ for postcursors.

mu_sigmaTheta – This is the mean of Θ.

sigma_sigmaTheta – This is the standard deviation of Θ.

mu_RL – This is the mean of reflection loss.

sigma_RL – This is the mean of reflection loss.

DielectricConstant – This is the dielectric constant of the material.

8 Output (Block 6)

The final output consists of ray's attributes namely path loss, delay, phase, AoA, AoD at every time step and node combination. Output consists of node postions at every time step. Output also consists of files which aid in visualizing the rays. Ouput files are generated and saved in the *Output* folder. *Output* folder further contains two folders: *Ns3* and *Visualizer*.

Ns3 further has 2 folders- *NodesPosition* and *QdFiles*.

1. ***NodesPosition*** - this folder consists of *NodesPosition.txt* file. The file contains the node postions at first time interval. This is equivalent to *nodes.csv* file in Input folder.

2. ***Qdfiles*** - this folder consists of *Tx(i-1)Rx(j-1).txt* trace files for ith and jth node that will used as input for NS-3. The file format is:

   (a) number of rays occupies the first row

   (b) Delay of each ray is stored in the second row

   (c) pathGain of each ray is stored in third row

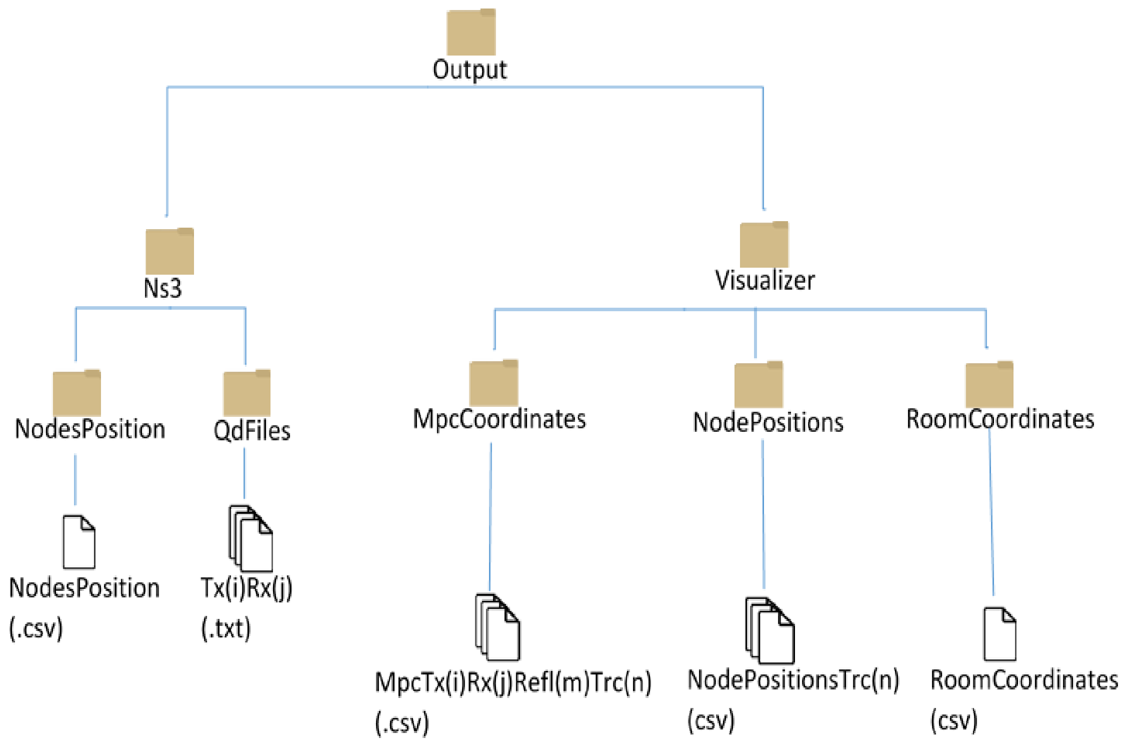


Figure 30: File Structure of Output.

(d) phase offset of each ray is stored in fourth row

(e) Angle of Departure, Elevation of each ray is stored in fifth row

(f) Angle of Departure, Azimuth of each ray is stored in sixth row

(g) Angle of Arrival, Elevation of each ray is stored in seventh row

(h) Angle of Arrival, Azimuth of each ray is stored in eighth row

This format is repeated for every time instance if mobility is present. This means ninth row will be number of rays, tenth row will be delay of each ray and so on.

Visualizer has 3 folders - *Coordinates, NodePositions and Roomcoordinates*

1. ***MpcCoordinates*** - this folder contains multiple files whose nomenclature is given by *MpcTx(i-1)Rx(j-1)Refl(m)Trc(n).csv.* Here i and j are nodes, m is the

order of reflection and n is the number of time instance. In the file, the first column gives the order of reflection. The number of columns after the first column is 3*(m+2), where m is order of reflection. The 2-4 columns are one of the node positions x,y,z parameters and the last three columns are the other node positions x,y,z. The rest of the unmentioned column are points of intersections. To model the ray, one has to simply connect the points in columns 2-4 to that of the columns in next three columns. The point in this set of three columns must be connected to the next three columns. This must be repeated until the last three columns.

2. ***NodePositions*** - this folder consists of *NodePositionsTrc(n).csv* files - these are the node positions of nth time instance. These files are equivalent to *nodes.csv* file in Input folder.

3. ***RoomCoordinates*** - this folder consists of RoomCoordinates.csv file. This file has coordinates of the CAD file used. In our case, it is a room. The format for *RoomCoordinates.csv* is described by a 2D array. Each row represents a triangle. Each row is given as follows:

   x1,y1,z1,x2,y2,z2,,x3,y3,z3

   where x1,y1,z1 are x,y,z coordinates of 1st vertex; x2,y2,z2 are x,y,z coordinates of 2nd vertex and x3,y3,z3 are x,y,z coordinates of 3rd vertex.

9 Helper Functions

Raytracer folder has a total of 31 functions. *Raytracer.m* is the main function. There are 9 functions dedicated to CAD Data Extraction out of which 3 are dedicated to Mobility. 2 functions are dedicated to Backtracking algorithm. There are 3 functions dedicated to Method of Images. There are 17 helper functions in this code.

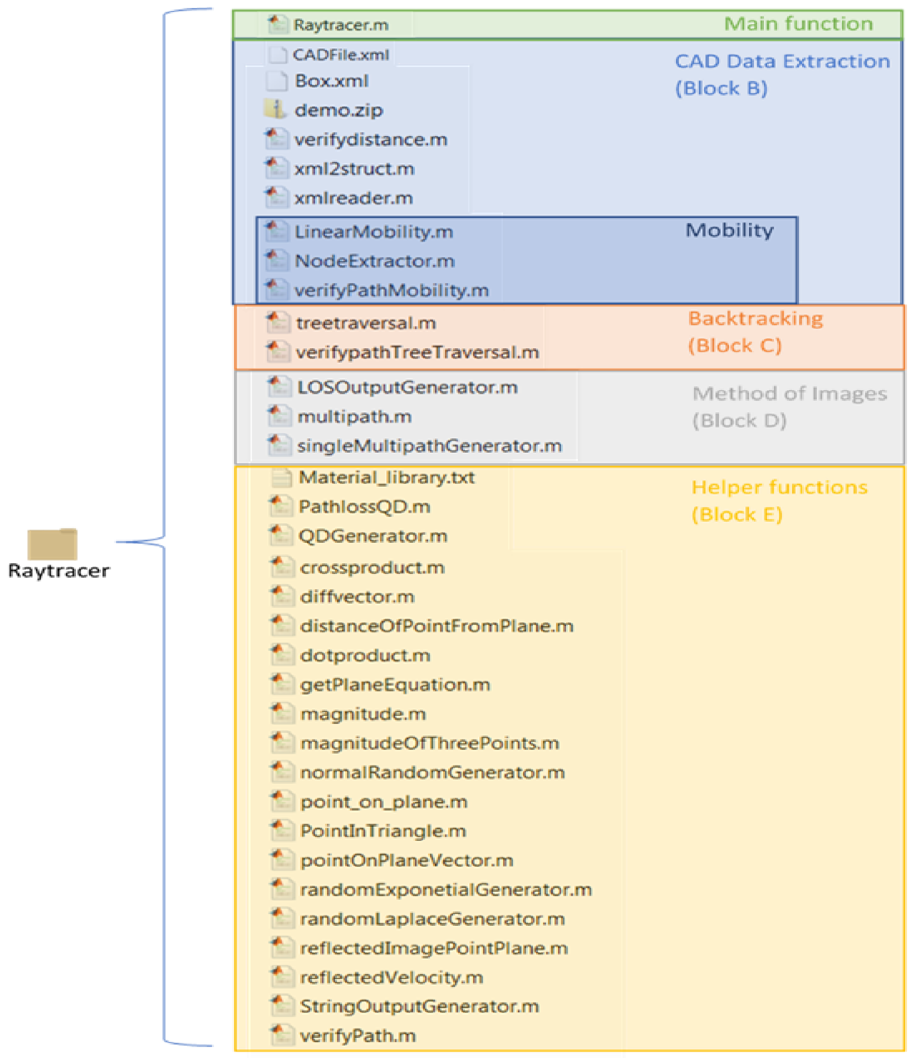


Figure 31: Files present in Raytracer folder.

A brief description for each of these functions is given below:

- ***crossproduct.m*** : This function returns the cross product between two vectors.
- ***diffvector.m*** : This function returns the difference vector between two position vectors (points).

- ***distanceOfPointFromPlane.m*** : This function returns the normal distance of a point from a plane.
- ***dotproduct.m*** : This function gives the dotproduct between two vectors.
- ***getPlaneEquation.m*** : This function constructs a plane equation when normal and a point on plane are given.
- ***magnitude.m*** : This function returns the magnitude of a vector.
- ***magnitudeOfThreePoints.m*** : This function returns magnitude of the position vector of a point in 3D space (Hence 3).
- ***normalRandomGenerator.m*** : This function generates a random number using normal distribution
- ***point_on_plane.m*** : This function calculates the projection of a point on to plane, by constructing a vector passing through the point along plane's normal.
- ***PointInTriangle.m*** : This function verifies whether the point lies in the triangle using barycentric coordinate system.
- ***pointOnPlaneVector.m*** : This function returns the intersection of a vector with plane. The point in input is the through which vector passes.
- ***randomExponetialGenerator.m*** : This function generates a random number using exponential distribution.
- ***randomLaplaceGenerator.m*** : This function generates a random number using exponential distribution.
- ***reflectedImagePointPlane.m*** : This function returns the image of a point with respect to a plane (assuming the plane is a mirror).

- ***reflectedVelocity.m*** : This function computes the image velocity of a mobile point with respect to a plane.
- ***StringOutputGenerator.m*** : This function generates the string output which is then written onto a text file.
- ***verifyPath.m*** : Given the CAD model and the vectors one can verify if the vector passes through any one of the planes in the CAD model. While verifying about the intersection of line with triangle we consider intersection inside triangle case only (not on triangle).

10 Time Complexity

NIST Q-D channel realization software is a deterministic raytracer combined with a statistical model. If one is interested in simulating multiple nodes or a large scenario, one has to know the time complexity to decide whether a given scenario is feasible to simulate or not. The time complexity of the NIST Q-D channel realization software is given by

$$\mathcal{O}(n) = rp^2n^{2m+2}$$

where, r is the number of time samples (mobile nodes), p is the number of nodes, m is the order of reflections, n is the number of faces.

To reduce the time complexity the biggest contributors n and m must be minimized. This can be done by limiting order of reflections to at most 2 (preferably one). The number of triangles can be decreased by eliminating triangles which lie beyond a certain distance from Tx and Rx. To limit the number of paths in the output, one can limit the paths based on path loss. Duplicate paths must be avoided. The nodes which are too far away from each other can be ignored.

11 Scenarios

There three scenarios that are predefined for the user to explore the QDSoftware.

- ***Indoor1*** : This scenario is a simple box with nodes present within the box given by 'box.xml' file. This is the most common scenario. The *indoorSwitch* is activated and is denoted by the value '1'. Only box.xml can be used for generating random node locations and hence the *switchRandomization* is activated by giving a value of '1'.
- ***Indoor2*** : This scenario is an indoor structure with nodes present within the icasohedron (low resolution sphere) given by 'sphere.xml' file. The *indoorSwitch* is activated and is denoted by the value '1'.
- ***Outdoor1*** : This scenario is an outdoor location with nodes present outside in a city block given by 'cityBlock.xml' file. The city block is an outdoor location so the *indoorSwitch* is deactivated and is denoted by the value '0'. This is a very large scenario with over hundred thousand triangles. Not all triangles are useful for computation, as few triangles are far off from the nodes. Extra triangles can by eliminated by limiting them by distance. The *referrencePoint* is the center of limiting sphere and is taken as [285.27,178.7,4], which is close to the first node. *selectPlanesByDist* is the radius of the limiting sphere and is taken as 10.

  Note:If few nodes are present within the buildings and few outside the buildings, then we have to select the *generalizedScenario* ='1'.

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