CHAPTER 2

DESIGN AND MODELING OF EXPONENTIALLY TAPERED SLOT ANTENNA

This chapter begins with an introduction of ETS antenna, characteristics and design considerations will give a better insight into the operations of the antenna.

2.1 CONTEXTUAL

The pioneering work in the area of MmW, performed by J. C. Bose, a physicist from Kolkata, India, during 1894-1900, is reviewed and appraised. The various measurement techniques and circuit components, developed by him a hundred years ago, are still being used [73]. The choice of antennas for MmW WLAN/WPAN depends on the applications and the propagation environment, but clearly a high gain and broad-beam antenna is required. However, a category of antenna may be either the directional antenna or the omnidirectional antenna based on designing. Recently, the technology of planar integrated antenna has been developed for MmW applications due to the trend of the integration in radio frequency front-end circuits and systems.

The TSAs are travelling wave antennas. In general, all antennas whose voltage or current distribution can be exhibited by one or more travelling waves are called travelling wave antennas. Distinct standing wave antennas, the phase distribution along a traveling wave antenna cannot be assumed to be constant [74]. The reflected wave in resonant antennas is moderately minimized in the traveling wave antennas by proper termination. An example to this phenomenon is the long wire antenna which is actually a resonant dipole antenna terminated by a matched load.
The TSA uses a slot line etched on a dielectric material, which is widening through its length to produce an endfire radiation [75]. An EM wave propagates through the surface of the antenna substrate with a velocity less than the speed of light which makes TSA gain slow wave antenna properties. The EM wave moves along the increasingly separated metallization tapers until the separation is such that the wave detaches from the antenna structure and radiates into the free space from the substrate end. The E-plane of the antenna is the plane containing the electric field vectors of the EM waves. For TS antennas, this is parallel to the substrate since the electric field is established between two conductors that are separated by the tapered slot. The H-plane, the plane containing the magnetic component of the radiated EM wave runs perpendicular to the substrate.

TSAs have moderately high directivity and narrow beamwidth because of the traveling wave properties and almost symmetric E-plane and H-plane radiation patterns over a wide frequency band as long as antenna parameters like shape, total length, dielectric thickness and dielectric constant are chosen properly. Other important advantages of TSAs are that they exhibit broadband operation, low side lobes, planar footprints and ease of fabrication. A TSA can have large bandwidth if it exhibits a good match both at the input side (transition from the feed line to slot line) and the radiation side (transition from the antenna to free space) of the antenna. The gain of a TSA is proportional to the length of the antenna in terms of wavelength. Tapered slot antennas are also suitable to be used at high operating frequencies (greater than 10 GHz), where a long electrical length corresponds to a considerably short geometrical length. The main disadvantage of the TSA is that only linear polarization can be obtained with conventional geometries.

Most common types are Linearly Tapered Slot Antenna (LTSA), Vivaldi or Exponentially Tapered Slot Antenna (ETSA) and Constant Width Slot Antenna (CWSA). These three main types of TSAs are compared in [76] in terms of beamwidths and side lobe levels. For a TSA with the same antenna length, aperture width and substrate parameter, CWSA has the narrowest beamwidth, followed by LTSA and then ETSA. The side lobe levels are highest for CWSA, followed by LTSA and then ETSA.
TSAs are first introduced in 1979 in the 9th European Microwave Conference by two independent presentations [77, 78]. In [77], an ETSA to be used in an 8-40 GHz video receiver module is proposed. The antenna had a usable bandwidth of 2-20 GHz with a gain of approximately 10dB and -20dB side lobe level. Exponential taper was chosen in this work in order to achieve a wideband performance with an aperiodic continuously scaled structure. It is stated that the energy in the travelling wave on the tapered slot becomes weaker as the separation between the arms of the slot line increases and at last the energy couples to the radiated field.

In [78], an X-band LTSA excited by a microstrip line on alumina substrate is proposed. The antenna was designed to be used in short range radar and phased array systems. The LTSA had a gain of 6dB and a side lobe level of -10dB. The antenna had a 5% bandwidth centered at 9 GHz. The slot width at the open end of the slot line was changed while keeping the antenna length constant and the change in the gain and side lobe levels were observed.

In 1985, CWSA is proposed in [79]. In this study, the effective thickness values required for compliance with Zucker’s curves for travelling wave antennas are stated. Effects of the parameters of the dielectric substrate and the dimensions of the antenna on the radiation characteristics of the antenna were investigated experimentally for LTSA, ETSA and CWSA geometries.

Until 1986, only experimental studies had been conducted for the analysis of TSAs. The numerical analysis of TSAs through the use of Method of Moments (MoM) is first proposed by Janaswamy in his Ph.D. dissertation [80]. In 1989, Johansson also demonstrated the MoM analysis of LTSAs to determine the surface currents on the antenna [81]. In [82], analyses of TSAs are also performed by MoM and the dielectric constant profile of the substrate is optimized to achieve a required radiation pattern.
After the work of [76] that emphasizes the easy integration feature of TSAs, they started to be widely used in MmW and array applications. TSAs operating at MmW band are designed and studied in [83-85]. In [83], two types of TSAs (LTSA and ETSA) operating at 23-80 GHz band are designed. According to simulation results the input return loss values of both of the antennas are below -10dB within the frequency band. However, when the radiation characteristics of the antennas are investigated, it is observed that the antenna starts to be more directive as the frequency increases. Therefore the gain of the antenna varies between 7-12 dB for the LTSA and between 8-10 dB for the ETSA. It is concluded that the radiation pattern bandwidth of the ETSA is wider compared to LTSA.

In [84], a LTSA operating at 45-75 GHz band is designed on a low temperature co fired ceramic (LTCC) substrate. It is observed that the high dielectric constant of the LTCC substrate degrades the radiation characteristics of the antenna by lowering the gain and distorting the radiation pattern. Therefore an air cavity at the back of the antenna is introduced to lower the effective dielectric constant of the substrate. In this way, the distortions in the radiation pattern of the antenna are eliminated but still a variation of 4.9dB to 5.9dB is observed in the gain of the antenna within the frequency band. In [85], the effective dielectric constant of the substrate is reduced by selectively machining holes in the dielectric substrate. The radiation characteristics of the designed antenna are investigated at 24, 30 and 36 GHz both with and without holes. It is observed that the introduction of the holes lowers the side lobe levels, significantly decreases 10dB beamwidths and increases the gain of the antenna. However, the dependency of the gain of the antenna on frequency is same as the examples discussed so far. Arrays of TSAs can be used to obtain higher directivity and some demonstrative TSA antenna array examples can be found in [86, 87].

2.2 ETS ANTENNA CHARACTERISTICS

The ETS antenna belongs to the general class of end-fire travelling wave antennas and consists of a tapered slot etched onto a thin film of metal. This is done either with or without a dielectric substrate on one side of the film. Besides being
efficient and lightweight, the more attractive features of ETS antennas are that they can work over a large frequency bandwidth and produce a symmetrical end-fire beam with appreciable gain and low side lobes [88]. An important step in the design of the antenna is to find suitable feeding techniques for a slot line excited ETS antenna. Understanding the characteristics of the TSA is fundamental and would help a great deal in designing the antenna. From research journals on the TSA, we can confirm that TSAs generally have wider bandwidth, higher directivity and are able to produce symmetrical radiation patterns [89].

### 2.2.1 Radiation Characteristics

As the ETS antenna is a travelling wave antenna, the phase velocity and the guide wavelength, \( \lambda_g \), varies with the change in thickness, dielectric constant and taper shape. Having the gain proportional to \( L/\lambda_g \), parameters such as length, width and taper profiles also have direct impact on the radiation patterns, directivity and cross-polarization level of the antenna. The radiation characteristics of the antenna are also affected by the substrate thickness and ground plane.

### 2.2.2 Bandwidth Characteristics

The ETS antenna is capable of having an operating bandwidth within a frequency range of 2 GHz to 90 GHz. To achieve a wider bandwidth, it is ideal for the ETS antenna to have a perfect impedance match at both the feed transition and the slot termination. Different methods for bandwidth broadening depend on the feed methods chosen. The bandwidth is normally proportional to the change in frequency [90].

### 2.3 DESIGN CONSIDERATIONS

The ETS antenna is formed by slowly increasing the width of a slot from the point of its feed to an open end of width generally greater than \( \lambda_0/2 \) [78]. Experimental results done in various journals have confirmed that the impedance, bandwidth and
radiation patterns are greatly affected by parameters such as length, width and taper profile of an ETS antenna. The dielectric substrate's thickness and relative permittivity are also important as they contribute to the efficiency of the antenna.

2.3.1 Taper Profiles

Many taper profiles exist for a normal TSA. Figure shows different planar designs and we can observe that each antenna differs from one another only in the taper profile of the slot. Of all the designs illustrated in Figure 2.1 [90], only the Vivaldi [91] and linearly tapered profile [78] have been thoroughly studied over the past few years.

Planar tapered slot antennas have two common features. The radiating slot acts as the ground plane for the antenna and the antenna is fed by a balanced slot line. However, drawbacks for a planar TSA come in the form of using a low dielectric constant substrate and obtaining an impedance match for the slot line. By fabricating on a low dielectric constant substrate, relatively high impedance is obtained for the slot line. If a microstrip feed is chosen, it makes matching very difficult. Thus, the microstrip to slot transition will limit the operating bandwidth of the TSA.
Figure 2.1 Different taper profiles of a TSA: (a) Exponential (b) Tangential (c) Parabolic (d) Linear (e) Linear-constant (f) Exponential-constant (g) Step-constant (h) Broken linear [92]

2.3.2 Effect of Curvature on Taper Profile

Tapered slot antennas with linear, exponential or constant taper profile are commonly reported and their journals can be easily found. However, information on the effects of the curvature on a taper profile is not readily available. From [93], we are able to obtain experimental investigation and results on the effects. Figure 2.2 shows the schematic of linear (a) and exponential (b), (c) and (d) taper profiles of a TSA. As seen in the Figure 2.2, four TSAs of same length and terminating slot width, but with different taper profiles, were fabricated and tested. Fabrication was done on the same type of substrate with the same relative permittivity. The cross polarization is generally improved with the decrease in the radius of the curvature except for the E-plane, which will not show any improvement. More importantly, the decrease on the radius of the curvature also reduces the bandwidth of the antenna.

Figure 2.2 Schematic of TSA taper profiles [93]
2.3.3 Methods of Feed

Tapered slot antennas are extensions of a slot line, so feeding a TSA often requires designing a transition between a slot line and some other transmission media [94]. Thus, the slot line must be coupled to the actual antenna feed with an appropriate transition. Such a transition should be compact, low loss, and easy to fabricate. In addition, the transition should have small parasitics over a wide bandwidth. There are several papers that propose to solve this problem using either a broadband balun or an alternate type of feed. A very wideband balun is difficult to design and also increases the cost of the system.

Figure 2.3 illustrates a number of feeding techniques for a TSA. The transitions used between a slot line and the actual antenna feed may be of two types – electromagnetically coupled transitions, where the coupling is through EM fields rather than direct electrical contact, and directly coupled transitions, where there is a direct current path like a wire or a solder connection. Examples of electromagnetically coupled transitions are those that use a microstrip line, conventional coplanar waveguide (CPW), grounded coplanar waveguide with a finite width ground plane (FCPW) or a stripline. Transitions that use a coaxial line, bond wires or ribbons are directly coupled. A transition from a rectangular waveguide to a slot line may also be designed by orienting a double ridged waveguide structure in such a way that its E-field direction matches that of the slot line. Another solution is to employ a transition from a microstrip line to a printed twin line, or two sided slot line transition as proposed in [95]. Variations of the Vivaldi antenna for which a twin line feed is used are the antipodal Vivaldi antenna and the balanced antipodal Vivaldi antenna. The FCPW, stripline, antipodal TSA and balanced antipodal TSA feeds can be used only with two-sided TSAs. In the rest of this section, feed structures employing microstrip/stripline to slot line transitions are discussed first, followed by feed structures with microstrip to substrate integrated waveguide.
2.4 DESIGN AND MODELING OF EXPONENTIALLY TAPERED SLOT ANTENNA

Experimental investigations have revealed that the electrical and structural properties contribute to the overall performance of the radiating structure. Antenna parameters such as dielectric substrate, its thickness, associated tangential loss; the permittivity variation with frequency and the temperature significantly affect the overall performance of the planar ETSA, especially under high-frequency operations. Other parameters affecting performance include: size of the ground plane, its conductivity (material used), thickness, dimensions of the slot, the microstrip feed line, taper/flare angle, opening width of the tapered structure at the space interface, lateral edge and feed location.
2.4.1 Design Guidelines

The design of ETSA has been primarily based on empirical approach, which as an initial step, could start with the following simple guidelines [96]:

- Aperture width of slot: \( W \geq \lambda_0 \)
- Effective thickness: \( 0.005 \lambda_0 \leq t_{\text{eff}} \leq 0.03 \lambda_0 \)
- Taper angle \((\alpha)\) is typically 5 to 12°
- Length of antenna \((L)\) is typically 2 to 12 \(\lambda_0\)

Where \(\lambda_0\) is free space wavelength. The choice of dielectric substrate plays an important role in the design and simulation of the microstrip transmission line as well as any other antennas. Some important dimensions of the dielectric substrate are:

- The dielectric constant.
- The dielectric loss tangent that sets the dielectric loss.
- The thermal expansion and conductivity.
- The cost and manufacturability.
- The thickness of the copper surface.

There are many types of substrates that can be used for the design of antennas. They frequently have different characteristics and their dielectric constants. The thick substrates with low relative dielectric constants are often used as they provide better efficiency and a wider bandwidth. However, using thin substrates with high dielectric constant would result in smaller antenna size. But this also results negatively on the efficiency and bandwidth. Therefore, there must be a design trade-off between antenna size and good antenna performance [97].

Tapered slot antennas are well behaved travelling wave antennas as long as a condition about the parameters of the substrate is satisfied. In order to state this
condition, first the effective thickness of the dielectric substrate \( t_{\text{eff}} \) need to be defined as follows [98],

\[
t_{\text{eff}} / \lambda_0 = (\sqrt{\varepsilon_r} - 1)(t / \lambda_0)
\]  

(2.1)

Where \( \lambda_0 \) is the free space wavelength at the center frequency, \( t \) is the thickness and \( \varepsilon_r \) is the dielectric constant of the substrate. The necessary condition for a TSA to possess travelling wave antenna characteristics is [99]:

\[
0.005 \leq t_{\text{eff}} \leq 0.03
\]

(2.2)

As stated in [100], for a \( t_{\text{eff}} / \lambda_0 \) value below 0.005, the antenna will have decreased directivity whereas for values larger than 0.03, unwanted substrate modes will develop that will deviate the antenna from travelling wave antenna characteristics and introduce grating lobes to the radiation pattern.

In general, the design of ETSA involves two major tasks:

- The design of a broadband transition and feed structure with very wide frequency range and low return loss.
- Determining the dimensions and shape of the antenna in accordance with the required beam width, side lobe, and back lobe etc. over the operating frequency range.

### 2.4.2 Microstrip Design Formulas

To design a basic microstrip transmission line, one must be able to obtain dimensions such as effective dielectric constant, wavelength and characteristic impedance. This can be calculated through the following equations [101].

Aperture length and width of the antenna is given as,

\[
W \gg \lambda_0, \ L = 5\lambda_0
\]

(2.3)
Dielectric thickness, \( h \gg 0.003\lambda_o \) \hspace{1cm} (2.4)

The conductor thickness \( t \) is approximately \( 1/\lambda_o \) satisfying the condition, \( t \leq 1/(0.5\lambda_o) \) \hspace{1cm} (2.5)

Length and width of the slot line is given by,
\[
L_s = 0.4\lambda_o \text{ to } 0.5\lambda_o, \quad W_s = 0.2\lambda_o \hspace{1cm} (2.6)
\]

Length and width of the Microstrip line is given by,
\[
L_m = \frac{c}{2f_r\sqrt{\varepsilon_{\text{eff}}}}
\]
\[
W_m = \frac{7.48H}{\exp\left(0.33(\sqrt{\varepsilon_r+1.41})\right)-1.25t} \hspace{1cm} (2.8)
\]

2.4.3 Effective Dielectric Constant

One might think that the effective dielectric constant \( \varepsilon_{\text{eff}} \) is the same as the dielectric constant, \( \varepsilon_r \) of the substrate. This appears to be true only for a homogeneous structure and not for a non-homogeneous structure. For microstrip structures, we are able to calculate the effective dielectric constant that comes in two different cases. These two cases are illustrated in Figure 2.4 whereby the top diagram shows a microstrip with width, \( w \), greater than the thickness, \( h \), of the substrate (\( w \geq h \)). The opposite can be said about the bottom diagram.

By looking at the diagram with \( w \geq h \), we can conclude that the circuit performs similar to having two parallel planes as most of the fields as kept under the wide microstrip width. Thus, \( \varepsilon_{\text{eff}} \) is approximately equivalent to \( \varepsilon_r \). When \( w \leq h \), half of the fields will be in air with \( \varepsilon_r = 1 \), while the other half of the fields will be confined to the substrate with \( \varepsilon_{\text{eff}} = 1/2(\varepsilon_r +1) \).
Therefore, the range of a dielectric constant can be said to be:

\[
\frac{1}{2} (\varepsilon_r + 1) \leq \varepsilon_{\text{eff}} \leq \varepsilon_r
\]  
(2.9)

The following equations can be used to obtain a precise value of \( \varepsilon_{\text{eff}} \). Following equations take into consideration negligible thickness of the microstrip.

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_{se} + 1 + \frac{\varepsilon_{se} - 1}{2} \left[ \left( 1 + \frac{12}{w/h} \right)^{1/2} + 0.04 \left( 1 - \frac{w}{h} \right) \right]}{2} ; \text{for } \frac{w}{h} \leq 1
\]  
(2.10)

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_{se} + 1 + \frac{\varepsilon_{se} - 1}{2} \left[ \left( 1 + \frac{12}{w/h} \right)^{1/2} \right]}{2} ; \text{for } \frac{w}{h} \geq 1
\]  
(2.11)

2.4.4 Wavelength

For a propagating wave in free space, the wavelength of that medium is equal to the speed of light divided by its operating frequency. To obtain the wavelength of a
given wave-guide or antenna, the free space wavelength is simply divided by the square root of the effective dielectric constant of the wave-guide. These are shown in equations below.

\[
\lambda_o = \frac{c}{f_o} \quad (2.12)
\]

\[
\lambda_m = \lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_{ef}}} \quad (2.13)
\]

\[
\lambda_s = \frac{\lambda_o}{\sqrt{\varepsilon_{si} + 1}} \quad (2.14)
\]

Where \(c\) is speed of light, \(f_o\) is operating frequency, \(\lambda_o\) is free space wavelength, \(\lambda_m\) is medium wavelength and \(\lambda_g\) is the guide wavelength.

2.4.5 Characteristic Impedance

The characteristic impedance \(Z_o\) of any line is the function of its geometry and dielectric constant. For a microstrip transmission line, the characteristic impedance is defined as the ratio of voltage and current of a travelling wave. For a microstrip line with width, \(w\), we are able to calculate the characteristic impedance through the following two equations:

\[
Z_o = \frac{60}{\sqrt{\varepsilon_{ef}}} \ln \left[ \frac{8}{w/h} + 0.25 \frac{w}{h} \right] \text{; for } \frac{w}{h} \leq 1 \quad (2.15)
\]

\[
Z_o = \frac{120\pi}{w/h + 1.393 + 0.667 \ln \left( \frac{w}{h} + 1.444 \right)} \text{; for } \frac{w}{h} \geq 1 \quad (2.16)
\]
2.5 SIMULATION TOOLS

This work uses two 3D EM Simulation tools, CST MWS and Ansys HFSS. The idea behind using two simulation tools is to first design and simulate the antenna using CST MWS and to compare the results with the results obtained in HFSS. The use of two simulation tools will provide strength and allow reliability in the results obtained from CST MWS. A short discussion is made in later subsections on the design tools and their properties.

2.5.1 CST MicroWave Studio

The CST MWS is a specialist tool for the 3D EM simulation of high frequency components. CST MWS unparalleled performance making it first choice in technology leading R&D departments. CST MWS enables the fast and accurate analysis of high frequency (HF) devices such as antennas, filters, couplers, planar and multi-layer structures and Signal Integrity (SI) and EMC effects. Exceptionally user friendly, CST MWS quickly gives you an insight into the EM behavior of your high frequency designs [102].

CST promotes Complete Technology for 3D EM. Users of our software are given great flexibility in tackling a wide application range through the variety of available solver technologies. Beside the flagship module, the broadly applicable Time Domain solver and the Frequency Domain solver, CST MWS offers further solver modules for specific applications. Filters for the import of specific CAD files and the extraction of SPICE parameters enhance design possibilities and save time. In addition, CST MWS can be embedded in various industry standard workflows through the CST user interface. CST MWS is seen by an increasing number of engineers as an industry standard development tool.
The Transient Solver of CST MWS is a general purpose 3D EM simulator. Real time domain simulation is useful for studying the field propagating through a component or along the traces of a PCB, and can be used in a huge range of EM applications. Time Domain Reflectrometry (TDR) comes naturally with such a solver, but also SI applications benefit from the capability to use arbitrarily shaped time signals. Besides the specific capabilities in time domain, the transient solver also delivers broadband frequency domain results like S-parameters. These simulations can be performed with an arbitrarily fine frequency resolution without extra computational cost, thus avoid missing single resonances inside the spectrum. Field results for many frequencies can be derived from one single simulation run. CST MWS can be easily distinguished from other time domain tools.

Antennas are used in a vast variety of applications, and thus take come in a vast variety of form factors and radiation mechanisms. The range of simulation methods in CST MWS allows the engineer to choose the best technique for each application. The transient solver could be best for wideband or planar antennas, the frequency domain solver may be more suitable for electrically small antennas, while the integral equation solver can efficiently simulate electrically large or wire antennas. The powerful automated post-processing allows you to extract every magnitude of interest for an antenna designer – near field plots, SAR, phase center, directivity or far field gain for single antennas or arrays - and to process those data further for use in parameter sweeps or optimizations in order to improve the performance of antenna design.

Here in this work, transient solver is used for simulating the antenna. The types of antenna and other structures that can be designed on CST MWS is shown in Figure 2.5 taken as a snapshot from the simulator interface. The user interface is shown in Figure 2.6.
Figure 2.5 Types of antenna templates in CST MWS

Figure 2.6 User interfaces of CST MWS
2.5.2 Ansys HFSS

The Ansys pioneered the use of the Finite Element Method (FEM) for EM simulation by developing/implementing technologies such as tangential vector finite elements, adaptive meshing, etc. HFSS is a high performance full wave electromagnetic field simulator for arbitrary 3D volumetric passive device modeling that takes advantage of the familiar Microsoft Windows graphical user interface. It integrates simulation, visualization and automation in an easy to learn environment [103]. The HFSS user interface is shown in Figure 2.7,

![Figure 2.7 HFSS user interface](image)

The HFSS Window has several optional panels, listed below.

- A Project Manager which contains a design tree which lists the structure of the Project.
- A Message Manager that allows you to view any error or warning that occurs before you begin a simulation.
- A Property Window that displays and allows you to change model parameters or attributes.
• 3D Modeler Window which contains the model and model tree for the active
design.

The Ansys HFSS Desktop provides an intuitive, easy-to-use interface for
developing passive RF device models. Creating designs, involves the following:

• Parametric Model Generation - creating the geometry, boundaries and
  excitations
• Analysis Setup - defining solution setup and frequency sweeps
• Results - creating 2D reports and field plots
• Solve Loop - the solution process is fully automated

The basic mesh element used is a tetrahedron, which allows the user to mesh
any arbitrary 3D geometry, such as complex curves and shapes. The mesh can be
defined automatically by the solver, but quite often this does not give satisfactory
results and the user has to define mesh operations, such as, seeding the mesh, maximum
aspect ratio and curve surface 40 approximations. The above descriptions of the design
tools are a summarized version obtained from the user manual of CST MWS and Ansys
HFSS [102,103].

2.5.3 Wireless Insite

Wireless Insite (WI) is a powerful electromagnetic modeling tool for predicting
the effects of buildings and terrain on the propagation of EM waves. It predicts how the
locations of the transmitters and receivers within an urban area affect signal strength.
WI models the physical characteristics of the rough terrain and urban building features,
performs the EM calculations, and then evaluates the signal propagation characteristics.
The virtual building and terrain environment is either constructed using WI’s editing
tools or imported from a number of popular file formats, such as DXF, shape file,
DTED and USGS. Transmitter and receiver locations can be specified using WI’s
powerful site-defining tools, or imported from an external data file. Separate calculations for portions of the overall area may be specified by defining study areas. The calculations are made by shooting rays from the transmitters, and propagating them through the defined environment. These rays interact with environmental features and make their way to receivers. Interactions include reflections from feature faces, diffractions around objects, and transmissions through features.

The WI uses advanced high-frequency electromagnetic methods to provide accurate results over a frequency range from approximately 50 MHz to 100 GHz. The effects of each interaction along a ray’s path to the receiver are evaluated to determine the ray’s electric field. At each receiver location, contributions from arriving ray paths are combined and evaluated to determine predicted quantities such as electric and magnetic field strength, received power, interference measures, path loss, delay spread, direction of arrival, impulse response, electric field versus time, electric field versus frequency, and power delay profile.

The WI presents results in a number of ways. It provides visual representation of some results, such as transmitter coverage areas and power distributions, placing these visually within the modeled environment. WI is also capable of playing movies of time domain electric and magnetic field evolution. For other types of data, WI provides an advanced plotting system. Overlays of data allow quick comparison to imported measurements, or even previous WI calculations. All output files produced by WI are in a readable ASCII format. The Figure 2.8 shows the WI project hierarchy [104].
From this chapter, a better understanding on the characteristics and design considerations inevitably supports in the designing and constructing of an ETS antenna. Various taper profiles and feeding techniques were described and illustrated to give the different options while designing an ETS antenna. The effects the angle of the taper profile has on the antenna were also emphasized. The overall design of the wide band ETS antenna was closely modeled after some of the figures presented in this chapter.