The proposed design of the soil monitoring system consists of a soil sensor that provides output in the form of RF spectra and the signal processing unit used for the estimation of an unknown concentration of a particular soil constituent. To obtain accurate estimations, it is required that the soil sensor must be immune to any external electromagnetic interference. The RF spectra obtained from the sensor must have a high SNR to obtain the relevant information of a particular soil nutrient.

3.1 Soil Sensor Cell Design

Various techniques such as electromagnetic, electrical, electrochemical, radiometric and optical as discussed in the previous chapters are available for the design of a soil sensor. The current work is based on RF spectroscopy and as such various designs based on HF coils, four probe method were tried which are discussed in the following sections.

3.1.1 Design using HF coils

The soil sensor was initially designed to work on the non contact principle. A HF voice coil was used for inducing current into the soil. The influence of the soil on the induced current is determined by measuring the magnitude of the output signal. It was observed that there was no significant difference between the amplitudes of the input and output signals which indicated that the coil was not able to induce sufficient current into the soil. The voice coil was replaced with coils wound on ferrite core and the results were found to be similar to that of voice coil. A low power signal generator of frequency up to 2.2 MHz was used for inducing the signal into the soil, but it was observed that in order to induce sufficient current into the soil, a high power instrument is required. Since the basic objective was to design a user friendly and portable instrument, this design had to
be discontinued because of the requirement of high power oscillator. The coils constructed for inducing current into the soil are as shown in figure 3.1.

![Figure 3.1: Coils used in the design of soil sensor](image)

### 3.1.2 Design using 4 probes

Due to the non availability of high power oscillator the non contact method using coils had to be discontinued. A new sensor based on the contact method using 4 probes was designed. The soil sensor is a rectangular cell made of acrylic sheets with four electrodes. Two electrodes were placed at the opposite ends of the cell and two electrodes were placed at the centre of the cell. The sample to be tested was placed in the cell. The input signal was applied between the outer two electrodes and the output response was obtained between the inner two electrodes. The designed cell is as shown in figure 3.2.
The sensor response for the sample under test was found to be unsteady. This may be due to the attenuation in the signal caused because of the cable length and also due to the presence of large number of signals present in the surroundings used in wireless communication. At high frequencies the wavelength becomes comparable with the length of the cables being used which results into the cables acting as radiators at high frequencies. Loss of signal takes place due to its radiation into free space, thus giving an unsteady response. Thus taking into consideration all these factors the sensor design was changed which was based on the dielectric principle.

3.1.3 Design Based on Dielectric Principle

The soil sensor was redesigned and reconstructed to work on the dielectric principle. Dielectrics are materials that conduct electricity only to a certain degree. The dielectric properties of a material determine its behavior under the influence of electric field. The speed of propagation of an electromagnetic wave through a medium depends on the electromagnetic characteristics of the medium. In case of free space the electromagnetic wave travels with the speed of light. The propagation of electromagnetic wave through
any material is controlled by two factors: the magnetic permeability and the electrical permittivity. In soil, the propagation of electromagnetic wave is a function of electrical permittivity since soil is non magnetic. The electrical permittivity is frequency dependent and various dielectric mechanisms contribute to the overall permittivity of a material. The frequency response curve of various dielectric mechanisms is as shown in figure 3.3.

![Figure 3.3: Frequency response of dielectric mechanisms](source)

The frequency response of dielectric mechanisms shown in figure 3.3 is plot of frequency in Hz v/s attenuation in dB. Each of the dielectric mechanism shown in figure 3.3 has a characteristic cutoff frequency. The magnitude and the cutoff frequency are unique for each dielectric mechanism for different materials [97].

The sensor is based on the measurement of the loss in the RF signal transmitted through the soil sample placed in the sensor. The soil sensor is a cell fabricated using PMMA sheets and has a rectangular shape with the outer dimensions as 13cmx2cmx2.5cm. The inside surface of the cell is lined with gold foil and the outer surface of the cell is covered with a copper foil. Both the inside gold foil and the outer
copper shield are connected together through the feed connectors so as to provide the necessary shielding effect. A wire made of gold runs through the centre of the cell and is connected from the input feed connector to the output feed connector. The cell holds the samples for which the RF spectra are to be recorded. The schematic diagram of the cell is as shown in fig. 3.4 and the constructed cell is as shown in fig. 3.5.

Figure 3.4: Schematic diagram of the cell

Figure 3.5: The constructed cell

3.2 Soil Monitoring System Design

The Block diagram of the proposed design for Soil Monitoring System is as shown in Figure 3.6.
The design consists of RF data obtained from Scalar Network Analyzer fed as input to Altera DE2 board with target as NIOS II processor running on CYCLONE II FPGA. The RF data is obtained from the soil sensor connected between a tracking generator and a spectrum analyzer.

The central gold wire in the cell (soil sensor) carries an RF signal towards the receiver end, during which the signal radiates into the sample which is absorbed as per the characteristics of the sample. Thus, the cell which consists of the central wire, the outer copper shield and the sample forms a dielectric loss cell. The signal strength starts reducing as it propagates through the central wire from the input feed connector to the output feed connector of the cell. Due to the above, the output signal is proportional to the absorption loss of the sample solution and is captured by the RF spectrum analyzer connected at the receiver end of the cell. Signal Hound USB-TG44A tracking generator and Signal Hound USB-SA44B spectrum analyzer are used with both the instruments working in the frequency range of 1Hz-4.4GHz.
3.3 Network Analyzer

It is an instrument used for the analysis of a circuit or a device under test at RF or microwave frequencies. A network analyzer can be used for the measurement of both the amplitude and phase characteristics of a device over a wide range of frequencies. It is used in the study of the linear and non linear behavior of both passive and active devices. The block diagram of a generalized network analyzer is shown in fig. 3.7.

![Diagram of Network Analyzer](Source: www.rf-mw.org)

The block diagram of a network analyzer is divided into four sections. The first section consists of the signal source which is required to activate the device under test (DUT). This section makes use of integrated synthesized sources that provide a very high frequency resolution and stability. The signal separation section needs to perform two basic functions. The first function is the measurement of a part of the incident signal that
is used to provide a reference. Generally, splitters or directional couplers are a part of the signal separation block. The second function that it performs is the separation of the incident signal and the reflected signal at the input of the DUT. Either couplers or bridges are used to perform this function. The next section of the network analyzer is the signal detection block which uses either a diode detector or a tuned receiver. The last section which forms an important block in the network analyzer is the display or processor section. In this section, the data is formatted in such a way that it is easily interpretable. The display may be provided in various formats such as markers, limit lines, pass/fail indicators, linear/log formats and grid/polar/smith charts.

Network analyzers can be classified into two types based on the types of measurements it can do, the Scalar Network Analyzer (SNA) and the Vector Network Analyzer (VNA). The SNA is used when only the amplitude characteristics of a circuit or a device under test are required in the study. The VNA is used to measure high frequency characteristics of both active and passive devices in their linear mode of operation. The network parameters called as S-parameters are measured as a function of frequency. The S-parameters provide an accurate representation of the linear behavior of the device under test. The applicability of VNA can be extended to measure noise parameters and the non linear characteristics such as compression and inter modulation through the addition of extra hardware.

A VNA can not only perform the functions of SNA, but it can also provide additional information such as the phase characteristics of devices with much more accuracy and over a greater dynamic range. The phase information can be used to provide new features for complex measurements such as Smith charts, group delay and time domain [98, 99].
3.4 Scalar Network Analyzer (SNA)

In this study SNA is used, since it involves the measurement of only the amplitude characteristics of the sample under test. Though VNA provides readings with much more accuracy as compared to SNA, the cost of VNA is much higher than SNA. Since the main objective of the research work is to design a portable, low cost soil monitoring system, the SNA was preferred over VNA.

The scalar network analyzer consists of a tracking generator and a spectrum analyzer that measures the amplitude properties of the sample under test. The tracking generator generates a sweep signal that has the same frequency as that of the signal received by the spectrum analyzer. The spectrum analyzer generates a frequency response that shows variations in amplitude of the received signal at various frequencies.

3.4.1 Spectrum Analyzer

A spectrum analyzer can be designed to work on two different principles, the superheterodyne principle and the Fast Fourier Transform (FFT) principle. In the case of FFT spectrum analyzer, a signal in the time domain is digitized using digital sampling and is processed using the FFT method to get the signal in the frequency domain. In the case of the superheterodyne or the swept tuned analyzer, the full frequency range required for the analysis is swept across, displaying all the frequency components present. The working of both the types of spectrum of analyzer is discussed below.
i) Superheterodyne or The Swept Frequency Spectrum Analyzer

![Superheterodyne Spectrum Analyzer](Source: wwwglobalspec.com)

The RF attenuator at the input adjusts the level of the signal to its optimum value so that the input signal does not load the mixer. The Low Pass filter removes any unwanted HF signals at the input from getting mixed up with the local oscillator frequency and generating unwanted responses in the IF stage of the spectrum analyzer. The mixer stage consists of a high performance device which must be able to operate over a wide range of frequencies and do away with any spurious noise signals. The IF amplifier provides the necessary gain to the IF signal. The resolution bandwidth filter is a narrow band pass filter which controls the frequency resolution of the spectrum analyzer. The local oscillator is the key element which must be capable of tuning to a wide range of frequencies so that the required frequency range can be scanned. The ramp generator is used to control the sweep of the local oscillator and the display wherein the horizontal axis of the display is linked to the frequency. The IF signal is converted into a voltage
signal by the envelope detector. This signal is then displayed as the output signal on the LCD display.

ii) FFT Spectrum Analyzer

![FFT Spectrum Analyzer Diagram](source: www.radio-electronics.com)

The first stage of the FFT spectrum analyzer is an attenuator or the gain stage which is used to ensure that the input signal is at the required optimum level for further processing. The low pass filter removes any unwanted HF signals that can create problems while sampling the signal. The sampler is designed to take samples of the signal at discrete time intervals as per the Nyquist theorem. The analog to digital converter (ADC) converts these signals into digital output which is further processed to convert it into the frequency domain by using the FFT analyzer. The display provides the output and various other controls required for processing of the signal.
iii) **The Signal Hound Spectrum Analyzer**

The spectrum analyzer used in the soil monitoring system is the Signal Hound SA-44B model. The instrument is shown in fig. 3.9 and the specifications of this model are as follows.

![SA44B Signal Hound Spectrum Analyzer](image)

**Figure 3.10: SA44B Signal Hound Spectrum Analyzer**

The SA-44B operates in the frequency range of 1Hz to 4.4GHz. The front panel has a 50Ω SMA RF input and the rear panel has three connectors. A 10MHz reference input connector, a USB B type connector and a BNC connector that may be used as a TTL/CMOS trigger input, a Self Test Signal output, a Tracking Generator Sync signal, or a generic CMOS Sync Output. The functioning of this connector is controlled by the Signal Hound software. It has two span modes: the centre frequency span and the start and stop frequency span mode. It has a minimum span of 10Hz or zero span and maximum span of 4.4GHz.
3.4.2 Tracking Generator

A tracking generator is basically used to enhance the measurement capabilities of a spectrum analyzer. It is a sweep generator that generates RF signals and the sweep rate is matched to that of the spectrum analyzer. The same frequency is tracked by the tracking generator and the spectrum analyzer, and hence if the output of the tracking generator is connected directly to the input of a spectrum analyzer, a single flat line is observed on the display with the output level representing the level of the input signal. If a device under test is connected between a tracking generator and a spectrum analyzer, then the amplitude level of the output signal of the analyzer will change as per the response of the device under test.

i) Signal Hound Tracking Generator

The tracking generator used in the study is the Signal Hound TG-44A model. The signal hound tracking generator USB-TG44A operates in the frequency range of 10Hz to 4.4GHz. It has an amplitude range of -30dBm to -10dBm. The front panel consists of a 50Ω SMA RF input as shown in figure 3.11.

![Figure 3.11: Front panel of TG-44A](image)

The rear panel has three connectors: 10 MHz Reference output provided through a BNC connector, USB type B connector and TG Sync provided through a BNC connector.
The Signal Hound tracking generator TG-44A consists of a 32 bit programmable Direct Digital Synthesizer (DDS). Frequencies in the range of 10Hz to 28MHz are directly generated by the DDS, whereas higher frequencies above 28 MHz are generated by multiplying the signal by an integer ranging from 5 to 200. Harmonics are generated and these are not filtered as they are found to have not much impact on the measurement since they lie well outside the spectrum analyzer input bandwidth [100].

3.4.3 Experimental Setup

The experimental setup for the recording of RF spectra consists of Signal Hound tracking generator at the input of the cell in which the soil sample whose spectra are to be recorded is placed. At the output Signal Hound spectrum analyzer is connected for recording the signal spectra. The cell as shown in figure 3.5 is enclosed inside an iron box to shield the RF signal from any external influence of noise signals. The experimental setup is as shown in figure 3.12.

![Figure 3.12: Experimental Setup](image)

Depending on the dielectric properties of the sample placed in the cell, frequency response is obtained. These responses are then processed to estimate the unknown concentration of a constituent in the soil sample.
3.5 Sample Preparation

Five different soil constituents are taken for the study namely urea, potash, phosphate, sodium chloride and calcium carbonate (lime). Samples for the study were prepared in the laboratory by mixing a specific amount of these constituents with distilled water. The amount of urea to be added to distilled water is calculated as follows: the molecular weight of urea is calculated which is found to be 60gms. To prepare one quarter molar solution, the amount of urea to be added to 1L of water is 15gms. From this, the amount of urea to be added to 15ml of water, which is the capacity of the designed cell, is calculated as 225gms. This concentration of urea is the normal concentration and is denoted as 1Urea in the study. Likewise, the concentrations of the remaining four constituents are calculated and the normal concentrations of these are as follows: 1Potash is equal to 279.5mg, 1Phosphate is equal to 3.78gms, 1NaCl is equal to 219.75mg and 1CaCO$_3$ is equal to 375mg.

Apart from the normal concentration, samples of these constituents with other concentrations are also prepared. These are denoted as 0.5, 0.75, 1.25, 1.5, 2, 2.5 and 3, with each number representing the amount of concentration times the normal concentration. The RF spectra of each sample with varying concentrations are measured using the cell. To estimate the unknown concentration of a particular constituent, it is required that the RF spectra of samples obtained should have variability in the attenuation levels as per the change in the concentrations of each sample.
3.6 Spectrum Processing

To estimate the unknown concentration of a constituent in a sample, the detected spectra containing the signature of the required constituent along with the other constituents is passed through a signal conditioning stage. The output from Spectrum Analyzer is stored in the computer. This data is then fed to a CYCLONE II device with Altera NIOS II processor running on it. The recorded spectra are then passed through SIMPLS algorithm based on the Partial Least Square Regression (PLSR) technique running on NIOS II processor. The algorithm estimates the unknown concentration of a constituent and displays the result on LCD or a computer screen. The SNR of the detected spectra must be sufficiently high so as to provide reliable constituent specific information and therefore data processing is needed to identify spectral features of a constituent from the combination spectra originating from interfering matrix constituents.