8-17-2020

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Salam, Abdul and Raza, Usman, "Electromagnetic Characteristics of the Soil" (2020). *Faculty Publications*. Paper 38.
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Chapter 2

Electromagnetic Characteristics of the Soil

Abstract The electromagnetic characteristics of the soil are discussed in this chapter. Characteristic of porous bedrock, soil medium, and impacts of rain attenuations are also presented. The models of dielectric soil properties are studied with a rigorous focus on the constitutive parameters of subsurface soil medium. Moreover, the permittivity and wavenumber in soil is explained. In addition, the frequency–dependent dielectric properties such as dispersion in soil, absorption characteristic and penetration depth versus frequency are reviewed. Furthermore, the effective permittivity of soil-water mixture for through-the soil-propagation mechanism is analyzed thoroughly.

2.1 Introduction

Sub-surface electromagnetic (EM) wave propagation is governed by the structure of earth crust and its electrical properties. Earth crust is a relatively cool area above the earth's core and mantle. Its thickness is upto 30 miles. The characteristic of this layer, as a transmission medium, determines the feasibility of propagation of EM waves. Particular characteristics of interest are thickness, different formations, type of the rock, and electrical conductivity.

An ideal earth crust is composed of 5% sedimentary rocks and 95% igneous rock. Sedimentary rocks are shale, sandstone and limestone whereas igneous rocks are granite and basalt. Most sedimentary rocks are composed of the deposits from ocean bottom, therefore, pore spaces have high conductivity due to conducting sea water and it is not suitable for EM waves propagation. However, terrestrial and chemical deposited rocks (e.g., chemically precipitated dense limestones) are different and this rule doesn't apply to them.

Under the highly conductive sedimentary rock lies igneous rock. Igneous rock is formed by crystallization of molten rock material. The igneous rock has thickness ranging from 1000 feet to 30 miles below the surface. Owing to its origin, it can accumulate the ocean water and are very suitable for the communication experiments. This rock is homogeneous formation of granite and basalt between the mantle and

sedimentary surface. However, sedimentary and upper granite are relatively less homogeneous.

EM propagation in earth depends upon the conductivity σ and dielectric constant ϵ of the earth medium (soil), however, upper portion (few thousand feet above) is rather a complex medium for radio propagation with continuous and sudden changes in the condition. The propagating surface has varying conductivity and dielectric constants for upto few miles. After the sedimentary section, the rock structure is more relatively uniform in the higher depths. There has been many measurements done for dielectric constants and conductivity of the rock. As per minéralogie character, conductivities shows variations over large magnitude, however, dielectric constants doesn't change much. Conductivity of a rock is an important parameter as path loss is dependent upon it. The conductivity of a rock is majorly determined by the water content and minorly by mineral content. Conductivity varies greatly for the dry and wet rocks. Granite is the most suitable rock for the communication due to its low conductivity. Water content in the rock has great effect on the performance of the communication, therefore, antennas are buried deeply into the ground to reach low conductivity rock (granite). The conductivity value of granite in Appalachian Mountain chain from Maine to Pennsylvania was measured as 10^{-5} mhos/meter by Dr. G. V. Keller of the United States Geological Survey. The conductivity decreases with an increase in the depth. However, this trend is observed only for the depth of few miles. The temperature induced conductivity comes in effect as the depth goes beyond several miles. The conductivity value increase significantly (same as conductivity values in the crust) with the increase in temperature. If the in-homogeneity of the rock is ignored, the ideal model of rock conductivity is obtained as follow: the upper layer of the earth is relatively thin and has high conductivity whereas lower layer is thick (upto 20 miles) and have low conductivity values. This act as the middle layer between the upper thin layer and very low high temperature and high conductivity layers.

The knowledge of dielectric properties of rocks, both solid and in powdered form, comes very handy while working on geophysical and geological applications. Rock are the collection of mineral grains bounded together by molecular interaction forces. Dielectric properties can be measured in many ways. For example, in [43, 65, 72], authors perform a broadband measurement for dielectric permittivity. The real part of the permittivity, between 450 MHz and 35 GHz, for around 5-6 for granite rocks. It does not depend on the frequency as the loss factor is very low, i.e, around 0.01 to 0.05. In another study [34, 44, 66], Parkhomenko list very detailed dielectric property form various minerals in the frequency region of MHz and below.

2.1.1 Porous Bedrock

Bedrock is very heterogeneous ranging from microscopic hair cracks to very large scale of heterogeneity. They are porous allowing water to flow through them. The level of porosity varies from less than 1% (certain granite) to even 20-40% (shale

Fig. 2.1: Organization of the Chapter

and sandstone) [22, 28, 39]. The dielectric property is water dependent, therefore, it also depends upon the rock's porosity and micro-geometry.

At lower frequencies, the conductivity is found to be greater than the dielectric property of the brine-saturated water. Therefore, a relation between the porosity and conductivity of the medium can be found. Archie's Law [3, 37, 38] give one such approximate relation between water conductivity σ_w and mixture conductivity σ_{eff} :

$$\frac{\sigma_w}{\sigma_{eff}} = f^m \quad (2.1)$$

where f is the porosity, m is the cementation exponent and predicts the conduction behavior based on various factors in present in the rock. Its value for clay-free sedimentary rock is between 1.3 and 4. For decades, Archie's law is being used to estimate water saturation from electrical conductivity (EC) in borehole logging.

There are other different models for the percolation process, e.g., Bruggeman model, Maxwell Garnett model or Coherent potential model. These models predict whether a non-zero porosity value f_c , also known as percolation threshold. At

f_c , macroscopic conductivity changes suddenly, and above f_c , the conductivity is proportional to $(f - f_c)^m$. However, Archie's law gradually measures the increasing conductivity and starts from the percolation threshold value of zero. Therefore, Archie's law is not compatible with the mentioned models of percolation process [29, 42, 54].

There are some model which are compatible with the Archie's law. For example, model presented in Sen et al. [65] measures effective permittivity as:

$$\frac{\epsilon_{eff} - \epsilon_e}{\epsilon_i - \epsilon_e} = f \left(\frac{\epsilon_{eff}}{\epsilon_i} \right)^{1/3} \quad (2.2)$$

where host (ϵ_e) is the rock matrix, the inclusions (ϵ_i) represents water phase having volume fraction f same as porosity.

If we apply the equation 2.2 to water-saturated rock matrix then ϵ_e will be real because of insulating environment, and inclusion conductivity will become $\epsilon_i = \epsilon'_i - j\sigma_w/\omega$. Imaginary part will be dominant at lower frequencies, hence, $\epsilon_i \approx j\sigma_w/\omega$, and the effective permittivity will be:

$$\left(\frac{\sigma_{eff}}{\sigma_w} \right)^{2/3} = f \quad (2.3)$$

where the real part negligible and imaginary part will be: $\epsilon_{eff} = \epsilon'_{eff} - j\sigma_{eff}/\omega \approx -j\sigma_{eff}/\omega$ which leads to Archie's law: $\sigma_{eff}/\sigma_w = f^{2/3}$ having value of exponent $m = 1.5$. The exponent value of 1/3 in Sen et al. model is because of considering different sized spheres; for ellipsoids with depolarization factor N , the will become as:

$$\frac{\epsilon_{eff} - \epsilon_e}{\epsilon_i - \epsilon_e} = f \left(\frac{\epsilon_{eff}}{\epsilon_i} \right)^N \quad (2.4)$$

which predicts conductivity at low-frequency limit as per: $\epsilon_{eff}/\epsilon_w = f^{1/(1-N)}$. It gives the freedom to choose the cementation exponent value as depolarization factor, in case of ellipsoid, is between 0 and 1.

In the light of current research, Archie's Law seems to be an oversimplification [24, 47, 66] because it fails in carbonate rocks which having very in-homogeneous structure and complex pore structure. It has economical significance when it is applied in important application of estimating hydrocarbon reservoirs of the world.

Anisotropy plays an important role in rock material. Fig. 2.2 shows that special directions visible in sedimented rocks and stones. Anisotropy is highly dependent upon the scale, e.g., the dielectric anisotropy for Gypsum can be around 1.5-2 at lower frequencies.

Fig. 2.2: The near-IR spectra of representative samples [18, 44, 52]

2.1.2 Soil

Soil is the complex substance made up of different components. It contains different solid materials, air, free and bound water. there are different types of soil covering the surface of the earth. It is useful to separate the dry and wet component of soil while estimating soil's dielectric properties. The permittivity of dry soil is better understood than the wet soil because dielectric losses can occur to water contribution [34, 41, 48].

Dry soil is a two-component mixture. The inclusion of rock material takes certain volume in air ¹. Soil can be classified in to three types: clay, silt and sand. This classification is on the basis of size of the soil's inclusions and increasing order particles coarseness. However, dielectric properties of the soil are independent of the particle. size. Soil permittivity ϵ_s can approximately related to soil density ρ_s .

¹ This oversimplified assumption for modeling the dielectric. Soil is a complex fragmented rock consisting of plants microscopic organisms, fungi, plant and other inorganic matter

In literature, the relation between the soil density and soil permittivity is given as a polynomial, e.g., in [67] it is given as follow:

$$\epsilon_s/\epsilon_0 = (1 + 0.5\rho_s)^2 \quad (2.5)$$

where the soil density is measured as g/cm^3 . Dobsen et al. [13], performs the modeling on the basis of measurements taken in the range of 1.4 GHz and 18 GHz. It gives slightly lower prediction as:

$$\epsilon_s/\epsilon_0 = (1.01 + 0.44\rho_s)^2 - 0.062 \quad (2.6)$$

The above models are empirical models. Birchak refractive index model average out the square roots of permittivity of all components and can be connected to above-mentioned models. Of course, the soil density is directly proportional to the amount of solid matter present in the soil and it is raised to second power while calculating permittivity [30, 46, 55].

Campbell-Ulrichs [7, 33, 35] studied different type of terrestrial rocks and includes extensive measurements. They also proposed a classical mixing model for predicting dielectric properties of powdered rocks. The result was that Maxwell Garnett mixing model, having spherical inclusions, matches the measurements from rocks like olivine peridotite powder and olivine basalt. However, it doesn't work well with some other rock types such as granite and aplite. Bruggeman model worked better for these rocks. All measurements were done at 450 MHz.

The permittivity was measured for dry Saharan desert [26, 46, 51] between the frequencies of 245 MHz and 6 GHz. The real component (around $\epsilon_s/\epsilon_0 \approx 2.53$) of the permittivity remained constant above 1 GHz. Along with the sand density of $1.45g/cm^3$, these measurements follow the model presented in equations 2.5 and 2.6. In microwave region, the imaginary part was shown to be decreasing. The Debye-type spectrum suggests relaxing the frequency around 270 MHz.

The permittivity of the dry soil is not affected much by the dry soil, however, it is not true in case of wet or moist soil. A clay surface area is much greater than the sand because clay has much larger, in many order of magnitude, number of particles as compared to sand. Therefore, the liquid water distribution is completely different for both of the cases. Moreover, the surface absorbs more liquid water than the bound water, hence, more dependency of soil texture on permittivity can be expected [25, 26, 65].

In Hallikainen et al. [17, 27, 46, 49], the effect of temperature, soil type, frequency and wetness, on the wet soil permittivity. It concludes that the permittivity is highly dominated by the water phase. For example, values for real and imaginary part of relative permittivity are 25 and 10 for 1 GHz frequency and water fraction of 0.4. The imaginary part is over two order of magnitude as compared to what it is for dry sand. The results also clearly show that soil type dependency [33, 71]. This dependency is more evident for lower frequencies. Even with the same moisture, coarse-structured soil (sand and loam) have higher permittivity as compared to fine-grained soil (silt and clay). This may be because of greater specific surface area, fine-grained soil attaches more water to the surface, and sand has more free water. The permittivity of the free

Fig. 2.3: Variation of the median values of decay parameter with rain rate. [31]

water is greater than the bound water. The reason for this is because water molecules are bounded in bound water and does not respond freely to the electric field.

2.1.3 Rain Attenuation

Fog is very transparent at microwave frequencies, however, rain is not. For a rainy troposphere, The attenuation in radio signals can be calculated by measuring the loss of air-precipitation mixture effective permittivity, however, water fraction in air must be known for that.

The size of a raindrop, within the rain, depends on the intensity of the rainfall. Mostly Marshall-Palmer drop size distribution is used in the literature which calculates number of drops having diameter d per unit volume from the following distribution:

$$p(d) = N_0 e^{-bd} \quad (2.7)$$

where $N_0 = 8.0 \times 10^6 m^{-4}$ and exponent b is calculated as follow:

$$b = 4100 R_r^{-0.21} [1/m] \quad (2.8)$$

where rain rate is measured in $mm\ h^{-1}$. The relation between rate rate and fraction volume f of water phase in air is given by integration as:

$$f = 8.894 \times 10^{-8} R_r^{0.84} \quad (2.9)$$

The attenuation A is calculated using the imaginary part of effective permittivity of dilute water-air mixture:

$$A = \frac{8686\pi}{\lambda} \epsilon_{eff,r}'' [\text{dB km}^{-1}] \quad (2.10)$$

where wavelength λ is in meters, and imaginary part of relative effective permittivity is given as:

$$\epsilon_{eff,r}'' = -3f \text{Im} \left\{ \frac{\epsilon_w - \epsilon_0}{\epsilon_w - 2\epsilon_0} \right\} \quad (2.11)$$

and raindrops are assumed to be spherical. Small rain drops are spherical for sure, however, as the size increases the start to resemble oblate ellipsoid [27, 53]. Fig. 2.3 plots attenuation with rain rate at 1 GHz of frequency. It shows that attenuation is directly proportional to the rain rate. Only the absorption was considered for the calculation. However, this assumption was undermined with increasing frequency mainly because of increase in scattering and, secondly, it is not possible to calculate absorption while assuming that internal field of raindrop remains same throughout the volume (a quasi-static assumption). However, even in the cases where rain rate is higher, the dilute mixture assumption remains valid because inclusion fraction is below the order of 10^{-6} .

An experiment was performed to estimate the safety of neglecting contribution due to high frequency in Fig 2.3. The experiment compared absorption due to quasi-static assumption with extinction efficiency Q_{ext} of a spherical raindrop. Q_{ext} is estimated by full Mie theory.

$$Q_{abs,qs} = 4x \text{Im} \left\{ \frac{\epsilon_w - \epsilon_0}{\epsilon_w + 2\epsilon_0} \right\} \quad (2.12)$$

where $x = k_0 a$ is the size of sphere.

Fig. 2.4 plots the comparison where the extinction is plotted with the frequency. Here, the extinction is calculated with the raindrop having diameter of 1 mm. After 5 GHz, the quasi-static assumption about absorption fails. There are different drop size in the rain and the average drop size is directly proportional to the rain rate as shown by Marshall-Palmer distribution function.

[28] presents a survey on scattering from hydrometers. The review of mixing approach and connection of back scattering and mixing approach can be seen in [5, 6].

2.2 Dielectric Soil Properties Model

Soil is considered as a dielectric material which is composed of bound water, air, free water, and bulk soil. It is mainly described by its relative permittivity or dielectric

Fig. 2.4: Variations of penetration depth vs. frequency. [16]

constant. EM waves are affected by the permittivity of the medium through which they pass. relative permittivity has a direct relation with EM wave propagation, i.e., smaller the permittivity, better will be EM propagation. Soil with smaller bulk density will be more porous having more air in the medium, therefore, causing lower attenuation in EM waves. The presence of water in the soil has direct relation with the attenuation in the soil and soil parameters like the volumetric water content (VWC) are the main causes of attenuation in EM wave propagation [1, 1, 43, 59, 60, 70].

VWC is made up of the bound water and the free water. The bound water is a thin layer of water which strongly bounded to the surface of the soil. The free water is loosely or freely held water molecule in the soil [4, 44]. therefore, even if the VWC value of two soil samples is same, one sample may contain more free water as compared to others because of different sample texture. Bound water is determined the texture and clay quantity in the soil [4, 15, 36]. This will further be explained in Section 2.4, where power is varied more than 20 dB for samples having same VWC but different texture. This is because of difference in dielectric properties of bound and free water. Therefore, dielectric model weighs the bound and free water differently.

Fig. 2.5: (a) Change in β_s / β_0 [35], (b) Effect of soil moisture on the parameter λ_s / λ_0 in three different soil types [35], (c) Effect of soil moisture on the relative permittivity in three different soil types at different frequencies [35]

A soil with predominantly clay particles is worse for underground communication as compared to sandy soil. A well-known fact is that one gram of clay retains more water as compared similar amount of sand or silt [15, 32]. A surface area of soil particle is directly proportional to the water absorption in soil and inversely proportional to the size of soil particles. Clay particle has high surface area and small particle size. Therefore, they absorb more water as compared to sand and silt.

Soil permittivity also depends on the frequency of the signal, hence, in addition to VWC, soil permittivity is also effected by frequency of the signal [4, 20, 41]. Therefore, it can be said that frequency, indirectly effect the attenuation of EM waves.

Soil conductivity, along with certain frequency ranges, causes the signal attenuation in soil [4, 23]. This negates the general belief of lower signal attenuation under low frequencies [4, 28]. It is true for most of the cases, however, there are some exceptional frequency range which does not support this argument. Even if values for all soil parameters are available, there is no direct method or formula for calculating soil permittivity using these parameters and, without soil permittivity, it is not possible to estimate signal attenuation in soil.

There has been many frequency specific dielectric model proposed to lessen the severity of above problem [4, 8, 40]. As these models were for some specific applications with restricted frequency ranges, many assumptions can be made to simplify the model. Thus, the model is simplified without losing its accuracy. Consequently, it is important to determine what frequencies must be used in WUSNs while developing dielectric model of Zenneck waves (ZW).

Frequencies around 1 GHz are used for practical wireless communication and microwave remote sensing and gives smaller values of soil permittivity [1, 19, 28, 50]. Signal can have smaller attenuation under the frequencies lower than 300 MHz, however, smaller frequencies cause increase in wavelength and antenna size. Therefore, it is not recommended to use frequencies below 300 MHz in WUSNs. Considering these facts about frequency, ZW model employ a balanced approach of achieving practicality with accuracy. Therefore, semi-empirical soil dielectric model presented in [28] is selected for ZW model. This model limits the frequency range to 300 MHz - 1300 MHz.

2.3 Permittivity and Wavenumber in Soil

This section discuss the analysis of the constitutive parameters of the soil at different soil moisture levels. It also studies the dielectric constant in siltloam and sandy soil types at different frequency and water content levels. A detailed analyses of the impact of soil moisture variations on permittivity and wavenumber in soil has also been carried out. This section also presents the effect of change in soil moisture on wavenumber and soil permittivity. Phase constant in soil is given by β_s and that of air is represented by β_0 . Similarly, wavelength in soil is represented by λ_s , and λ_0 is the wavelength in air. Complex wavenumber $k_s = \beta_s + i\alpha_s$, where α_s represents the attenuation constant in soil, is used to calculate β_s/β_0 , and λ_s/λ_0 . Figs. 2.5 plots change in these parameters with change in soil moisture for sandy, silt loam, and silty clay loam soil types. It can be observed in Fig. 2.5(a) increasing the soil moisture results in increase of β_s/β_0 . For example, when soil moisture is 40%, the phase shift increases 5% more than what it is in free space β_0 . Fig. 2.5(b) plots the change in wavelength λ_s/λ_0 with OTA wavelength. It is observed that frequency shift is comparatively less than that of OTA and is in direct relation with soil moisture levels, i.e., decrease with decreasing in soil moisture level and vice versa. Moreover, difference in frequency shift for different soil types shrinks as the soil moisture levels increases. This behavior is because of high permittivity of the soil.

Fig. 2.6: Soil moisture effect on real and imaginary part of dielectric constant different frequencies

Fig. 2.5(c) plots relative permittivity with soil moisture for silt loam and sandy soil. The experiment uses frequency of 200 MHz and 600 MHz. It can be observed that: a) relative permittivity of sandy soil is effected more than that of silt loam soil, and b) frequency does not have any effect on soil permittivity. This is due to dielectric and conduction losses. Dielectric losses causes soil moisture to change because of water held by the soil is released [7, 27].

Underground wireless signal can propagate through three different paths namely reflected, directed and lateral as shown in Fig. 7.2(a). Directed and reflected are the possible signal paths in the soil and they remain completely in the soil. However, lateral component can pass along soil-air interface right above the soil surface. All three UG channel components are studied with great detail in [41, 61], [42, 145].

Figs. 2.6 plots dielectric constant with soil moisture levels. The experiments are performed for sandy and silt loam soil at frequency of 200 MHz and 600 MHz. It can be seen that ϵ_s' is directly proportional to VWC, i.e., increasing linearly with increase in VWC.

Fig. 2.7: The three components of the wireless subsurface propagation channel in soil [145].

2.4 Impact of Soil on Wireless Underground Communication

This section discusses how wireless communication is affected by the soil. There are mainly three ways in which soil can impact the communication: return loss of the antenna, the path loss of the propagation, and bandwidth of the antenna. Soil permittivity is affected greatly by change in soil moisture and frequency. In coming sections, all three impacts are studied separately [46, 54].

2.4.1 Relative Permittivity of Soil

The permittivity of soil is higher than the air due to which it changes the wavelength of EM waves incident upon it. Soil permittivity rely on many soil parameters such as: soil texture, bulk density, salinity, soil moisture (Volumetric Water Content), and temperature. There been intensive investigation for modeling the characteristics of relative permittivity [13, 26, 65]. These models explains the relative permittivity of various soil-water mixture components: free water, soil, air, and bounded water [13]. The effective permittivity of soil-water mixture is overall permittivity of air, soil and water and is a complex number.

Fig. 2.8: Models: (a) Return loss of an antenna estimated at different soil moisture values, (b) Bandwidth at non-resonant frequency, (c) Channel Model [10].

2.4.2 The Impact of soil on the Return Loss of an Antenna

The return loss of buried antenna changes because of permittivity of the soil. Moreover, change in soil moisture causes change in soil permittivity and antenna return loss. Fig. 2.9(a) shows the result of the experiments performed with a 70 mm monopole antenna with different soil moisture level which confirms that increasing soil moisture causes resonant frequency, corresponding to return loss, to shift in lower spectrum.

The return loss occurs due to impedance mismatch, therefore, it is important to calculate the impedance first. However, there is no closed form representation of an arbitrary antenna but a good impedance approximation for dipole antenna is provided in [19, 23, 43, 74]. The analysis of impedance model in [23, 33] is analyzed below. As per [23], the input impedance of a dipole can be approximated by using induced-emf method as follow:

$$Z_a \approx f_1(\beta l) - i \left(120 \left(\ln \frac{2l}{d} - 1 \right) \cot(\beta l) - f_2(\beta l) \right) \quad (2.13)$$

where

Fig. 2.9: (a)Return Loss, (b) Bandwidth, (c) Path loss in UG2AG channel, [10]

$$f_1(\beta l) = -0.4787 + 7.3246\beta l + 0.3963(\beta l)^2 + 145.6131(\beta l)^3,$$

$$f_2(\beta l) = -0.4456 + 17.0082\beta l - 8.6793(\beta l)^2 + 9.6031(\beta l)^3$$

β is a real part of wave number, diameter of d is given as d , and half of the length of the dipole is given as l . βl is expressed as :

$$\beta l = \frac{2\pi l}{\lambda_0} Re\sqrt{\epsilon_s}, \quad (2.14)$$

where λ_0 is the wavelength in the air, and ϵ_s is the soil relative permittivity [26]. As the ϵ_s relies on frequency so βl is not linear function of l/λ_0 . Therefore, the resonant frequency changes which in turn changes the impedance at those frequency values when the antenna is moved from air to soil [26, 35].

The return loss is because of mismatch in impedance. The return loss of antenna is express in dB and is calculated as:

$$RL_{dB} = 20\log_{10} \left| \frac{Z_s + Z_a}{Z_s - Z_a} \right|. \quad (2.15)$$

which approximately matches the experiment results.

2.4.3 The Impact of Soil on Bandwidth

Channel capacity increases with the increase in bandwidth, hence, bandwidth also effect the performance of underground communication. In wireless communication, bandwidth is affected by antenna and return loss of antenna is calculated from bandwidth. Return loss RL (see Fig. 2.9(a)) is the function of frequency ($RL = R(f)$). When antenna is excited at resonant frequency, the bandwidth refers to the spectrum where negative of the return loss $< \delta$. Bandwidth always remains smaller than the resonant frequency when no resonant frequency is being used. Bandwidth is calculated as:

$$B = \begin{cases} 0 & if -R(f) > \delta, \\ 2(f - f_m) & if -R(f) \leq \delta \text{ and } f < f_r, \\ 2(f_M - f) & if -R(f) \leq \delta \text{ and } f \geq f_r, \end{cases} \quad (2.16)$$

where f_r is the resonant frequency, f_m and f_M represents the lowest and highest frequency at which $R(f) \leq \delta$.

Fig. 2.9(b) plots negative of RL , i.e., S_{11} with frequency f . Operational frequency is higher and there is a difference of 24 MHz between operational frequency and resonant frequency, and $\delta = -10$ dB. It can be seen that $S_{11} < \delta$ for whole spectrum and bandwidth is 14 MHz.

2.4.4 The Impact of Soil on Path Loss

In [8, 19, 37, 42], aboveground-to-underground (AG2UG) and underground-to-aboveground (UG2AG) channel in WUSN are studied in detail. Fig. 2.9(c) depicts the communication path where attenuation in EM waves passing through the soil is the function of distance, soil moisture and soil type. Irrespective of the direction, path loss is given as:

$$L = (L_{ug}(d_{ug}) + L_{ag}(d_{ag}) + L_{(R, \rightarrow)}), \quad (2.17)$$

where $L_{ag}(d_{ag})$ and $L_{ug}(d_{ug})$ are the loss at above-ground and underground portions, respectively. $L_{(R, \rightarrow)}$ is the refraction loss on the basis of direction of the propagation, $\rightarrow$, i.e., $ug2ag$ or $ag2ug$.

The UG and AG losses from equation 2.17 can be calculated as:

$$L_{ug}(d_{ug}) = 6.4 + 20\log d_{ug} + 20\log \beta + 8.69\alpha d_{ug}, \quad (2.18)$$

$$L_{ag}(d_{ag}) = -147.6 + 10\eta \log d_{ag} + 20\log f, \quad (2.19)$$

respectively, η represents the attenuation coefficient in air, β is the phase shifting constant, f is the operational frequency, and α denotes the attenuation constant. $\eta > 2$

because of ground reflection. The η range is 2.8–3.3 and is estimated by empirical experiments [7]. Last two terms in equation 2.18 gives the effect of soil properties on attenuation, where α and β are calculated as:

$$k_s = \alpha + i\beta = i\omega\sqrt{\mu_0\epsilon_s}, \quad (2.20)$$

where k_s denotes the propagation constant in soil, ϵ denotes the effective soil permittivity, and μ_0 denotes permeability in free space. EM waves can only enter the soil-air interface if the incident angle is small, otherwise, it is refracted and reflected at the interface. It is mainly because of high permittivity value of the soil [28, 38]. Only waves having small incident angle θ_t , as shown in fig. 2.9(c), will transmit to air in UG2AG propagation. In AG2UG propagation, the propagation in soil is in the vertical direction dn refracted angle approximate to zero. Therefore, the underground distance in both links can be approximated as $d_{ug} \simeq h_u$ where h_{ug} denotes the burial depth and aboveground distance in both links can be approximated as $d_{ug} = \sqrt{h_a^2 + d_a^2}$ where h_a denotes the height of the AG node and d_g horizontal distance between the node.

Maximum power path is considered for the AG2UG link where incident angel $\theta_i \rightarrow 0$. Therefore, refraction loss $L_{(R,\rightarrow)}$ from equation 2.17 can be approximated as [26]:

$$L_{(R,ag2ug)} \simeq 20\log \frac{n+1}{4}, \quad (2.21)$$

where refractive index of soil is represented by n and calculated by [19] as:

$$n = \sqrt{\frac{\sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon'}{2}}. \quad (2.22)$$

The signal in UG2AG link, propagates form higher density medium to lower density medium in a perpendicular direction, hence, all energy is refracted, i.e., $L_{(R,ug2ag)}=0$.

2.4.5 The Impact of Soil on Frequency

In soil, higher frequencies suffer more attenuation because when EM waves propagate their wavelength shortens due to higher permittivity of soil than the air. Hence, due to less effects of permittivity of soil on lower frequency spectrum, it is more suitable for UG2UG communication as larger communication distances can be achieved. In order to have minimum attenuation, an operation frequency should be selected, for each distance and depth, such that attenuation is minimized. This is important from IOUT topology design perspective because deployment needs to customized to the soil type and frequency range of sensors being used for deployment.

In Fig. 3.30, attenuation with frequency at different distances of up to 12 m are presented. Transmitter and receiver depths are set to 20 cm. At 2 m distance,

Fig. 2.10: Attenuation with frequency [51].

attenuation increases by 24 dB when frequency increases from 200 MHz to 400 MHz. Similarly, for 200 MHz, attenuation is increased from 51 dB to 92 dB (80 %) when distance increases from 50 cm to 12 m.

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