Terahertz Channel Modeling of Underground Sensor Networks in Oil Reservoirs

Mustafa Alper Akkaş *‡, **Ian F. Akyildiz** † and **Radosveta Sokullu** *

‡ This work was completed during his stay in the Broadband Wireless Networking Laboratory

* Department of Electrical & Electronic Engineering
Ege University
Bornova IZMIR 35100 TURKEY
Email: {alper.akkas, radosveta.sokullu}@ege.edu.tr

† Broadband Wireless Networking Laboratory School of Electrical and Computer Engineering
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
Email: {akkas, ian}@ece.gatech.edu

Abstract— **Future enhanced oil recovery technology requires wireless sensor networks to effectively operate in underground oil reservoirs. In this case, the millimeter scale sensor nodes with the antennas at the same scale have to be deployed in the confined underground oil reservoir fractures. This necessitates the sensor nodes to be operating in the THz frequency range. In this paper, the propagation based on electromagnetic (EM) waves in the Terahertz band (0.1-120.0 THz) through a crude oil/water mixture and soil medium is analyzed in order to explore its applicability in underground oil reservoir assessments. The developed model evaluates the total path loss and the absorption loss that an EM wave experiences when propagating through the crude oil/water mixture and soil medium. Our results show that sensors can communicate successfully for distances up to 1 centimeter and we have determined the existence of two transmission bands, in which the path loss is below 100 dB. Among those, the frequency window, which provides best performance, determined as 70 to 85 THz. Different path and absorption loss schemes considered, which suggests that the 70 to 85 THz band is suitable for sensor communications in a medium of crude oil/water mixture and soil.**

Keywords: - Terahertz Band; Channel Model; Electromagnetic Absorbance; Crude Oil; Water

I. INTRODUCTION

Due to its high energy density, easy transportability and relative abundance, oil has become the world's most important source of energy since the mid-1950s. Petroleum is also the raw material for many chemical products, including pharmaceuticals, solvents, fertilizers, pesticides, and plastics; the 16% not used for energy production is converted into these other materials. Petroleum is found in porous rock formations in the upper strata of some areas of the Earth's crust. There is also petroleum in oil sands. Known oil reserves are typically estimated at around 190 km^3 (1.2 trillion barrels) without oil sands, or 595 km^3 (3.74 trillion barrels) with oil sands. Consumption is currently around 84 million barrels (13.4×10^6 m^3) per day, or 4.9 km^3 per year. Which in turn yields a remaining oil supply of only about 120 years, if current demand remain static [1].

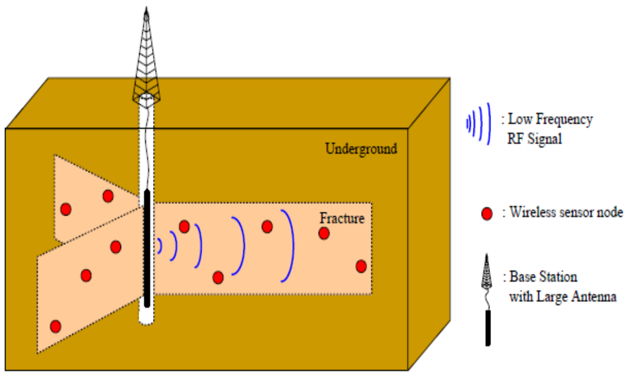

Figure 1. System architecture of the wireless sensor network for oil recovery

The typical oil well illustrated in Fig. 1 is created by drilling a hole into the earth with an oil rig. A steel pipe is placed in the hole, to provide structural integrity to the newly drilled wellbore. Holes are then made in the base of the well to enable oil to pass into the bore. Afterwards, an underground explosion makes a medium of 3-D hydraulic fracture with the size about 100m*3m*1cm (length * height * width). From one hole, water and carbon dioxide is pumped periodically to remove to oil to the ground. Finally, a collection of valves is fitted to the top in order to regulate the pressures and control the flows.

As a promising approach to increase the oil recovery factor, deploying sensing agents in the 3-D hydraulic fracture of oil field can enable real-time oil reservoir monitoring by providing comprehensive sensing measurements such as pressure, temperature, oil saturation and fluid type. As illustrated in Fig. 1. The underground sensor network for oil recovery consists of a base station (data sink) located at the wellbore and a large number of wireless sensor nodes deployed in a uniformly distributed manner in the fracture of the oil reservoir. Since the base station does not have size and power constraints, it can be equipped with a large size antenna and high power transceiver. The wireless sensor nodes are injected into the fracture with the fluid during the hydraulic fracturing process. After the proppants are injected, the sensor nodes are fixed on the fracture wall. It should be noted that those low-cost sensor nodes are small in size and have very limited power. The system functionalities depend on the wireless communications between the base station and the numerous wireless sensor nodes in the fracture of the oil reservoir.

The wireless communication channel in the sensor network for oil reservoirs described above is two directional: from the base station to sensor nodes and from the sensor nodes to the base station or to other sensor nodes. Since the base station can be equipped with large size antenna and high power transceiver the communications initiated from the base station can use low frequency and high-power RF signals and effectively radiate RF signals through the fluid medium inside the fracture. However, when the wireless communication initiated from the wireless sensor nodes is considered, existing techniques fail to operate satisfactorily in the fracture of the oil reservoir. The major challenges are created by the following factors :

- The wireless sensor nodes are deployed underground in a 3-D hydraulic fracture with the size 100m*3m*1cm (length * height * width). Since the width of the structure is less than 1cm, the size of the sensor agents falls in the millimeter magnitude. In this case, the millimeter scale sensor nodes necessitate the antennas at the same scale. This implies that the operating frequency has to be in the THz range.
- Consisting mainly of water and crude oil, but also containing other diverse fluids in lesser amounts. In such fluid transmission medium, an EM signal with frequency in the THz range will experience severe medium absorption, which leads to extremely high path loss and short transmission radius [2,3].

To encounter above challenges and enable the development of effective communication protocols for underground sensor networks in oil reservoirs. In this paper we will develop a comprehensive propagation model for THz bands in the crude oil/water mixture and soil medium. This model evaluates the total path and the absorption loss that an EM wave experiences when propagating through the crude oil/water mixture and soil medium operating in the THz band. Since the Terahertz band EM waves experience intensive material absorptions while traveling through the mixed fluid environment. The path loss fluctuates as the operating frequency changes due to the summation of EM waves with different phases caused by the mixed materials in the fluid. Our objective is to set the operating frequency at the point where the path loss experiences deep fading so that the path loss is minimized and the transmission range is maximized.

The paper is organized as follows. In Sec. II, the Terahertz band EM wave-based communication is introduced. In Sec. III, IV and V, the absorption properties in water medium, crude oil and soil in 0.1-120.0 THz band are provided respectively, emphasizing the water, crude oil and soil absorption and path loss in the Terahertz band. Based on the findings in Sec. III, IV and V. VI we provide combined results in accordance with the Beer-Lambert law. Finally, we conclude the paper in Sec. VII.

II. TERAHERTZ BAND EM WAVE-BASED TECHNIQUE

As mentioned in the introduction part , due to the extremely thin fracture environment, the millimeter-scale antenna necessitates the Terahertz band (0.1-120.0 THz) signals when EM waves are utilized. Moreover, the fracture in the oil reservoir is filled with a mixture consisting of larger proportions of water and crude oil, among other fluids. The Terahertz band EM waves experience intensive material absorption while traveling through the fluid environment [4]. Since the size of the sensors is very small and has very limited power source, it is impossible to use high power to achieve the acceptable communication range. Hence, new low-power signal propagation models and technique need to be developed.

The different medium components impose different attenuation and phase shifting effects on the EM waves in the Terahertz band. As a result, the path loss fluctuates as the operating frequency changes due to the summation of EM waves with different phases. It is possible to set the operating frequency at the point where the path loss experiences deep fading so that the path loss is minimized and the transmission range is maximized. Considering the extremely high frequency, even a very narrow deep fading channel of the path loss can bring more than enough bandwidth. Moreover, since the EM waves are transmitted inside the fracture, the walls of the fracture limit the spread of the signal energy by reflecting the signal back into the fracture medium, which may reduce the total path loss but may also add additional fluctuations in the path loss [5]. We investigate the channel characteristics of the Terahertz EM waves in oil reservoir environments to determine an optimal frequency band that minimizes the total path loss and maximizes the transmission radius for an underground sensor network. Once the optimal operating frequency is determined, the channel and network capacity can be analyzed based on the developed channel model.

Several molecules present in a standard medium are excited by EM waves at specific frequencies within the Terahertz Band. An excited molecule internally vibrates, i.e., its atoms show periodic motion while the molecule as a whole has constant translational and rotational motions. As a result of this vibration, part of the energy of the propagating wave is converted into kinetic energy or, from the communication perspective, simply lost [4]. EM waves at this specific frequencies within the Terahertz Band encounter much higher attenuation in soil and liquid compared to air. This severely hampers the communication quality. Therefore, advanced models are necessary to accurately and completely characterize the underground channel and to lay out the foundations for efficient underground communication.

III. CHANNEL ABSORPTION PROPERTIES IN WATER MEDIUM IN THE 0.1-120 THZ BAND

Absorption spectrum of water at various temperatures in the whole infra red (IR) region ($0 <$ wave number $\tilde{\nu} < 4000\ cm^{-1}$) can be obtained from ATR spectra recorded in the mid-IR region combined with absorption spectra measured in the FIR region. Then, the absorption spectrum L_{abs} water (in dB) of the EM waves in a sample of pure water within distance d can be calculated according to the Beer-Lambert law [6, 7]:

$$L_{abs}^{water} = k_{water}(f) \cdot d \cdot 10\log(e). \qquad (1)$$

where d is the transmission distance; $k_{water}(f)$ is the absorption coefficient, which is a function of the operating frequency f and is influenced by the liquid temperature. The value of $k_{water}(f)$ and temperature can be looked up in Fig. 1 in [6].

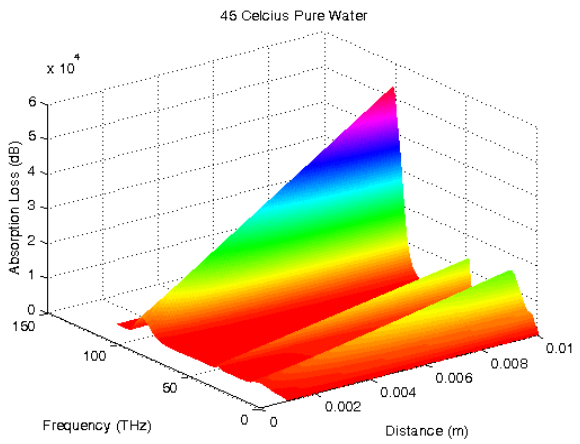

Figure 2. Path loss of pure water at 1mm distance between 70 and 85 THz

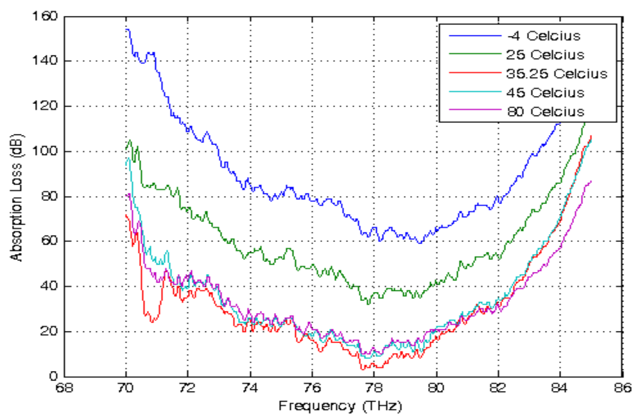

Figure 3. Path loss of pure water chancing the distance from 1mm to 10mm.

Based on (1), we can numerically analyze the water medium channel for the Terahertz EM waves. Results given in Fig. 2 show that there exist several transmission windows from 30 to 45 THz and from 65 to 85 THz. The best window for our purposes is from 70 to 85 THz because there is least absorption loss there, showed at Fig. 3. The feasible communication range for the Terahertz EM wave in water medium is around 1 cm and the bandwidth is around 15 THz.

Up to this point of Sec. III we investigated absorption spectrum of pure water but usually sea water is used at oil recovery process. Absorption spectrum of salty water can be analyzed according to (2)-(7)

$$\alpha' = \frac{4\pi\kappa}{\lambda_0}; \qquad (2)$$

$$\alpha' = \alpha \cdot In(10); \qquad (3)$$

$$\alpha = \frac{4\pi\kappa}{\lambda_0 \cdot In(10)}; \qquad (4)$$

$$T = \frac{I}{I_0} = 10^{-\alpha l}; \qquad (5)$$

The absorption coeffcient, α' ,can be expressed in terms of the imaginary part of the refractive index,κ, and the wavelength of the light (in free space), λ_0. I_0 and I are the intensity (or power) of the incident light and the transmitted light, respectively. Combining (4) with the Beer–Lambert law for liquids (5), we obtain (6).

$$T = \frac{I}{I_0} = 10^{-5.4575 \cdot \frac{\kappa}{\lambda_0} l}; \qquad (6)$$

or in dB

$$T = \frac{I}{I_0} = -54.575 \cdot \frac{\kappa}{\lambda_0} \cdot l. \qquad (7)$$

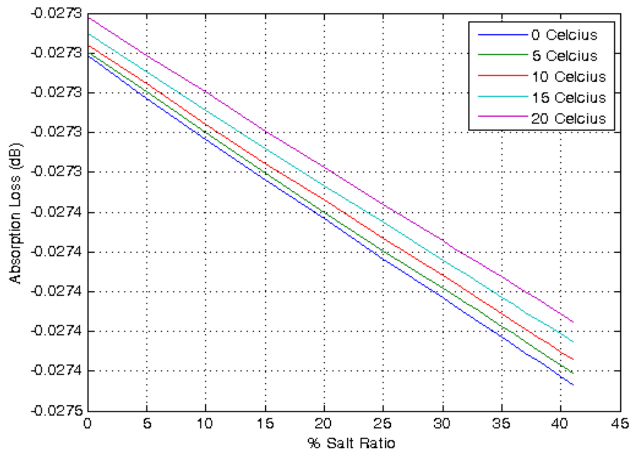

Figure 4. 1 cm distance water absorption loss up to 41% salinity at 80 THz

By substituting the refractive index of sea water in eq. (7), we plot Fig. 4 where we show that the absorption loss decreases as the salinity increases. There are at most 0.2 % differences between 0% salinity and 41% salinity of water. It should be noted that thess results are also proved at different spectrum in [8, 9].

IV. CHANNEL ABSORPTION PROPERTIES IN CRUDE OIL MEDIUM IN THE 0.1-120 THZ BAND

Similar to the analysis for the water medium, the absorption loss caused by the crude oil can be calculated using:

$$L_{abs}^{oil} = k_{oil}(f) \cdot d \cdot 10\log(e). \qquad (8)$$

To derive the absorption loss in crude oil, we also need the absorption spectrum of oil $k_{oil}(f)$ in the whole infrared region. For the purpose of deriving the absorption spectrum, infrared spectroscopy (IR spectroscopy) is utilized [10, 11].

Infrared spectroscopy exploits the fact that molecules absorb specific frequencies that are characteristic of their structure. Crude oil is a mixture of a very large number of different hydrocarbons. The most commonly found molecules are alkanes (linear or branched), cycloalkanes, aromatic hydrocarbons, or more complicated chemicals like asphaltenes [12]. Each crude oil variety has a unique mixture of molecules, which defines their physical and chemical properties. As an example we analyze the absorption spectrum of four typical molecules contained in the crude oil in order to estimate the position and bandwidth of the transmission window of the Terahertz EM waves in the crude oil. It should be noted that the absorption spectrums are derived by the Fourier transform infrared (FTIR) spectroscopy technique provided in [12].

In Fig. 5 we show the infrared spectrum of Octane. Four high-absorption bands are found: 1) the 3000-2850 cm^{-1} band due to the C-H stretch; 2) the 1470-1450 cm^{-1} band due to the C-H bend or scissoring; 3) the 1370-1350 cm^{-1} band due to the C-H rock, methyl; and 4) the 725-720 cm^{-1} band due to the C-H rock, methyl that is only seen in long chain alkanes. Note that in Fig. 5 transmittance is used to express the absorption spectrum.

According to Fig.5 and also the infrared spectrum of different hydrocarbons like 1-Octene, 1-Hexyne and Toluene etc , we can conclude that a common transmission window for the Terahertz EM waves in crude oil is between 2300 and 2800 cm^{-1} (respectively 70 and 85 THz in terms of frequency). Fig. 5 shows the general regions of the infrared spectrum in which various kinds of vibrational bands of C bonds are observed: the blue colored sections above the dashed line refer to stretching vibrations; the green colored band below the line indicates bending vibrations. It should be noted that the vibrational bands are the main enemy of the EM waves.

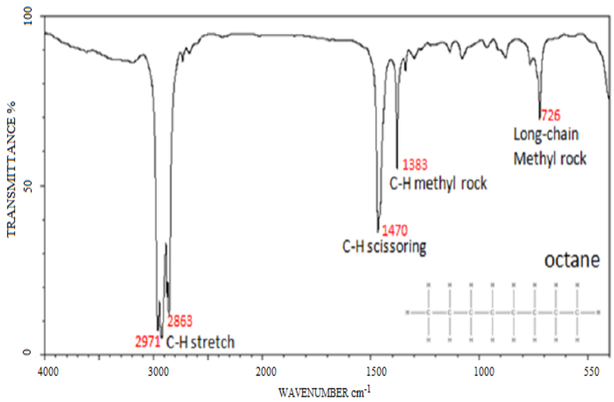

Figure 5. Infrared Spectrum of Octane.

As mentioned before, crude oil is a mixture of a very large number of different hydrocarbons. Fortunately, the hydrocarbons compounds contain only C-H and C-C bonds so in Fig. 6, we generalize the C bonds at the mid-infrared spectrum, which shows that there are no vibrational bands in the transmission window between 2300 and 2800 cm^{-1} (70 and 85 THz) Based on the above discussion, we can conclude that the derived channel model is not limited to certain molecules in the crude oil but can be applied to all types of crude oil. The presented analysis allows us to justify its use with all types of crude oil.

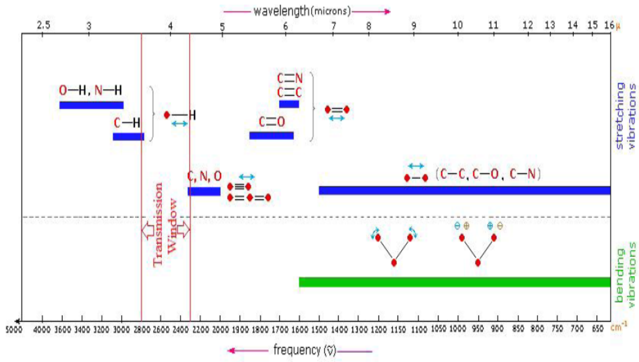

Figure 6. Infrared Spectroscopy Correlation Table with Transmission Window.

V. Wireless Communication Through Crude Oil And Water Mixture Using Electromagnetic Waves

The total path loss L_{EM} of the Terahertz EM waves in oil reservoirs can be decomposed into three components (or is due to the following three major factors): the path loss caused by signal spread L_{spread}, the absorption loss due to the water medium L_{water}, and the absorption loss due to the crude oil L_{oil} . Therefore,

$$L_{EM} = L_{spread} + L_{abs}^{water} + L_{abs}^{oil};$$
$$L_{EM} = 20 \cdot 10\log 10(\frac{4\pi \cdot f \cdot d}{c}) + k_{water}(f) \cdot d \cdot 10\log(e) + k_{oil}(f) \cdot d \cdot 10\log(e). \quad (9)$$

where f is the operating frequency; d is the transmitting distance; and c is the velocity of light in vacuum; $k_{water}(f)$ and $k_{oil}(f)$ are the absorption coefficients in water and crude oil, respectively. The value of $k_{water}(f)$ can be looked up in [13]. The value of $k_{oil}(f)$ can be derived by utilizing the infrared spectroscopy (IR spectroscopy) [10, 11].

The signal spread loss L_{spread} can be derived using the Friis equation, i.e.

$$L_{spread} = 20 \cdot 10\log 10(\frac{4\pi \cdot f \cdot d}{c}); \quad (10)$$

where f is the operating frequency; d is the transmitting distance; and c is the velocity of light in vacuum. Based on (10), we can numerically determine the spread loss for the Terahertz EM waves. The spread loss of the EM waves in the Terahertz is much larger than that assumed in classical wireless communications.

There are many different kinds of crude oil [14] and the absorption spectrum of some types can be looked up in [14, 15, 16, 17, 18, 19, 20, 21, 22]. According to these absorption spectrums, the absorption coefficient of most crude oil $k_{oil}(f)$ at room temperature is approximately 0.02 for the transmission window considered (70 and 85 THz). Then the absorption loss of the Terahertz EM waves in crude oil in the transmission window can be calculated based on (8).

In Fig. 7, the absorption loss and total path loss of Terahertz EM waves in oil and water mixture are plotted. The path loss is calculated using (9). If we assume 0 dBm transmitting power and minimum received signal power at -100 dBm, the numerical results show that the communication range of the Terahertz EM waves in oil and water mixture is no more than 1 cm in the 0.1 THz to 120.0 THz band.

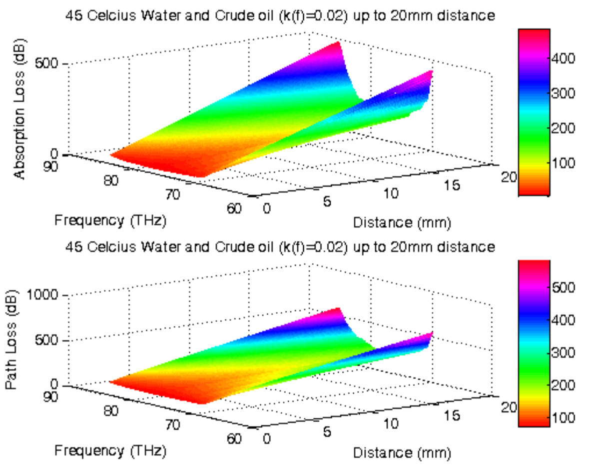

Figure 7. Absorption loss and total path loss of Terahertz EM waves in oil and water mixture.

Finally it can be stated that wireless communication in a crude oil/water mixture using Terahertz EM waves is a multifaceted and challenging task. The model proposed in this study allows the determination of the maximum transmission distance taking into account the total path loss and the frequency. Due to the complex composition of the crude oil and the high absorption of water, by modeling the transmission channel we able to determine that there exist a transmission window in the Terahertz band (0.1- 120.0 THz) that allows up to 1 cm transmission range.

VI. Wireless Communication Through Both Soil And Crude Oil/Water mixture Using Electromagnetic Waves

A channel model for EM waves in soil medium is developed in [2,3]. Similarly we utilize the Peplinski principle to characterize the propagation of EM waves in the soil part of the oil reservoir environments. In this paper, we extend this model to investigate the propagation of Terahertz EM waves in soil medium. The absorption loss of the EM waves in soil medium L_{soil} is given by (11), where α is the attenuation constant with the unit of 1/m, and β is the phase shifting constant with the unit of radian/m.

$$L_{abs}^{soil} = 20\log(\beta) + 8.69\alpha d. \qquad (11)$$

The values of α and β depend on the dielectric properties of soil:

$$\alpha = 2\pi f \sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1+(\frac{\epsilon''}{\epsilon'})^2} -1\right]}; \qquad \beta = 2\pi f \sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1+(\frac{\epsilon''}{\epsilon'})^2} +1\right]}. \qquad (12)$$

where f is the operating frequency, μ is the magnetic permeability, ϵ' and ϵ'' are the real and imaginary parts of the relative dielectric constant of soil medium:

$$\epsilon' = 1.15[1+\frac{\rho_b}{\rho_s}(\epsilon_s^{\alpha'}) + m_v^{\beta'}\epsilon_{fw}'^{\alpha'} - m_v]^{1/\alpha'} - 0.68; \qquad \epsilon'' = [m_v^{\beta''}\epsilon_{fw}''^{\alpha'}]^{1/\alpha'}. \qquad (13)$$

where m_v is the volumetric water content (VWC) of the soil medium, ρ_b is the bulk density, $\rho_s = 2.66$ g/cm^3 is the specific density of the solid soil particles, α' = 0.65 is an empirically determined constant, ϵ' free water and ϵ'' free water are the real and imaginary parts of the relative dielectric constant of water, β' and β'' are empirically determined constants, dependent on soil composition in terms of sand and clay.

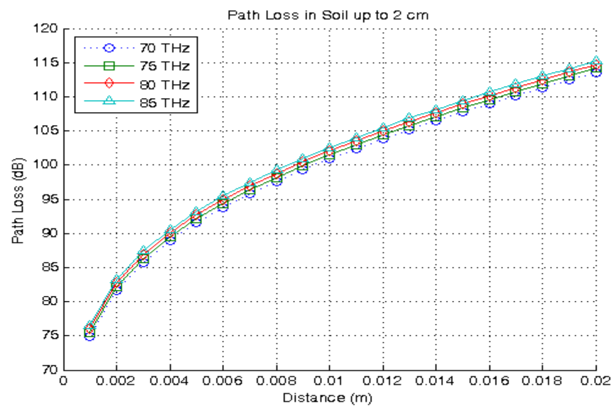

Figure 8. Path loss versus operating frequency and transmission distance in soil environments

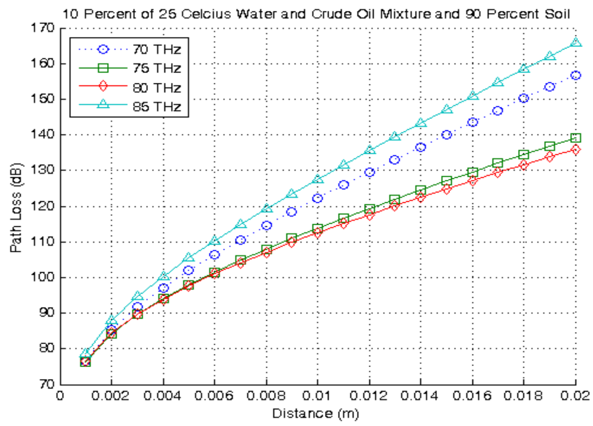

Figure 9. Path loss versus operating frequency and transmission distance in oil reservoir environments with 90% soil medium and 10% water/oil mixture.

Based on the above channel model, we can numerically evaluate the path loss of Terahertz EM waves in soil medium. In the evaluations, we utilize the parameters that reflect a typical soil condition as reported in [2,3]. We set the Volumetric Water Content as 5%, the sand particle percent as 50%, the clay percent as 15%, the bulk density as 1.5 g/cm^3. The operating frequency is chosen between 0.1 and 120 THz. In Fig. 8, the path loss is shown as a function of transmission distance with 70 to 85 THz band operating frequency. It shows that the path loss increases dramatically as the operating frequency increases.

In Fig. 9, we evaluate the total path loss of the Terahertz EM waves in our transmission window in the oil reservoir environments with 90% soil medium and 10% water/oil mixture. It shows that in the hybrid environments, although the transmission range slightly increases, it is still less than 1 cm.

VII. CONCLUSIONS

The different medium components impose different attenuation and phase shifting effects on the EM waves in the Terahertz band. The path loss fluctuates as the operating frequency changes due to the summation of EM waves with different phases. It is possible to set the operating frequency at the point where the path loss experiences deep fading so that the path loss is minimized and the transmission range is maximized. In this paper, we have presented results on the investigation of the transmission characteristics of crude oil/water mixture and soil for future EM networks in the Terahertz band (0.1-120.0 THz). We have found that in water there exist several possible transmission bands from 30 to 45 THz and 65 to 85 THz but the one best fitting the requirements is the window from 70 to 85 THz band because there are least absorption and path loss of the electromagnetic waves. Furthermore, we have examined different path and absorption loss schemes and, have proved that the 70 to 85 THz band is suitable for EM based communication both in crude oil/water mixture and soil even the window from 76 to 80 THz band have deepest absorption and path loss of the electromagnetic waves ratios. Our results show that the Terahertz communication channel has a strong dependence on both the molecular composition of the medium and the transmission distance. In the short range, i.e., for a transmission distance in the order of centimeters but this short range transmission distance can be extended by long tail flexible antennas. In the future, the work presented here can be extended to model the transmission characteristics with long tail flexible antenna. The Terahertz band can be considered as a single transmission window almost 15 THz wide. The very high channel capacity of the Terahertz band does not only support very high transmission bit rates, but it also enables new information encoding and modulation techniques as well as novel networking protocols more suited for resource-limited devices [4]. The window from 76 to 80 THz band still have 4 THz wide transmission window and this is also provides high channel capacity and support very high transmission bit rates.

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