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Wireless Underground Communications in Sewer and Stormwater Overflow Monitoring: Radio Waves through Soil and Asphalt Medium †

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Abstract: Storm drains and sanitary sewers are prone to backups and overflows due to extra amount wastewater entering the pipes. To prevent that, it is imperative to efficiently monitor the urban underground infrastructure. The combination of sensors system and wireless underground communication system can be used to realize urban underground IoT applications, e.g., storm water and wastewater overflow monitoring systems. The aim of this article is to establish a feasibility of the use of wireless underground communications techniques, and wave propagation through the subsurface soil and asphalt layers, in an underground pavement system for storm water and sewer overflow monitoring application. In this paper, the path loss analysis of wireless underground communications in urban underground IoT for wastewater monitoring has been presented. The dielectric properties of asphalt, sub-grade aggregates, and soil are considered in the path loss analysis for the path loss prediction in an underground sewer overflow and wastewater monitoring system design. It has been shown that underground transmitter was able to communicate through thick asphalt (10 cm) and soil layers (20 cm) for a long range of up to 4 km.

Keywords: signals in the soil; electromagnetic waves; urban underground infrastructure monitoring; wireless underground communications; underground sensing; underground antenna

1. Introduction

Internet of Underground Things (IOUT) provide two major functionalities: sensing and communications. To sensing end, IOUT uses various underground things (UTs), which are buried, to perform in situ sensing of the underground data (e.g., soil moisture, salinity, pH, nitrogen, etc.) generated by applications and various environmental phenomenons (e.g., wind and rain information, and solar potential) [1]. To the communication end, IOUT gives a consistent access to sensed data using the combination of underground & above-ground networking infrastructure, and the internet. For example, timely communication of the sensed data allows the users to make real-time decisions preventing potential financial or human loss. Due to these reasons, IOUT is being employed in many applications such as precision agriculture [2–37], border monitoring [38,39], landslide and pipeline monitoring [5,40,41], indoor localization system [42], and power-efficient wireless positioning systems [43].

In recent years, rapid development of cities has made underground urban units a valuable and scarce resource [44]. A huge portion of governments annual budget goes into maintaining the underground public infrastructure. Therefore, it is important to develop new and smart technologies towards building a sustainable urban underground infrastructure. To that end, the works in [45,46] list physical characteristics that need to be considered while planning urban underground infrastructure, the authors of [47] list changes required to improve current urban underground infrastructure, and the authors of [48] use ground-penetrating radar (GPR) technology for detecting damage in underground pipes. Finally, the authors of [49] provide a detailed survey that studies various urban indicator (systems) and argues the inclusion of urban underground space into the list of indicators.

Wastewater facilities make up an important part of an urban infrastructure. City governments establish facilities for collection and treatment of the wastewater. These facilities process millions of gallons of wastewater on a daily basis. The main purpose of these facilities is to look after the quality and quantity of wastewater being collected at the collection system and reaching recovering facilities. It is important because, if not monitored properly, thousands of gallons of water flowing underground can result in overflow of sanitary sewers. Therefore, a smart solution is required for timely detection and prevention of any disaster occurring due to inefficient monitoring of wastewater. However, city governments do not have affordable underground communication and sensor technologies. Moreover, there exist limited cost-efficient underground IoT solutions because of connectivity challenges in UG environment. Another issue is the extensive cabling required to connect with existing over-the-air communication solutions [50,51]. To that end, the contribution of this paper is to improve the connectivity and communication in an underground environment, which is achieved by performing the path loss analysis for urban underground IoT application of wastewater monitoring [52,53].

The wastewater flow monitoring application is implemented using IOUT, i.e., sensors, wireless underground communication technology [54], and the road side urban traffic infrastructure. Figure 1 shows the architecture of IOUT-based urban wastewater monitoring system. The figure includes both sensing and communication components of IOUT with their deployment locations in smart wastewater monitoring system. It includes possible sources of wastewater (e.g., manhole and storm water etc.), sensors, and transmitters attached to pipes for taking the data from underground pipes, and base stations for receiving senor's data via transmitter and sending it to the control room/cloud for further decision making.

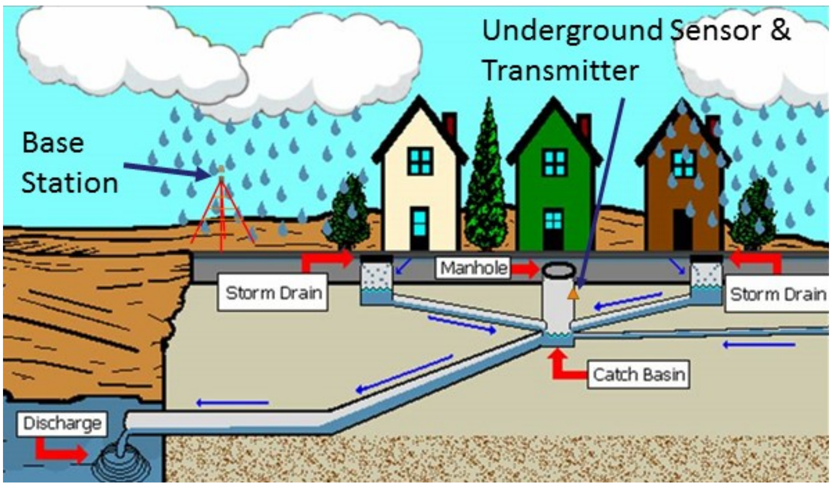

Figure 1. The architecture of urban underground IoT for wastewater monitoring.

Wireless underground communication technology gives the flexibility of burying IoT radios [4]. The pipe monitoring sensors are wirelessly connected with the roadside traffic poles using software defined radios. This wireless communication technology has ability to communicate over the distance of 100–200 m [51]. As UTs are buried underground and has to communicate through roads, a stratified medium made up of asphalt and soil layers, to monitor pipes. Therefore, to achieve a long-range communication, it is very important to study the impact of these layers of communication medium over the propagating signal. This work presents a theoretical path loss analysis for communication through asphalt for designing long-range communication radios. It will reduce the amount of underground cabling while maintaining the communication connectivity [9,55–57]. The information can be provided to users on mobile devices for emergency situations by timely dissemination of information to mobile devices that too on a very large scale. Furthermore, wireless traffic generated from this application can be used to evaluate for other underground wireless solutions.

The organization of the remaining article is as follows. In Section 2, the path loss model for stratified media to air communications is discussed. Section 3 presents the dispersion of the layers of the communication medium used in the sewer overflow monitoring system. Finally, Section 4 evaluates the model using different parameters and Section 5 concludes the article.

2. Path Loss Model for Stratified Media to Air Communications

In this section, we present the attenuation in the stratified medium and dispersion of sub-grade of soil.

Attenuation in the Stratified Medium

The layered structure of the underground medium is shown in Figure 2. While determining path loss of wave propagating in a stratified medium, it is important to consider properties of all layers of the medium participating in the communication [58].

Free Space Path Loss: From the Friis equation [59], the power of the signal at receiver at distance r from the sender can be calculated on logarithmic scale as follows,

$$P_r = P_t + G_r + G_t - L_{fs} \ , \tag{1}$$

where P_t is the power of the signal at sender, G_r is the receiver antenna gain, and G_t is the transmitter antenna gain. L_{fs} is the over-the-air path loss in free space expressed in dB. It is calculated as follows,

$$L_{fs} = 33.2 + 20log(d) + 20log(f) \ . \tag{2}$$

where the length of total transmission path, i.e., the distance between sending and receiving antennas, is denoted by d and expressed in meters (m). f is the operating frequency of the communication system and is expressed in MHz.

We consider transmission loss at two levels: (1) free space path loss and (2) loss through stratified layers.

Propagation Loss in the Layered Medium: For a layered medium, properties of different layers may also affect the propagation loss. Therefore, it is important to determine the effect of a layer properties on the communication loss. Accordingly, the received signal strength can be rewritten as [60]

$$P_r = -L_m + G_r + P_t + G_t \ , \tag{3}$$

where $L_m = L_{fs} + L_l$ and L_l denote the added attenuation due to transmission of EM waves through the stratified medium. The extra attenuation is calculated by comparing the difference between EM wave propagation in layered medium with that of the free space. Therefore, extra prorogation wave loss, L_l, will be the sum of loss in all layers of a stratified medium:

$$L_l = \sum_{n=0}^{N-1} L_n, \tag{4}$$

where L_n represents attenuation (propagation loss) in the nth layer for each of the N layers.

Figure 2. The layered structure of the underground medium.

L_n is mainly dependent on the dielectric permittivity, and the wavenumber of the medium in that particular layer, which can be expressed as $j\beta + \alpha = \gamma$ given as

$$\alpha = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1+(\frac{\epsilon''}{\epsilon'})^2}-1\right]}, \quad (5)$$

$$\beta = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1+(\frac{\epsilon''}{\epsilon'})^2}+1\right]}, \quad (6)$$

where the ω, which is equivalent to the $2\pi f$, denotes the angulated spectrum of the frequency, the magnetized permeableness is expressed as the μ, and the imaginary and real components of the permittivity of the material are denoted as ϵ'' and ϵ', respectively (9). Consequently, the propagation loss, L_n, for a particular layer in the stratified medium is found as [61]:

$$L_n[dB] = 20.\gamma.d.\log 10(e) \quad (7)$$

where $e = 2.71828$, and d is thickness of the nth layer.

It can be observed that the propagation loss is dependent upon number of factors: complex propagation constant of EM wave, operating frequency f, thickness of the layer d, and other properties of the medium. Next, we consider the dispersion of next layer involved in the sewer overflow monitoring system.

3. Dispersion in Different Subsurface Layers

The amount of electric charge that a material can hold in subsurface layer is quantified as its permittivity. The permittivity of a material depends upon its potential to absorb EM waves. An oscillating electric field gives rise to two charge components of the current: positive and negative. The heat loss is the thermal energy that is dissipated because of thermal excitation. Soil and asphalt polarization in subsurface layers is combined with dielectric properties and can be classified into (a) dipolar, (b) electric types, and (c) atomic. Moreover, it is also dependent upon the frequency as different carriers exhibits different polarization response as well as dielectric properties are also different. The next section discuss the dispersion of materials in subsurface layers and presents the expressions for predicting permittivity of a material.

3.1. Dispersion of Sub-Grade of the Soil Medium

The results from the empirical campaign are applied on soil permittivity given in [62], which gives the permittivity spectrum of a medium. Using the frequency range of 300 to 1300 MHz, the permittivity spectra is calculated as follows,

$$\epsilon_s = -j\epsilon_s'' + \epsilon_s' , \tag{8}$$

$$\epsilon_s' = 1.15[1 + \frac{\rho_b}{\rho_s}(\epsilon_s^{\alpha'}) + m_v^{\beta'} \epsilon_{fw}'^{\alpha'} - m_v]^{1/\alpha'} -0.69, \quad \epsilon_s'' = [m_v^{\beta''} \epsilon_{fw}''^{\alpha'}]^{1/\alpha'} , \tag{9}$$

where α' = 0.65, ϵ gives the relative complex dielectric permittivity of the soil, ρ_b is the compaction indicator of the soil, and m_v represents the amount of volumetric water content in the soil. ρ_b is measured in $\mathrm{g/cm^3}$ and is used in relation to ρ_s of solid soil particles ($\rho_s = 2.65\ \mathrm{g/cm^3}$). β'' and β' are the experimental constants, which are calculated as follows,

$$-0.52S + 1.28 - 0.16C = \beta' , \tag{10}$$

$$-0.61S + 1.34 - 0.17C = \beta'' , \tag{11}$$

where S and C quantify the sand and soil particles present in the soil, respectively. The real and imaginary components of relative dielectric permittivity of the free water are represented by $\epsilon' f_w$ and $\epsilon'' f_w$, respectively.

3.2. Dispersion of Asphalt

The communication medium in sewer overflow monitoring application is composed of multiple layers. Given this fact, it is important to calculate the dielectric value of Asphalt layer which constitute the top layer of the medium as shown in Figure 2. The formula for the Asphalt dielectric values is given as follows,

$$\epsilon' = \frac{3}{4\pi} \frac{\epsilon_0 - 1}{\epsilon_0 + 2} , \tag{12}$$

It is important to note that Asphalt dielectric constant has a direct relation with the frequency, i.e., increased frequency will result in increased dielectric constant value. This frequency dependency is due to di-polar polarization. Moreover, asphalt substance (bitumen) is made up of asphaltene and aromatic molecules, therefore, also dependent upon applied electric field.

3.3. Dispersion of Base Gravel Aggregate

The base gravel aggregate layer of the medium is haphazardly composed (aggregation) of heterogeneous material such as sand, stones, pebble, and air voids. As the material is randomly organized,the dispersion in the layer is a function of size and wavelength of the particle. The effective permittivity for this layer is calculated as [63]

$$j \frac{\epsilon_0 - 1}{\epsilon_0 + 2\epsilon'} , \tag{13}$$

where j denotes the volume of solid material and is expressed in percentage.

4. Model Evaluations

This section discuss the path loss analysis. The following parameters are analyzed; thickness of soil and asphalt layers, soil moisture, operational frequency, and transmission power. Table 1 list the values for other parameters of the experiment. The soil and asphalt layer thickness is 20 cm and 10 cm, respectively, with soil moisture level of 5%. The operation frequency of 433 MHz is used with transmission power of 20 dBm. Figure 3 shows the effect of asphalt layer thickness on propagation loss. It can be seen that there is a direct linear relation between the thickness and propagation loss. Propagation loss is increasing with the increase in the thickness value. The propagation loss increases gradually (5dB) until thickness remains less than 1m. However, a sudden increase of 18 dB in propagation loss is experience when thickness goes over 1m. Propagation loss is increased for 5 dB to 18 dB for an increase of 5m in thickness, i.e., after 1m till 6m.

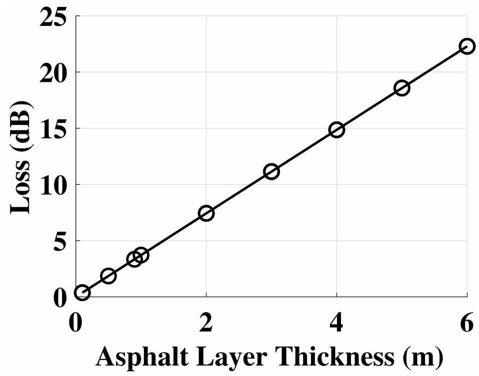

Figure 3. The propagation loss in the asphalt medium with change in layer thickness.

Table 1. Model evaluation parameters.

Parameter	Value
P_t	20 dBm
Thickness of the Soil Layer	20 cm
Thickness of the Asphalt Layer	10 cm
Frequency	433 MHz
Noise Floor	−90 dBm
Soil Mositure	5% by Volume
Asphalt Temprature	300 K/80.33 F/26 C

Figure 4 plots the effect of communication distance on path loss. In general, path loss is increasing with increasing distance. Path loss value remains less than 100dB for the distances of up to 4 km. After 4 km, it increases slowly and reaches to 107 dB till 10 km and becomes constant beyond the distance of 10 km. Received signal strength indicator (RSSI) is the remaining strength of a signal received by a radio client. The effect of increasing distance on RSSI is shown in Figure 5. RSSI is inversely proportional to the communication distance, i.e., it decreases with an increase in distance. However, the decrease is rapid for a distance <2 km. For the subsequent distance increase, i.e., distance >2 km, RSSI decreases slowly and gradually. The received signal strength is −80 dB even at the distance of 4 km. This strength is pretty good and shows that underground things (UTs) can communicate with the road-side urban infrastructure located at long distance.

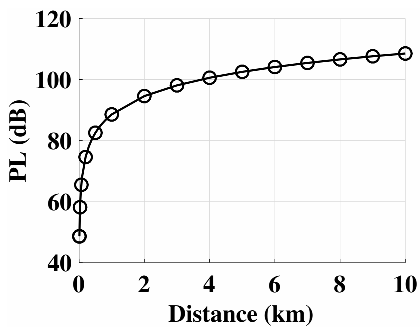

Figure 4. The path loss with change in distance.

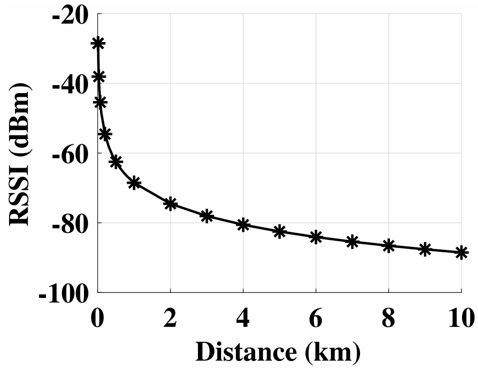

Figure 5. The received signal strength indicator with distance.

As in case of asphalt, the propagation loss and thickness of the soil are also directly proportional (see Figure 6). Figure 6 shows that value of propagation loss is 37 dB, 57 dB, and 90 dB against the soil thickness of 2 m, 4 m, and 6 m, respectively. Although the trend between propagation loss and soil thickness is similar to that of asphalt (see Figure 6), the loss is higher in soil medium than asphalt. This is because soil can hold more water, and therefore has higher permittivity than asphalt.

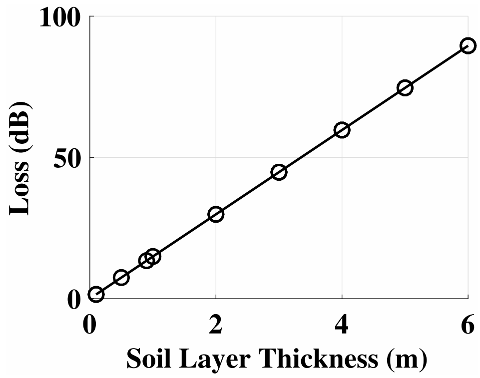

Figure 6. The propagation loss in the soil medium with change in layer thickness.

As asphalt gets hot quickly in the summer, it is important to study the effect of asphalt temperature on communication. Figure 7 plots the effect of temperature of asphalt on signal propagation loss. Overall, propagation loss increase with the increase in temperature. However, the propagation loss is less than 3.6 dB for the temperature of 360 K. The temperature of asphalt varies from one season to another season. Therefore, it is important to consider the temperature of asphalt in different weather conditions when designing communication solutions for IOUT urban monitoring applications.

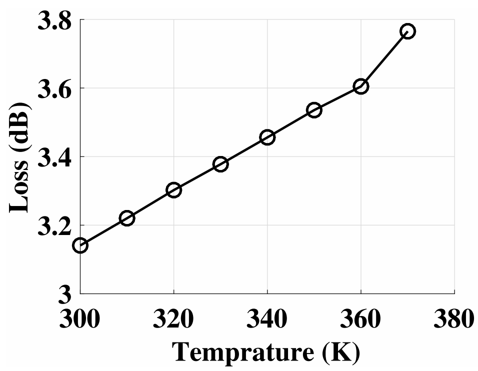

Figure 7. The effect of temperature change on propagation loss in asphalt.

5. Conclusions

This paper focuses on improving the IOUT application of wastewater monitoring system in urban infrastructure. To that end, this work performs path loss analysis for underground wireless channel. For path loss model, signal attenuation in the layered underground medium and free space, and dispersion in different sub-layers of the medium was presented. For evaluation of the model, it was investigated how communication media (soil and asphalt), thickness within the layers of communication media, temperature of communication media, and communication distance can affect the communication system. It was observed that, for both asphalt and soil, signal path loss increases with the increase in layer thickness; however, soil suffers greater path loss than asphalt. It was also observed that, for asphalt layer, propagation loss was also increased with the increase in temperature and distance.

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