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Urban Underground Infrastructure Monitoring IoT: The Path Loss Analysis

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***Abstract*—The extra quantities of wastewater entering the pipes can cause backups that result in sanitary sewer overflows. Urban underground infrastructure monitoring is important for controlling the flow of extraneous water into the pipelines. By combining the wireless underground communications and sensor solutions, the urban underground IoT applications such as real time wastewater and storm water overflow monitoring can be developed. In this paper, the path loss analysis of wireless underground communications in urban underground IoT for wastewater monitoring has been presented. It has been shown that the communication range of up to 4 kilometers can be achieved from an underground transmitter when communicating through 10cm thick asphalt layer.**

I. Introduction

Internet of Underground Things (IOUT) has numerous applications in the field of precision agriculture [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20] [21]. Another important application is in the area of border monitoring, where this technology is being employed for border enforcement and to curtail infiltration [22], [23]. Moreover, IOUT is also being utilized for landslide and pipeline monitoring [4], [24], [25]. IOUT provides seamless access of information collected from agricultural fields through the Internet. IOUT include in situ soil sensing capabilities (e.g., soil moisture, temperature, salinity), but also provide the ability to communicate through plants and soil, and real-time information about the environment (e.g., wind, rain, solar) [26]. When interconnected with existing machinery on the field (seeders, irrigation systems, combines), IOUT enable complete autonomy on the field, and lead to development of enhanced food production applications [27]. At agricultural farm level, IOUTs are being used to provide valuable information to the farmers.

Urban areas have public infrastructure worth billions of dollars located underground. City governments spend significant budget annually to support this underground infrastructure. The underground IoT solutions are rare due to challenges in connectivity and needs for extensive cabling to leverage over-the-air communication solutions, which increases costs. By combining wireless underground technology and sensor solutions [28], [27], many transformative urban underground IoT application such as real time flow monitoring, intrusion and infiltration (I&I) isolation and smart manhole lids can be developed.

The city waste water bodies are responsible for collecting and treating wastewater at wastewater recovery facilities by processing many million gallons a day. Cities have a strong need to monitor the quantity and quality of wastewater entering the collection system and reaching these recovery facilities. Extra quantities of water entering the pipes can cause backups that result in sanitary sewer overflows. Eliminating I&I is important for controlling the flow of extraneous water into the pipeline. However, currently most cities do not have access to affordable underground sensor and connectivity technologies designed to detect problems in time to take preventive action. In this paper, we present the path loss analysis of wireless underground communications using urban underground IoT for wastewater monitoring. The architecture of urban underground IoT for wastewater monitoring is shown in Fig. 1.

The wastewater flow monitoring application can utilize wireless underground communication technology [29], which allows IoT radios to be buried underground [3]. Underground pipe monitoring sensors, connected to wireless underground software defined radios, can wirelessly connect to the roadside urban infrastructure at the nearest traffic light pole. This wireless underground technology has been shown to be successful in agricultural fields for several years with effective communication ranges of 100-200m [27]. We present a theoretical path loss analysis for wireless underground communication through asphalt to design long-range wireless communication radios, which will allow underground radios to be deployed sufficiently deep to keep cabling to the underground pipes at a minimum while maintaining connectivity [8], [30]. Providing this information to mobile devices will enable large-scale dissemination of timely alerts during emergencies. This application can also drive realistic wireless traffic for evaluating solutions for wireless underground networks.

This rest of the paper is organized as follows: the path loss model for stratified media to air communications has been presented in Section II. In this section, attenuation in the stratified medium and dispersion of sub-grade of soil has been described. In Section III, the model evaluations are performed using different parameters. The paper is concluded in Section IV.

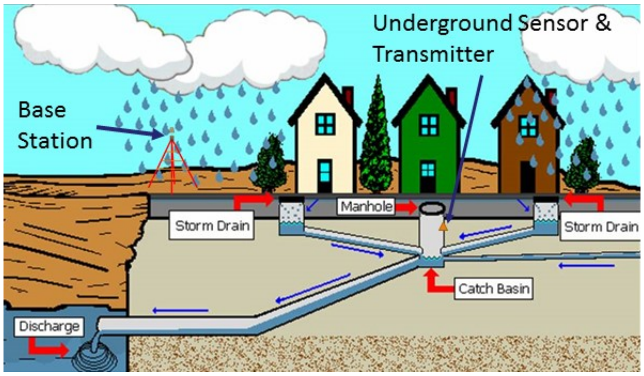

Fig. 1: The architecture of urban underground IoT for wastewater monitoring.

II. 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.

A. Attenuation in the Stratified Medium

The layered structure of the underground medium is shown in Fig. 2. The unique characteristics of signal propagation in stratified medium require derivation of the path loss considering the properties of different layers involved in communication [31].

We consider propagation loss at two levels: 1) free space path loss, 2) loss through stratified layers.

Free Space Path Loss: From Friis equation [32], the received signal strength in free space at a distance r from the transmitter is expressed in logarithmic form as:

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

where P_t is the transmit power, G_r and G_t are the gains of the receiver and transmitter antennas, and L_{fs} is the path loss in free space in dB, which is given by

$$L_{fs} = 32.4 + 20log(d) + 20log(f) \ . \tag{2}$$

where d is the distance between the transmitter and the receiver in meters, and f is the operation frequency in MHz.

Propagation Loss in the Layered Medium: For the propagation through layered medium, loss through medium should account for the effect of the properties of different layers involved in communication. As a result, the received signal can be rewritten as [33]:

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

where $L_m = L_{fs} + L_l$, and L_l stands for the additional path loss caused by the propagation of EM waves through the stratified medium, which is calculated by considering the following differences of EM wave propagation in layered medium as compared to that of free space. The additional path loss, L_l, in stratified medium is, hence, composed of loss of the total number of layers:

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

where L_n is the attenuation loss in the nth layer for each of the N layers.

Propagation loss in the L_n, depends on the complex propagation constant of the EM wave in that layer, which is given as $\gamma = \alpha + j\beta$ with

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

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

where $\omega = 2\pi f$ is the angular frequency, μ is the magnetic permeability, and ϵ' and ϵ'' are the real and imaginary parts of the dielectric constant as given in (9), respectively. Consequently, the path loss, L_n, in for a particular layer is found as [34]:

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

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

It can be seen that the propagation loss depends on the complex propagation constant of the EM wave in medium, layer thickness d, operating frequency, f, and other properties of the medium. Next, we consider the dispersion of next layer involved in the sewer overflow monitoring system.

B. Dispersion of Sub-grade of Soil

Using Peplinski's principle [35], the dielectric properties of soil in the 0.3-1.3 GHz band can be calculated as follows:

$$\epsilon = \epsilon' - j\epsilon'' \ , \tag{8}$$

$$\epsilon' = 1.15[1 + \frac{\rho_b}{\rho_s}(\epsilon_s^{\alpha'}) + m_v^{\beta'}\epsilon_{fw}'^{\alpha'} - m_v]^{1/\alpha'} - 0.68, \quad \epsilon'' = [m_v^{\beta''}\epsilon_{fw}''^{\alpha'}]^{1/\alpha'} \ , \tag{9}$$

respectively, where ϵ is the relative complex dielectric constant of the soil-water mixture, m_v is the water volume fraction (or volumetric moisture content) of the mixture, ρ_b is the bulk density in grams per cubic centimeter, $\rho_s = 2.66g/cm^3$ is the specific density of the solid soil particles, $\alpha' = 0.65$ is an

Fig. 2: The layered structure of the underground medium.

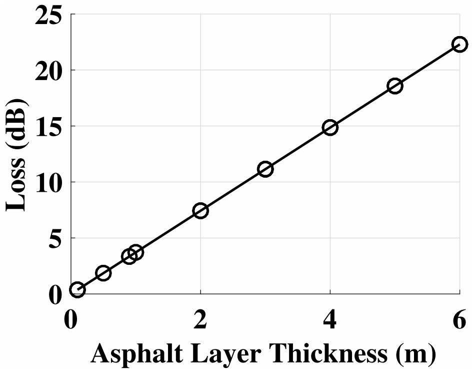

Fig. 3: The propagation loss in the asphalt medium with change in layer thickness.

TABLE I: Model evaluation parameters.

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

empirically determined constant, and β' and β'' are empirically determined constants, dependent on soil-type and given by

$$\beta' = 1.2748 - 0.519S - 0.152C\ , \quad (10)$$

$$\beta'' = 1.33797 - 0.603S - 0.166C\ , \quad (11)$$

where S and C represent the mass fractions of sand and clay, respectively. The quantities ϵ'_{f_w} and ϵ''_{f_w} are the real and imaginary parts of the relative dielectric constant of free water.

III. Model Evaluation

In this section, we present the path loss analysis. The model parameters considered for this evaluation are shown in Table I. 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. In Fig. 3, the propagation loss in the asphalt medium with change in layer thickness has been shown. It can be observed that with layer thickness of less than 1m, the propagation loss is less than 5dB. However, it increases with increase in layer thickness. It increases to 15dB for the 4m thick asphalt layer.

The path loss with change in distance is shown in Fig. 4. It can be observed that for communication distances up to 4km, the path less is less than 100dB. It increases to 107dB for a distance of 10km. The received signal strength indicator (RSSI) with distance is shown in Fig. 5. It can be observed that the RSSI decreases with distance. This decrease is abrupt for distances less than 2km. Afterwards, it decreases gradually. At communication distance of 4km, the -80dBm RSSI indicates that underground nodes in urban underground infrastructure monitoring IoT can effectively communicate with urban road-side wireless communication infrastructure.

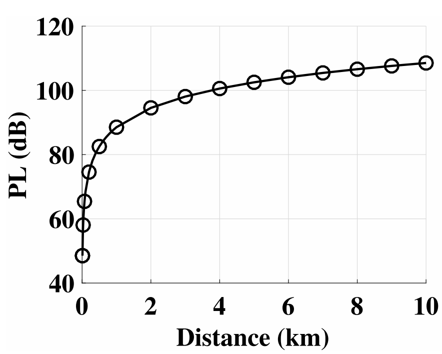

Fig. 4: The path loss with change in distance.

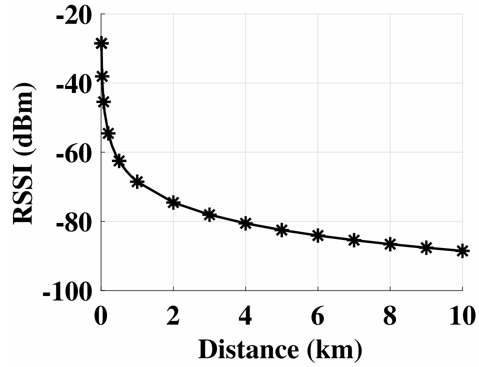

Fig. 5: The received signal strength indicator with distance.

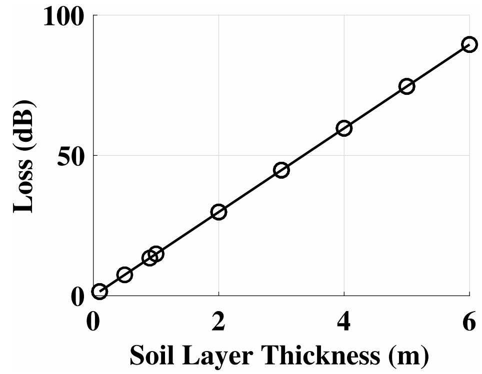

Fig. 6: The propagation loss in the soil medium with change in layer thickness.

In Fig. 6, the propagation loss in the soil medium with change in layer thickness has been shown. It can be observed that with layer thickness of less than 2m, the propagation loss is less than 37dB. However, it increases with increase in thickness. It increases to 57dB for the 4m thick soil layer. Moreover, it can also be observed that soil medium has higher loss as compared to the asphalt medium. This is caused by the the higher permittivity of the soil as compared to the asphalt. The higher water holding capacity of the soil in comparison to asphalt medium leads to the higher permittivity of soil.

The effect of temperature change on propagation loss in asphalt is shown in Fig. 7. It can be observed that with change in asphalt temperature from 300K to 360K, the path loss increases to 3.6dB. Therefore, the wireless communication system in urban underground infrastructure monitoring IoT should be design by considering the temperature change of the asphalt medium in different weather conditions.

IV. Conclusions

In this paper, the path loss analysis of wireless underground communications in urban underground IoT for wastewater

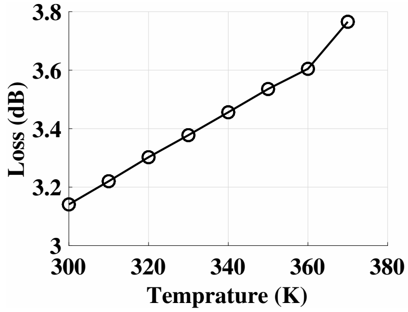

Fig. 7: The effect of temperature change on propagation loss in asphalt.

monitoring has been presented. It has been shown that by combining wireless underground technology and sensor solutions, many transformative urban underground IoT application such as real time flow monitoring, intrusion and infiltration (I&I) isolation and smart manhole lids can be developed. The path loss model evaluations have been done in different communications media under different layers thickness levels.

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