

## Article

# Soil–Water–Air (SWA) Interface Channel Model for River Bridge Pillar Health Monitoring Using WSN

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## Abstract

Wireless sensor networks are installed beneath the earth's surface to track and assess the condition of the below-ground structures. In these systems, buried sensor nodes identify structural anomalies and transmit the sensed information through both soil and air to a sink node located above the ground. In a river-bridge-pillar-monitoring setup, the sensor node located at the pillar's base sends signals that propagate through soil, water, and air before being received by the sink positioned beneath the bridge. This signal transmission involves transmission through soil, water, and air media. The transmission of signals through soil, water, and air media is yet to be explored through a defined channel model. This study introduces a channel model where the signal traverses through soil, water, and air, and derives an analytical formulation to represent the associated path loss. In addition, experimental validation of the obtained analytical path-loss was conducted using a LoRa setup. It was observed from analytical and experimental results that soil depth and water level individually affect the path loss significantly. This severe attenuation needs to be addressed before the actual deployment of the network.

**Keywords:** wireless sensor network; underwater; reflection; path loss; refraction; LoRa; underground



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## 1. Introduction

A wireless underground sensor network (WUSN) is an interconnection of sensor nodes buried underground that extract underground information of interest. They have been applied in smart agriculture, mine safety, disaster alerts, military applications, underground pipeline monitoring, and underground infrastructure health-monitoring systems [1–7]. Monitoring the health of river bridges is necessary as damage to any bridge may lead to severe rail and road accidents. A wireless sensor network (WSN) can be used to monitor the health of a bridge [8,9]. However, monitoring the health of a river bridge pillar that is submerged in water using WUSN is a challenge.

A WUSN-based river bridge pillar-health-monitoring (PHM) system is illustrated in Figure 1. In a PHM system, sensor nodes are placed at different points on the pillar in order to trace any damage to the pillar. Information sensed by the sensor nodes is transmitted to the sink (placed below the river bridge). The sensor positioned at the top portion of the

pillar communicates with the sink through the air–air channel. The path loss in an air–air channel is mainly influenced by the air medium characteristics and the signal propagation distance [10]. Usually, the sensor placed in the middle of the pillar is submerged in water. So, the information sensed by these sensor nodes travels toward the sink unit through a water–air channel. Signal attenuation in a water-to-air transmission link depends on the depth of water, characteristics of the water, and the distance between the sink and water level [11,12]. Mostly, the sensing node located at the base of the pillar is covered with soil and water above it. Thus, the data transmission from these sensor nodes propagates toward the sink unit, through soil–water–air (SWA) medium. In an SWA channel, transmission from the sensor node to the sink depends on the characteristics of soil–water, water–air, and air–air channels. To the best of our knowledge, a communication channel consisting of a soil–water–air medium has not been analysed thus far. Thus, it is necessary to model the SWA channel. Characterization of the signal transmission through the SWA channel and analysis of the path loss is essential before the WUSN setup can be established. Thus, in this paper, we introduce an SWA channel model aimed at analysing the signal attenuation in the PHM system efficiently. Along with modelling the path loss for SWA channel, some of the other contributions of this paper can be summarised as follows:

- Wireless communication schemes that are required to monitor the health of a bridge pillar completely were identified.
- Based on the wireless schemes identified, a wireless underground communication channel model for signals that transmit through the soil, water, and air was developed.
- An experimental setup using LoRa-based sensor nodes [13] was arranged to validate the performance of the SWA channel path-loss model.
- The impact of varying water levels, soil burial depths, frequencies, and inter-node separations (across both vertical and horizontal directions) on the path loss of the SWA channel was analysed.
- The different components of path loss in the SWA channel were identified, and their effect on net path loss was analysed.

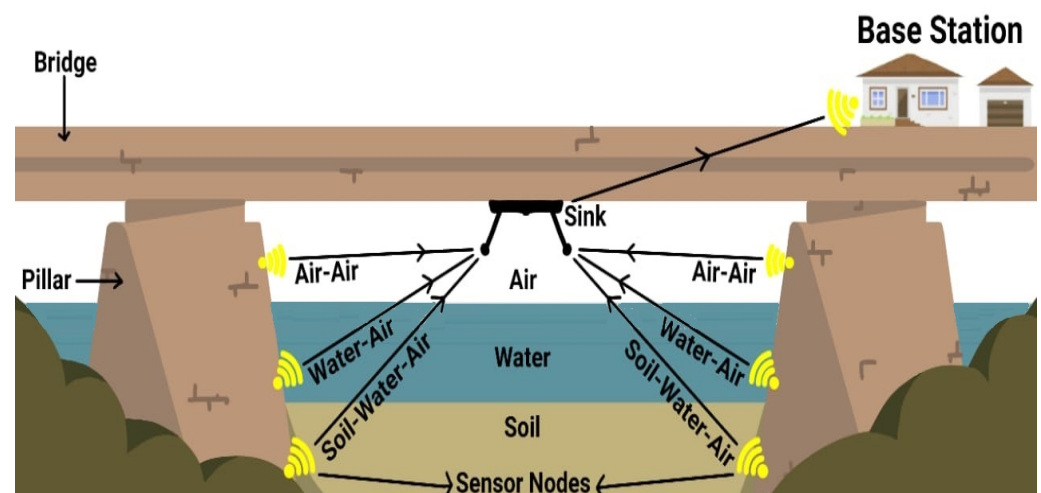


**Figure 1.** Communication in a WUSN-based PHM system.

The upcoming section of this paper are structured as follows: Section 2 details prior research work that has been done relating to signal traversal across various difficult transmission media. Section 3 provides an in-depth description of the suggested SWA channel model. Section 4 outlines the description of the testbed used to verify the theoretical outcomes of this work. Subsequently in Section 5, the outcomes of the proposed SWA model are compared against the results obtained from our experimental observations and is accompanied by an analysis of how changing distance parameters affects channel path loss. The

final section, Section 6, presents the conclusions that were drawn from the analysis done in this work.

## 2. Related Works

The challenges encountered in deploying sensor networks that communicate through the air–air channels are discussed in [14]. Signals that completely travel through the air in terrestrial wireless sensor networks (WSNs) and implementations of terrestrial WSNs are discussed in [15]. These research findings show that path loss in the air varies with the frequency of the signal, horizontal and vertical inter-node separation, and antenna gains [10,16].

The development of terrestrial sensor networks has generated interest among researchers in exploring the prospects of sensor networks in other challenging transmission media such as water and soil. The signals travelling through the soil in WUSNs and their applications are analysed in [17–19]. Signals in underground networks follow one-ray [20] and two-ray [21] propagation mechanisms. Path loss in underground networks is significantly affected by changing soil burial depth and inter-node distance [20,21].

Similar to underground applications, sensor networks are also implemented under the water [22–24]. Underwater sensor networks have been applied in the field of river data collection [25,26] and in communication and navigation [27]. Usually, acoustic signals are preferred for underwater networks [28,29], as water presents a very high resistance to signal transmission. However, radio-frequency (RF)-wave propagation through water has been studied in [30,31]. Further, signal transmission in seawater differs significantly from that of freshwater [32]. Thus, in underwater networks, the signal frequency, salinity, and conductivity of water affect the path loss [33,34].

The path-loss models discussed above involve transmission through a single transmission medium. However, the SWA channel involves signal transmission through three different media simultaneously. Path-loss analysis through combined media of soil and asphalt resembling the structure of roadways has been presented in [4]. Path-loss analysis through a combination of air and soil has been presented in [35,36]. These works introduced refraction loss into the path-loss model, along with losses due to the transmission medium. In another work [37] related to underground–aboveground (UG-AG) and aboveground–underground (AG-UG) channels, reflection loss was also integrated into the path-loss model. With the addition of reflection loss in the path-loss model, the accuracy of path-loss estimation improved. Since electromagnetic waves are reflected and refracted at the medium interface [38], reflection and refraction losses are also included into the channel model. Further, the signal also reflects and scatters due to obstacles [17], such as stone and plant roots. Loss due to these obstacles is considered a part of multi-path fading loss [17,39].

The above-discussed works have given us the roadmap toward designing a combinational channel model such as SWA where the signal propagates across soil, water, and air media simultaneously. However, the presence of soil and water in the channel makes it a highly lossy channel, limiting the communication range. The problem of communication range in SWA is eliminated by using some low-power wireless communication technologies. Some of the low power wireless area network (LPWAN) technologies currently in use are NB-IoT [40], SigFox [41], and LoRa [13,42,43]. Amongst these technologies, LoRa provides the advantage of long communication range, low power, and low data rate [42,44]. Moreover, LoRa modules function using the 433 MHz band, which helps in achieving efficient underground communications. During underground communications, the use of devices operating at frequencies greater than 1 GHz results in severe attenuation, and devices with operating frequencies less than 300 MHz require sensor nodes with large

antenna sizes [17]. Hence, in this work, experimental implementation of the SWA channel was carried out with the help of LoRa-based sensor nodes.

### 3. Proposed Path-Loss Model

This section presents the attenuation model used for assessing the structural health of a bridge pillar. Figure 2 depicts a typical scenario, where the health of the underground portion of the pillar is sensed by the node and sends the sensed data to the node placed just under the bridge. It is assumed that the sensor placed at the bottom of the pillar has soil and water above it. The water above the soil surface is assumed to be still in this work. Further, the received signal consists of a signal from a direct path and several reflections from multiple paths. However, for simplicity, we have considered the two-ray model as depicted in the figure. Thus, it can be observed from the figure that the transmitted signal travels to the receiver through soil, water, and air in two different paths.

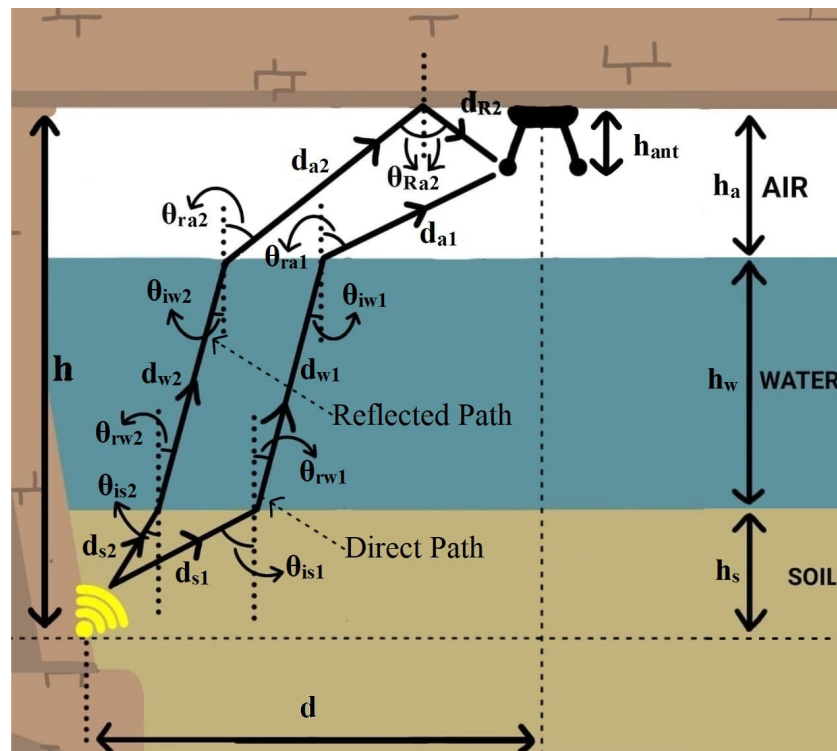


Figure 2. Signal transmission in an SWA channel.

In the figure, the total horizontal and vertical distance between the transmitting and receiving nodes is given by  $d$  and  $h$ , respectively.  $h_{ant}$  depicts the vertical distance between the receiver antenna and bottom of the bridge.  $h_s$ ,  $h_w$ , and  $h_a$  represent soil burial depth, water level, and aerial height between the top of the water level and bottom of the bridge, respectively. In direct-path transmission,  $\theta_{ix1}$  and  $\theta_{rx1}$  represent the angle of incidence and refraction through the transmission medium  $x$ , respectively; and  $x$  represents either soil ( $s$ ) or water ( $w$ ) or air ( $a$ ). Similarly, during propagation through the reflected path,  $\theta_{ix2}$  and  $\theta_{rx2}$  represent incident and refracted angles through the medium  $x$ , respectively. The incident and reflected angle at the air–bridge interface are equal and are symbolized as  $\theta_{Ra2}$ . The signal's travel distance in medium  $x$  is indicated by  $d_{x1}$  for the direct path and  $d_{x2}$  for the reflected route.  $d_{R2}$  is the distance covered by the signal after it bounces off the bridge surface.

$P_r$  symbolises the power of the received signal in SWA channel, which is expressed as [39]:

$$P_r = P_t + G_t + G_r + 10\log\chi^2 - PL_{tot} \quad (1)$$

where  $P_t$  corresponds to the power engulfed within the transmitted signal,  $G_t$  and  $G_r$  represent the amplification factors of the sending and receiving antenna systems, and  $PL_{tot}$  represents the total attenuation encountered by the signal along its path. The attenuation caused by signal reflections and scattering is expressed as  $10\log\chi^2$  [17,39]. Multi-path fading in SWA channel is represented by a random variable  $\chi$  that follows Rayleigh distribution [17,39].  $f(\chi)$  is referred to as the probability distribution function (PDF) of  $\chi$  and is given by the following:

$$f(\chi) = \frac{\chi}{\sigma_R^2} e^{-\chi^2/2\sigma_R^2} \quad (2)$$

where the value of the Rayleigh distributed parameter ( $\sigma_R$ ) is obtained from the field-based experimental results within a specific setting.

Since the transmission in an SWA channel follows a two-ray propagation mechanism, the overall propagation loss encountered by the signal can be described by Equation (3)

$$PL_{tot} = PL_1 + PL_2 \quad (3)$$

where  $PL_1$  and  $PL_2$  denote the path attenuation encountered along the direct and reflected propagation routes, respectively.

### 3.1. Signal Attenuation Due to the Direct Route

Five factors contribute to the total path loss during direct path propagation of the signal.

- Attenuation due to air ( $PL_{a1}$ ).
- Attenuation due to water ( $PL_{w1}$ ).
- Attenuation due to soil ( $PL_{s1}$ ).
- Attenuation due to refraction ( $PL_{ref1}$ ).
- Attenuation due to reflection ( $PL_{rl1}$ ).

Thus, the overall signal attenuation ( $PL_1$ ) along the direct route in an SWA channel is denoted as follows:

$$PL_1 = PL_{a1} + PL_{w1} + PL_{s1} + PL_{ref1} + PL_{rl1} \quad (4)$$

Assuming the antenna gain is equal to 1, signal weakening in air can be modelled with the help of the Friis transmission relation [18], as outlined in Equation (5).

$$PL_{a1} = -147.6 + 20\log(d_{a1}) + 20\log f \quad (5)$$

$f$  indicates the frequency (measured in Hz) of the signal emitted from the transmitter in the SWA channel.

Path loss through water [11,30] and soil [21] is represented by Equation (6) and Equation (7) respectively.

$$PL_{w1} = 20\log(d_{w1}) + 6.4 + 8.69\alpha_w d_{w1} + 20\log(\beta_w) \quad (6)$$

$$PL_{s1} = 20\log(d_{s1}) + 6.4 + 8.69\alpha_s d_{s1} + 20\log(\beta_s) \quad (7)$$

$\alpha_w$  and  $\alpha_s$  signify the attenuation factor of water and soil, respectively, while  $\beta_w$  and  $\beta_s$  represent the phase-shifting factor of water and soil, respectively.  $\alpha_w$ ,  $\beta_w$ ,  $\alpha_s$ , and  $\beta_s$  are evaluated from Equations (8), (9) and (10), respectively.

$$\alpha_w + j\beta_w = j2\pi f \sqrt{\mu_0 \epsilon_0} \sqrt{\mu_w \epsilon_w - j \frac{\sigma_w \mu_w}{2\pi f \epsilon_0}} \quad (8)$$

$$\alpha_s = 2\pi f \sqrt{\frac{\mu_0 \mu_s \epsilon_0 \epsilon'_s}{2} \left[ \sqrt{1 + \left( \frac{\epsilon''_s}{\epsilon'_s} \right)^2} - 1 \right]} \quad (9)$$

$$\beta_s = 2\pi f \sqrt{\frac{\mu_0 \mu_s \epsilon_0 \epsilon'_s}{2} \left[ \sqrt{1 + \left( \frac{\epsilon''_s}{\epsilon'_s} \right)^2} + 1 \right]} \quad (10)$$

Components of soil's dielectric constant are indicated as  $\epsilon'_s$  (real) and  $\epsilon''_s$  (imaginary) in Equations (9) and (10), respectively. The dielectric constant of the soil is estimated using MBSDM [45], as it outperforms the Peplinski model [46,47] and GRMDM [48] in terms of accuracy.  $\mu_s$  and  $\mu_w$  represent the magnetic permeability of soil and water, respectively, and are considered to be unity for non-metallic soil and water [49,50].  $\epsilon_w = \epsilon'_w - j\epsilon''_w$  represents the dielectric permittivity of water which is evaluated using the Debye equation [51]. The conductivity of water is represented by  $\sigma_w$ , and this is considered to be 0.01 S/m [33] for freshwater.

Apart from the losses due to transmission media, the signal also experiences refractions and reflections at the soil–water and water–air interface [37,38]. Path loss due to refraction and reflection [20] is given by Equations (11) and (12), respectively.

$$PL_{ref1} \approx 10 \log_{10} \left| \frac{1}{v_{sw1}} \right|^2 + 10 \log_{10} \left| \frac{1}{v_{wa1}} \right|^2 \quad (11)$$

$$PL_{rl1} \approx 10 \log_{10} \left| \frac{1}{\rho_{sw1}} \right|^2 + 10 \log_{10} \left| \frac{1}{\rho_{wa1}} \right|^2 \quad (12)$$

where,  $\rho_{sw1}$  and  $\rho_{wa1}$  are the reflection coefficient at the soil–water and water–air interface respectively. Similarly,  $v_{sw1}$  and  $v_{wa1}$  are the refraction coefficient at the soil–water and water–air interface, respectively.

The values of reflection and refraction coefficients depend on the signal traversal path [38]. The path traversed by a signal across two media is depicted in Figure 3. Assuming both the transmission mediums are non-magnetic in nature ( $\mu_1, \mu_2 = 1$ ), the reflection coefficient ( $\rho_{rl}$ ) and refraction coefficient ( $v_{ref}$ ) for the perpendicularly polarized waves can be presented in Equations (13) and (14) [38].

$$\rho_{rl} = \frac{\sqrt{\epsilon_1} \cos \theta_1 - \sqrt{\epsilon_2} \cos \theta_2}{\sqrt{\epsilon_1} \cos \theta_1 + \sqrt{\epsilon_2} \cos \theta_2} \quad (13)$$

$$v_{ref} = \frac{2\sqrt{\epsilon_1} \cos \theta_1}{\sqrt{\epsilon_1} \cos \theta_1 + \sqrt{\epsilon_2} \cos \theta_2} \quad (14)$$

where  $\epsilon_1$  and  $\epsilon_2$  represent permittivity of medium1 and medium2, respectively;  $\theta_1$  and  $\theta_2$  are the reflection and refraction angles, respectively.

It can be noticed that reflection coefficients ( $\rho_{sw1}, \rho_{wa1}$ ) in Equation (13) and the refraction coefficients ( $v_{sw1}, v_{wa1}$ ) in Equation (14) depend on the angle of incidence and angle of refraction at each medium interface. The incident/refraction angles at medium interfaces can be calculated using Snell's law [52]. Applying Snell's law at the soil–water and water–air interface, we obtain

$$\frac{\sin \theta_{is1}}{\sin \theta_{rw1}} = \frac{\eta_w}{\eta_s} = \frac{\sqrt{\epsilon'_w}}{\sqrt{\epsilon'_s}} \quad (15)$$

$$\frac{\sin \theta_{iw1}}{\sin \theta_{ra1}} = \frac{\eta_a}{\eta_w} = \frac{\sqrt{\epsilon_a}}{\sqrt{\epsilon'_w}} \quad (16)$$

In Equations (15) and (16),  $\eta_a$ ,  $\eta_w$ , and  $\eta_s$  represent the refractive indices of air, water, and soil, respectively. Further, from Figure 2, we observe that

$$\theta_{iw1} = \theta_{rw1} \quad (17)$$

$$h_s \cos \theta_{is1} + h_w \cos \theta_{iw1} + h_a \cos \theta_{ra1} = d \quad (18)$$

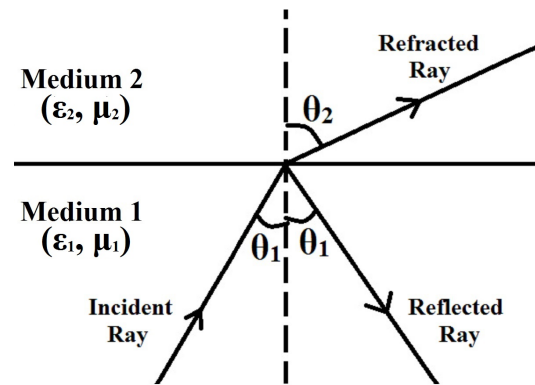


Figure 3. Signal propagation through different transmission media.

After the non-linear system of Equations (15)–(18) are solved, the incident/refraction angles can be evaluated. The obtained angle values are utilized in Equations (13) and (14) to estimate the reflection and refraction coefficients.  $\{\rho_{sw1}, \rho_{wa1}, v_{sw1}, v_{wa1}\}$  values are input into Equations (11) and (12) to obtain path loss due to refraction and reflection, respectively.

Other than refraction and reflection path-loss components,  $PL_{a1}$ ,  $PL_{s1}$ , and  $PL_{w1}$  are function of transmission distances  $d_{a1}$ ,  $d_{s1}$ , and  $d_{w1}$ , respectively. The relation between transmission distances and incident/refraction angles as observed from Figure 2 can be represented as follows:

$$d_{a1} = \frac{h_a}{\cos \theta_{ra1}}; d_{w1} = \frac{h_w}{\cos \theta_{iw1}}; d_{s1} = \frac{h_s}{\cos \theta_{is1}} \quad (19)$$

Calculated values of transmission distances ( $d_{a1}$ ,  $d_{s1}$ ,  $d_{w1}$ ) are used in Equations (5)–(7) to calculate  $PL_{a1}$ ,  $PL_{s1}$ , and  $PL_{w1}$  respectively. Finally, the values of different path-loss components are substituted in Equation (4) to realize the overall path attenuation experienced during direct route transmission in an SWA channel.

### 3.2. Signal Attenuation Due to the Reflected Route

Transmission of a signal through a reflected path encounters reflection and refractions at the soil–water and water–air interface, along with the reflection at the air–bridge interface. However, reflection and refraction losses at the soil–water and water–air interfaces have already been included in the direct path loss. Thus, path loss along the reflected route comprises of a single component only [17].

- Attenuation occurring during reflection at the air–bridge interface ( $PL_{R2}$ ).

Thus, the total signal attenuation ( $PL_2$ ) occurring during transmission through the reflected route is given by

$$PL_2 = PL_{R2} \quad (20)$$

Reflection loss at the air–bridge interface is presented in [17] and is expressed in Equation (21).

$$PL_{R2} = -10 \log \left( \sqrt{1 + (\tau e^{-\alpha_a \Delta r})^2} + 2\tau e^{-\alpha_a \Delta r} \cos(\phi - \beta_a \Delta r) \right) \quad (21)$$

where  $\alpha_a$  signifies the attenuation factor of air, while  $\beta_a$  represents the phase shifting factor of air;  $\tau$  (amplitude) and  $\phi$  (phase) represent the reflection factor at the air–bridge interface; and  $\Delta r$  represents the variation in direct and reflected path lengths and is estimated as per Equation (22).

$$\Delta r = d_2 - d_1 = (d_{s2} + d_{w2} + d_{a2} + d_{R2}) - (d_{s1} + d_{w1} + d_{a1}) \quad (22)$$

$d_1$  and  $d_2$  represent the distance covered by the signal during direct and reflected path propagation, respectively. It can be observed from Equation (21) that the path-loss component  $PL_{R2}$  of the reflected path depends on the values of the incident/refracted angles  $\{\theta_{is2}, \theta_{iw2}, \theta_{rw2}, \theta_{ra2}\}$  and the distance travelled by the signal through each medium  $\{d_{s2}, d_{w2}, d_{a2}, d_{R2}\}$ . Evaluation of incident/refracted angles and transmission distances can be performed using the system of Equations (23)–(29).

$$\frac{\sin\theta_{is2}}{\sin\theta_{rw2}} = \frac{\eta_w}{\eta_s} = \sqrt{\frac{\epsilon'_w}{\epsilon'_s}} \quad (23)$$

$$\frac{\sin\theta_{iw2}}{\sin\theta_{ra2}} = \frac{\eta_a}{\eta_w} = \sqrt{\frac{\epsilon_a}{\epsilon'_w}} \quad (24)$$

$$\theta_{iw2} = \theta_{rw2} \quad (25)$$

$$\theta_{ra2} = \theta_{Ra2} \quad (26)$$

$$h_s \tan \theta_{is2} + h_w \tan \theta_{iw2} + h_a \tan \theta_{ra2} + h_{ant} \tan \theta_{Ra2} = d \quad (27)$$

$$d_{a2} = \frac{h_a}{\cos\theta_{ra2}}; d_{w2} = \frac{h_w}{\cos\theta_{iw2}} \quad (28)$$

$$d_{s2} = \frac{h_s}{\cos\theta_{is2}}; d_{R2} = \frac{h_{ant}}{\cos\theta_{Ra2}} \quad (29)$$

The calculated incident/refracted angles and transmission distances are used suitably in Equation (21) to evaluate the signal attenuation components of the reflected route. The obtained value of  $PL_{R2}$  is used in Equation (20) to determine the overall attenuation encountered in the reflected route ( $PL_2$ ). Finally, the net path loss occurring during transmission through the direct ( $PL_1$ ) and reflected path ( $PL_2$ ) is used in Equation (3) to determine the total path loss occurring in an SWA channel.

## 4. Experimental Setup

This part outlines the experimental configuration employed to verify the effectiveness of the proposed path loss model for the SWA channel.

### 4.1. Framework

As carrying out real-time experiments at the pillar of a bridge would be physically challenging, we developed a prototype depicting the scenario of transmitting a signal from a node positioned at the bottom of the pillar to the node positioned below the bridge. The prototype experimental setup and real-time communication scenario in a PHM system are presented in Figure 4. In rivers, water and soil are spread over several kilometres, but inside a bucket, water and soil extend up to a few centimetres only. Yet, the transmitting signal follows an identical trajectory in both the experimental setup and SWA channel model, as shown in the figure. Since water exhibits a significantly high dielectric value, the receiver receives only those signals which are transmitted with low incident angles [11]. Thus, a low incident angle means nearly vertical transmission, and the extent to which soil and water are spread becomes irrelevant.

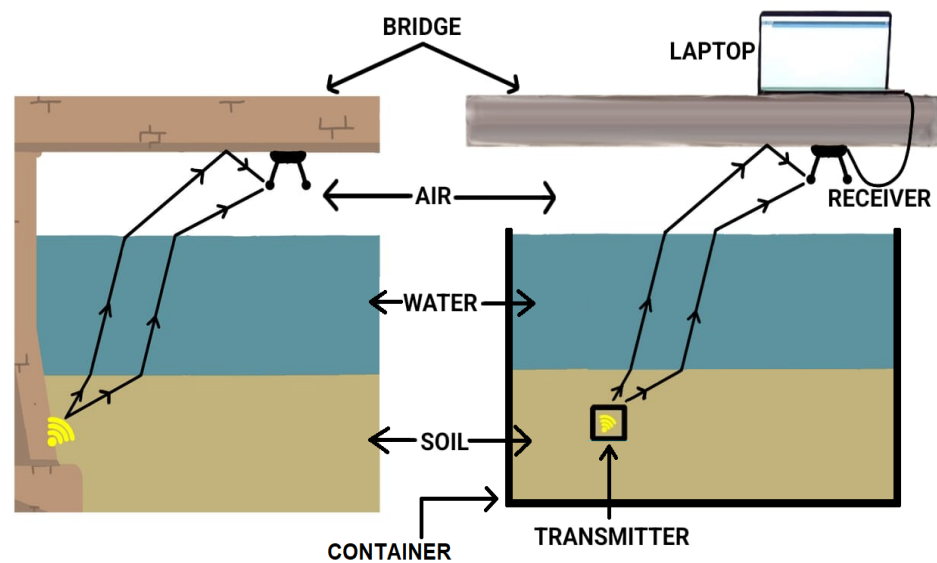


**Figure 4.** Analogy between communication in a PHM system and our experimental setup.

The practical setup used to perform our experimental work is shown in Figure 5. We placed the transmitter at the bottom of the bucket and covered it completely with sandy soil. Since riverbeds are usually sandy in nature, sandy soil was intentionally chosen for experimentation. The composition of the soil considered in our experiments is presented in Table 1.

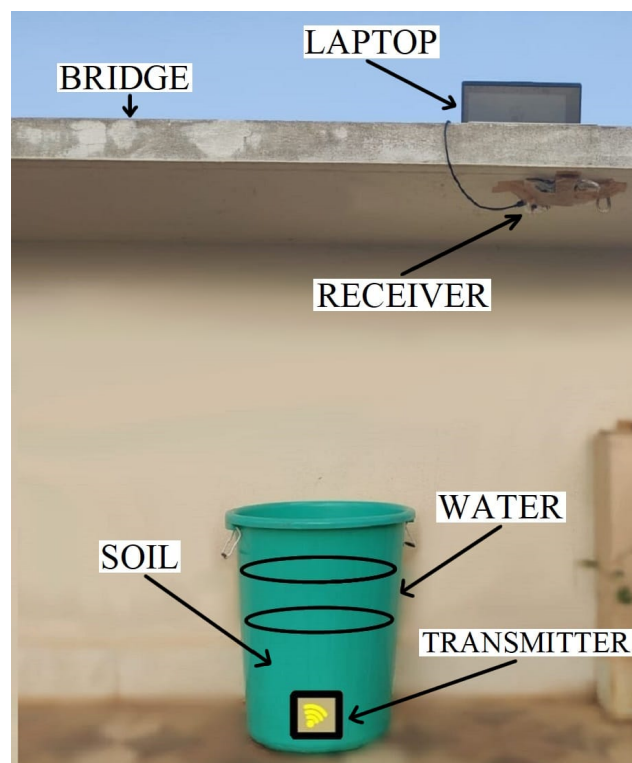


**Figure 5.** Experimental setup used for performance analysis of the SWA channel.

Once the transmitter was covered with sand to the desired level, water was poured into the bucket to the level suitable for the experiment. The transmitter was sealed inside a bottle (size 15 cm × 10 cm × 10 cm) in order to prevent contact between the transmitter and water. In terms of dimensions, the bottle was considerably smaller than the bucket (size 30 cm × 30 cm × 80 cm). Since the signal travels a distance of under one meter within the

confines of the bottle, the air-loss inside the bottle was neglected [37]. Further, the air loss inside the bottle was very small compared to the attenuation in soil and water. This is because dielectric constant of air (nearly equal to 1 [53]) is much lower as compared to that of soil (nearly equal to 9 [45]) and water (nearly equal to 81 [34]). Thus, the signal from the transmitter reached the receiver by overcoming the resistance offered by soil, water, and air media. Finally, the receiver, which was positioned below the concrete structure (resembling a bridge) as depicted in the figure, was connected to the laptop, and the readings corresponding to the received signals were recorded.

**Table 1.** Results of soil sample analysis.

| Soil Constituent Attribute | Value of the Attribute |
|----------------------------|------------------------|
| Soil's moisture content %  | $16.2 \pm 2.1$         |
| Sand %                     | $98.3 \pm 0.6$         |
| Silt %                     | $1.3 \pm 0.4$          |
| Clay %                     | $0.4 \pm 0.2$          |

#### 4.2. Communication Process

The process of communication occurring in the experimental work is depicted in Figure 6. In our experiment, the underground pillar parameter was sensed and transmitted to the receiver placed below the bridge. At the transmitter side, data sensed by the sensor was provided as input to the Arduino UNO board. The recorded value was processed by Arduino and sent to the LoRa transmitter for further transmission. The transmitted data was received by the LoRa receiver. Data from the received signal was extracted by the Arduino UNO connected to the receiver side. The extracted information was observed on the laptop that was connected to the Arduino board.

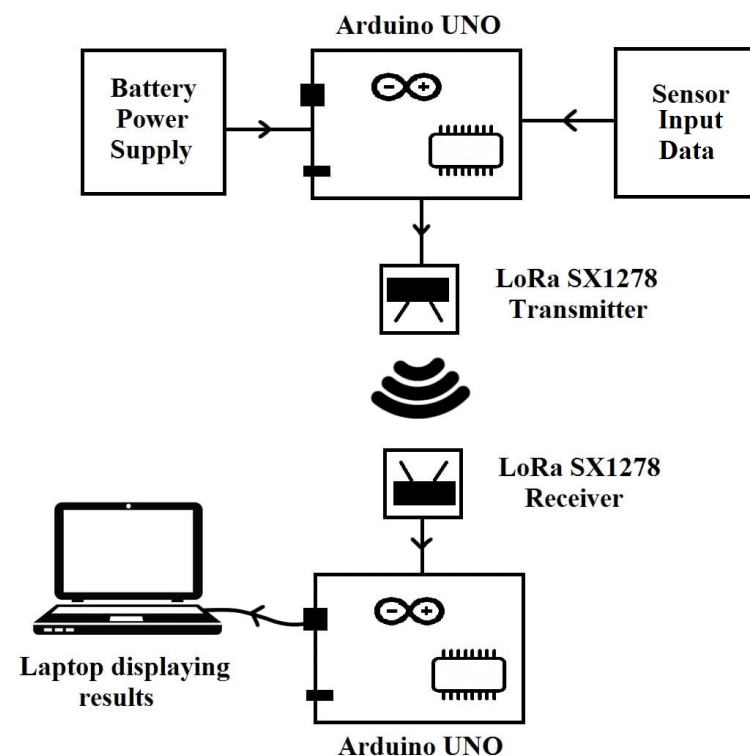


**Figure 6.** Block diagram depicting the communication process occurring in the experimental setup.

#### 4.3. Experimental Procedure

The configuration for the experiment was organized in accordance with the layout illustrated in Figure 5. Underground soil burial depths of 0.1 m and 0.2 m were implemented in the experiment. Similarly, water levels of 0.1 m, 0.2 m, 0.4 m, and 0.8 m were considered in the measurement of RSS. The parameters which were used for the experimentations are presented in Table 2.

**Table 2.** Compiled key metrics relating to signal propagation characteristics.

| Physical Attribute             | Value of the Attribute                               |
|--------------------------------|------------------------------------------------------|
| Frequency                      | 433 MHz                                              |
| Bridge height                  | 0.5–5 m                                              |
| Transmission power             | 20 dBm                                               |
| Receiver antenna gain          | 1.5 dBi                                              |
| Soil's bulk density            | 1.5 g/cm <sup>3</sup>                                |
| Horizontal inter-node distance | 0–28 m                                               |
| Dielectric constant of bridge  | 6.93–j0.93 (at 433 MHz and 5% moisture content) [54] |
| Receiver node's antenna height | 10 cm                                                |
| Transmitter antenna gain       | 1.5 dBi                                              |
| Soil's particle density        | 2.66 g/cm <sup>3</sup>                               |

Experiments began with the transmission of a packet from the transmitter to receiver. The packet consisted of a preamble, frame delimiter for synchronization, a PHY header, payload, and a cyclic redundancy check (CRC) field [55]. In each experiment, 50 packets were transmitted, and each packet was sent at a delay of 5 s. The RSS of the successful packets received was recorded from the laptop. The recorded RSS values were averaged and noted as the RSS value corresponding to the performed experimental parameters.

## 5. Results and Discussion

This section presents a detailed evaluation of the SWA channel model's performance under varying configuration parameters, focusing on metrics such as path loss, received signal strength (RSS), and bit error rate (BER). The results of our proposed model was also validated through comparison with the results obtained from field experiments. In each set of experiment, root mean square error (RMSE) and mean absolute error (MAE) were computed, which gives an estimation for the error in the estimations obtained from the analytical model. RMSE and MAE for a set of experimental values obtained within a specific setting can be obtained through Equations (30) and (31) [56].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_{exp}(i) - y_{th}(i))^2} \quad (30)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_{exp}(i) - y_{th}(i)| \quad (31)$$

where  $y_{exp}$  and  $y_{th}$  correspond to experimental and analytical observations, respectively.

### 5.1. Effects of Horizontal Inter-Node Separation and Water Level Variation

The variation of path loss for an SWA channel with changing horizontal inter-node separation and water level is presented in Figure 7. At a water depth of 0.1 m, a consistent rise in path-loss is observed as the distance between nodes increases. The path-loss variation follows a similar trend for the water level maintained at 0.2 m. Also, a remarkable increase in path loss is observed when the water level increases from 0.1 m to 0.2 m at a fixed value of inter-node separation distance.

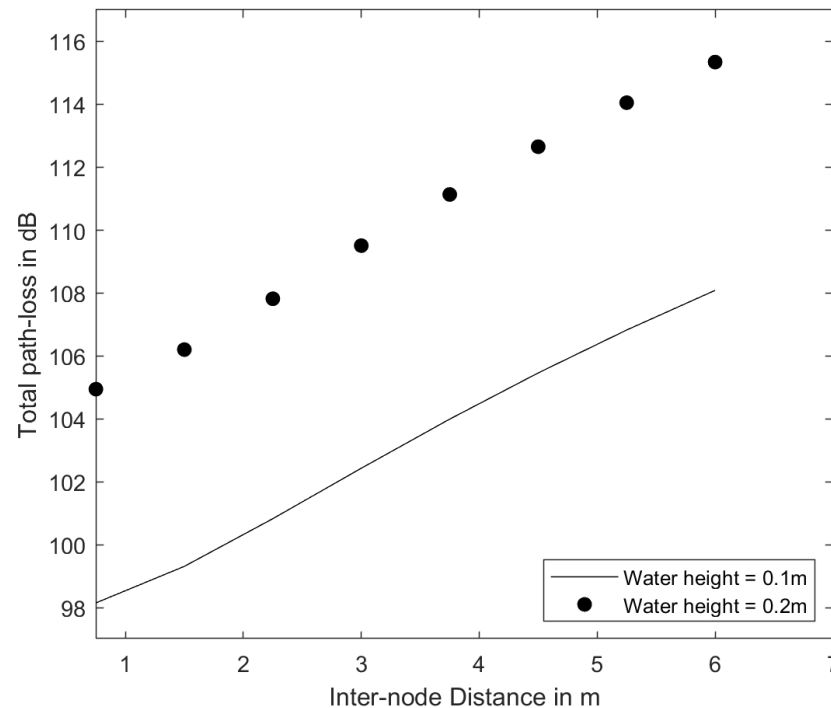


**Figure 7.** Path loss vs. horizontal inter-node distance with different water levels; soil burial depth = 0.2 m, bridge height = 2.2 m.

Further, as discussed in Sections 3.1 and 3.2, it is known that the combination of different components makes up for the total path loss of the SWA channel. The contribution of each component towards the total path loss is estimated theoretically from expressions Equations (5)–(7), (11), (12) and (20) and is presented in Figure 8 to achieve a more comprehensive analysis. As observed in Figure 8, it is the air loss that increases with an increase in inter-node distance only. Although other components carry a loss, they do not vary with a change in inter-node separation distance. It should also be emphasized that water loss, soil loss, and air loss have a significant contribution to the total path loss. The next significant contributions (of around 8–17 dB) to the overall path loss is given by the path-loss components due to multi-path fading (Equations (1) and (2)), reflected path (Equation (21)), and reflection at the inter-media boundaries (Equation 12). The path-loss component due to refraction at the media borders (Equation (11)) contributes the least to the net path loss. Upon comparison, we observe that the loss due to the bridge-reflected path and the inter-media refractions and reflections has a smaller effect as compared to the other components.

Results obtained for RSS vs. inter-node separation distance through the practical procedure (as discussed in Section 4) are depicted in Figure 9, along with the theoretically computed values. The plots shown in the figure reveal that the RSS value obtained from the experimental procedure decreases with an increase in inter-node separation distance for a fixed water depth. As explained earlier, it is also noticed that with an increase in water level from 0.1 m to 0.2 m, the RSS decreases. Further, a key observation shows that the trend of variation in RSS is similar for both theoretical and experimental results which validates the analysis methodology. However, the exact values obtained in both procedures differ with a small differential error between them at different points. The RMSE and MAE for observations taken at different water levels are showcased in Table 3. The low values of RMSE and MAE depicted in Table 3 validate the analytical model.

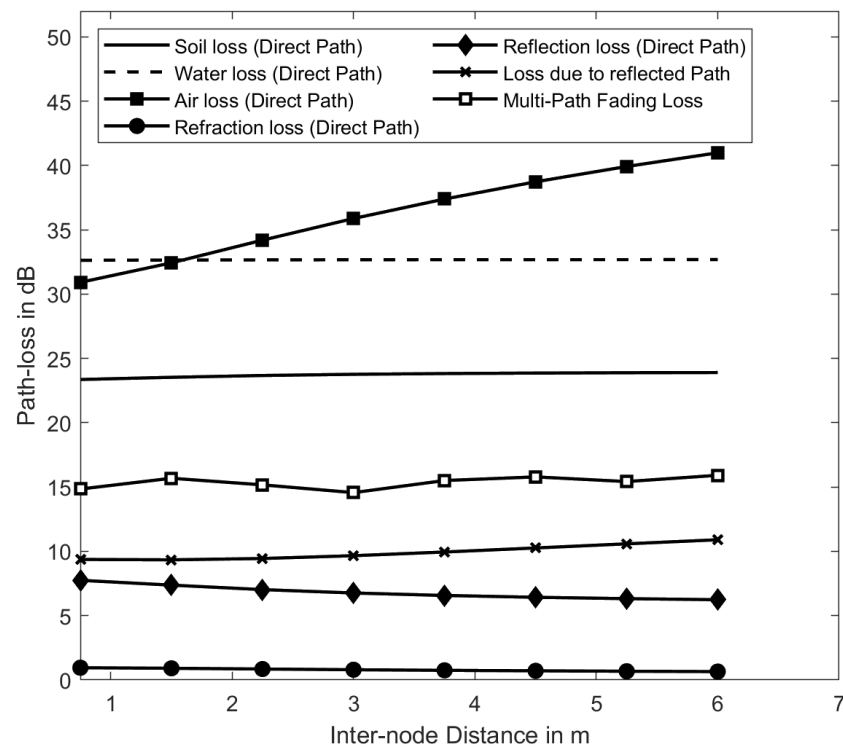


**Figure 8.** Component-wise path-loss vs. horizontal inter-node distance; water level = 0.2 m; soil burial depth = 0.2 m, bridge height = 2.2 m.

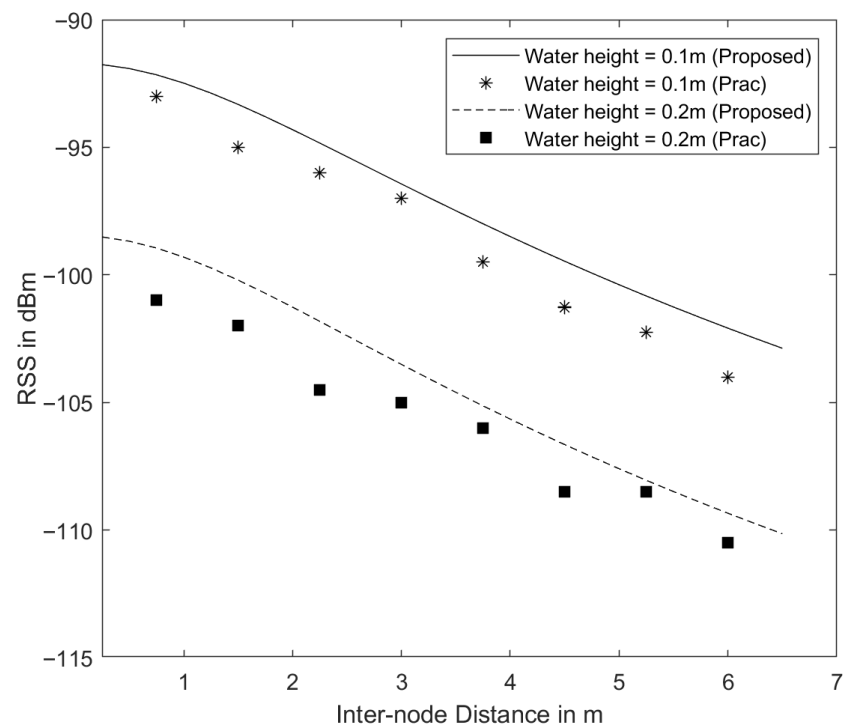


**Figure 9.** RSS vs. Horizontal inter-node distance with different water levels; soil burial depth = 0.2 m, bridge height = 2.2 m.

**Table 3.** Error analysis during water level variation experiment.

| Height of Water Level | RMSE (dBm) | MAE (dBm) |
|-----------------------|------------|-----------|
| 0.1 m                 | 1.43       | 1.806     |
| 0.2 m                 | 1.68       | 2.23      |

### 5.2. Effects of Horizontal Inter-Node Separation and Soil Level Variation

The influence of soil depth on channel path-loss is depicted in Figure 10. As presented in the figure, the signal encounters higher resistance with the increasing soil depth of the transmitter. So, we observe that the path loss at a soil depth of 0.2 m is more than that of the soil depth of 0.1 m for a fixed value of internode distance. An increase in horizontal distance between nodes leads to higher path loss, particularly observed when the transmitter is buried at depths of 0.1 m and 0.2 m below the soil surface.

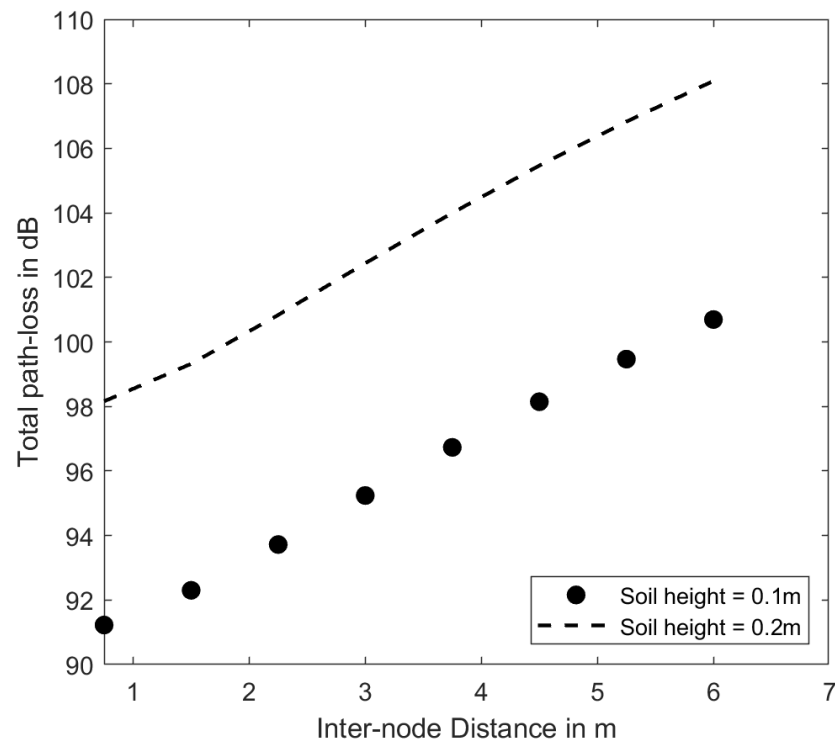


**Figure 10.** Path loss vs. horizontal inter-node distance with different soil burial depths; water level = 0.1 m, bridge height = 2.2 m.

Furthermore, it is also known that the RSS at the receiving end is greatly influenced due to the attenuation encountered during signal propagation. Consequently, Figure 11 illustrates how varying burial depths in soil impact the RSS across different distances between nodes. Both the experimentally and theoretically computed results shown in the figure highlight that the RSS deteriorates with a rise in the horizontal distance between the nodes, for a soil depth of 0.1 m. With an increase in the soil depth to 0.2 m, the RSS further weakens and follows a similar trend of decrease with an increase in inter-node distance. A close look at the plots presented in Figure 11 also reveals that the results obtained through the practical procedure are closer to the analytically computed results. Table 4 presents the RMSE and MAE for observations taken at different soil levels. The low values of error components presented in Table 4 support our analytical model.

**Table 4.** Error analysis during the soil level variation experiment.

| Height of Soil Level | RMSE (dBm) | MAE (dBm) |
|----------------------|------------|-----------|
| 0.1 m                | 1.49       | 1.87      |
| 0.2 m                | 1.43       | 1.806     |

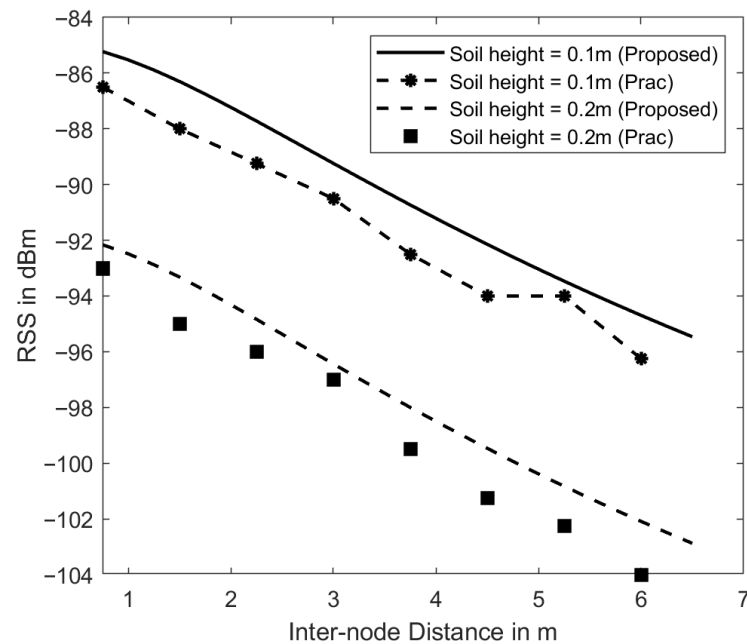


**Figure 11.** RSS vs. Horizontal inter-node distance with different soil burial depths; water level = 0.1 m, bridge height = 2.2 m.

### 5.3. Effects of Bridge Height Variation

Results obtained for the path-loss variation due to changes in bridge height are shown-cased in Figure 12. The figure illustrates that as the distance between nodes increases, path loss also rises, and this is observed consistently at bridge heights of 2.25 m and 3.25 m. Further, we can observe a considerable difference in path loss due to bridge height variation at lower inter-node separation (0.75 m) as path loss rises from 105.25 dB to 108.75 dB. However, at higher inter-node separation, bridge height loses its impact, and barely any difference in path loss is noticed due to changes in bridge heights.

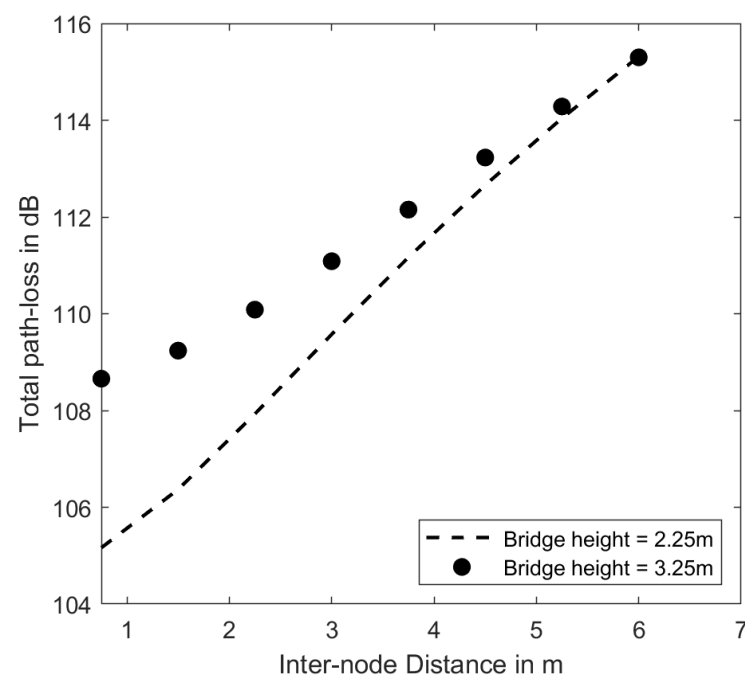


**Figure 12.** Path-loss vs. horizontal inter-node distance with different bridge heights; water level = 0.2 m, soil burial depth = 0.2 m.

The height of a bridge in the real world goes up to several meters. Hence, to have a more validated analysis, the results of RSS vs. higher bridge heights obtained from the theoretical and experimental procedure are presented in Figure 13. Observations corresponding to water levels of 0.1 m indicate a decrease in RSS with the increase in bridge height. An analogous pattern in RSS fluctuations is observed at a water depth of 0.2 m as well. However, the RSS varies considerably with changes in water depth from 0.1 m to 0.2 m irrespective of bridge height. Again, the experimental values shown in Figure 13 are observed to be very close to the proposed SWA channel model. Table 5 showcases the RMSE and MAE for observations taken at two different water levels. The low RMSE and MAE values presented in Table 5 validate our analytical model.

**Table 5.** Error analysis during the bridge height variation experiment.

| Height of Water Level | RMSE (dBm) | MAE (dBm) |
|-----------------------|------------|-----------|
| 0.1 m                 | 1.36       | 0.553     |
| 0.2 m                 | 1.56       | 0.942     |

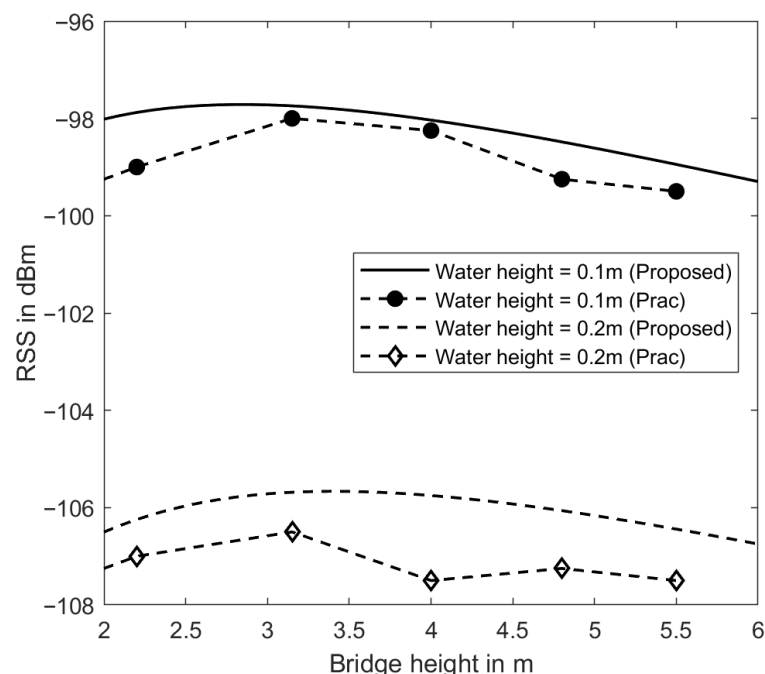


**Figure 13.** RSS vs. bridge heights with different water levels; soil burial depth = 0.2 m, horizontal inter-node distance = 6.5 m.

#### 5.4. Effects of Signal Frequency Variation

The impact of varying signal frequency on the path loss of the SWA channel is presented in Figure 14. The figure illustrates that with the rise in frequency of the transmitted signal, path loss also rises. This trend is noticed at soil levels of 0.1 m and 0.2 m consistently. We further notice a significant increase (around 9 dB) in path loss due to a mere 0.1 m rise in soil level. Due to the highly lossy nature of soil as a transmission medium, the frequency range of 300 MHz to 900 MHz is preferred for underground communications [17]. Any frequency beyond 900 MHz would result in large attenuation within the channel, and frequencies below 300 MHz would lead to a large communication setup. None of these frequencies are suitable for underground communication.

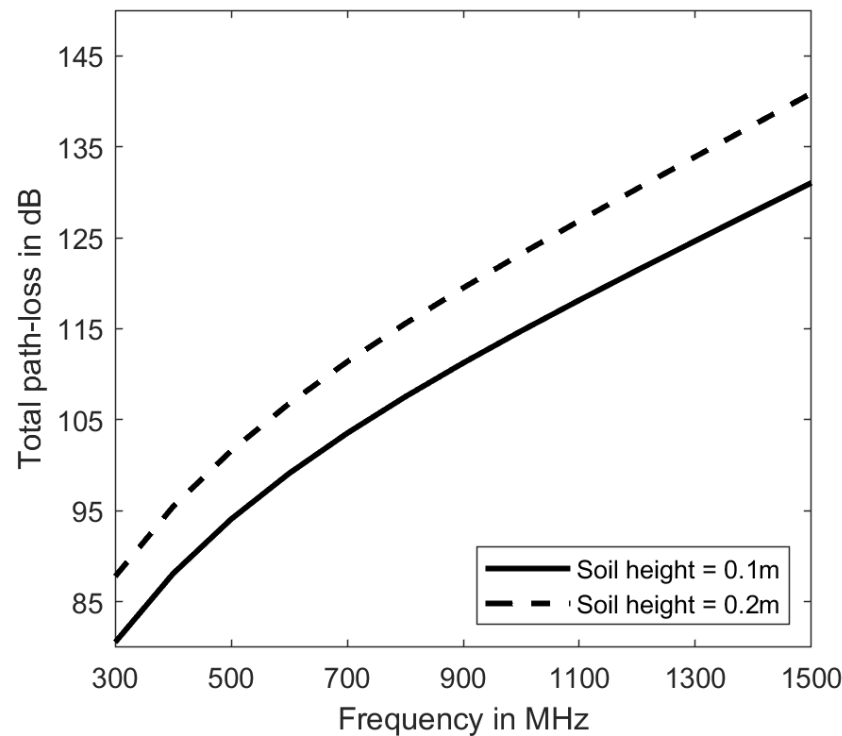


**Figure 14.** Path-loss vs. signal frequency with soil levels; water level = 0.1 m, horizontal inter-node distance = 4 m.

Also, the suitable frequency range discussed above is one of the main reasons for the selection of the LoRa module for our experimentation purposes in comparison to other LPWAN technologies (such as NB-IoT and SigFox). A comparative overview of the operating frequencies employed in these technologies is provided in Table 6 [57,58]. Amongst the three LPWAN technologies, LoRa operates at low frequency of 433 MHz and hence, we selected LoRa technology for the experimentation purposes [44].

**Table 6.** Operating frequencies of different LPWAN technologies [57,58].

| LoRa                        | SigFox                       | NB-IoT                          |
|-----------------------------|------------------------------|---------------------------------|
| 433–435 MHz;<br>865–868 MHz | 868 MHz, 902 MHz and 923 MHz | 700 MHz, 800 MHz, 900 MHz, etc. |

### 5.5. Effects of Seasonal Variation

The conceptual analysis indicates that the soil depth, water level, and separation between the nodes (vertical and horizontal) are some of the parameters that affect the net attenuation encountered during transmission of the signal. However, in a practical scenario, it is the water depth associated with a bridge pillar that changes with the season. Thus, there is a need to analyse the effect of season on the RSS.

In the rainy season, the river has high water levels, and moderate water levels are observed in winters. In summer, rivers almost dry up. RSS variation in summer (shallow water levels of 0.1 m and 0.2 m) has already been shown in Figure 9. Figure 15a depicts the theoretical RSS variation in the rainy and winter seasons. Transmission link quality in terms of analytical SNR and BER [18,59] is indicated in Figure 15b and Figure 15c, respectively.

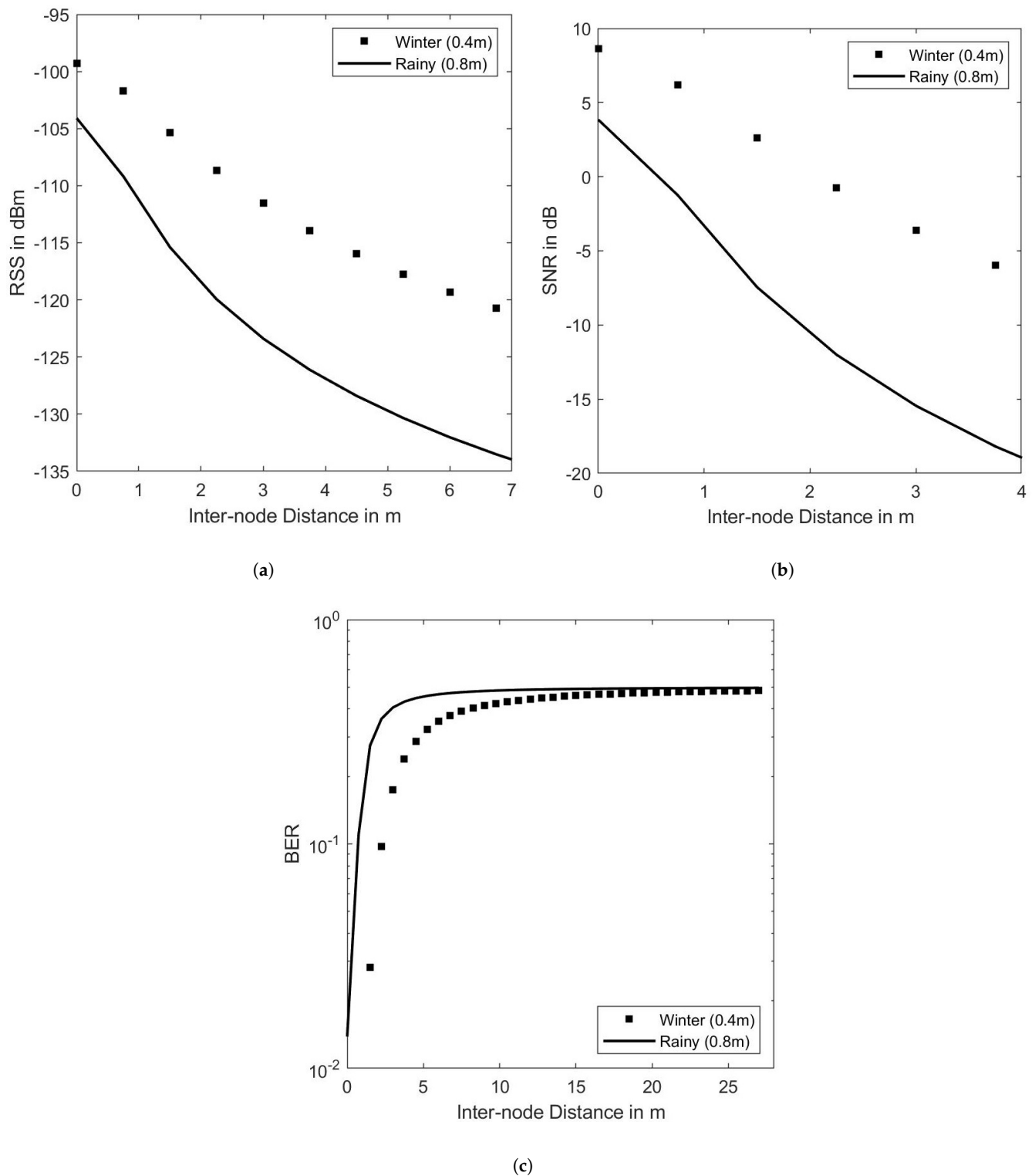


**Figure 15.** Variation in transmission link quality vs horizontal inter-node distance with diff for water levels during different seasons. Transmission link quality is represented by (a) RSS, (b) SNR, and (c) BER; soil burial depth = 0.2 m, bridge height = 1.5 m.

The plots in Figure 15a indicate that RSS at the receiving end is quite better during winter as compared to the rainy season. Due to improved RSS values in winter, higher SNR values are observed during winter, as shown in Figure 15b. Poor SNR values during the rainy season mean erroneous transmission, and hence higher BER values are noticed during the rainy season, as shown in Figure 15c. In the figure, the BER is 0.17 during the winter sea-

son for an inter-node separation of 3 m. However, for the same inter-node separation, a high BER of 0.41 is noticed during the rainy season. Thus, the communication channel is prone to error in the rainy season, and the error reduces as the water level lowers with the change in season.

## 6. Conclusions

This study presents the development of a channel model tailored for a PHM system utilizing WUSNs, aimed at accurately estimating the path loss encountered by the transmitted signal. The proposed model considers the transmission of the signal from a sensor node placed at the base of the bridge pillar to the node placed under the bridge through multiple transmission media consisting of soil, water, and air. We evaluated the effect of horizontal inter-node distance, water level, soil depth, and bridge height on the channel's performance. It was noted that the path loss intensifies as the horizontal distance between nodes, as well as the depth of water and soil, increases. This rise in path loss is primarily attributed to the greater distance the signal must traverse through the air as the inter-node spacing expands. Soil and water attenuation increases with the increase in soil and water levels, hence increasing the net path loss. It was further noticed that variation in bridge height contributes very little to the channel's path loss, provided constant burial depths, horizontal inter-node distance, and water levels are maintained. Path loss of the channel is also severely affected due to the change of seasons as the water level of a river varies in different seasons. Thus, we observed an extremely high BER during the rainy season as compared to that during winter and summer. It was realized that in an SWA channel, loss due to water, soil, and air contributes the most towards the total path loss. The RSS for various scenarios was evaluated and validated with a real-time experimental setup consisting of two LoRa-based sensor nodes. Under different scenarios, the experimentally obtained RSS values follow closely with the proposed analytical values (RMSE values for RSS obtained in all the scenarios were found to be less than 5 dBm).

Monitoring the health of a bridge pillar is extremely necessary. However, the presence of soil and water enhances the path loss of the SWA channel significantly, making it difficult to achieve reliable communication within the channel. Therefore, future studies should explore the strategic placement of the sensor nodes on the pillar to effectively mitigate significant path loss within the SWA channel. Furthermore, we intend to explore some of the following factors relating to SWA channel: (1) impact of ripples in flowing water on the performance of the SWA channel; (2) analysis of SWA channel performance under varying composition of soil and water; (3) enhancement of the network density to explore additional behavioural patterns such as cross-interference [26,60] and collision effect; (4) analysis and addressing of other challenges that usually occur in any WSN such as network lifetime, localization, packet error rate, etc.; and (5) development of a machine-learning-based model as it will be more realistic in nature. Analysis of all these factors will help to monitor the health of a submerged pillar effectively.

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