Designing and Implementing a Microstrip Antenna on LoRa Frequency for Smart Meter Communication

Phairote Wounchoum, Akekapong Kongsavat, and Chalakorn Karupongsiri

Abstract—The long-range wide area network (LoRaWAN) has been widely used for sensor networks, including smart meter (SM). The SM can report power consumption to the control center automatically via a communication link. An antenna is a key component to indicate an effective communication system. The microstrip antenna (MSA) works based on the unidirectional radiation pattern. The advantages of MSA are its light weight, small size, and ability to be easily etched on a print circuit board. These advantages are needed for the SM communication because SMs are installed on electric poles that have limited space. In this paper, we implement the MSA for SM communication on LoRaWAN technology that operates at a frequency of 920–925 MHz in Thailand. The proposed MSA is used to design a new path loss model for LoRaWAN in urban areas. Results show that our MSA is effectively close to commercial antennas in a 2.2 km range, with the packet delivery ratio reaching 52.93%. We analyze the results by using a mathematical equation that includes the free space model, the Okumura–Hata model, root mean squared error, and coefficient of determination.

Index Terms—LoRaWAN, path loss model implementation, microstrip antenna implementation, linear regression, LoRa, smart meter communication

Original Research Paper
DOI: 10.53314/ELS2226009W

I. INTRODUCTION

The smart meter (SM) is an electronic device that can measure electric energy and record power consumption. Those parameters can be monitored and data can be transmitted to the control center for billing purposes via a communication link [1]. Long-range wide area network (LoRaWAN) technology is invoked for SM communication because of its coverage area, large number of clients, low energy consumption, and noise tolerance [2]. The disadvantages of LoRaWAN technology are its low data rate and low duty cycle for transmitting data [3].

However, the lowest data rate of 0.3 kbps and 1% of duty cycle on the LoRaWAN are sufficient for SM communication [2], [4]. In practice, SMs are installed at electric poles that have a limited area. Thus, the rectangular microstrip antenna (MSA) is selected for implementation because of the size issue. The MSA works based on a unidirectional pattern that releases a radio wave in a unique direction. It can better reduce interference with another transmission source compared with an omnidirectional antenna [5]. The advantages of the MSA for SM communication are its light weight, small size, low cost, and low interference [6].

Performance analysis of wireless communication requires a path loss (PL) model to predict the loss between the transmitter (Tx) and the receiver (Rx). Each PL model was implemented in specific conditions or environments. In [7], a PL model of 868 MHz on LoRaWAN technology in urban areas was proposed. This model uses the empirical method and the linear polynomial fit to find the coefficient of the PL model, such as a PL exponent (PLE) and a PL intercept (PLI). In [8], a PL model was designed for a smart city. It operates at frequencies of 433 and 868 MHz on LoRaWAN in urban areas. Linear regression analysis was applied to create mathematical model of each frequency. The result shows that the prediction of the PL model is more accurate than that of traditional models. The experimental setup uses LoRa gateway at a height of 30 m and the end device (ED) is installed on a car roof at 1.7 m. Both the gateway and the ED height are close to the environment in our proposed model. In [9]-[10], a PL model is developed by using the empirical method. It is highly precise under similar conditions of frequency, Tx and Rx height, environments, and radio pattern. As seen above, most PL models are implemented to predict the PL accurately in specific scenarios.

In this research, we implement the rectangular MSA, which operates within a frequency range of 920–925 MHz for the LoRaWAN technology in Thailand. The MSA from our proposed method is used to develop a new PL model for SM communication. The proposed antenna is compared with a commercial antenna. The result shows that the proposed antenna performance is close to that of the commercial antenna, but it suffers when compared with a log-periodic antenna [11]-[12]. However, our MSA is low profile, small, and more easily installed at electric poles than other antennas. Moreover, the MSA is suitable for mass production because of its lower cost. The proposed PL model is more accurate than the Okumura–Hata model when estimated by the root mean squared error (RMSE) and the R-squared.
The rest of this paper is organized as follows: Section II introduces the background. Section III describes the MSA design. Section IV discusses the measurement setup. Section V analyzes the experimental result, and Section VI concludes the paper.

II. BACKGROUND

A. Unidirectional Antenna

A unidirectional antenna has a main lobe with one direction for transmitting radio frequencies to the air, such as Yagi–Uda, horn, and MSA [13]. The unidirectional antenna is used to increase the performance of communication systems. Tx and Rx are fixed systems, and the radio frequency can move directly from Tx to Rx with low interference [5]. Hence, the unidirectional antenna is suitable for fixed nodes. In contrast, the radio pattern of the omnidirectional antenna is transmitted around itself [14]. It is employed for moving nodes, such as mobile phones, walkie-talkies, and car radios. Figure 1 shows the SM installation at electric poles along the road. The SM scenario is used to compare the unidirectional and omnidirectional patterns. The energy of an omnidirectional pattern overlaps because of the nearby SMs. Therefore, all nodes may interfere with each other, including the gateway. In contrast, the unidirectional antenna has a unidirectional radiation pattern, thus reducing interference more than the omnidirectional antenna in the SM scenario.

Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Antenna A</th>
<th>Antenna B</th>
<th>Antenna C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Microstrip (Proposed)</td>
<td>Log-Periodic (Commercial)</td>
<td>Monopole (Commercial)</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>909–931 MHz</td>
<td>752–2700 MHz</td>
<td>800–825 MHz</td>
</tr>
<tr>
<td>Radiation Pattern</td>
<td>Unidirectional</td>
<td>Unidirectional</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>Realized Gain</td>
<td>1.04 dBi</td>
<td>8.20 dBi</td>
<td>−2.58 dBi</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.17</td>
<td>1.58</td>
<td>5.1</td>
</tr>
<tr>
<td>Return Loss (S11)</td>
<td>21.54 dB</td>
<td>12.88 dB</td>
<td>3.47 dB</td>
</tr>
<tr>
<td>HPBW (E, H-plane)</td>
<td>85°, 80°</td>
<td>60°, 85°</td>
<td>100°, 180°</td>
</tr>
<tr>
<td>Cable Loss (Lt)</td>
<td>0.48 dB</td>
<td>0.41 dB</td>
<td>0 dB (Directed)</td>
</tr>
<tr>
<td>Weight</td>
<td>0.2 kg</td>
<td>0.6 kg</td>
<td>0.01 kg</td>
</tr>
<tr>
<td>Dimensions (mm3)</td>
<td>170×170×10</td>
<td>282×210×65</td>
<td>10×10×50</td>
</tr>
<tr>
<td>Cost (USD)</td>
<td>$5</td>
<td>$40</td>
<td>$5</td>
</tr>
</tbody>
</table>

B. Overview of LoRa

Long-range (LoRa) technology is designed for long-distance communication (up to 15 km), low energy consumption (less than 50 mW) [3], [15], and high noise tolerance because of the chirp spread spectrum (CSS). The LoRa operates in a frequency range of 920–925 MHz in Thailand. The key operation of the CSS technique is the spreading factor (SF), which is represented by the number of bits in a symbol. The SF range is from 7 to 12. Hence, the SF is used for specific data rates (DR) in LoRa communication. The Rx sensitivity depends on the SF level. For example, SF7 can communicate the maximum data rate at 5.470 kbps with Rx sensitivity of −126.5 dBm. This value is the minimum sensitivity of the LoRa Rx, but it has the lowest coverage. Conversely, the −139.5 dBm sensitivity of SF12 can cover bigger areas than SF7, but it has a lower DR (lower than 250 bps) [16]. Therefore, the SF configuration is important for the LoRaWAN communication performance.

The LoRaWAN architecture consists of an ED, a gateway, a network server (NS), and an application server [17]. The LoRaWAN can be applied for a wireless sensor network [18] and [19] in agriculture. It can also be employed for the Internet of Things [20] and the smart grid network, including SM communication [2].

C. PL Model

PL is the predicted radio propagation loss over distance between Tx and Rx depending on environments. The PL is defined as transmitted power minus received power. To measure the PL in decibel (dB) for real environments, the Friis transmission equation can be applied [21].
The rectangular MSA is suitable for a SM antenna because of its unidirectional beam pattern, light weight, and very low cost [24]-[25]. Those key properties are needed for implementation in the SM scenario, as described above.

The structure of MSA consists of the following: 1) A patch is used to release the electromagnetic wave to the air; 2) a sub

### III. Microstrip Antenna Design

The rectangular MSA is suitable for a SM antenna because of its unidirectional beam pattern, light weight, and very low cost [24]-[25]. Those key properties are needed for implementation in the SM scenario, as described above.

The structure of MSA consists of the following: 1) A patch is used to release the electromagnetic wave to the air; 2) a sub-

strate is a layer of dielectric material that is used to separate conductors; and 3) a ground plane is a conductor plane that is opposite the patch. Figure 2 illustrates the MS parameters, which include patch width ($W$), patch length ($L$), width of the MS feed line ($W_f$), the inset-feed-point impedance ($r_0$), patch width inset ($W_i$), and length of square ground plane ($L_g$). The MSA is created by a printed circuit board (PCB), which is a low-cost material, as seen in Fig. 2. The parameters are calculated by Equations (2)–(5).

The glass epoxy substrate (FR-4) of the PCB is used to build the MSA. First, we assume a resonant frequency ($f_0$) of the MSA as 922.5 MHz, which is the center frequency of 920–925 MHz of the LoRaWAN Asia (AS923) standard [16]. Second, we define the following properties of the antenna: 1) antenna impedance is 50 ohm; 2) dielectric constant ($\varepsilon_r$) of the substrate is 4.4; 3) loss tangent (tan $\delta$) is 0.02; 4) copper plate thickness ($t$) is 0.035 mm; and 5) substrate height ($h$) is 1.6 mm. Next, a microstrip feed line is employed to connect with a subminiature version A (SMA) connector. Finally, we can calculate the shape of the rectangular microstrip patch antenna, as seen below [13], [24].

\[
W = \frac{c}{2f_r} \left[ \frac{\varepsilon_{re}+1}{2} \right]^{-1/2} \tag{2}
\]

\[
\varepsilon_{reff} = \frac{\varepsilon_{re}+1}{2} + \frac{\varepsilon_{re}-1}{2} \left[ 1+12 \left( \frac{h}{\delta} \right)^{1/2} \right] \tag{3}
\]

\[
\Delta L = 0.412 \cdot h \cdot \frac{\left( \varepsilon_{reff} + 0.3 \right)\left( \frac{W}{\delta} + 0.264 \right)}{\left( \varepsilon_{reff} - 0.258 \right)\left( \frac{W}{\delta} + 0.8 \right)} \tag{4}
\]

\[
L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{5}
\]

Parameter optimization in (2)–(5) was conducted by using the CST Microwave Studio. In practice, these calculated characteristics may be erroneous because of the dielectric constant of the FR-4 material. Therefore, the $y\theta$ of the MSA is optimized by considering the return loss (RL), which is more than 10 dB at the operating frequency, as seen in Fig. 3 [26]. The square marker in Fig. 3 shows the measured RL of the MSA, which is effective for transmitting power in the frequency range of 909–931 MHz. Table I describes the MSA structure when the RL is applied to match the operating frequency.

To verify our proposed antenna (antenna A), two commercial antennas are compared. The first one is antenna B, a log-periodic antenna that works based on unidirectional beam [2]. Antenna C is a monopole antenna that operates based on omnidirectional beam [1]. All of them are linearly polarized and transmit signals to a LoRa gateway. A gateway antenna is a monopole that can receive the LoRa signal of three EDs with all directions around the gateway.

Figure 3 demonstrates the RL measurement of all antennas by using a network analyzer [27]. The RL is a critical parameter to consider the antenna’s performance and its frequency ranges.

\[
\frac{2\Delta L}{L} = \frac{c}{2f_r}\sqrt{\varepsilon_{reff}} 
\]

\[
\Delta L = 0.412 \cdot h \cdot \frac{\left( \varepsilon_{reff} + 0.3 \right)\left( \frac{W}{\delta} + 0.264 \right)}{\left( \varepsilon_{reff} - 0.258 \right)\left( \frac{W}{\delta} + 0.8 \right)} \]
It should be more than 10 dB because the antennas can transmit a signal power of as high as 90.07% or the antenna reflected power is low as 9.93% [24], [28]. The RL of the antenna A is more than 10 dB between frequencies of 909–931 MHz, which indicates the frequency range of antenna A. The RL of antenna A is 21.54 dB at 922.5 MHz of the operation frequency. The RL of antenna B is more than 10 dB between frequencies of 752–2700 MHz, and the measured RL is 12.88 dB at the operating frequency. The RL of antenna C at the operating frequency is only 3.47 dB. Its frequency range is 800–825 MHz, which is shorter than that of the LoRa module reported in [12]. Although antenna C does not match the operating frequency, it can be used to verify the performance of our proposed model when the omnidirectional pattern is employed.

Table II compares the antenna specifications at the operating frequency of 922.5 MHz. The realized gain measurement of the antenna A is 1.04 dBi. With system management, the gateway should be installed at each community, which covers around 2 km², as planned in Section IV. Therefore, the realized gain is sufficient for a small area.

Moreover, the realized gain of the antenna C is a negative value because of the mismatch frequency at 922.5 MHz. However, antennas A and C are lower cost, being priced at approximately US$5. Antenna B has 8.2 dBi of realized gain and is more expensive than antennas A and C at around US$40. In addition, it has large dimensions and is unsuitable for installation at electric poles.

### Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realized Gain (dB)</td>
<td>A: 1.04, B: 8.2, C: 3.47</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>A: 909-931, B: 752-2700, C: 800-825</td>
</tr>
<tr>
<td>Gateway</td>
<td>STM32 LoRa Discovery kit (SX1276)</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>Gateway UfiSpace GPE810A-923U (SX1301)</td>
</tr>
<tr>
<td>SF</td>
<td>SF7, SF10, SF12</td>
</tr>
<tr>
<td>LoRa Bandwidth</td>
<td>125 kHz</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>12 dBm</td>
</tr>
<tr>
<td>Coding Rate</td>
<td>4/5</td>
</tr>
<tr>
<td>ED antenna high</td>
<td>2 m</td>
</tr>
<tr>
<td>RX antenna high</td>
<td>6.2 m</td>
</tr>
<tr>
<td>ED Ext. Module</td>
<td>Ublox NEO-6M GPS &amp; SD Card Module</td>
</tr>
</tbody>
</table>

Figure 4 shows the radiation pattern of three antennas on the E-plane and H-plane. The greatest signal power of antennas A and B is released at 0° of the E-plane and H-plane. Conversely, the signal power of antenna C is the greatest at 280° of the E-plane. On the H-plane, antenna C radiates a signal power surround itself. The radiation pattern at −3 dB is called the half power beam width (HPBW), which is the key to identifying antenna efficiency and polarization. The HPBW of antennas A, B, and C are approximately 85°, 60°, and 100°, respectively. If the HPBW is small, then the antenna's radiation is high in the desired direction. The interference from each other is too low when compared with the large HPBW, as described in Fig. 1 in Section II.

### IV. Measurement Setup

To create a new PL model for SM communication, Fig. 5 illustrates the LoRaWAN setting up for a SM scenario in Thailand. The proposed MSA is applied to investigate a new PL model by using the empirical method.
A. Sampling Environment

The Provincial Electricity Authority (PEA) controls most SM installations in Thailand. The PEA requires SMs to have a height of at least 1.7 m from ground level. The range of each electric poles is between 20 and 40 m along the roadside, as seen in Fig. 5. The sampling environment is an urban area in Narathiwat Province, Thailand, that covers approximately 7.5 km$^2$ with 13,000 customers. This area is classified into 35 communities, and each community area is around 1 km$^2$ [29]. The physical details enable us to design the LoRa gateway in each community to cover SMs as much as possible.

This information is useful for the planning and implementation of SM communication on LoRaWAN technology. A gateway is installed at the electric pole at a latitude of 6.425481 and a longitude of 101.825112. This location is a junction of the main road. For two EDs, they are installed on a stick with a height of 2 m. During radio signaling in the air, the EDs of the two antennas move out of the gateway. The position of the EDs is recorded to measure the distance between the EDs and the gateway. The signal-to-noise ratio and RSSI are used to calculate the PL at each position. Therefore, all parameters are used to analyze the link quality of the communication system.

\textit{LoRaWAN Setup}

The LoRaWAN architecture consists of four components. The LoRaWAN setup indicates the key parameters of each system, which affected the PL model below.

- **ED**
  The ED is used to connection with a SM and sends data to the gateway by using a microcontroller board model STM32 [12]. Antennas A and B are used in this section. First, the EDs of antennas A and B operate at the frequency of 923.2 and 923.4 MHz respectively, thereby avoiding any interference with each other. Second, the EDs obtain their position by using a global positioning system (GPS). The size of the GPS packet is 11 bytes. The data are sent to the gateway at five-second intervals. Third, the transmission power is fixed as 12 dBm with coding rate 4/5. Next, the SF of both EDs varied from SF7, SF10, and SF12 in every packet on a LoRa bandwidth of 125 kHz. Finally, all the ED parameters are recorded into a memory card for comparison with the received data from the NS, as seen in Table III.

- **Gateway**
  The LoRa gateway is employed to collect data from the EDs by using a monopole antenna. We use a commercial gateway of the UfiSpace model [30], which operates on the Internet protocol to send the ED data to the NS.

- **NS**
  The NS is applied for user authentication and management data from the EDs. The commercial NS used in our experiment is provided by the Communications Authority of Thailand Public Company Limited [31].

- **Application Server (AS)**
  Users can monitor or check the result from the EDs via the AS. In this research, message queue telemetry transport is used to select the data and display to the Line application on a smartphone with Hypertext Transfer Protocol [32].

V. Result and Discussion

LoRaWAN technology works based on the open systems interconnection (OSI) model. In this paper, we focus the RSSI on a physical layer of the OSI model. It operates within the frequency range of 920–925 MHz. We consider a PL in the SM communication environments. The results show the LoRa link quality, mathematical analysis, statistical evaluation, and model implementation.
### Table IV

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Link Quality</th>
<th>Path Loss Coefficient</th>
<th>Statistical Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Range (m)</td>
<td>PDR (%)</td>
<td>n</td>
</tr>
<tr>
<td>A (Proposed)</td>
<td>2,233.77</td>
<td>52.93</td>
<td>2.95</td>
</tr>
<tr>
<td>B</td>
<td>2,459.07</td>
<td>56.62</td>
<td>3.11</td>
</tr>
</tbody>
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### Table V

<table>
<thead>
<tr>
<th>Testing Site</th>
<th>Path Loss Model</th>
<th>RMSE (dB)</th>
<th>R²</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>Proposed</td>
<td>9.15</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>Okumura–Hata</td>
<td>10.19</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Free space</td>
<td>27.32</td>
<td>-1.52</td>
</tr>
<tr>
<td>II</td>
<td>Proposed</td>
<td>9.50</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Okumura–Hata</td>
<td>15.45</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Free space</td>
<td>24.73</td>
<td>-0.67</td>
</tr>
<tr>
<td>III</td>
<td>Proposed</td>
<td>8.79</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>Okumura–Hata</td>
<td>14.15</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Free space</td>
<td>20.82</td>
<td>-0.59</td>
</tr>
</tbody>
</table>

### A. LoRa Link Quality

The packet delivery ratio (PDR) and the RSSI are used to analyze the LoRa link quality. The PDR is calculated according to the ratio of the number of sending and receiving packets. In the experiment, the EDs of antennas A and B send 733 packets, and antennas A and B can receive 388 and 415 packets, respectively. Thus, the PDR can be rewritten as 52.93% and 56.62%, as seen in Table IV.

The distance of the transmission signal of the two antennas is investigated. The coverage area of antennas A and B is 2.2 and 2.5 km, respectively. Although antenna A has lower performance than antenna B, its coverage area is enough for the SM scenario implemented in a community area of approximately 1 km², as described in Section IV.

The RSSI measurement of antennas A and B is classified into high, medium, and low levels, as seen in Fig. 6 [7]. Antennas A and B have a high RSSI at a distance of 0–0.4 km, medium RSSI at a distance of 0.4–1.2 km, and low RSSI at a distance of more than 1.2 km. Moreover, the sensitivity of antennas A and B is more than -90 dBm when the minimum required on the LoRa is -126.5 dBm. This sensitivity offers a data rate up to 5.470 kbps [16]. However, the LoRa gateway is installed on an electric pole at a height of 6.2 m, which is lower than the building height. Taller buildings may obstruct the radio signal between the EDs and the gateway. Furthermore, a curvy stretch of the road may cause non-line-of-sight (NLOS) propagation, as seen in Figs. 6(b)–(c). Therefore, the gateway height and the NLOS issues may degrade the RSSI in real environments. The results show that the performance of the proposed MSA is close to that of commercial products.

### B. Mathematical Analysis

The empirical model is used to design our PL model by using the measured PL at each position [8], [21], [33], [34]. Equation (1) shows the PL of each antenna depending on a distance between EDs and gateway. It indicates the log scale by using the scatter plot, as seen in Fig. 7. The measured PL from each ED is linear. Thus, we can use linear regression analysis to build the fitting line to predict the PL. The empirical model and regression coefficients can be calculated by [35]-[36].

\[
PL_{EMP} = 10n \log_{10} (d) + \beta + \gamma
\]  

\[
n = \frac{\sum_{i=1}^{N}(d_{m(i)} - \bar{d}_{m}) 
(PL_{m(i)} - \overline{PL}_m)}{
\sum_{i=1}^{N}(d_{m(i)} - \bar{d}_{m})^2}
\]  

\[
\beta = \overline{PL}_m - n \cdot (\bar{d}_{m})
\]  

\[
\sigma (dB) = \sqrt{\frac{\sum_{i=1}^{N}(PL_{m(i)} - \overline{PL}_m)^2}{N-1}}
\]  

where \(PL_{EMP}\) is the empirical PL in dB, \(d\) is the distance between ED and a gateway in meters, \(n\) is the PLE, and \(\beta\) is the PLI in dB. \(\gamma\) is a random error of the zero mean Gaussian random variable with standard deviation (SD), which describes the shadowing effect. \(d_{m(i)}\) is the measured distance between each sample. \(PL_{m(i)}\) is the measured PL of each sample. and are the mean of measured distance and measured PL, respectively. \(N\) is the number of samples. The SD (\(\sigma\)) describes a deviation be-
between measured PL ($PL_m$) and predicted PL ($PL_p$) when expressed in dB, as seen in (6)–(9). Thus, the SD or the standard error is calculated as [33].

Table IV shows the regression coefficients of the measured PL using antennas A and B. They are represented by the fitting line A (solid line) and B (dashed line), as seen in Fig. 7. Each fitting line demonstrates the trend of the data by using the least squares method. The PLE represents propagation loss by a distance between the EDs and the gateway. The PLE of fitting lines A and B are 2.95 and 3.11, respectively. Both of them are in range of the urban area of 2.7–3.5 as mentioned by [37]. PLI is used to show the PL at 1 meter of a distance between the EDs and the gateway. The PLIs of fitting lines A and B are 32.27 and 37.94 dB, respectively. The PLI of the fitting line A is close to that of the free space model.

SD is used to illustrate a fluctuation of signal loss because of the shadow fading. As mentioned in [38], the SD in the urban area of the macrocell is 8 dB. Furthermore, the SDs of fitting lines A and B are 5.79 and 6.71 dB, respectively, which are lower than the SD level of the macrocell. The SD of our proposed MSA is close to that of the commercial product.

### C. Statistical Evaluation

To predict the PL, our PL model is verified by the statistical significance test. The significance test proceeds as follows: 1) F-test is used to verify our PL model’s accuracy; 2) the coefficient of determination or R-squared ($R^2$) is used to identify a relationship between the measured PL and the predicted PL; and 3) adjusted-$R^2$ is applied to verify the amount of sampling data [33], [36].

Table IV illustrates the result of the fitting line significance test when the significance level is 0.05. Results show the following: 1) The F-test is investigated by F-critical. If it is less than the F-statistic or the P-value is lower than 0.05, then the error on the prediction PL model of each fitting line is acceptable; 2) the R-squared of fitting lines A and B is 0.84 and 0.84, respectively. Normally, the R-squared should be more than 0.8, which means the data from the measured PL are less distributed around the fitting line, as seen in Fig. 7 [36]; and 3) the adjusted-$R^2$ is used to validate the R-squared. The adjusted-$R^2$ of fitting line A and B is 0.84 and 0.84, respectively, similar to the R-squared. Therefore, all the sampling data are sufficient to create a mathematical model for predicting the PL in the SM environment.

#### D. Model Implementation

To verify our proposed PL model, the proposed MSA is applied in other locations, including Sites I, II, and III, which are close to the previous environment. All gateways have a height of 6.2 m, and the parameters are the same as those in the first experimental configuration in Table III.

Figure 8 shows the measured PL of Sites I, II, and III by using the scatter plot and compares the proposed model with the traditional models. The PL prediction of our proposed model is closer to the measured PL than the free space model in all locations. Moreover, the Okumura–Hata model illustrates a trend line that is close to the measured PL. In addition, the RMSE and R-squared are used to validate model accuracy by considering the prediction errors [33]. Our proposed model can predict the PL more accurately than the Okumura–Hata model can in the SM scenario when Sites I, II, and III are compared, as seen in Table V.

#### VI. Conclusion

The rectangular patch MSA is implemented in the 920–925 MHz frequency range for LoRaWAN communication in an urban area of Thailand. The MSA is designed to create a new PL model for SM communication by using the empirical method. PL measurement and linear regression analysis are used to create the proposed PL model. The proposed MSA is compared with a commercial antenna with a coverage area of 2.2 km². Its LoRa radio signaling quality is good, being close to that of a commercial product. The proposed antenna has a lower cost and is smaller than commercial antennas. Therefore, the proposed antenna can be produced on a large scale for installation on electric poles. Furthermore, the proposed MSA is more accurate than the Okumura–Hata model, as verified by the RMSE and R-squared. Therefore, the proposed PL model and the MSA are useful for implementation in SM communication through LoRaWAN technology.

### References


[16] LoRaWAN™ 1.0.2 Regional Parameters, LoRa Alliance, 2017.


