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Evaluasi Kinerja LoRa E220-900T30D untuk Sistem Monitoring Wind Turbine: Pengukuran RSSI, Analisis Model Propagasi, dan Kepatuhan Regulasi Komunikasi Indonesia

Performance Evaluation of the LoRa E220-900T30D for Wind Turbine Monitoring Systems: RSSI Measurements, Propagation Model Analysis, and Compliance with Indonesian Communication Regulations

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Abstrak

Pemanfaatan Internet of Things (IoT) untuk memonitor turbin angin di wilayah rural menghadapi keterbatasan infrastruktur komunikasi. Penelitian ini mengevaluasi kinerja modul LoRa E220-900T30D dan memodelkan propagasi sinyal pada lingkungan persawahan di Bangkalan, Madura, dengan mempertimbangkan regulasi di Indonesia. Pengukuran dilakukan melalui pengiriman paket data pada jarak 10–2600 m dengan interval 100 m, serta pencatatan nilai RSSI pada setiap titik. Hasil pengukuran dibandingkan dengan model propagasi Free-Space, Two-Ray, dan Okumura-Hata. Hasil menunjukkan bahwa model Okumura-Hata memberikan pendekatan paling akurat terhadap data empiris. Berdasarkan model tersebut, dengan daya pancar 100 mW dan sensitivitas penerima −124 dBm, jangkauan komunikasi maksimum mencapai sekitar 6,8 km. Jangkauan dapat ditingkatkan hingga 9,5 km dengan meningkatkan sensitivitas penerima hingga −130 dBm, dengan konsekuensi penurunan data rate. Studi ini memberikan validasi empiris model propagasi LoRa pada lingkungan rural spesifik di Indonesia serta estimasi jangkauan realistis berdasarkan batasan regulasi nasional.

Kata kunci: Turbin angin, RSSI, LoRa, rural

Abstract

The implementation of the Internet of Things (IoT) for wind turbine monitoring in rural areas is constrained by the lack of reliable communication infrastructure. This study evaluates the performance of the LoRa E220-900T30D module and models signal propagation in a rural rice field environment in Bangkalan, Madura, while

considering regulatory constraints in Indonesia. Measurements were conducted by transmitting data packets over distances ranging from 10 to 2600 m with 100 m intervals, and recording RSSI values at each point. The measurement results were compared with Free-Space, Two-Ray, and Okumura–Hata propagation models. The results show that the Okumura–Hata model provides the closest fit to the empirical data. Based on this model, with a transmit power of 100 mW and a receiver sensitivity of −124 dBm, the maximum communication range is approximately 6.8 km. The range can be extended to 9.5 km by increasing the receiver sensitivity to −130 dBm, at the cost of reduced data rate. This study provides empirical validation of LoRa propagation modeling in a specific rural environment and offers a realistic range estimation under national regulatory constraints.

Keywords: Wind Turbine, RSSI, LoRa, rural

I. INTRODUCTION

Wind turbines require reliable monitoring systems to ensure optimal performance and minimize maintenance costs, particularly when deployed in remote areas [1] [2]. Continuous (real-time) monitoring through online condition monitoring systems enables early fault detection without interrupting turbine operation, making it more effective than conventional offline approaches. To support this functionality, Internet of Things (IoT) and Wireless Sensor Network (WSN) technologies are widely utilized to acquire environmental and turbine operational data and transmit them to centralized monitoring systems [3].

LoRa (Long Range) has emerged as a promising communication technology for such applications due to its low power consumption and long communication range. However, although LoRa is theoretically capable of achieving communication distances of up to 10 km in rural environments, its actual performance is strongly influenced by propagation characteristics, including terrain profile, ground reflection, and environmental conditions [4]. This limitation introduces a critical challenge in practical deployment, particularly in rural areas where empirical propagation data are scarce.

Existing studies on LoRa propagation have primarily focused on urban or suburban environments, while investigations in rural regions—especially in the Indonesian context—remain limited [3] [5]. Moreover, many previous works rely on generalized propagation models without validating their suitability against real field measurements [6] [7]. As a result, there is a lack of accurate and location-specific propagation models that can reliably predict LoRa communication performance in rural deployment scenarios. This gap highlights the need for empirical studies that integrate field measurements with propagation model evaluation.

To address this issue, this study conducts a comprehensive measurement and modeling of LoRa signal propagation in the rural area of Bangkalan, Madura. Field measurements are performed in the Socah region using the LoRa E220-900T30D module, with the Received Signal Strength Indicator (RSSI) as the primary evaluation metric. Measurements are carried out over distances ranging from 0 to 2.6 km under predominantly line-of-sight conditions, with systematic receiver displacement to capture spatial signal variation.

The measured data are then compared with several widely used propagation models, including Free-Space Loss (FSL), Okumura-Hata (rural), and the Two-Ray ground reflection model. Unlike previous studies that apply these models independently, this research evaluates their accuracy against real measurement data to determine the most representative model for rural Bangkalan conditions. The selected model is subsequently used to extrapolate signal attenuation up to 10 km, enabling assessment of communication feasibility for long-range wind turbine monitoring systems.

The main contributions of this study are as follows: (1) providing empirical RSSI measurement data for LoRa communication in a rural Indonesian environment, (2) evaluating the accuracy of multiple propagation models against real-world measurements, and (3) identifying a suitable propagation model for predicting long-range communication performance up to 10 km under regulatory constraints. These contributions are expected to support the design and deployment of reliable LoRa-based monitoring systems in similar rural scenarios.

Furthermore, this study ensures compliance with Indonesian regulations issued by the Ministry of Communication and Digital Affairs (Komdigi), particularly regarding frequency usage, bandwidth, and the maximum transmit power for Low-Power Wide Area Network (LPWAN) systems. Communication performance is analyzed by considering path loss, antenna characteristics, receiver sensitivity, and spreading factor (SF) configuration to ensure that the system operates reliably within these constraints.

The remainder of this paper is organized as follows. Section II presents the literature review. Section III describes the research methodology. Section IV discusses the results and analysis. Section V concludes the paper.

II. LITERATURE REVIEW

This subsection reviews prior studies on the use of Wireless Sensor Networks (WSNs) for wind turbine monitoring and evaluates the role of LoRa as a communication medium, with particular emphasis on RSSI-based performance assessment and propagation modeling.

a. WSN in Wind Turbine Monitoring

Previous studies have demonstrated that WSNs are effective for monitoring key turbine parameters, including mechanical (rotor speed, vibration), electrical (voltage, current), and environmental variables [8] [9]. However, most existing implementations rely on short-range communication technologies such as ZigBee or Wi-Fi, which are limited in coverage and require additional infrastructure for wide-area deployment [10] [11] [12]. While these approaches are suitable for compact wind farms, they are less effective for geographically dispersed or rural installations. In contrast, recent works have explored LoRa-based WSNs due to their long-range capability and low power consumption. Nevertheless, these studies primarily focus on system implementation rather than analyzing communication reliability under real propagation conditions.

b. LoRa and Network Quality Assessment

LoRa has been widely adopted for long-range IoT applications and is reported to achieve communication distances exceeding 10 km in rural environments [13] [14]. Prior studies typically evaluate LoRa performance using metrics such as RSSI, Signal-to-Noise Ratio (SNR), and Packet Delivery Ratio (PDR). Among these, RSSI is the most commonly used parameter due to its simplicity and direct representation of received signal strength [15]. However, most existing evaluations are conducted under controlled or limited scenarios and do not sufficiently consider spatial variation or terrain-specific effects. As a result, there is still a lack of empirical RSSI datasets that reflect real deployment conditions, particularly in rural areas such as Bangkalan.

In addition, although LoRa physical layer parameters—such as spreading factor, bandwidth, and transmit power—are known to affect communication performance, prior studies often analyze these parameters independently without linking them to propagation behavior [16][17]. This creates a gap in understanding how parameter configuration interacts with environmental factors to influence signal attenuation.

c. Propagation Models and Research Gap

To estimate radio signal attenuation, several propagation models have been widely used, including Free-Space Loss (FSL), Two-Ray ground reflection, and Okumura-Hata. Previous studies generally apply these models as theoretical references without validating them against field measurements. The FSL model assumes ideal line-of-sight conditions and is often used as a baseline, but it tends to underestimate losses in real environments [18]. The Two-Ray model improves accuracy by considering ground reflections, yet its applicability depends on antenna height and terrain characteristics. Meanwhile, the Okumura-Hata model is widely used for rural and urban planning due to its empirical basis, but its parameters are derived from measurements outside the Indonesian context, which may reduce its accuracy when applied locally [19].

Despite the availability of these models, comparative validation using real LoRa measurement data in rural environments remains limited. Most prior works do not systematically evaluate which model best represents actual propagation conditions, nor do they extend the validated model to predict long-range performance [20] [21]. In addition, most previous studies have focused on the application of LoRa to support various industries, rather than on evaluating its performance [22] [23]. Another limitation in previous studies is the lack of alignment with national regulatory constraints. In Indonesia, LoRa operation must comply with regulations that limit frequency bands (920–923 MHz), bandwidth (≤125 kHz), and transmit power (≤100 mW) [24]. Many experimental studies do not explicitly consider these constraints, which may lead to overestimation of achievable communication range.

Based on the above limitations, this study differs from previous works by (1) providing empirical RSSI measurements of LoRa communication in a rural Indonesian environment, (2) performing a comparative evaluation of multiple propagation models against real measurement data, and (3) identifying the most suitable model for predicting communication performance up to 10 km under regulatory constraints. This approach not only validates theoretical models but also bridges the gap between simulation-based analysis and real-world deployment.

d. Radio Waves Propagation Models

Radio wave propagation allows radio waves to travel from a transmitting antenna over thousands of kilometers. Understanding the propagation mechanism is crucial because it involves the obstacles and losses experienced by radio waves during their travel, which must be considered before designing and operating communications using radio waves. Radio wave propagation models are needed to predict the attenuation experienced as radio waves travel along their propagation path, which affects the loss experienced by the transmitter signal. Some frequently used propagation models are the free-space loss model, the two-ray model, and the Okumura-Hata model.

The free-space loss model is a simple radio propagation model that assumes that the path traversed by radio waves is a Line-of-Sight (LoS) path, so that the received power passes through no obstacles. This model is used as a baseline and for comparison with other models, and calculates losses without considering multipath. Propagation loss for a free-space path can be written [25]:

$$L_F(dB) = 10\log_{10}\frac{P_t}{P_r} \quad (1)$$

$$= -10\log_{10}G_T - 10\log_{10}G_R + 20\log_{10}f + 20\log_{10}d + k \quad (2)$$

where $k = 20\log_{10}\left(\frac{4\pi}{3\times10^8}\right) = -147.56$. In equation (1), $L_F(dB)$ is propagation loss for free-space links stated in dB, P_T is the power transmit and P_R, is the received power where both are in Watts or milliwatts. G_T and G_R are the transmit and receive antenna gain in dBi respectively, f is frequency in MHz, dan d is distance in meter.

Since the free-space model only considers one path, which can only be applied in conditions with no reflections, for more realistic radio wave propagation, a method that considers both the direct and reflected paths is used. One model that can be used is the two-ray model, which considers both the direct and reflected paths. The pathloss in dB with the two-ray model is expressed in the following equation:

$$P_L(dB) = 40\log_{10}d - 20\log_{10}G_T - 20\log_{10}G_R \quad (3)$$

The radio wave propagation model frequently used for network planning is the Okumura-Hata Model, which is based on empirical measurements conducted by Okumura. Hata developed equations based on graphical information generated by Okumura. This model is used because it is simpler in calculating loss, involving only location, frequency range, and area type (urban, suburban, or rural). The loss equation for rural areas is predicted using the following equation [25]:

$$L_{50}(dB) = L_{50}(urban) - 4.78(\log f_c)^2 + 18.33(\log f_c) - 40.94 \quad (4)$$

Meanwhile $L_{50}(urban)$ is a loss calculation for urban areas which is expressed in the following equation:

$$L_{50}(dB) = 69.55 + 26.16\log f_c - 13.82\log h_t - a(h_r) + (44.9 - 6.55\log h_t)\log d \quad (5)$$

where :

$150 \le f_c \le 1500$

$30 \le h_t \le 200$, h_t in meter

$1 \le d \le 20$, d in km

$a(h_r)$ is a correction factor for antenna height, where the value for small and medium cities is:

$$a(h_r) = (1.1\log f_c - 0.7)h_t - (1.56\log f_c - 0.8) \quad (6)$$

where $1 \le h_r \le 10$ meter.

III. RESEARCH METHOD

A wireless sensor network (WSN) for wind turbine monitoring is implemented using the LoRa E220-900T30D as a transceiver to enable communication between end nodes and the gateway. Data transmitted by the end nodes are received by the gateway via a LoRa link, and subsequently forwarded to the LoRa network server over an IP connection. In this system, the end nodes represent the monitored parameters of the wind turbine, while the gateway is deployed in a building located approximately 5–10 km from the turbine site. To ensure compliance with government regulations, the initial step is to perform a link budget calculation for the proposed WSN.

A. Measuring Device

The equipment used in the LoRa Link Budget measurement can be seen in Figure 1. The sensor data packets are processed in the ESP 32 device and then sent to the transmitting antenna via the LoRa gateway. At the receiving end, the LoRa receiver receives the data for PC monitoring. The LoRa E220-900T30D operates at the 920 MHz frequency permitted for use in Indonesia, with a bandwidth of 125 kHz, a spreading factor of 7, and an air rate of 2.4 kbps. The air rate is the data rate affected by the spreading factor. The transmitted data packets have a baud rate of 9600, supporting long-distance transmission.

In this measurement, the transmit power was set at 30 dBm. The antennas used for both the transmitter and receiver are magnetic routers operating at a frequency of 700–960 MHz with a gain of 5 dBi and a VSWR (Voltage Standing Wave Ratio) of 1.5. These antennas have an omnidirectional radiation pattern with a vertical orientation. The magnetic router antennas used are 30 cm long and mounted on a 3 m tall pole as one of the requirements for the LoRa E220-900T30D to achieve the maximum range.

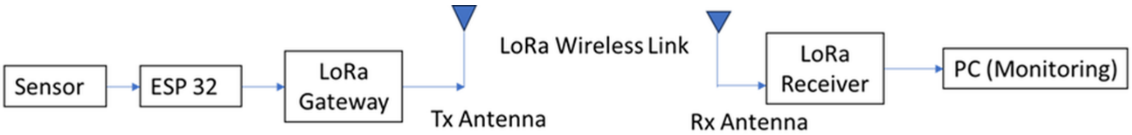

Figure 1. Measuring System Configuration

B. Design and Measurement Methods

To ensure the wind turbine monitoring system using LoRa communication complies with regulations, RSSI measurements were performed to determine the required transmit power, network quality, and path loss. These measurements were conducted in the Socah rice fields in Bangkalan (-7.128263, 112.735679), which, according to the Global Wind Atlas, has a mean power density of 77 W/m^2. This value is still considered high for a small project. Therefore, the wind turbine can be operated in this area at a height of 100 meters. The measurement location, a rice field, as a Non Line of Sight (NLOS) is shown in Figure 2. Figure 3 shows the types of the Tx and Rx antennas. The magnetic router antenna is positioned at the top of the tripod.

RSSI measurements are performed by sending data packets from the sensors. The computer at the receiver monitors the measurement conditions through the RSSI parameters and the status of the received packets. An RSSI is received when the packet is successfully stored for further processing. For each measurement distance, the packet is sent three times, then the average RSSI value is calculated and converted to dBm. The number that comes out of the LoRa device is in the form of an RSSI register. The RSSI register is converted to dBm using the method as in equation (7) mentioned in datasheet.

$$dBm = -(256 - RSSI) \tag{7}$$

Figure 2. Measurement location in rice field area in Socah, Bangkalan

RSSI in dBm units is expressed as P_r or received power, and is used to calculate the loss in a communication channel. Channel path loss (L) is calculated based on the received power and is expressed in dBm, using the following equation (8):

$$L = P_t + G_T + G_R - P_r \quad (8)$$

where P_T is power transmit which in this measurement is set at maximum power 1000 mW or 30 dBm, G_T and G_R is the gain of the transmitting and receiving antennas, each of which is 5 dBi.

Figure 3. Antenna used for the transmitter and receiver

Figure 4 shows a measurement scenario conducted in the rice field area with a link of 2600 m and a measurement interval of 100 m. The T_x location is at point (-7.128263, 112.735679) and is fixed, while the R_x is mobile every 100 m. The numbers on the blue bullets indicate the location of the first Rx to the last Rx location. The measurement sequence is as follows:

a. T_x sends data packets for one minute at a transmission interval of 1 s, resulting in 30 RSSI data samples per transmission session
b. The data packet is confirmed to be sent, and the RSSI value can be obtained
c. The data packets are sent twice and a third time and then stored
d. R_x antenna moves to the second 100 m
e. And so on, until RSSI values are obtained at the longest distance

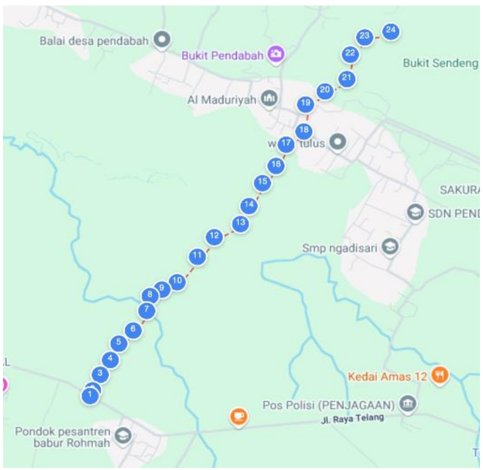

Figure 4. Measurement location and the scenario of Rx displacement in the bullet number

The RSSI value is displayed in negative dBm. The next step is to calculate pathloss (L) on a dB scale, using equation (1). From equation (1), 20 pathloss values were obtained, which were used for further calculations. Then, the 20 values were plotted together with the radio wave propagation models, namely the free-space loss, two-ray, and Okumura-Hata models. The free-space loss model equation used to calculate the loss is equation (2), while the loss calculated with the two-ray model is equation (3). The Okumura-Hata model used for the loss calculation is a radio wave propagation model in rural areas. This is because the measurement location is in a rural area without any significant building obstructions. The loss calculation with this model is conducted with equations (4) – (6). The f_c parameter in the Okumura-Hata model is the working frequency of 920 MHz, h_t and h_r as the height of the transmitting and receiving antennas of 3 m, while d or the distance is from 0 m to 2600 m. From the three models, the model that is closest to the measurement results is selected, and then this model is used to calculate the loss prediction from a distance of 0 m to 10,000 m.

The next step is to determine the value of P_r for a P_t of 100 mW according to the power permitted for use by LoRa, using the loss based on predictions from the specified model. The other measurement parameters used are the same as the measurement parameters. including f_c, g_t, g_r, h_t and h_r. The resulting P_r value is then compared to the required power received (P_{req}) of the LoRa device. This comparison is necessary to determine the distance at which the P_r value is greater than or equal to P_{req}, which is used to determine the actual range of the LoRa E220-900T30D at the measurement location.

If the range is less than 10 km, a review of the LoRa parameters used is recommended. This review is done by changing the Spreading Factor, which automatically reduces the P_{req} value of the LoRa device being used. Then, from this received power value, the device's received power will be predicted up to a distance of 10,000 meters. The prediction aims to determine the LoRa communication level used for that distance.

In this research, a 30 dBm transmit power is required to minimize the influence of power limitations on measurement results, so that RSSI variations better represent the characteristics of the propagation channel. Furthermore, testing with a 1 Watt power is used as a baseline to compare performance degradation in regulatory power scenarios. The procedure for calculating RSSI for 20 dBm power is to estimate propagation losses using the model, which is proven to be close to the measurement results. The measurement parameters, such as antenna, distance, and measurement scenario, used are the same, so the resulting losses are based on the same distance, environment, and equipment. Then, these losses are used to calculate P_r with P_t equal to 20 dBm.

IV. RESULTS AND DISCUSSION

The LoRa E220-900T30D characteristic measurements at the aforementioned location were conducted on August 25, 2025, from 9:00 AM to 4:00 PM (GMT + 7). These measurements generated RSSI values that were used to measure loss at a distance of 0 to 2600 m. The loss results compared to predictions from the free-space, two-ray, and Okumura-Hata models can be seen in Figure 5.

From Figure 5, it can be seen that the LoRa loss measurement results have the same pattern as the free-space, two-ray, and Okumura-Hata models, but have different values. The measurement loss has a higher value when compared to the free-space loss model of around 3-5 dB, but lower than the two-ray model. This is because the measurement location is in a rice field area that is expected to approach free-space loss, resulting in loss from obstacles in the form of grass. This grass is also a source of interference originating from multipath fading and fast fading. This multipath is caused by some of the signal being reflected by the grass, especially for signal waves with low angles or grazing angles [26]. Radio waves propagating near the ground surface are reflected by grass and nearby soil so that the signal can be constructive and destructive. The estimated attenuation produced by grass is around 0-3 dB at millimeter waves.

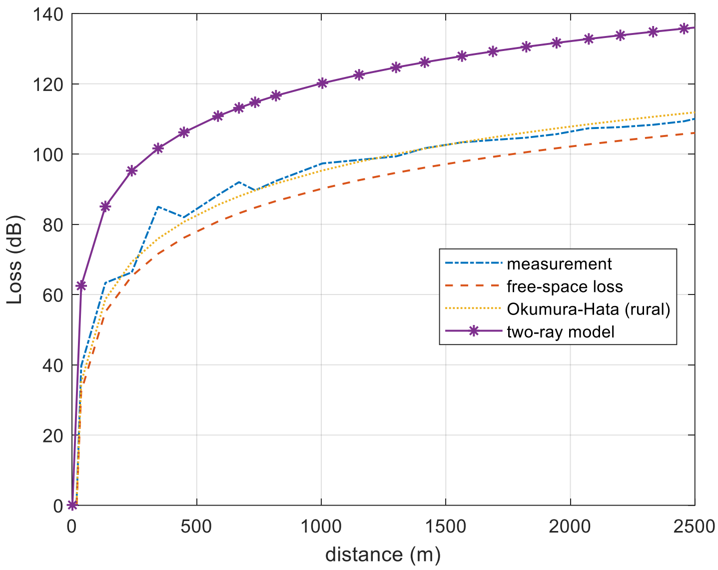

Figure 5. The measurement results are compared with the radio wave propagation model

The attenuation of the measured results is much lower than the results of the two-ray model. This is because the attenuation caused by grass is lower when compared to the interference effect in the two-ray model. The two-ray model, composed of direct paths and reflected paths, gets large fading from the reflected path, which can cause interference. In addition, this difference is also due to the ground surface at the measurement location having a less destructive reflective effect than the two-ray model so that it can strengthen the reception power. In addition, the antenna height is lower than the ideal antenna height for the two-ray model, which is 10 m, which is the cause of the less-than-ideal prediction results of the two-ray model, even though the maximum distance of 2.6 km is much greater than the length of the antenna.

The measured path loss, as can be seen in Figure 5, is closer to the Okumura-Hata model when compared to the other two models, except for the measurement fluctuations at a distance between 500 m and 700 m, where huts and several people passing by around it cause destructive interference compared to other measurement distances. The Okumura-Hata model used to predict path loss is the Okumura-Hata model for rural areas, where, in its preparation, the Okumura-Hata model is based on empirical measurements involving thousands of points, including rural areas, grasslands, and low-lying suburban areas [27]. The relatively low antenna height, the absence of strong reflective surfaces—which prevents destructive interference as observed in the Two-Ray model—and the grassland environment align well with the rural parameters defined in the Okumura–Hata model. Therefore, the Okumura-Hata model is then used to calculate path loss up to a distance of 10 km. The results of the loss prediction calculation at a distance of 10 km can be seen in Figure 6. Then this loss data is used to predict the maximum distance that can be received by LoRa by using the transmit power parameter (P_T) according to the government regulation, which is 100 mW or -10 dBm. While the minimum transmit power that can be received by the device (P_{req}) is -124 dBm used as a reference for the minimum transmit power, which indicates that LoRa can work optimally. Then, with equation (1), the received power is calculated for a distance of 0 to 2600 m and plotted P_{req} in one image with as shown in Figure 6. From that figure, it can be seen that the maximum distance that LoRa can work optimally is 6.8 km, where at that distance, the P_{req} is -124 dBm. This number is indicated by a red bullet. After that distance, the received power is less than P_{req} which indicates that the LoRa receiver cannot receive the signal properly.

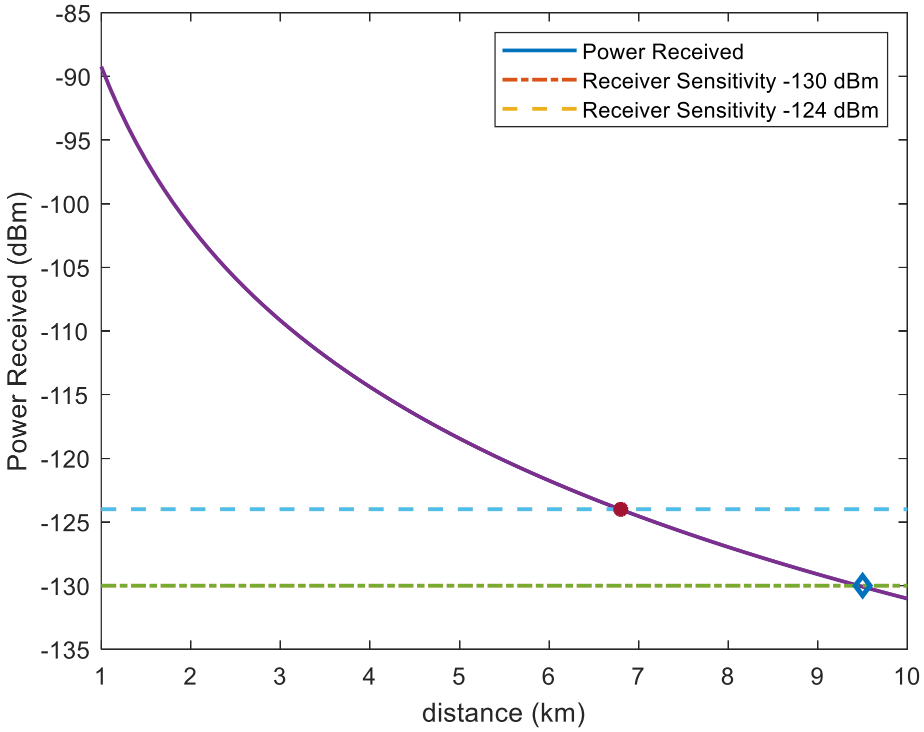

Figure 6. Maximum distance to the changed sensitivities

As discussed previously, LoRa was designed as a communication model between wind turbine monitoring sensors and a server located up to 10 km away. However, under power transmission regulations, the maximum achievable communication range is only 6.8 km. Therefore, optimization strategies are required to extend the coverage toward the 10 km target. There are several ways to do this, namely, increasing the antenna gain by more than 5 dBi with better VSWR. In addition to replacing the antenna, another method is to increase the SF from 7 to 9. Increasing the spreading factor (SF) enhances receiver sensitivity by increasing the number of chips per symbol [28], which results in a longer symbol duration and higher processing gain inherent to Chirp Spread Spectrum modulation [29]. This allows the receiver to integrate the signal over a longer time, improving the effective signal-to-noise ratio and enabling reliable detection of weak signals, even below the noise floor [30]. However, this improvement comes at the cost of reduced data rate, increased time-on-air, and higher energy consumption. This increase in SF increases the range because the P_{req} is reduced from -124 dBm to -130 dBm. In addition, the chip rate duration is also longer so that the receiver is able to detect weak signal power.

This effect is confirmed in Fig. 6, where the achievable distance increases from 6.8 km to 9.5 km. This number is shown by a blue diamond. However, there is a drawback when switching SF from 7 to 9, namely, the lower data rate than before, so transmission takes longer. Longer transmission times result in longer operating times, which are proportional to higher energy consumption and decreased network capacity. The trade-off of selecting the appropriate SF for this communication mode requires further study, including considering the data model required according to the characteristics of the wind turbine size being monitored as well as how long the data change interval must be adjusted to the measurement delay.

V. CONCLUSION

RSSI measurements of the LoRa E220-900T30D for wind turbine monitoring in Socah, Bangkalan Regency show that the observed path loss follows the rural Okumura–Hata model, with a reliable communication range of approximately 6.8 km under regulatory constraints. Range extension to 9.5 km is achieved by increasing the spreading factor (SF) from 7 to 9, at the expense of higher time-on-air and energy consumption, highlighting the trade-off between coverage and efficiency. These results provide empirical validation of LoRa performance for long-distance rural deployments under regulatory limits. However, the analysis is limited to RSSI measurements and does not consider additional performance metrics such as packet delivery ratio (PDR), signal-to-noise ratio (SNR), or environmental variability.

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AUTHOR CONTRIBUTION

IK led the determination of the contents of the paper. RA performed and analyzed the data. RB and MYS prepared the manuscript and revised the final version of the paper. IK and RA have read the final manuscript and approved the submission

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