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Coverage Estimation of LoRa Gateways for Tropical Regions (Benin City Metropolis)

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ABSTRACT: *Low Power Wide Area Network (LPWAN) Coverage Estimation are vital for accurate signal propagation in wireless channels. Empirical and deterministic models used in coverage predictions have not produced optimal results. This is because a model developed for a particular propagation environment performed optimally in that environment but failed when deployed to another environment. In a dense urban environment, predicting the optimal number of gateways in relation to their position is essential for ensuring reliable, stable communication and minimizing costs. Thus, this study underscores the importance of data collection in achieving optimal coverage estimation in LoRa deployments for Benin city. In this paper, an extensive dataset of LoRa propagation parameters (LPP) was obtained from measurement campaign in Benin city, a city in Nigeria, West Africa. Regression analysis was carried on the empirical data to determine which LPP criteria would suit the model development and the optimal cell placement for LoRa gateways for Benin city deployment. The major criteria for analysis were the Packet Distribution Rate (PDR) and Received Power Level represented by the Received Signal Strength Indicator (RSSI). Using the optimal placement model derived from the regression analysis and hexagonal arrangement, the LoRa coverage area and the optimal number of gateways require to cover Benin city was estimated. The result of the analysis show that the packet delivery ratio (PDR) has more correlation with distance than the received signal strength indicator (RSSI). It also shown that a high-performance matric was obtained using a total of 30 LoRa gateways covering 255 km square inhabited area, operating at +20 dBm, 868 Mhz,168 dB maximum link budget with a configuration setting of 4/5 code-rate, 7 spread-factor, 500Hz bandwidth, and an average optimal coverage of 1.4km at 96% PDR used in covered areas of Benin City.*

I. INTRODUCTION

Low Power Wide Area Network (LPWAN) is a wireless wide-area network technology that interconnects low-bandwidth, battery-powered devices with low bit rates over long ranges. This technology provides low-power wide-area coverage which is a requirement for a vast majority of WSNs [1]. It suits all IoT applications where small amounts of data are transmitted infrequently [2]. Created for machine-to-machine (M2M) and Internet of Things (IoT) networks, LPWANs operate at a lower cost with greater power efficiency than traditional mobile networks [3]. They are also able to support a greater number of connected devices over a larger area. LPWANs can accommodate packet sizes from 10 to 1,000 bytes at uplink speeds up to 200 Kbps. LPWAN's long range varies from 2 km to 1,000 km, depending on the technology (Kim B et al., 2017).

The commonly used wireless technologies in the long-range communication ecosystem are Low-Range (LoRa), Sigfox, Ingenu, Weightless, LTE-M, or NB-IoT and they have recently emerged with a common name of LPWANs, some of them being proprietary and patented solutions. Recently, LoRa and NB-IoT are by far the leaders of long-range communication infrastructure deployments and of the industrial community, respectively [5][6].

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Moreover, statistics have shown that LoRa is the most discussed LPWAN technology in the academic community or by hardware/software developers, due to its unlicensed spectrum operation and its ease to use (Petrariu, A.I., et al, 2021). Meanwhile, NB-IoT is operating in the licensed spectrum and it's mostly driven by leading telecommunication companies around the world, so its flexibility for the end-user is limited (Petrariu, A.I., et al, 2021). Another important facet of LoRa technology is the low cost of the device that is able to cover large areas, for more than a few kilometers (Petäjäjärvi, J., et al, 2017) [9].

LoRa is emerging as key technology in a wireless communication ecosytem for the next coming generation and inspiring a number of applications. However, even today there are still research issues need to be addressed before these technologies fulfil their potential.

LoRa technology is suited for different IoT applications, with the enormous potential of having certain capabilities, limitations, and features. Public and private

However, gateway placement helps to figure out the total number of gateways needed in the network and where they should be placed [10]. Since the wired links in gateway deployments are more expensive, the cost will drastically increase as more gateways are deployed. However, network throughput can be improved by adding more gateways and if gateways are well placed, network topology and traffic distribution can be enhanced [11].

The LoRa gateway has the primary task of providing connectivity for IoT devices, although the possibility remains of IoT devices without a connection due to inefficient network planning [12]. To cope with this issue, it is possible to introduce more LoRa gateways in the environment in order to improve coverage and network performance. Nevertheless, deploying LoRa gateways lead to high Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), including the cost of a LoRa gateway, of its leasing, and maintenance [13]. Hence, network planning, such as the LoRa gateways placement model, is a critical problem that influences Quality of Service (QoS) as well as the CAPEX and OPEX [13]. While previous research has examined LoRa gateway placement problems, to the best of our knowledge, none have investigated the minimum network performance along with cost efficiency for Benin city.

II. METHOD

This section involves creating models that can estimate the coverage area and the required number of gateways for Benin city deployment. The method adopted involves data collection from measurement campaign, optimal criteria selection, placement model development.

2.1 Measurement Campaign Scenario

Extensive field measurements were collected across predetermine sample points in eight zones in Benin city, Edo state located in the Southern part of Nigeria with the aid of route test. The received signal strength indicator (RSSI), transmission power and the packet delivery ratio (PDR) were all measured during the route test which was carried out at every 500m. The height of the base transceiver station for the urban centers where field measurements were collected is 8 m. The receiver antenna height used is 3m. The reference distance used was 100m and the collated data were recorded spanning a transmitter-receiver distance of 5 km. At each distance, 3 to 4 readings were recorded and the average was taken in order to ensure data accuracy.

2.2 Measurement Environment

To achieve the measurement campaign in this location, the study area of Benin City was divided into eight zones to adequately cover the entire geographic make- up of the city:

i. Zone 1

The first zone covers the Sapele Road to Airport Road axis of the Benin city metropolis and measur34.84 km2 shown in figure 1. This zone spans over the Government Reservation Area (G.R.A) which has tall buildings with few open spaces. It is the administrative quarter of the state. The features of all the zones are summarized in Table 1.

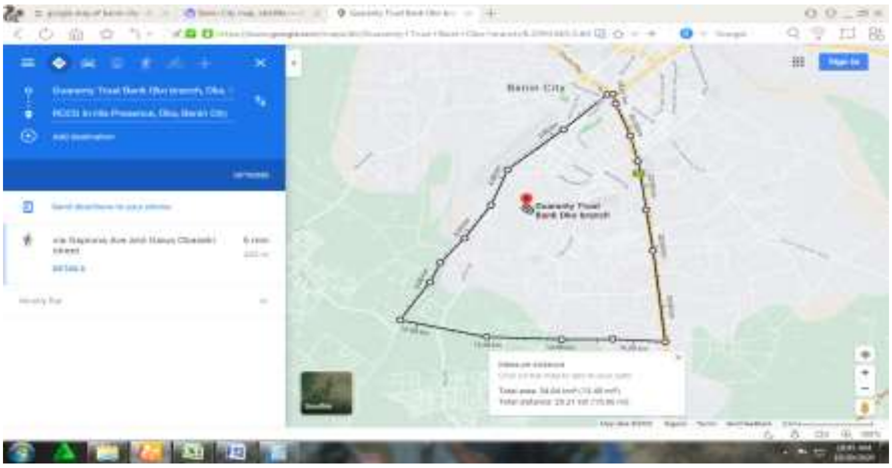

Figure 1: Screenshot of Google Map of Airport-road to Sapele road zone

Table 1: Summary of topological features of zones in Benin City

Zone	Square Area	Coverage Area	Topographical Features
1	34.84km^2	Sapele-road to Airport-Road	Administrative, commercial and resident buildings with little open spaces.
2	29.10km^2	Airport Road to Ekehuan road	It has buildings, valley with streams, hill and some vegetation
3	30.80km^2	Ekehuan road to Siluko road	It has buildings, valley and some vegetation just like Ekehuan axis at the outskirts.
4	15.06km^2	Benin Auchi - Benin Agbor road	most part have vegetation and buildings and the smallest zone.
5	42.64km^2	Benin Agbor road to Sokponba road	most part have vegetation, buildings, valleys, hills and river.
6	32.81km^2	Siluko road axis to Benin Ore Road	some parts have buildings and thick vegetation
7	44.06km^2	Benin Ore Road to Benin Auchi road	most part have vegetation, buildings and has valleys and rivers.
8	25.86km^2	Sokponba road to Sapele road	most part have buildings.

2.3 Setup of LoRa Measuring Equipment for Data Collection

The equipment consists of a transmitter and a gateway.

Figure 2: (a)and (b): Installation of the gateway by the researcher

The gateway was encased in a white panel box casing and were mounted on metallic poles with the solar panel, charge controller, and battery in place, the gateway was placed in strategic locations within the eight zones in Benin City.

Figure 3: (a) and (b): Installation of the gateway in a Federal College Road, Benin city

2.4 Field Data Presentation

Table 2 shows the summering of the field data obtained for zone one in Benin city at 500 Mhz. Where the transmission distance is represented by Tx, BW= Bandwidth, SNR = signal to noise ratio, CR = code rate, SF = spread factor, B =bite rate, Pkts sent and Rcvd = packet sent and received respectively. ET = average elapse time, PTX = transmission power.

Table 2: LoRa measured data for Zone 1 "Benin City" at 500 KHz

S/N	BW (KHz)	Tx distance	RSSI	SNR	CR	SF	Bite rate (bps)	Pkts. Sent	Pkts. Rcvd	PDR	ET	PTX
1	500	0.5	-106.7	2	4/5	7	21875	529	529	100	0.1024	20
2	500	0.5	-107.7	1.5	4/5	8	12500	529	529	100	0.2048	20
3	500	0.5	-108.8	1.5	4/5	10	3906.25	529	529	100	0.8192	20
4	500	0.5	-109.1	1.1	4/5	12	1171.875	529	529	100	3.2768	20
5	500	1	-108.1	-2	4/5	7	21875	513	513	100	0.2048	20
6	500	1	-109.1	-2	4/5	8	12500	513	513	100	0.4096	20
7	500	1	-110.3	-2.1	4/5	10	3906.25	513	513	100	1.6384	20
8	500	1	-111.9	-2.3	4/5	12	1171.875	513	513	100	6.5536	20

Table 3: LoRa measured data for Zone 2 "Benin City" at 500 KHz

S/N	BW (KHz)	Tx (kM)	RSSI (dBm)	SNR	CR	SF	Biterate (bps)	Pkts. Sent	Pkts Rcvd	PDR	ET	PTX
1	500	0.5	-98.3	-6.1	4/5	7	21875	309	309	100	0.1024	20
2	500	0.5	-99.2	-6.1	4/5	8	12500	316	316	100	0.2048	20
3	500	0.5	-100.3	-6	4/5	10	3906.25	310	310	100	0.8192	20
4	500	0.5	-101.2	-7	4/5	12	1171.875	318	318	100	3.2768	20
5	500	1	-101.7	-6	4/5	7	21875	315	315	100	0.2048	20
6	500	1	-102.2	-8.2	4/5	8	12500	310	310	100	0.4096	20

7	500	1	-103.4	-7.8	4/5	10	3906.25	309	309	100	1.638 4	20
8	500	1	-104.4	-7.4	4/5	12	1171.875	311	311	100	6.553 6	20

2.3 Selection of Performance Metric for Evaluating Signal Quality

The major criteria for analysis were the Packet Distribution Rate (PDR) and Received Power Level represented by the Received Signal Strength (RSSI). To determine which of the criteria would suit the development of the placement model, a linear regression analysis between the RSSI and PDR against distance was carried out based on the experimental data from each of the eight zones. Most data analysis software (Excel, 2019) or programming languages offer built-in functions for linear regression. They have capacity to show the derived regression model and it correlation value. The formula for this model is:

$$RSSI(d)\ vs\ d \qquad (1)$$

$$PDR(d)\ vs\ \ d \qquad (2)$$

Where:

- RSSI(d) is the received signal strength at distance d.
- PDR(d) is the packet delivery ratio at distance d

2.4 Development of the Placement Models

The placement models for LoRa coverage estimation were developed using the regression analysis of PDR with their corresponding transmission distances as obtained from measurement campaign conducted in Benin city metropolis. To determine the numbers of LoRa gateway required to cover each of the zones, the estimated coverage area of LoRa gateway was divided by the square area of each zone with consideration fot the hexagonal arrangement of LoRa gateways.

III. Results of the Analysis for the Optimal Criteria Selection

The result of the analysis for the optimal criteria selection are presented in table 4 to 11.

Table 4: PDR and RSSI Regression data (Zone 1)

ZONE 1		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9345	0.8438
250	0.9374	0.9374
125	0.9374	0.9094

Table 5: PDR and RSSI Regression data (Zone 2)

ZONE 2		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9451	0.3434
250	0.9502	0.3434
125	0.9546	0.3434

Table 6: PDR and RSSI Regression data (Zone 3)

ZONE 3		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9374	0.3958
250	0.9374	0.3958
125	0.9374	0.3956

Table 7: PDR and RSSI Regression data (Zone 4)

ZONE 4		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9324	0.8317
250	0.9374	0.9519
125	0.9374	0.9419

Table 8: PDR and RSSI Regression data (Zone 5)

ZONE 5		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9374	0.9232
250	0.9374	0.9320
125	0.9374	0.9539

Table 9: PDR and RSSI Regression data (Zone 6)

ZONE 6		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9374	0.9538
250	0.9374	0.9538
125	0.9374	0.9538

Table 10: PDR and RSSI Regression data (Zone 7)

ZONE 7		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9374	0.5293
250	0.9374	0.5879
125	0.9374	0.6130

Table 11: PDR and RSSI Regression data (Zone 8)

ZONE 8		
Bandwidth (kHz)	PDR R^2 value	RSSI R^2 value
500	0.9324	0.8317
250	0.9374	0.9519
125	0.9374	0.9419

As can be seen from tables 4 to 11 which represent the eight (8) different zones there is generally less regression of data from the fit for the PDR compared to the RSSI as the R^2 value is generally higher and more consistent. This indicates that the PDR metric would be a more reliable criterion on which to develop the placement models.

3.2 Results of Placement Models

3.3 Zone 1 (500 kHz) placement model:

Figure 4 shows the plot of PDR with transmission distance at 500 kHz bandwidth. From the plot, the following model was obtained for the specific environment:

$$PDR = -9.5\ X\ Distance(km) + 110 \qquad (1)$$

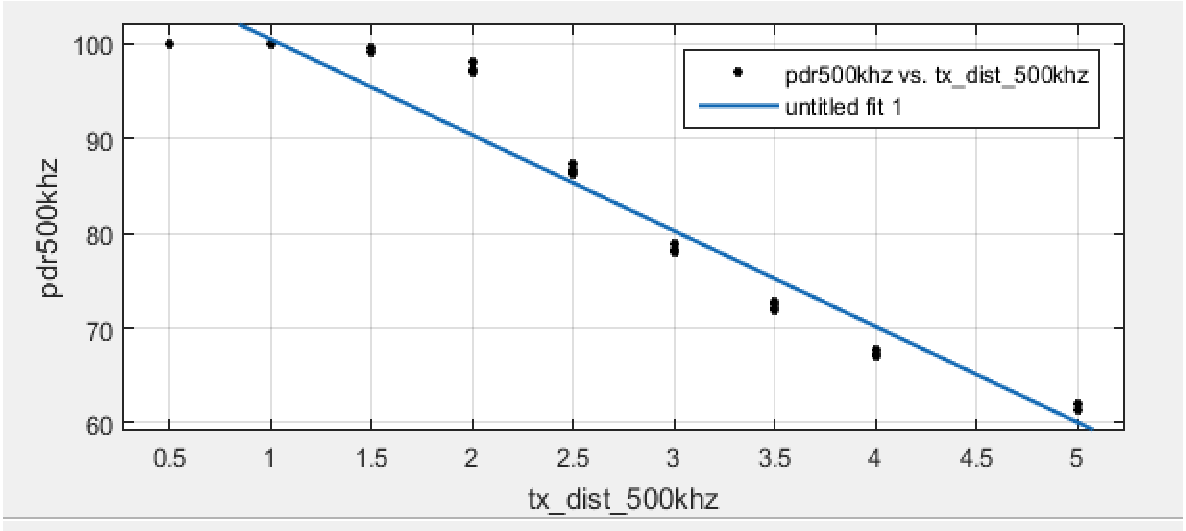

Figure 4: PDR vs. Transmission Distance (500kHz Bandwidth) Zone 1

3.4 Zone 1 (250 kHz) placement model

Figure 5 shows the plot of PDR with transmission distance at 250 kHz bandwidth. From the plot, the following model was obtained for the specific environment:

$$PDR = -9.723\ X\ Distance(km) + 110 \quad (2)$$

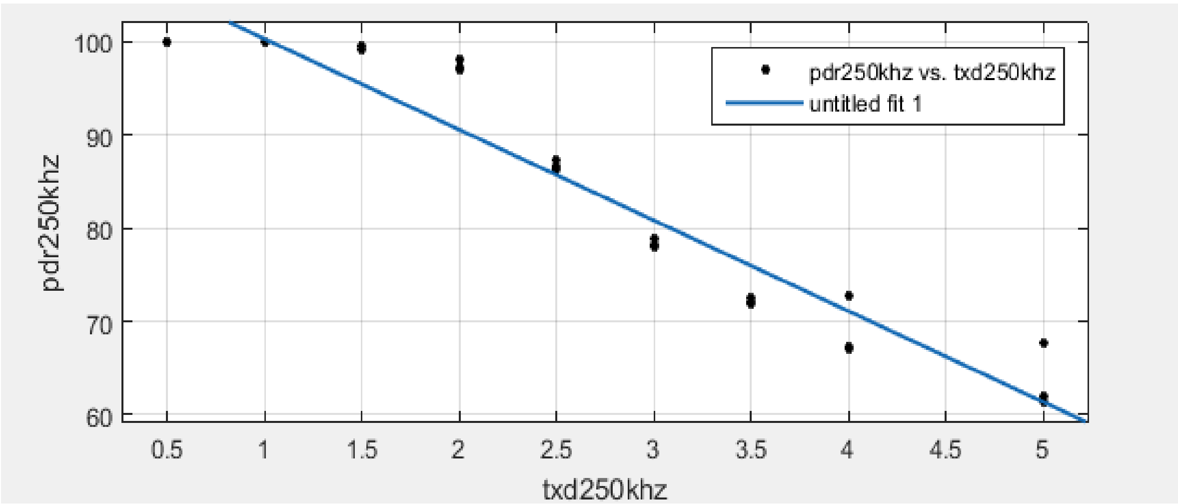

Figure 5: PDR vs. Transmission Distance (250 kHz Bandwidth) Zone 1

3.5 Zone 1 (125 kHz) placement model

Figure 6 shows the plot of PDR with transmission distance at 125 kHz bandwidth. From the plot, the following model was obtained for the specific environment:

$$PDR = -10\ X\ Distance(km) + 110 \quad (3)$$

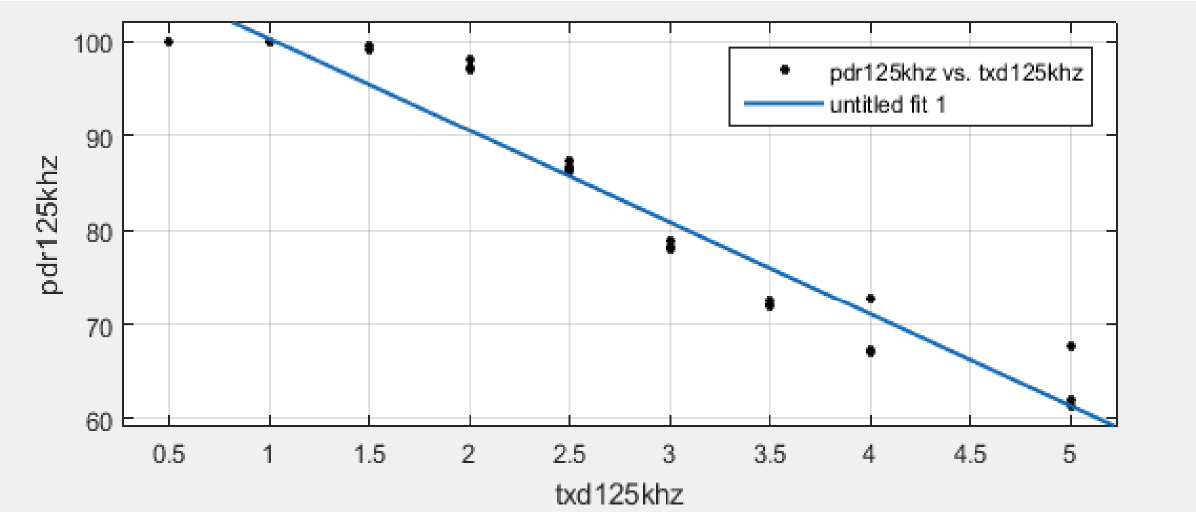

Figure 6: PDR vs. Transmission Distance (125 kHz Bandwidth) Zone 1

3.6 Numbers of LoRa Gateway Required for Zone Deployment

3.7 Zone 1:

Using the lower end of the transmission range radius of the field test for the transmitter, which is 1.4km range at 96% of the transmitted data packets delivery ratio, thus

Radius r = 1.4km, Length l = 2r (twice radius make a full length)

Assuming square coverage area (D_x), Area covered by a gateway = $(2r)^2$ = $(2 \times 1.4)^2$ = 7.84Km^2.

The deployment square area $R_x = 34.84m^2$ between Sapele road and Airport Road. Thus, the total number of gateways required using hexagonal arrangement = $\frac{\pi}{2\sqrt{3}}[\frac{R_x}{D_x}]$= 0.9069(34.84/7.84) = 4 gateways approximately.

Table 12: Summary of Developed Models at Different Bandwidth

ZONE	Models/ Developed at 125khz	Models Developed at 250kHz	Models Developed at 500khz
1	$PDR = -10\ X\ Distance(km) + 110$	$PDR = -9.723\ X\ Distance(km) + 110$	$PDR = -9.5\ X\ Distance(km) + 110$
2	$PDR = -12\ X\ Distance(km) + 110,$	$PDR = -11\ X\ Distance(km) + 110,$	$PDR = -10\ X\ Distance(km) + 110$
3	$PDR = -10\ X\ Distance(km) + 110$	$PDR = -9.5\ X\ Distance(km) + 110$	$PDR = -8.9\ X\ Distance(km) + 110$
4	$PDR = -9.7X\ Distance(km) + 110$	$PDR = -9X\ Distance(km) + 110$	$PDR = -8X\ Distance(km) + 110$
5	$PDR = -9.9\ X\ Distance(km) + 110$	$PDR = -9\ X\ Distance(km) + 110$	$PDR = -8\ X\ Distance(km) + 110$
6	$PDR = -10\ X\ Distance(km) + 110$	$PDR = -10\ X\ Distance(km) + 110$	$PDR = -10\ X\ Distance(km) + 110$
7	$PDR = -10\ X\ Distance(km) + 110$	$PDR = -9\ X\ Distance(km) + 110$	$PDR = -7.8\ X\ Distance(km) + 110$
8	$PDR = -10\ X\ Distance(km) + 110$	$PDR = -9\ X\ Distance(km) + 110$	$PDR = -7.8\ X\ Distance(km) + 110$

Assuming an average square coverage area (D_x), Area covered by a gateway = $(2r)^2$ = $(2 \times 1.4)^2$ = 7.84Km^2.

The deployment square area $R_x = 255m^2$ for Benin city. Thus, the total number of gateways required using hexagonal arrangement = $\frac{\pi}{2\sqrt{3}}[\frac{R_x}{D_x}]$= 0.9069(255/7.84) = 30 gateways approximately.

IV. CONCLUSION

This research aim was to develop LoRa coverage estimation models for optimal solutions of LoRa planning and deployment for a typical tropical region in this case, Benin city. This was achieved by leveraging on data collected from 8 zones in Benin city and linear regression analysis of the data. By conducting a comprehensive analysis of field data, the coverage area and the total required of LoRa gateway was estimated for Benin city. It was found that LoRa-based models and data presented in this research offers an optimized solution for achieving widespread coverage and reliable connectivity for IoT and WSN devices deployment in regions.

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