An optimization of multiple gateway location selection in long range wide area network networks

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ABSTRACT

The adoption of smart agricultural technology in rural areas is still limited in terms of network infrastructure supported. As a result, farmers continue to practice traditional farming that mainly focuses on human labor and requires experience in planning the production of agricultural products in unstable weather conditions, which makes the farmers highly risky. Currently, long range (LoRa) technology is a smart agriculture support tool that will enable the Internet of Things devices to a large number of end nodes distributed over a wide geographical area. They could access cloud computing from a long distance, kilometers, for processing via long range wide area network (LoRaWAN) communication protocol. When choosing a multiple gateway location for LoRaWAN networks, big networks must consider the spatial distribution of clients, radio signal propagation, and the cap on the number of devices served access. In this study, a mathematical model is developed to optimize coverage. The LINGO modeling program, an exact software method, was used to test the model. The findings indicated that the best six gateways at the optimal LoRaWAN gateway location. The gateways can provide signal coverage for all end nodes and can manage the capacity of the LoRaWAN gateway to support the proper number of end nodes.

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1. INTRODUCTION

Farmers in Thailand still encounter high production costs. In addition, the soil and weather conditions are uncertain. Agricultural products are low in price, as well as the population entering the aging society. Therefore, the idea of using Smart agriculture to replace human labor [1]. Smart agriculture is to take the innovation and to use data analytics in farm management to better accurately plan the production of agricultural products [2]. This reduces costs and ensures quality agricultural products. However, the adoption of smart agricultural technology in rural areas in Thailand is still limited in terms of internet networks which have not been yet supported due to the farmer's farm's large size and remote location from the city. It is not worthed to invest in an Internet service provider's infrastructure, particularly in Warin Chamrab, Ubon Ratchathani province, Thailand. This area is 600 kilometers away from Bangkok, the capital city of Thailand. However, some argrucultureres bring internet of things (IoT) into farming by installing a Wi-Fi router using a subscriber identity module (SIM) card to distribute the Internet wirelessly to enable internet of things devices to log into cloud computing for processing to control and monitor agricultural crops. These devices are still limited in terms of signal transmission over a long distance. One of the most widely utilized technologies is cellular networks. Wi-Fi is best used at communication distances is less than 100 meters [3]. It cannot reach vast agricultural areas. Smart agriculture in rural areas may still not be financially feasible if the signal reaches the entire region, because it may require significant network infrastructure expenditure.

Low power wide area networks (LPWAN) technology is a smart agriculture support tool that will enable the internet of things devices to access cloud computing for processing [4]–[6] which [7], [8] compared LPWAN networks technologies and found that LoRa technology was well suited for application to large-scale internet of things technologies. Truong *et al*. [9] studied the performance of different wireless sensor networks by using LoRa-Zigbee hybrid communication, and they could work together efficiently. [4] they have investigated the acoustic fish telemetry and LoRa-based LPWAN networks to provide real-time access to the telemetry data enabling farmers to obtain remote fish behavior data in their fish farms. For LPWANs used in smart agriculture IoT applications, LoRaWAN is regarded as the most appropriate communication network [3] and suitable for smart agriculture in rural areas. For the application of LoRa technology to communicate with IoT devices with a large number of nodes distributed over a wide geographical area over a distance of several kilometers via the LoRaWAN communication protocol, multiple gateways are used. To choose the most suitable gateway location In a LoRaWAN network, the distribution of the signal must be considered to cover the end nodes, and the service gateway limitations such as the gateway capacity must be considered to support the number of end nodes [10].

A large-scale long range wide area network (LoRaWAN) network has been the subject of numerous investigations on multiple gateways [11], they have explored the impact of nodes and gateway scaling and densification while accounting for the capture effect, on the system's reliability, and suggest an optimization problem to determine the end nodes distribution at various spreading factors in LoRaWAN with multiple gateways. The results show the performance of the algorithm improves the throughput and packet delivery ratio in the networks [12]. A comprehensive study of long range (LoRa) scalability is carried out by taking into account various channel parameters and employing various tools from stochastic geometry. The results show that including more gateways in the model reduces the coverage probability even further. Matni *et al*. [13], proposed the DPLACE model for LoRaWAN gateway placement, which accounts for buildings, device behavior following the Poisson pattern, and gateway failure. The simulation results demonstrated that DPLACE model performance in terms of operational expenditure, capital expenditure, and quality of service. Romero *et al*. [14], a collision avoidance resource allocation algorithm, was created with the goal of increasing the capacity of LoRaWAN. The results show the performance of the solution outperforms standard LoRaWAN networks, achieving a capacity gain of 95.2%. Matni *et al*. [15], study of placing multiple gateways in an area considering quality of service (QoS), capital expenditure, and operational expenditure requirements. The algorithm used the fuzzy C-means to compute the gateway placement. The results show that PLACE was reduced by 36% of the Capital expenditure. Based on gradient optimization, [16]'s research proposes a heuristic algorithm for selecting access point locations from a given set of candidate locations. The proposed method allows for the selection of a sub-optimal set of locations that provide full coverage while taking capacity dimensioning based on the Spreading Factor and expected channel utilization into account. Lavric and Popa [17]' work examines the LoRaWAN performance level by focusing on the maximum number of end nodes that can communicate on a LoRa. The results show the configuration with the lowest transfer rate is the source of collisions. At the application level, a possible solution for raising the transfer rate or declining the duty cycle parameter. The impact of known causes of packet loss in an uplink-only LoRaWAN on the overall quality of service for two gateways is also investigated [18]. To maximize the packet delivery ratio, two gateways should not be placed too close or too far apart, and should avoid SF11 and 12. Bor *et al*. [19] investigated the capacity limits of LoRa networks to develop models describing LoRa communication behavior, and he used models to parameterize a LoRa simulation to study scalability. According to the results, a typical smart city deployment can support 120 end nodes per 3.8 ha, which is insufficient for future IoT deployments. LoRa networks can scale quite well if dynamic communication parameter selection is used. Petäjäjärvi *et al*. [20] analyzed and reported on experimental validation of the LoRaWAN technology's various performance metrics. The results revealed that using a transmit power of 14 dBm and the highest spreading Factor of 12, more than 60% of packets were received from a distance of 30 km on water. When lower spreading factors are used, the communication link becomes more reliable. Georgiou and Raza [21]'s has been analyzed and modeled using stochastic geometry for a single cell. Due to signal interference when using the same spreading sequence, the probability of coverage decreased exponentially as the number of end devices increased.

This article proposes radio planning with a solution of an optimization of multiple gateway location selection in LoRaWAN. The problem is based on a real-life case study in Warin Chamrap district, Ubon Ratchathani Province, Thailand. The project site consists of 50 villages with 7,139 end nodes. Gateway location selections were considered from gateway maximal capacity and the distance between the gateway locations for deciding proper gateway locations [11], [16] by considering the distance between gateways that should not be too short or to far also, spreading of the end nodes according to the gateway distance should avoid spreading factors SF11 and SF12 [17]. In this paper, a mathematical model with the objective function of coverage maximization is developed. The model was validated using the LINGO modeling program, which is a precise software method. After that, the results were analyzed and the quantum geographic information system program was used to display the location and coverage of each signal gateway in a map format. This is to be a guideline for setting up a network infrastructure for IoT devices in rural areas for community development to be ready to produce quality agricultural products that are sufficient to meet consumer demand. This study's method is divided into five sections: introduction, overview of LoRa and LoRaWAN, mathematical model formulation, results and discussion, and conclusions.

2. LORA AND LORAWAN OVERVIEW

LoRa is a physical layer radio frequency modulation technology for low-power and wide-area networks (LPWANs). LoRa, enables long-distance communications of up to 5 kilometers in urban areas and up to 15 kilometers in rural areas [6]. LoRa uses chirp spread spectrum (CSS) signal modulation to spread a narrow-band signal over a wider channel bandwidth. Because of the processing gain of the spread spectrum technique, this technique makes the signal resistant to interference. The end nodes located close to a gateway should transmit data at a low spreading factor. An end node located several kilometers from a gateway will need to transmit with a higher spreading factor. LoRa is standardized to support multiple frequency bands. For Thailand, it is licensed to operate in the 920-925 MHz frequency band, which meets the AS923 MHz standard, which is an unlicensed band [22]. Important parameters for the modulation are bandwidth (BW), spreading factor (SF), and code rate (CR). LoRa modulation has a total of six spreading factors (SF7 to SF12) [5], [23]. The LoRa transmission speed depends on the frequency change of each chip signal determined by the spreading factor, bandwidth, bitrate, time on air (ToA), and transmission distance (Range) as shown in Table 1 [6], [24].

Table 1. Spreading factor (SF) versus bitrate, time on air (ToA) and range

Spreading factor	Bitrate (bps)	Time on air (ms)	Range (km)
SF7	5470	56	2
SF8	3125	100	4
SF9	1760	200	6
SF10	980	370	8
SF11	440	740	11
SF12	290	1400	14

Table 1 shows the LoRaWAN protocol spreading factor versus bitrate, range, and time on air, which can be used for uplink messages on bandwidth 125 kHz. It shows the equivalent bit rate as well as the estimated range in the rural environment. It also shows the dwell time, or Time on Air, values for a 10-byte payload for each of the six spreading factors. If the spreading factors are low, the transmission rate (Bitrate) is large, the time on air is less, and the transmission distance (Range) will be short. On the other hand, if the Spreading Factors are a lot, the bitrate is small, and time on air; the transmission distance (Range) will be distant.

Long range wide area network (LoRaWAN) is a medium access control (MAC) layer protocol above it. LoRa communication could reduce noise, interference, and increase channel capacity and expand wide area network (WAN) which can connect the end nodes with cloud computing through LoRaWAN gateway. The LoRaWAN is appropriate for sending data with small data packets, such as sensor reading data [25]. The LoRaWAN standard is based on the LoRa Alliance, a leading non-profit organization for communications worldwide. to drive and standardization of LoRaWAN communication network technology by LoRaWAN network architecture as shown in Figure 1.

From Figure 1, it shows the LoRaWAN architecture consisting of four parts: end nodes, gateway, network server, and application server, which can be applied in a variety of applications. Examples include smart agriculture, smart home, wireless sensor networks, the internet of things, early warning, and smart city. The LoRaWAN architecture is composed of end nodes that transmit sensor data or receive commands from a network server for data access or device control. By accessing data or controlling devices according to LoRaWAN requirements, there are three classes which are classes A, B, and C. All devices must be responsible for class A operation. These modes of operation deal with how the devices interact with the network. Gateway is an intermediary connection between end nodes and network server by intercepting the preamble of LoRa signals sent from each end nodes and forwarding the data set to the server through internet protocol (IP) which can have a gateway, which could be more than one gateway (multi gateway). Network server or computer server that provides services in the LoRaWAN network brings data sets from the gateway to the process. The application server or application is a part of the use of data obtained from the server such as a data reporting system or display data with graphs, database system or reporting data to smartphone applications, etc. The capacity of a LoRaWAN network is determined by the density of its gateways. Using an adaptive data rate (ADR) mechanism to maximize network capacity is important. End nodes closest to a gateway transmit with the lowest spreading factor, reducing their time on air. More distant end nodes transmit at a greater spreading factor.

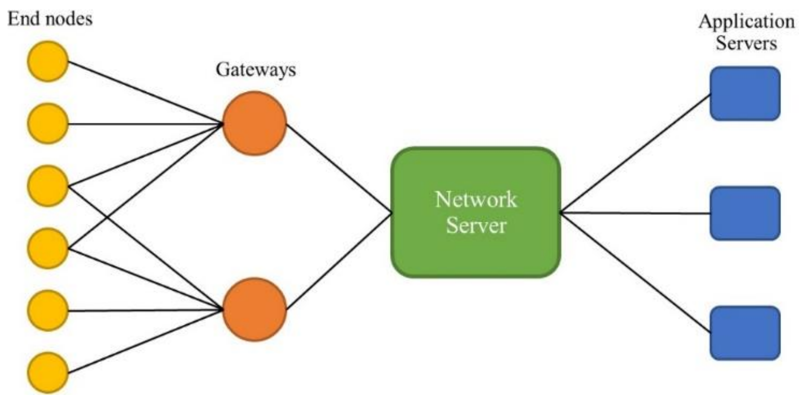


Figure 1. LoRaWAN architecture

3. MATHEMATICAL MODEL FORMULATION

The multiple gateway location selections in LoRaWAN and extensive networks must consider the spatial distribution of the end node, radio signal propagation, and the cap on the number of devices served access. This section presents the construction of the problem definitions and the mathematical model formulation, which is applied to compute radio planning with a solution for optimizing multiple gateway location selections in LoRaWAN, a case study based on a real-life in Warin Chamrap district, Ubon Ratchathani Province, Thailand, which is defined as shown in problem definitions and mathematical model.

3.1. Problem definitions

To select a gateway location in a large LoRaWAN network where the signal can cover end nodes in every village, it is possible to set 50 gateways according to the coordinates of the villages and 7,139 end nodes distributed in each village, as an example shown in Table 2. gateway location selections are based on i) gateway maximal capacity that can support 2,000 end nodes, ii) the signal service range of each getways that allows end nodes to transmit in a spreading factor of SF7-SF10 using distance. Determine, and iii) the distance between gateways by defining the maximum distance between a LoRaWAN gateway and a village (T^1) is 8 kilometers, while the minimum distance between two LoRaWAN gateways (T^2) is 10 kilometers. Table 2 shows an example of possible locations to set a gateway based on village coordinates. Variables containing id is Village id, x is Longitude, y is Latitude, and pop is the number of end nodes in the village. The possible number of the gateway location set up is 50 according to the coordinates of the villages.

Table 2. Examples of possible locations to set up a gateway

Variables	Description				
id	1	2	3	…	50
x	104.891022	104.901194	104.71463	…	104.915719
y	15.147308	15.15089263	15.135502	…	15.216261
pop	95	184	161	…	214

3.2. Mathematical model

The gateway location selections must consider the spatial distribution of the end node, radio signal propagation, maximal gateway capacity, and the distance between the gateway locations for deciding the proper gateway locations. The mathematical model developed for the proposed problem is applied to compute the radio planning with a solution of optimization of multiple gateway location selection in

LoRaWAN. In this study, a mathematical model is developed to optimize coverage. The mathematical model is defined as shown in Indices, Parameters, Decision Variables, Objective Function, and Subject To.

Indices

r LoRaWAN gateway location r..1…R
l LoRaWAN gateway location l..1…R
v Village v=1…V

Parameters

R Maximum possible location to locate LoRaWAN gateway R
V Total number of villages
T^1 Maximum allowed distance of LoRaWAN gateway and village
T^2 Minimum distance between two LoRaWAN gateways
P_v Number of populations used LoRaWAN gateway in village v
D_{rv} Distance between r and v
C_r Capacity of LoRaWAN gateway r
M Big M, great number
S_{rl} Distance between r and l

Decision variables

$$Y_r = \begin{cases} 1 \; if \; location \; r \; is \; used \; to \; locate \; the \text{ LoRaWAN} \\ 0 \; otherwise \end{cases}$$

$$X_{rv} = \begin{cases} 1 \; if \; location \; r \; serve \; village \; v \; and \; the \; distance \; of \; r \; and \; v \; higher \; than \; T^1 \\ 0 \; otherwise \end{cases}$$

$$Z_{rv} = \begin{cases} 1 \; if \; location \; r \; and \; village \; v \; has \; distance \; more \; than \; T^1 \\ 0 \; otherwise \end{cases}$$

$$W_{rl} = \begin{cases} 1 \; if \; location \; r \; and \; l \; is \; in \; used \\ 0 \; otherwise \end{cases}$$

H_{rl} = Distance between LoRaWAN r to LoRaWAN l

Objective function

$$Max\ Z = \sum_{v=1}^{V} \sum_{r=1}^{R} (1 - X_{rv}) P_v \quad (1)$$

Subject to

$$\sum_{r=1}^{R} X_{rv} \geq 1 \qquad \forall \text{ v = 1…V} \quad (2)$$

$$X_{rv} \leq Y_r \qquad \forall \text{ v = 1…V,r = 1…R} \quad (3)$$

$$X_{rv} D_{rv} \leq T^1 Z_{rv} \qquad \forall \text{ v = 1…V,r = 1…R} \quad (4)$$

$$\sum_{v=1}^{V} X_{rv} P_v \leq C_r \qquad \forall \text{ r = 1…R} \quad (5)$$

$$W_{rl} = Y_r Y_l \qquad \forall \text{ r = 1…R, l = 1..R} \quad (6)$$

$$H_{rl} = (1 - W_{rl}) M + S_{rl} \qquad \forall \text{ r = 1…R, l = 1..R} \quad (7)$$

$$H_{rl} \geq T^2 \qquad \forall \text{ r = 1…R, l = 1..R} \quad (8)$$

The objective function is (1), which attempts to maximize the number of populations covered by the LoRaWan. According to (2) specifies that each village must have at least one LoRaWan. As shown in (3) ensures that LoRaWan r can only serve village v when it is operational and located, whereas (4) ensures that the maximum distance between LoRaWan r and village v must be less than T^1. According to (5) ensures that the total population of LoRaWan r is less than its capacity. According to (6), (7), and (8) are used to ensure that the distance between two LoRaWan gateways is greater than T^2. To calculate the distance between villages, as shown in (9) is employed.

$$\sqrt{((x_2 - x_1)^2 + (y_2 - y_1)^2)} \quad (9)$$

where:
x_1 = Longitude of location 1
y_1 = Latitude of location 1
x_2 = Longitude of location 2
y_2 = Latitude of location 2

4. RESULTS AND DISCUSSION

LoRaWAN gateway location is selected by using mathematical modeling for multi-gateway location selection problems in large LoRaWAN networks. The samples in this experiment were from 50 villages in Warin Chamrap district, Ubon Ratchathani Province, with 7,139 end nodes using Lingo version 13 to process. The results of the experiment found that the most suitable LoRaWAN gateway location is 6 gateways, each gateway sends a signal to different villages. The results of the LoRaWAN gateway location selection are as follows.

Table 3 shows the most appropriate number of LoRaWAN gateways is 6, and each sends the signal to different villages. Gateway 1 located in village 5 serves 11 villages, gateway 2 located in village 19 serves 11 villages, gateway 3 located in village 23 serves 8 villages, gateway 4 located in village 31 serves 8 villages, gateway 5 located in 40 serves 6 villages, and gateway 6 located in village 49 serves 6 villages. The Spreading Factor covering end nodes from the LoRaWAN gateway signaling service is shown in Figure 2. Figure 2 shows spreading Factor values covering 7,139 End notes by using LoRaWAN gateway signal service with SF7 covering 1,427, SF9 covering 874 end nodes, SF9 covering 2,243 end nodes, and SF10 covering 2,595 end nodes. LoRaWAN capacity of the end nodes service is shown in Figure 3.

Table 3. LoRaWAN gateways location serving to villages

Gateways	Gateways location	Villages ID
GW 1	5	**5**, 6, 7, 8, 15, 26, 35, 36, 37, 38, 39
GW 2	19	1, 2, 17, 18, **19**, 20, 27, 33, 43, 44, 48
GW 3	23	13, 16, **23**, 24, 25, 42, 46, 47
GW 4	31	14, 21, 22, **31**, 41, 32, 45, 50
GW 5	40	9, 10, 11, 12, 28, **40**
GW 6	49	3, 4, 29, 30, 34, **49**

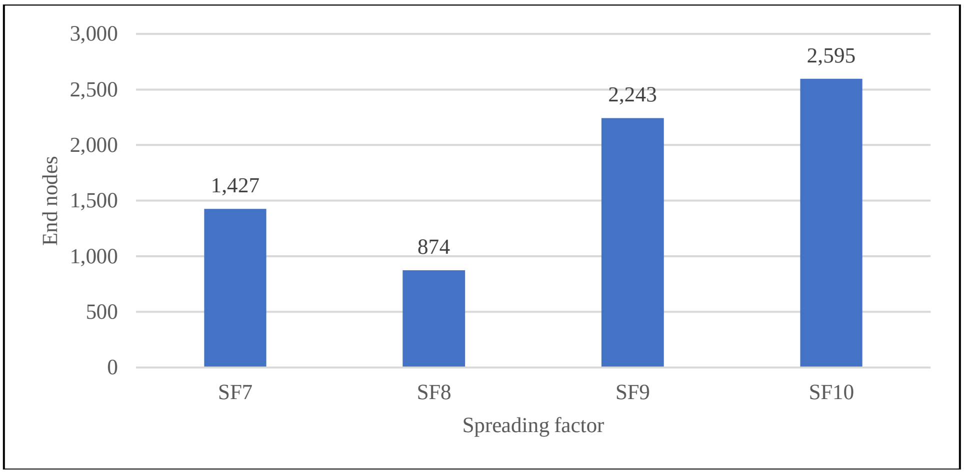


Figure 2. Spreading factor values covering end nodes

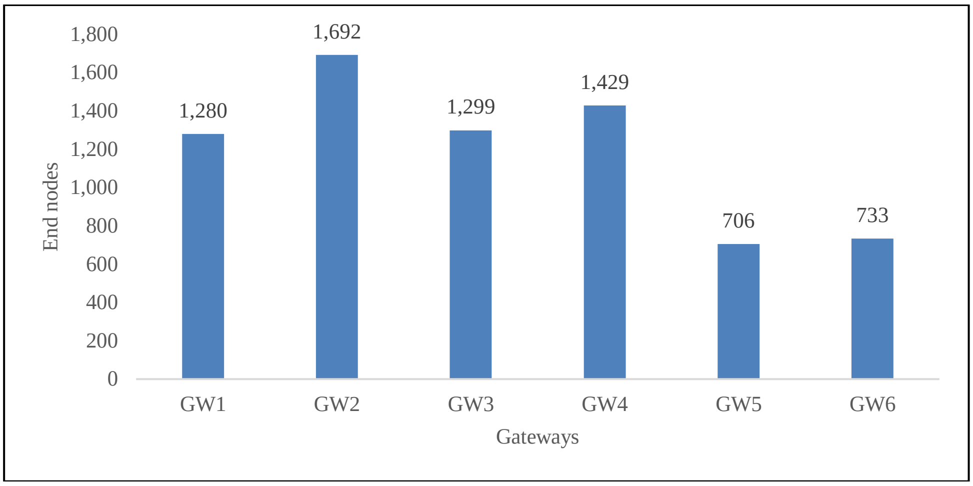
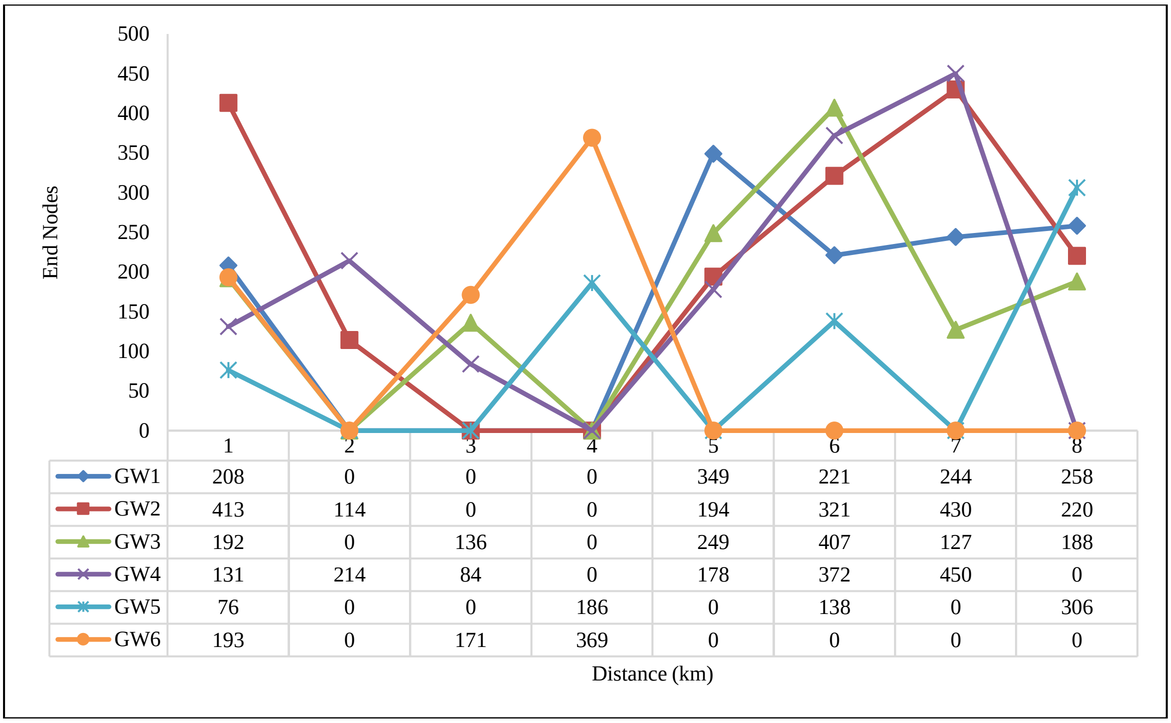


Figure 3. LoRaWAN capacity of end nodes service

Figure 3 shows the LoRaWAN capacity of the end nodes service of each LoRaWAN gateway. Gateway 1 serves 1,280 end nodes, gateway 2 serves 1,692 end nodes, gateway 3 serves 1,299 end nodes, gateway 4 serves 1,429 end nodes, gateway 5 serves 760 end nodes, and gateway 6 serves 733 end nodes. LoRaWAN gateway signal service covers the end nodes of each gateway by 1 to 8-kilometer distance as shown in Figure 4.



	1	2	3	4	5	6	7	8
GW1	208	0	0	0	349	221	244	258
GW2	413	114	0	0	194	321	430	220
GW3	192	0	136	0	249	407	127	188
GW4	131	214	84	0	178	372	450	0
GW5	76	0	0	186	0	138	0	306
GW6	193	0	171	369	0	0	0	0

Figure 4. LoRaWAN gateway signal service covering end nodes based on the distance

From Figure 4, the LoRaWAN gateway signal service covers end nodes based on distance (km). In the first kilometer, gateway 2 covers the highest number, 413 end nodes, while gateway 5 covers the lowest number of 413 end nodes. In the 2nd kilometer, gateway 4 covers the highest number of 214 end nodes, gateways 1, 3, 5, and 6 do not cover any end nodes. In the 3rd kilometer, gateway 6 covers the highest number of 717 end nodes, gateways 1, 2, and 5 do not cover any end nodes. In the 4th kilometer, gateway 6 covers the highest number of 369 end nodes, gateways 1, 2, 3, and 4 do not cover any end nodes. In the 5th kilometer, gateway 1 covers the highest number of 349 end nodes, gateways 5 and 6 do not cover any end nodes. In the 6th kilometer, gateway 3 covers the highest number of 407 end nodes, gateway 6 does not cover any end nodes. In the 7th kilometer, gateway 4 covers the highest number of 450 end nodes, gateways 5 and 6 do not cover any end nodes. In the 8th kilometer, gateway 5 covers the highest number of 306 end nodes, gateways 4 and 6 do not cover any end nodes.

The experiment conclusions of optimizing multiple gateway location selection in LoRaWAN networks indicate six gateways could cover all end nodes. Gateway 1 located in village 5 serves 11 villages with 1,280 end nodes, gateway 2 located in village 19 serves 11 villages with 1,692 end nodes, gateway 3 located in village 23 serves 8 villages with 1,299 end nodes, gateway 4 located in village 31 serves 8 villages with 1,429 end nodes, gateway 5 located in 40 serves 6 villages with 706 end nodes, and gateway 6 located in village 49 serves 6 villages with 733 end nodes. Moreover, LoRaWAN gateway could appropriately manage the supporting capacity of end nodes. When the data is processed in the quantum geographic information system program, it concludes the LoRaWAN gateway location that provides signal services to end nodes in villages on a map as shown in Figure 5.

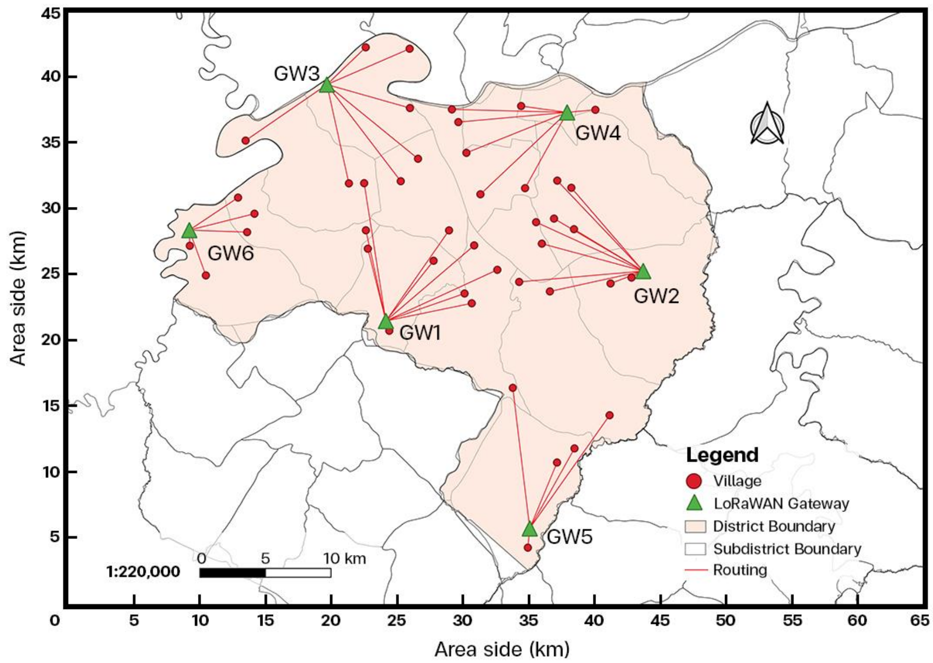


Figure 5. LoRaWAN gateway location

Figure 5 shows map data in Warin Chamrap district, Ubon Ratchathani Province, Thailand. It consists of the LoraWAN gateway location of the six gateways connecting with the 50 villages. end nodes provided in each village receive signals sent from LoRaWAN gateway, which could be directions for setting up the Network Infrastructure in the rural area. This possibly promises sufficient quality of agricultural products responding to the consumers' requirements.

5. CONCLUSION

We proposed a method for optimizing the location of multiple gateways in LoRaWAN networks. The problem is based on a real-life case study in Warin Chamrap district, Ubon Ratchathani Province, Thailand. We want to reduce network infrastructure constraints. in bringing the Smart agriculture system into rural areas of Thailand so that farmers can reduce production costs and make agricultural products of good quality. As a result, a solution for gateway location selection in LoRaWAN has been proposed using a mathematical model with the objective function of coverage-maximizing. The model was validated using the LINGO modeling program, which is a precise software method. The results demonstrate that an optimization of multiple gateway location selection in LoRaWAN with six gateways could support signal service for all end nodes. Besides, the supporting capacity of end nodes by LoRaWAN gateway could be appropriately managed. The solution could also define gateway location in LoRaWAN to plan and improve the network infrastructure in the rural areas to be ready for producing sufficient and quality agricultural products responding to the consumers' requirements. Suggestions for further studies are expanding the experimental area, increasing end nodes, and using metaheuristic algorithms or other algorithms capable of potentially better processing experimental results.

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