Energy-aware wireless mesh network deployment using optimization mechanism

Aphirak Jansang, Chayathorn Simasathien, Anan Phonphoem
Intelligent Wireless Network Group (IWING), Department of Computer Engineering, Kasetsart University, Chatuchak, Bangkok 10900, Thailand

Article Info

Article history:

Received Feb 22, 2022
Revised Jul 26, 2022
Accepted Aug 10, 2022

Keywords:

Energy consumption
Energy-aware deployment
Optimization
Router placement
Wireless mesh network
Wireless network planning

ABSTRACT

Wireless mesh networks are widely used to create network infrastructure in rural areas due to their flexible properties, such as self-healing mechanisms and associated redundant paths. For example, a wireless mesh network can suitably operate with limited battery power in wildlife monitoring applications. The locations of mobile routers to support mobile sensor nodes are essential for extending the system lifetime. This study proposes an energy-aware wireless mesh network deployment optimization mechanism. The goal is to determine a suitable location for the mesh routers with the aim of maximizing network lifetime. After the location solution is obtained from the proposed mechanism, it is then evaluated for system lifetime and network performance by the network simulator (ns-3). The proposed method outperforms the brute-force method in terms of computation time for all amounts of mesh clients. For example, for 30 mesh clients, the proposed method uses only a few minutes, while the brute-force mechanism requires more than 200 minutes to complete the process. Furthermore, compared to the brute-force method, it achieves nearly the same system lifetime and other performance parameters, such as throughput, packet delivery ratio, and packet inter-arrival time. In the real implementation, in which the sensor node placements can be changed during the installation period owing to the environmental status or the recommendation of the installers, the results can be recalculated in a short period.

Corresponding Author:

Anan Phonphoem
Intelligent Wireless Network Group (IWING), Department of Computer Engineering, Kasetsart University
Chatuchak, Bangkok 10900, Thailand
Email: anan.p@ku.ac.th

1. INTRODUCTION

Currently, Internet access is widely deployed in both urban and rural areas. High access speeds in the range of gigabit per second can be achieved owing to the availability of fibre to the home (FTTH) and asymmetric digital subscriber line (ADSL) in urban areas. The technologies are for fixed line location and too costly for long cable installation that are not suitable for remote scattering locations in rural areas. Conversely, wireless cellular technologies, such as 3G and LTE, are more popular due to their coverage areas and mobility support. High speed Wi-Fi is an another solution that is used in household and public areas. However, its coverage area is limited up to 50 m – 100 m.

For wildlife monitoring applications [1], [2], such as tiger monitoring or forest protection [3], wireless communications are required for real-time and near real-time monitoring. In large wildlife sanctuary areas, such as Huai Kha Khaeng located in Uthai Thani and Tak provinces, Thailand, services of cellular technologies are only available at the edge of the forest. Unfortunately, at the monitoring site, wildlife animals usually live in deep forest where no wireless signal is available at all.

To perform wildlife and forest monitoring, standalone camera traps are installed by wildlife patrollers in the deep forest. After depletion of batteries that last for about 30–45 days, camera traps are brought back to the camp site for retrieving captured pictures or video stored in the SD card. Patrollers must visit each site in harsh walking conditions at least twice. Furthermore, if suspicious or abnormal events occur, it is too slow for officers to adopt a decision and take any action that does not cause severe damage to the natural resources.

New versions of camera traps are equipped with a wireless communication capability for data uploading via 3G, LTE, or Wi-Fi. However, to deploy the camera traps, wireless network infrastructure is required at the monitoring site. Extending the coverage signal of the cellular network is not a feasible solution due to its restricted installation and operation cost for the service providers.

Specifically, Wi-Fi mesh network exhibits ad hoc network topologies and is an interesting solution to create a network infrastructure. Additionally, Wi-Fi mesh network is a self-healing network that is designed to recover communication problems due to broken links or malfunctioned nodes by using any alternative routes. In forest, all nodes are evidently operated with limited battery power that can be recharged by its installed solar power system. However, the solar charger may not always work due to cloudy skies or tree canopy conditions. Furthermore, batteries replacement requires significant time and efforts. Therefore, it is necessary to minimize energy usage to prolong network system up time.

To minimize energy usage, many routing management techniques are proposed, including spectral efficiency routing protocol [4], flow and power allocation routing protocol [5]–[7], load-aware routing algorithm [8], [9], harvesting energy mechanism based on energy-efficient routing protocol [10] and an energy-efficient routing protocol with node mobility support [11]. Besides, a hybrid (proactive and reactive) routing protocol [12] has also been proposed. Some other mechanisms include software-defined energy-aware routing protocol [13], [14], admission control for preventing fast battery depletion [15], operating certain nodes in sleep mode [16], limiting certain router functions for a period of a time [17], [18], energy aware multi-layer design [19] and topology control mechanism [20], [21]. For channel management, a dynamic channel assignment for wireless mesh network [22] or implementing a genetic algorithm and neural network to optimize energy [23] are also presented.

All the aforementioned energy aware techniques are performed during operational period after nodes are installed at the predefined location. Evidently, locations of all nodes are a major factor for system energy usage. Inappropriate node locations can shorten system lifetime. When certain nodes are idle, some nodes can constitute a system bottleneck wherein energy is quickly drained and cannot be alleviated by any routing adjustment techniques.

It is possible to determine optimal locations of all router nodes off-line by using a brute force technique before the installation period. However, the calculation time can be excessively long. In a real deployment situation, locations of all sensor nodes are carefully selected by patrollers. During the installation period, the sensor node locations normally require some adjustments based on the site environment and animal trails. Exact sensor node locations may not be known before-hand, thus the mesh router location findings must be completed in a limited period during the installation phase.

In the study, an Energy-aware wireless mesh network deployment optimization is proposed. The main objective is to determine appropriate locations of all mesh routers in a short period of time by implementing optimization using the R-module. Additionally, selected placement locations should maximize the system lifetime for effectively operating and maintaining the system in the forest. Hence, after obtaining optimization results, the system lifetime and network performance parameters of all sensors and router nodes are evaluated and compared with brute-force mechanism by using an ns-3 simulator.

Related extant studies are presented in the next section. Subsequently, the proposed mechanism, problem formulation and performance evaluation are described in section 3, section 4, and section 5, respectively. The simulation results are presented in section 6. Finally, section 7 concludes the study.

2. RELATED WORK

For the wireless mesh network placement, most extant studies minimize the deployment cost. For example in [24], the mixed-integer linear programming model to reduce the installation cost of the wireless mesh network is proposed by accounting for traffic routing, interference, rate adaptation, and channel assignment.

Furthermore, the mechanism can improve the calculation time with the same network performance by using a heuristic algorithm. However, energy awareness is not considered. By extending the algorithm ffrom [24], an enhanced algorithm [25] uses the traffic profiles to turn some nodes on and off to minimize energy usage while the required node transmission is still satisfied.

Later, two mathematical models [26], subsequence improvement [24], [25], for energy-aware wireless mesh network management have been proposed to find the balance between the installation cost and energy management operation cost. The first model aims at location findings based on installation cost. In contrast, the second model seeks to minimize energy by turning on-off routers during the operation period based on network demands.

Nevertheless, for rechargeable MR placement with battery limited, two MR association mechanisms for each node have been proposed [27]. Furthermore, the energy charging and discharging models are also included in the proposed optimization models to protect router energy from being depleted. Similarly, Wang *et al.* [28] used the same constraints in the optimization model. However, not only the MR placement but also the Internet gateway have been incorporated to minimize the installation and energy consumption costs by using the time-division multiplexing slotted mechanism for traffic transmission. In [24]–[28], all mechanisms focus on finding the MR location. However, in the case of the installed mesh network, adding more gateway for reducing the energy usage has been proposed [29]. The mixed-integer linear programming and a greedy algorithm are presented and compared. The results show that the mixed-integer mechanism gives the optimal result. Meanwhile, only 5% gains the optimal solution for the greedy algorithm with only one percent of the computational time.

A heuristic method [30] is proposed to find the maximum number of noninterfering links for creating concurrent transmission paths in a fixed installed node environment scenario. The energy-saving component was not addressed in this study. Two mixed-integer linear programming and a local search algorithm to determine the optimal gateway candidate location [31] is proposed with the assumption of unlimited power source for mesh router.

The node placement mechanisms by using intelligent hybrid system consisting of particle swarm optimization, hill climbing, and simulated annealing [32] is proposed. By fixing the number of mesh routers, the routers are placed for optimal coverage for all client nodes based on computational time concern. However, performance evaluation is omitted. Another mesh router placement is proposed by implementing the electromagnetism-like mechanism (EM) metaheuristic technique [33]. The study focuses on network connectivity of all client nodes. Energy harvest is mentioned in a future study.

The optimizing goal of most previous research initially focuses on minimizing the installation cost. The energy awareness is the next interesting objective. However, the proposed protocol also focuses on maximizing lifetime besides energy awareness. Related research is summarized as shown in Table 1.

Table 1. Related work comparison

Related work	Energy-ware design	Rechargable enenrgy	Optimization method	Minimize installation cost	Maximize lifetime
Amaldi *et al.* [24]	x	x	✓	✓	x
Capone *et al.* [25]	✓	x	✓	✓	x
Boiardi *et al.* [26]	✓	x	✓	✓	x
Huan *et al.* [27]	✓	✓	✓	✓	x
Wang *et al.* [28]	✓	✓	✓	✓	x
Ashraf [29]	✓	✓	✓	✓	x
Gokbayrak and Yildirim [30]	x	x	x	✓	x
Gokbayrak [31]	x	x	x	✓	x
Sakamoto *et al.* [32]	x	x	x	✓	x
Sayad *et al.* [33]	x	x	x	✓	x
Proposed system	✓	x	✓	x	✓

3. PROPOSED MECHANISM

The scope of the study is to determine appropriate mesh router (MR) locations in a forest in a short period of time. All sensor nodes are termed as mesh client (MC) including camera traps that are assumed to be placed in the forest for only uploading information to MR, which is eventually forwarded to the gateway. The locations of sensing devices, MCs, are determined by the patrol officer in a range of few kilometers.

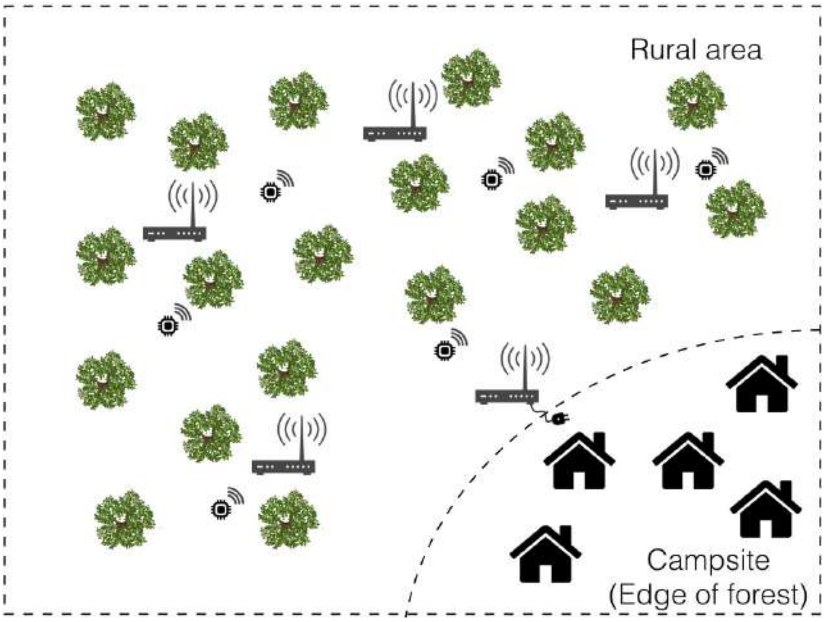


Figure 1. Human habitat and forest area

Cellular services are not available. Furthermore, sensing information can be varied by a few bytes involving temperature and humidity values to capture images or videos with large file size, and thereby necessitating high data transmission rates. Evidently, the required scenario cannot be supported by the LoRA technology that is designed for long range communications with low power and a very limited transmission rate. The gateway is located at the forest edge near a village, campsite, or human habitat where Internet access and electricity are available. The deployment scenario example map is shown in Figure 1.

3.1. Proposed system model

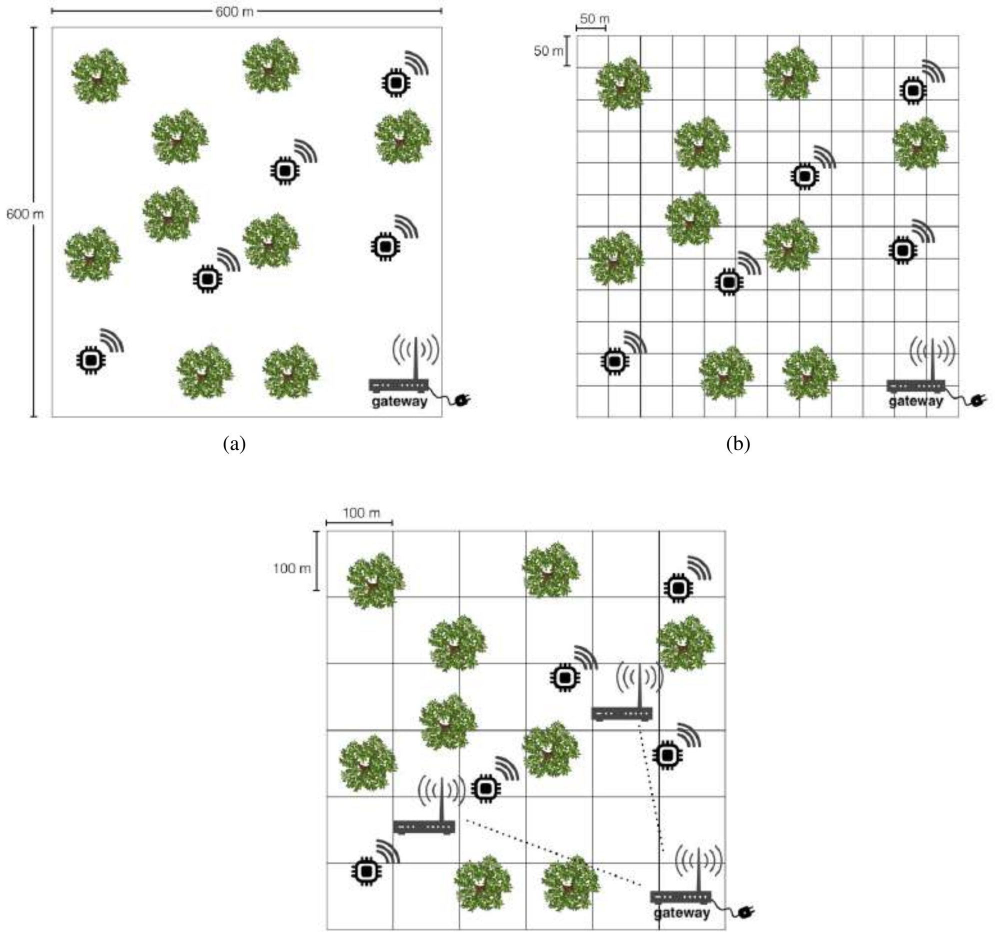
In the study, each MR is operated only by a standalone battery without solar system. Hence, the MR lifetime depends upon its operation and transmission activities. We assume that all MRs are installed with same battery capacity. In order to evaluate the scenario, Wi-Fi communication (IEEE 802.11g, 2.4 GHz, 54 Mbps) technology is selected.

The monitoring area is defined as $M \times M$ meters, which is divided into small grid cells based on its Wi-Fi communication capabilities. In the study, the placement scenario example is shown in Figure 2(a) where M equals 600 m. The MC can be placed anywhere in the monitoring area that is then mapped into the center of a MC grid cell, $50m \times 50m$ in size, as shown in Figure 2(b). After performing the optimization, all MR locations can be found and placed in the center of a MR grid cell, $100m \times 100m$ in size, as shown in Figure 2(c). It is noted that to decrease the MR location search space in our proposed optimization model, the MR grid cell is twice the MC grid cell.

By assuming that the transmission range for each sensing node to MR and vice versa is set to 250 m from the center, it approximately equals to the next 4 MC grid cells. Conversely, the transmission range between MRs is set to 550 m, which approximately corresponds to the next 5 MR grid cells. Hence, with respect to $600m \times 600m$, four MRs can extend coverage in all the areas. However, the addition of one more MR increases flexibility for MR location adjustments.

The constraint for the MR placement is that each MC must be covered by at least one MR to ensure connectivity. We assume that all sensing devices are equipped with an SD card and are used to periodically upload information at a constant bit rate (CBR). Furthermore, physical data transmission rate is considered as a fixed value independent of the communication distance.

The proposed model is formulated as a mixed integer linear programming. In order to determine the optimized solution, R program with the linprog package [34] is used. From a network viewpoint, the derived locations from the model are evaluated with ns-3 (network simulator 3) [35] for network performance and battery utilization that are subsequently compared with the brute-force mechanism.



(a) (b) (c)

Figure 2. Device mapping in the monitoring area in (a) sensing device and gateway locations, (b) MC grid cell ($50m \times 50m$) and (c) MR grid cell ($100m \times 100m$)

4. PROBLEM FORMULATION

4.1. Data pre-processing

The locations of all MCs and gateway are used as the input of the proposed model that is subsequently mapped to grid cells in the optimization model parameters, as shown in Figure 2(a). Let $C = \{1, ..., c\}$, $R = \{1, ..., r\}$, and $G = \{1, ..., g\}$ be the set of MC, MR, and gateway grid cells, respectively. Each MC location is assigned such that it is a member of a corresponding MC grid cell. In MC grid cell i point of view, the reachable parameter a_{ij} of each MR grid cell j that communicates with (from each MC location to reachable MR location) each $i \in C, j \in R$ is:

$$a_{ij} = \begin{cases} 1, & \text{MC grid cell } i \text{ covered by MR grid cell } j \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

All the reachable cells between each candidate location are calculated and stored as MR range parameter b_{jl} $j, l \in R$:

$$b_{jl} = \begin{cases} 1, & \text{if MR in location } j \text{ and } l \text{ are in each} \\ & \text{communication range} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

All the reachable cells from gateway are calculated and stored as gateway range parameter w_{jg} $j \in R, g \in G$:

$$w_{jg} = \begin{cases} 1, & \text{if MR in location } j \text{ and gateway in location} \\ & g \text{ are in each communication range} \\ \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Next, we define a decision variable. The MR assignment variable z_j for each $j \in R$:

$$z_j = \begin{cases} 1, & \text{if MR is installed at location } j \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

The MC assignment variable x_{ij} for each $i \in C, j \in R$:

$$x_{ij} = \begin{cases} 1, & \text{if MC at location} i \text{ connect with MR at location } j \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

The MR connection variable y_{jl} for each $j, l \in R$:

$$y_{jl} = \begin{cases} 1, & \text{if MR at location } j \text{ connect with MRat location } l \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

The gateway assignment variable Y_{jg} for each $j \in R, g \in G$:

$$Y_{jg} = \begin{cases} 1, & \text{if MR at location } j \text{ connect with gateway at location } g \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

4.2. Optimization model

From the objective function, the optimal location for all specific number of MRs that makes the longest operation lifetime is calculated. The system lifetime that is defined as one of MRs is depleted. Given certain constraints, the system lifetime T is maximized (or minimizing the inverse of T) (8).

The x_{ij} is a binary operator that controls the association between MR and MC. If MC i can connect with MR j, the sum of x_{ij} for each MC i should be at least 1. Therefore, constraints (9) ensures that MC i can associate with only one MR j. While constraints (10) are coherence conditions to guarantee that MC i can be associated with MR j only if there exists MR at j is within communication range of MC at i.

Constraints (11) is defined the flow balance at MR j, which is the inbound data rate that needs to be equal to the outbound data rate. Let d_i be a demanded data rate that MC i to send to any MRs. Let Fr_{lj} be the data rate that MR l requires to send to MR j and let Fg_{jg} be the data rate that MR j requires to send to gateway g. The term $\sum_i d_i \cdot x_{ij}$ is the total needed data rate to transmit to associated MR j. $\sum_l Fr_{lj}$ is the total data rate that MR i needed to send to MR j. It is the total inbound traffic for MR j. In contrast, $\sum_l Fr_{jl}$ and $\sum_g Fg_{jg}$ are the total traffic of MR j sent to other MRs and gateways, respectively, which is the outbound direction.

Let Cap_{jl} be the capacity of the wireless link between MR j and MR l. Constraints (12) ensure that the link between MR j and MR l exists and the sum of the outbound data rate and inbound data rate between MR j and MR l must not exceed the link's capacity. Constraints (13)–(15) define the existence of a wireless link between MR j and MR l, which depends on the existence of MR at location i, location l and communication range variable b_{jl}. Constraints (16) ensure that the number of links between MR to MR and MR to gateways does not exceed the link's degree. Thus, the sum of any MR j's links (MR to MR, MR to gateways) must not surpass its Deg_j, where Deg_j be the maximum degree of MR j.

Since the connection from any MRs to the gateway is only uplink direction. Thus, constraints (17) ensures that link from MR j to gateway g must exist and limit by Cap_{jg}, and only outbound traffic from MR j to the gateway g is considered. Let Cap_{jg} be the capacity of the wireless link between MR j to the gateway g. Constraints (18) define the existence of a wireless link between MR j and gateway g, which depends on the existence of MR at location i, the gateway at location g, and the communication range variable w_{jg}. Constraints (19) ensure that the total number of links from any possible MRs to gateway g must not exceed its degree, as denoted by Deg_g.

Let $Ener_j$ be the initial energy of MR j. Let T denote the system lifetime that starts from the startup time until the first MR runs out of battery. The number of required MRs is defined by variable $numr$. Given that energy consumption on each MR depends on its data rate and system lifetime T. The outbound data rate for MR j is summing up the data rate from other MRs to MR j (defined as $\sum_l Fr_{lj}$) and its required data rate to gateway g (defined as $\sum_g Fg_{gj}$). Then, the constraint (20) is used to ensure that the energy usage of each MR j ($\sum_l Fr_{lj} + \sum_g Fg_{gj}$ multiplied by time T) will not exceed its $Ener_j$. Constraints (21) ensure that the total number of selected MRs ($\sum_j z_j$) must not exceed $numr$.

From the equation shown above, there are many possible sets of MR locations (z_j) that are qualified by all constrains. However, the objective of the proposed mechanism is to find for the best outcome of z_j which yields the longest system lifetime. Therefore, the optimization solver is required for obtaining z_j, which delivers the best result.

Maximize:

$$T \tag{8}$$

Subject to:

$$\sum_j x_{ij} = 1,\ \forall i \in C \tag{9}$$

$$x_{ij} \leq a_{ij} \cdot z_j,\ \forall i \in C, \forall j\ \in\ R \tag{10}$$

$$\sum_i d_i \cdot x_{ij} + \sum_l Fr_{lj} = \sum_l Fr_{jl} + \sum_g Fg_{jg},\ \forall j\ \in\ R \tag{11}$$

$$Fr_{jl} + Fr_{lj} \leq Cap_{jl} \cdot y_{jl},\ \forall j, l\ \in\ R \tag{12}$$

$$y_{jl} \leq b_{jl}, \forall j, l\ \in\ R \tag{13}$$

$$y_{jl} \leq z_j, \forall j, l\ \in\ R \tag{14}$$

$$y_{jl} \leq z_l, \forall j, l\ \in\ R \tag{15}$$

$$\sum_l y_{jl} + \sum_g Y_{jg} \leq Deg_j, \forall j \in R \tag{16}$$

$$Fg_{jg} \leq Cap_{jg} \cdot Y_{jg},\ \forall g \in G,\ \forall j \in R \tag{17}$$

$$Y_{jg} \leq w_{jg},\ \forall g \in G,\ \forall j \in R \tag{18}$$

$$\sum_j Y_{jg} \leq Deg_g,\ \forall g \in G \tag{19}$$

$$(\sum_l Fr_{lj} + \sum_g Fg_{gj}) \cdot T \leq Ener_j, \forall j \in R \tag{20}$$

$$\sum_j z_j \leq numr, \forall j \in R \tag{21}$$

5. PERFORMANCE EVALUATION

In the study, five cases of various MC nodes (i.e. 15, 20, 25, 30, and 45) are evaluated. In each case, three replications of the MC locations are randomly generated with uniform distribution. The gateway location is assumed as fixed for all cases. For system lifetime evaluation, each brute-force solution (from all possible MR locations) for each case is simulated and compared with the corresponding optimization solution.

5.1. Extracting optimization results

Before the proposed optimization model can determine the results of potential MR locations on the map, the basic information from the actual map, such as the MCs' locations and the location of the gateway used to relay data, must first be gathered. The collected data will then be converted into the model's initial vector variables, such as matrix a_{ij} for MC locations, w_{jg} for gateway locations, which is described in section 4.1. Next, initialize the model's variables by calculating all possible MR location pairs in the deployment area from vector b_{jl} and generating them into the grid cell as matrix w_{jg}. At the same time, the matrix Y_{jg} is generated from vector w_{jg} to keep all possible MR locations that can communicate with gateway g. The other required vector variables (e.g. z_j, x_{ij}, and y_{lj}) and all constraints are set up before running the linear optimization solver. Subsequently, the program for solving linear equations will then start to search for the possible solutions that make the most extended system lifetime while satisfying all constraints. The software is written in R and solves linear programming tasks with the $linprog$ package. After obtaining the optimization result for the MR's locations in grid cell format, it will convert them back to their actual map locations before being used in the real implementation. The flowchart in Figure 3 illustrates the process of extracting the results from the proposed optimization model.

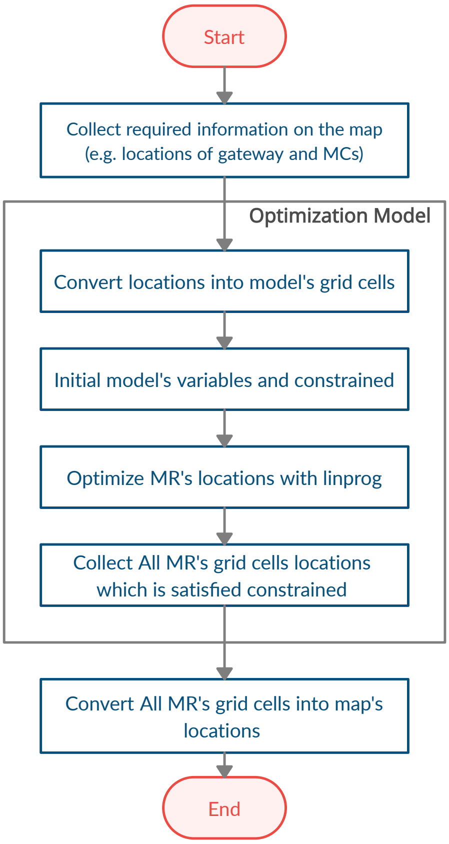


Figure 3. The process of extracting the results from the proposed optimization model

5.2. Simulation setup

To compare the network performance between the proposed and brute-force mechanisms, the optimization results from the R-program are simulated by ns-3 simulator. The simulation field area is defined as $600 \times 600\ m^2$. The MC grid cell are defined as $50 \times 50\ m^2$ for placing each MC. Conversely, the MR grid cell of $100 \times 100\ m^2$ is used for MR placement. The MC traffic patterns for uploading data to the gateway are defined at a constant bit rate of 1 Mbps. All MRs are deployed with the same initial capacities and energy discharge model. Specifically, IEEE 802.11g with fixed propagation delay with the default range propagation loss model is used throughout the simulation. We modified the optimized link state routing protocol (OLSR) to support an energy-aware routing protocol by considering the remaining energy in each path before transmitting the data. The total simulation time corresponds to 80 s. Each MC automatically starts uploading at the 40th second after the simulation is started. The simulation parameters are listed in Table 2.

Table 2. Parameter of simulation

Parameters	Value
Field size	$600 \times 600\ m^2$
Client's grid size	$50 \times 50\ m^2$
Router's grid size	$100 \times 100\ m^2$
Communication range (router-client)	250 m
Communication range (router-router)	550 m
Client's application	CBR at 1 Mbps per MC
Energy model	ns-3 energy model
Initial energy	80 J
Wireless standard	IEEE 802.11g / 54 Mbps
Delay model	Constant speed propagation
Loss model	Range propagation
Routing protocol	OLSR with energy-aware support
Total simulation time	80 s
Application start time	40th s
Number of clients per case	15 / 20 / 25 / 30 / 45
Number of experiments per case	3
Number of router	5
Searching method	Optimization/brute-force

5.3. Energy Usage Model

The default ns-3 energy model is used throughout the simulation. The energy usages are based on its activities, namely transmit, receive, or idle, as shown in Table 3. Each MR stops working if it runs out of energy.

Table 3. Energy model used in ns3 [35]

Activity	Current usage (ampere)
Idle	0.273
Receive	0.313
Transmit	1.800

6. SIMULATION RESULTS

The proposed mechanism is evaluated for the computation time and network performance by comparing it with the brute-force method. As shown in Figure 4, the computational times (including the simulation times) for various MCs of the proposed optimization are almost constant. Furthermore, the brute-force mechanism computation time is significantly varied and significantly high when compared to the proposed mechanism. With respect to network performance, the system life times, as shown in Figure 5, for both mechanisms are almost identical, and they both run out of battery at approximately 65th second. For the average throughput and packet delivery ratio, shown in Figures 6 and 7, for the low number of clients, the predefined condition of the optimization might restrict the allowable degree of MC connecting for each MR. Therefore, once the increasing number of clients reaches 30, both brute-force and optimization mechanisms perform the same due to the limited choices of MR location for covering all MCs. However, in Figure 8, the average delay variation of the brute-force mechanism for many connecting clients shows a significant variation due to the unbalanced connecting degree for each MR.

From Figure 9, an example of 25 clients randomly scattered on the map is presented. The results of the different methods for determining the placement of 5 MR locations are shown in Figure 10. The optimization solution (shown in Figure 10(a) and Figure 10(b)) yields more scatter MR locations than the brute-force mechanism (shown in Figure 10(c) and Figure 10(d)) because the optimization mechanism tried to limit the degree of connecting MC for each MR, which is more apparent in the case of the higher number of required MRs.

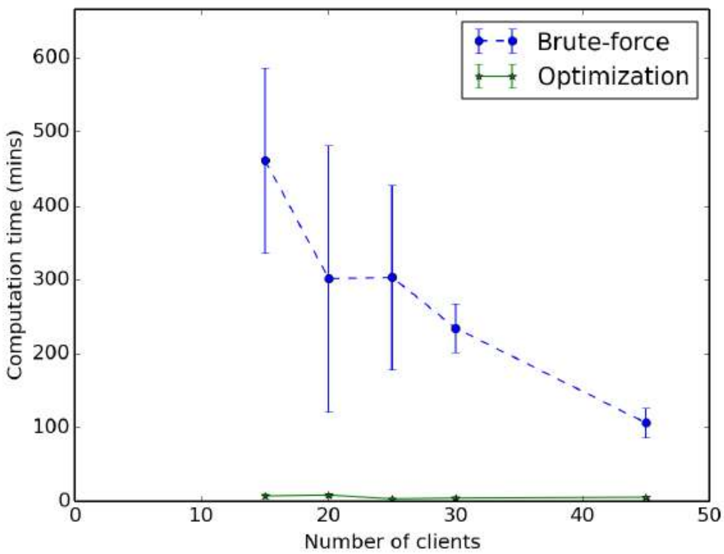


Figure 4. Comparison of computation time between methods

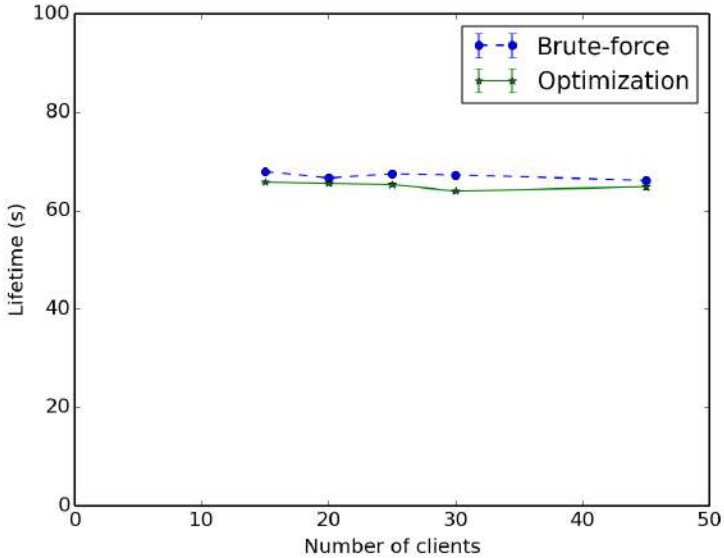


Figure 5. Comparison of lifetime between methods

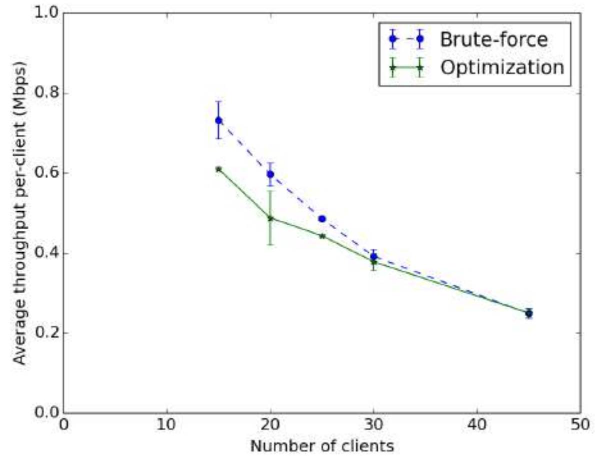


Figure 6. Comparison of average throughput between methods

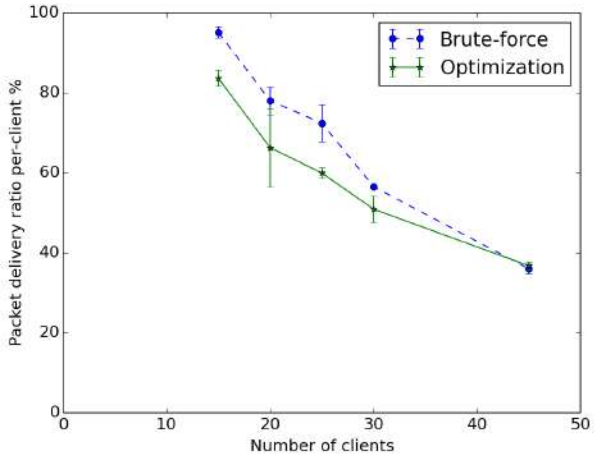


Figure 7. Comparison of packet delivery ratio between methods

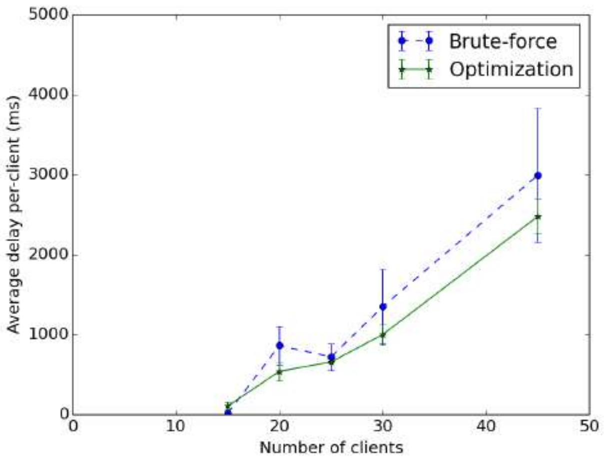


Figure 8. Comparison of average delay between methods

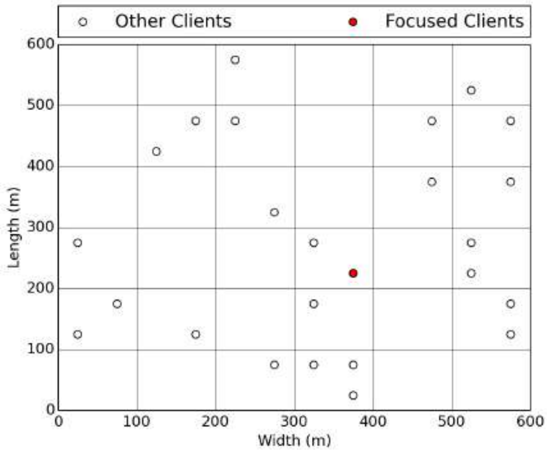


Figure 9. Client locations

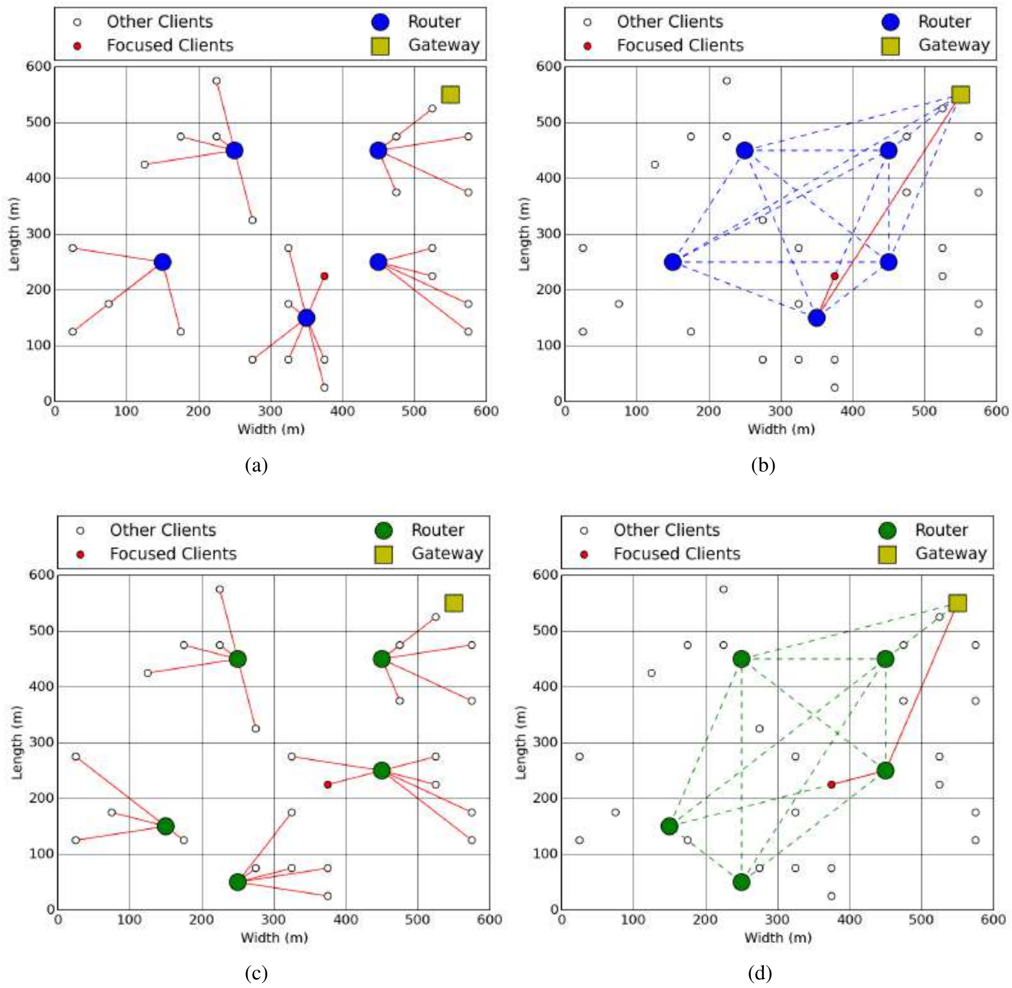


Figure 10. Comparison of MR placement between brute-force and optimization methods (for 25 clients) in (a) client connection: brute-force method, (b) router connection: brute-force method, (c) client connection: optimization method, and (d) router connection: optimization method

The inter-arrival time of the case of 25 MCs (from Figure 10) is shown in Figure 11. Given the cumulative distribution function (CDF) value of 0.80, the performance of the optimization methods exceeds that of the brute-force method. Additionally, with respect to different number of MC nodes, the average of inter-arrival time at 80 th percentile is shown in Figure 12. The performance of the proposed method slightly exceeds that of the brute-force method for a high number of MC nodes. When compared to the brute-force mechanism, the network performance obtained by our proposed mechanism are significantly identical while the computation time significantly outperforms the brute-force mechanism.

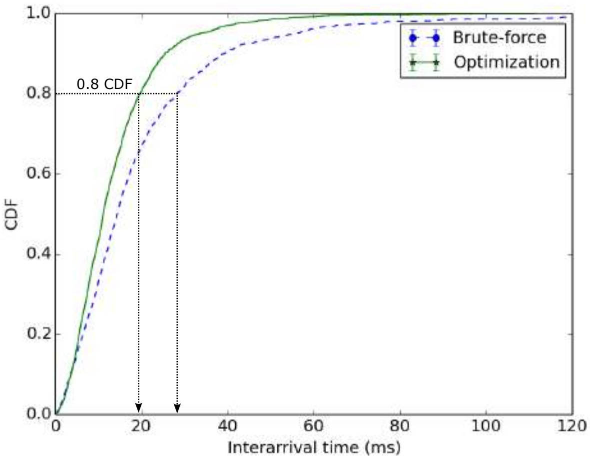


Figure 11. Inter-arrival time of 25 clients

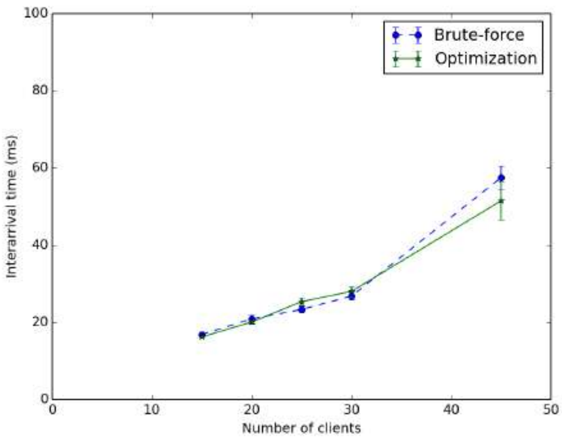


Figure 12. The average of inter-arrival time at 80th percentile

7. CONCLUSIONS

In the study, we proposed the optimized wireless router placement method with energy aware for wireless mesh network in a rural area. Our optimization goal involves achieving the longest lifetime of the system compared with brute-force method. The simulation results indicate that the optimization method yields significantly less computation time while obtaining the same results in term of network parameters. This is significantly crucial in the real deployment situation where sensor node (client) locations are mandatory adjusted based on the environmental status or the recommendation of the patrollers. Each adjustment requires a new calculation. Therefore, the proposed mechanism becomes more desirable due to its short computation time. Furthermore, the heuristic approach can be implemented for better performance.

REFERENCES

[1] A. M- Badescu and L. Cotofana, "A wireless sensor network to monitor and protect tigers in the wild," *Ecological Indicators*, vol. 57, pp. 447-451, Oct. 2015, doi: 10.1016/j.ecolind.2015.05.022.

[2] H. J. Griebling, C. M. Sluka, L. A. Stanton, L. B. Barrett, J. P. Bastos and S. B-Amran, "How technology can advance the study of animal cognition in the wild," *Current Opinion in Behavioral Sciences*, vol. 45, Jun. 2022, doi: 10.1016/j.cobeha.2022.101120.

[3] "Emerging Technologies: Smarter ways to fight wildlife crime," *JEnvironmental Development*, vol. 12, pp. 62-72, Oct. 2014, doi: 10.1016/j.envdev.2014.07.002.

[4] L. Zhou, G. Kang, N. Zhang, and J. Cheng, "Spectral efficiency guaranteed sustainable routing for energy renewable wireless mesh networks," *2015 International Conference on Wireless Communications Signal Processing (WCSP)*, Oct. 2015, doi: 10.1109/WCSP.2015.7341063.

[5] C. Luo, S. Guo, S. Guo, L. T. Yang, G. Min, and X. Xie, "Green Communication in Energy Renewable Wireless Mesh Networks: Routing, Rate Control, and Power Allocation," *IEEE Transactions on Parallel and Distributed Systems*, vol. 25, no. 12, pp. 3211 - 3220, Dec. 2014, doi: 10.1109/TPDS.2013.2297922.

[6] A. S. Arezoomand and M. Pourmina, "Prolonging network operation lifetime with new maximum battery capacity routing in wireless mesh network," *2010 The 2nd International Conference on Computer and Automation Engineering (ICCAE)*, Feb. 2010, pp. 319-323, doi: 10.1109/ICCAE.2010.5451679.

[7] S. Avallone and A. Banchs, "A Channel Assignment and Routing Algorithm for Energy Harvesting Multiradio Wireless Mesh Networks," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 5, pp. 1463 - 1476, May 2016, doi: 10.1109/JSAC.2016.2520238.

[8] Y. Chai, W. Shi, and T. Shi, "Load-aware cooperative hybrid routing protocol in hybrid wireless mesh networks," *AEU - International Journal of Electronics and Communications*, vol. 74, pp. 135-144, Apr. 2017, doi: 10.1016/j.aeue.2017.02.002.

[9] N. A. Macabale *et al.,* "CRADLE: Cross-Layer Design for Load-Aware Routing in IEEE 802.11-based Wireless Mesh and Sensor Networks," *2020 10th Annual Computing and Communication Workshop and Conference (CCWC)*, Jan. 2020, pp. 0970-0974, doi: 10.1109/CCWC47524.2020.9031245.

[10] Y. Yu, Y. Peng, Y. Liu, L. Guo, and M. Song, "Survivable Routing Protocol for green wireless mesh networks based on energy efficiency," *China Communications*, vol. 11, no. 8, pp. 117 - 124, Aug. 2014, doi: 10.1109/CC.2014.6911093.

[11] R. Almesaeed and A. Jedidi, "Dynamic directional routing for mobile wireless sensor networks," *Ad Hoc Networks*, vol. 110, Jan. 2021, doi: 10.1016/j.adhoc.2020.102301.

[12] Y. Chai, W. Shi, T. Shi, and X. Yang, "An efficient cooperative hybrid routing protocol for hybrid wireless mesh networks," *Wireless Networks*, vol. 23, pp. 1387–1399, 2017. [Online]. Available: https://link.springer.com/article/10.1007/s11276-016-1229-8

[13] H. Lin, J. Hu, L. Xu, Y. Tian, L. Liu, and Stewart Blakeway "A trustworthy and energy-aware routing protocol in software-defined wireless mesh networks," *Computers Electrical Engineering*, vol. 64, pp. 407-419, Nov. 2017, doi: 10.1016/j.compeleceng.2016.10.015.

[14] Y. Chai and X-J. Zeng "Load Balancing Routing for Wireless Mesh Network With Energy Harvesting," *IEEE Communications Letters*, vol. 24, no. 4, pp. 926-930, Apr. 2020, doi: 10.1109/LCOMM.2020.2969194.

[15] L. X. Cai, Y. Liu, T. H. Luan, X. S. Shen, J. W. Mark, and H. V. Poor, "Sustainability Analysis and Resource Management for Wireless Mesh Networks with Renewable Energy Supplies," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 2, pp. 345-355, Feb. 2014, doi: 10.1109/JSAC.2014.141214.

[16] S. Chen and G. M. Muntean, "E-Mesh: An energy-efficient cross-layer solution for video delivery in wireless mesh networks," *IEEE international Symposium on Broadband Multimedia Systems and Broadcasting*, 2012, pp. 1-7, doi: 10.1109/BMSB.2012.6264252.

[17] A. Gladisch, R. Daher, P. Lehsten, and D. Tavagarian, "Context-aware energy management for energy-self-sufficient network nodes in wireless mesh networks," *2011 3rd International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, Oct. 2011, pp. 1-8. [Online]. Available: https://ieeexplore.ieee.org/document/6078992

[18] S. Mamechaoui, F. Didi, S. M. Senouci, and G. Pujolle, "Energy-aware design for wireless mesh networks," *2014 Global Information Infrastructure and Networking Symposium (GIIS)*, Sep. 2014, pp. 1-6, doi: 10.1109/GIIS.2014.6934259.

[19] J. Hu, L. L. Yang, and L. Hanzo, "Energy-Efficient Cross-Layer Design of Wireless Mesh Networks for Content Sharing in Online Social Networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 9, pp. 8495 - 8509, Sep. 2017, doi: 10.1109/TVT.2017.2678167.

[20] A. V- Rodas and L. J. D. L. C. Llopis, "A centrality-based topology control protocol for wireless mesh networks," *Ad Hoc Networks*, vol. 24, pp. 34-54, Jan. 2015, doi: 10.1016/j.adhoc.2014.07.026.

[21] I. L- Cherif, L. Zitoune, and V. Veque, "Energy Efficient Routing for Wireless Mesh Networks with Directional Antennas: When Q-learning meets Ant systems," *Ad Hoc Networks*, vol. 121, Jul. Oct. 2021, doi: 10.1016/j.adhoc.2021.102589.

[22] N. Zlobinsky, D. L. Johnson, A. K. Mishra, and A. A. Lysko, "Comparison of Metaheuristic Algorithms for Interface-Constrained Channel Assignment in a Hybrid Dynamic Spectrum Access – Wi-Fi Infrastructure WMN," *IEEE Access*, vol. 10, pp. 26654-26680, Feb. 2022, doi: 10.1109/ACCESS.2022.3155642.

[23] B. Prakash, S. Jayashri, and T. S. Karthik, "A hybrid genetic artificial neural network (G-ANN) algorithm for optimization of energy component in a wireless mesh network toward green computing," *Soft Computing*, vol. 23, pp. 2789–2798, Jan. 2019. [Online]. Available: https://link.springer.com/article/10.1007/s00500-019-03789-8

[24] E. Amaldi, A. Capone, M. Cesana, I. Filippini, and F. Malucelli, "Optimization models and methods for planning wireless mesh networks," *Computer Networks*, vol. 52, no. 11, pp. 2159-2171, Aug. 2008, doi: 10.1016/j.comnet.2008.02.020.

[25] A. Capone, F. Malandra, and B. Sanso, "Energy Savings in Wireless Mesh Networks in a Time-Variable Context," *Mobile Networks and Applications*, vol. 17, pp. 298–311, Apr. 2022. [Online]. Available: https://link.springer.com/article/10.1007/s11036-011-0339-x

[26] S. Boiardi, A. Capone, and B. Sanso, "Joint design and management of energy-aware Mesh Networks," *Ad Hoc Networks*, vol. 10, no. 7, pp. 1482-1496, Sep. 2012, doi: 10.1016/j.adhoc.2012.04.005.

[27] X. Huan, B. Wang, Y. Mo, and L. T. Yang, "Rechargeable router placement based on efficiency and fairness in green wireless mesh networks," *Computer Networks*, vol. 78, pp. 83-94, Feb. 2015, doi: 10.1016/j.comnet.2014.10.035.

[28] B. Wang, X. Huan, L. T. Yang, and Y. Mo, "Hybrid Placement of Internet Gateways and Rechargeable Routers with Guaranteed QoS for Green Wireless Mesh Networks," *Mobile Networks and Applications*, vol. 20, pp. 543–555, Apr. 2015. [Online]. Available: https://link.springer.com/article/10.1007/s11036-015-0607-2

[29] U. Ashraf, "Energy-Aware Gateway Placement in Green Wireless Mesh Networks," *IEEE Communications Letters*, vol. 21, no. 1, pp. 156-159, 2016, doi: 10.1109/LCOMM.2016.2618378.

[30] K. Gokbayrak and E. A. Yildirim, "Exact and heuristic approaches based on noninterfering transmissions for joint gateway selection, time slot allocation, routing and power control for wireless mesh networks," *Computers and Operations Research*, vol. 81, pp. 102-118, May 2017, doi: 10.1016/j.cor.2016.09.021.

[31] K. Gokbayrak, "Robust gateway placement in wireless mesh networks," *Computers and Operations Research*, vol. 97, pp. 84-95, Sep. 2018, doi: 10.1016/j.cor.2018.04.018.

[32] S. Sakamoto, K. Ozera, M. Ikeda, and L. Barolli, "Implementation of Intelligent Hybrid Systems for Node Placement Problem in WMNs Considering Particle Swarm Optimization, Hill Climbing and Simulated Annealing," *Mobile Networks and Applications*, vol. 23, pp. 27–33, 2018, doi: 10.1007/s11036-017-0897-7.

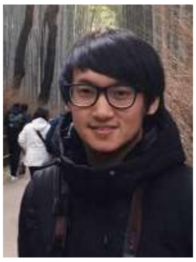
[33] L. Sayad, L. B. Medjkoune, and D. Aissani, "An Electromagnetism-like mechanism algorithm for the router node placement in wireless mesh networks," *Soft Computing*, vol. 23, pp. 4407–4419, 2019. [Online]. Available: https://link.springer.com/article/10.1007/s00500-018-3096-y

[34] A. Henningsen, "linprog: Linear programming / optimization," Mar. 2022. [Online]. Available: https://cran.r-project.org/web/packages/linprog/linprog.pdf

[35] G. F. Riley and T. R. Henderson, "The ns-3 network simulator" *Modeling and tools for network simulation*, pp. 15-34, 2010, doi: 10.1007/978-3-642-12331-3-2.

BIOGRAPHIES OF AUTHORS

Aphirak Jansang received his B.Eng., M.Eng. and D.Eng. degrees in Computer Engineering from Kasetsart University, Bangkok, Thailand, in 2000, 2003 and 2012, respectively. He is currently an Assistant Professor at the Department of Computer Engineering, Kasetsart University, Thailand. He is also a team leader of Intelligent Wireless Network Group (IWING). His research interests include wireless networks, resource management and quality of service support. He can be contacted at email: aphirak.j@ku.ac.th.



Chayathorn Simasathien received the B.Eng. and M.Eng. degree in Computer Engineering from Kasetsart University, Bangkok, Thailand, in 2014 and 2020 respectively. He is also a team member of Intelligent Wireless Network Group (IWING). He is currently working at KASIKORN Business-Technology Group (KBTG), THAILAND. He can be contacted at email: chayathorn.s@ku.th.

Anan Phonphoem received his Ph.D. in Electrical and Computer Engineering (2000) from University of Massachusetts Amherst, M.S. in Computer Engineering (1996) from University of Southern California (USC), and B.Eng. in Electrical Engineering (1990) from Prince of Songkla University, Thailand. He is currently an Associate Professor and the director of the Intelligent Wireless Network Group (IWING) at Computer Engineering Department, Kasetsart University, Thailand. His research interests include wireless networks, ad hoc networks, performance evaluation, and protocol design and analysis. He can be contacted at email: anan.p@ku.ac.th.