Optimal RF Repeater Placement for Power Transformer Monitoring Systems

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***Abstract*—This study is driven by the challenge of optimizing connectivity and performance in communication networks with multiple interconnected components. The primary objective is to ensure a consistent and reliable signal strength across the entire coverage area, with a particular focus on monitoring critical infrastructure systems like power transformers. To achieve this goal, an innovative approach is introduced, leveraging the optimization of RF repeaters within these systems. The study combines the power of a path planning algorithm and linear optimization techniques to identify the most suitable locations for repeaters within the RF network. The widely recognized A* (A-Star) path planning algorithm, implemented using the MATLAB Robotics Toolbox, guides this process. Additionally, the Longley-Rice model is utilized to calculate RF data, taking into account factors such as terrain, clutter, and other environmental variables. To enhance the usability and practicality of the optimization process, a user interface (UI) is developed using MATLAB App Designer. This UI enables users to access comprehensive simulation data, including metrics such as signal strength, link margin, SINR (Signal-to-Interference-plus-Noise Ratio), path loss, and distance. By providing detailed insights and analysis, the UI facilitates effective RF repeater placement and optimization within the system. Overall, this approach offers a valuable solution for achieving optimal performance in Power Transformer Monitoring Systems through informed RF repeater positioning.**

***Index Terms*—Optimal placement, RF repeaters, linear optimization, A* (A-Star) algorithm, Longley-Rice Model**

I. INTRODUCTION

The growing trend of smart campuses (SC) in the field of education has driven the integration of technology to enhance the quality of education, improve student experiences, ensure campus safety, and optimize operational efficiency [1]. Mindanao State University - Iligan Institute of Technology (MSU-IIT) recognizes the significance of transitioning into a smart campus environment to provide quality education, and is faced with the challenge of optimizing energy consumption.

This paper presents a research study focused on optimizing the placement of RF repeaters in the Power Transformer Monitoring System (PTMS) at MSU-IIT. The PTMS plays a critical role in monitoring electrical energy consumption across the university. However, the current power transformer installations do not meet the requirements of a smart campus, hindering efficient data gathering.

To address this issue, a non-intrusive wireless communication system utilizing RF technology is proposed as an alternative to traditional IoT devices commonly used in smart campuses. The RF-based PTMS offers advantages such as longer range, reduced complexity, and independence from internet connectivity, overcoming security, complexity, and network dependency concerns associated with IoT devices [2].

The successful placement of RF repeaters ensures reliable data transmission and efficient installation of the PTMS, enabling MSU-IIT to optimize energy consumption within its smart campus infrastructure.

II. RF RELAY / REPEATER OPTIMIZATION

Several studies have contributed to the deployment of relays/repeaters in various communication systems. These studies have explored topics such as relay node placement methods for free-space optical (FSO) communication systems [3], challenges in relay-assisted millimeter-wave (mmWave) cellular systems [4], and the mitigation of mmWave communication blockages through relay selection algorithms [5].

Furthermore, environmental variables have been considered in the optimum placement of radio relays, including the effect of rain on transmitted information [6] and the joint effects of path loss, correlated shadowing, and flat Rayleigh fading [7]. These studies highlight the importance of considering environmental factors in relay placement and emphasize that the optimal relay position may not necessarily be on the direct line between the source and destination in certain scenarios.

In the context of Wireless Sensor Networks (WSNs), optimization models have been developed to address factors such as capacity, coverage, and connectivity between smart meters and hubs [8]. These models aim to improve resource efficiency and energy consumption by integrating different wireless communication technologies and minimizing the number of data aggregation points.

Collectively, these studies contribute to the understanding of relay and transmitter placement in diverse communication systems, addressing challenges related to blockage, coverage probability, and environmental factors.

III. PATH LOSS MODELS

Path loss modeling studies have significantly contributed to our understanding of signal behavior in wireless communication systems. Within this field, various studies have made notable contributions. For instance, one study investigated antenna height's impact on propagation in forest terrain, revealing the dominant role of foliage excess loss within the first 1000 meters [9]. Another study proposed a smart deployment method considering micro-variations in the environment, with a specific focus on tree canopies [10]. In terms of path loss prediction, an approach utilizing earth bulge and Fresnel-Kirchhoff's Knife Edge diffraction theory demonstrated improvements over geometric range in flat terrain scenarios [11]. Furthermore, the Longley-Rice model's effectiveness in predicting radio signal propagation in rural railway areas with diverse terrain profiles was evaluated, showcasing its superiority over the Okumura-Hata model in accurately capturing communication behavior in irregular railway environments [12]. Additionally, simplified propagation models were explored, including direct transmission through trees and simplified multiple-edge diffraction, offering promising accuracy for coverage prediction in forested and mountainous areas [13], [14]. Collectively, these studies enhance our understanding of path loss modeling and prediction techniques, providing valuable insights and practical approaches for wireless communication systems in various environments.

IV. DEVELOPMENT OF THE SYSTEM

The proposed system aims to determine the optimal locations for placing RF repeaters, considering factors such as signal strength, path loss, interference, and coverage requirements. By strategically positioning repeaters, the system improves network performance, minimizes interference, and maximizes signal coverage. The methodology involves data acquisition, selection of a suitable propagation model, integration into the planning system, and the use of optimization algorithms to identify optimal repeater locations.

A. Data Acquisition

Two crucial data elements required for this project are the topographic data of the designated test area and the specifications of the repeater to be used. To obtain the required topographic data for this project, OpenStreetMap (OSM) was employed. OSM is an openly accessible and continuously updated geographic database maintained by a collaborative community of volunteers. The software tool used allowed the extraction of latitude, longitude, and terrain data specific to the area of interest, in this case, MSU-IIT.

The next set of data required pertains to the specifications of the repeater to be utilized for the application. The researcher considered several repeater parameters such as the transmitter power, gain, repeater height, and receiver sensitivity.

B. Selection of Pathloss model

Once the necessary data has been collected, the researcher utilized it as inputs for simulating path loss in the designated area. The path loss model used in the simulation is based on the widely used "Longley-Rice" model. The model takes into account various factors that affect radio wave propagation, including terrain irregularities, Earth curvature, diffraction, and tropospheric scattering. It is based on extensive measurements and observations of radio wave behavior over different types of terrain.

C. Development of Location Optimization Algorithm

The Location Optimization model was formulated as a Linear Optimization problem, with the objective function aimed at minimizing the number of repeater while adhering to a predefined set of constraints. In developing this algorithm, inspiration was also taken from a path planning algorithm utilized in MATLAB for autonomous vehicles and robots.

1) Linear Optimization problem : To address the challenge of finding the optimal placement for transmitters, a linear optimization approach was adopted. Introducing a variable Z to represent each potential site, with a value of 1 indicating that the site satisfied the specified constraints and 0 otherwise. Additionally, the total number of candidate sites defined on the map was denoted by the variable M. The objective function of the optimization model can be formulated as follows:

$$\text{minimize} \quad \sum_{j=1}^{M} Z_j \tag{1}$$

subject to the following constraints:

$$Z_j = 0, \quad \text{if } D \geq Z_{\text{r\_max}} \tag{2}$$

$$Z_j = 0, \quad \text{if } X_j = 1 \tag{3}$$

$$Z_j = 0, \quad \text{if } Z_{j\_xy} \in S_{xy} \tag{4}$$

where:

D: the distance between succeeding repeaters

$Z_{\text{r\_max}}$:the maximum repeater range derived from the inputted specifications

X_j: represents the function obs$\{Z_j, Z_{j-1}\}$, takes the value 1 if an obstacle exists between subsequent repeaters, 0 otherwise

S_{xy}: pre-defined set containing the x-y coordinates of roads, pathways and other restricted areas

Z_{j_xy}: x-y coordinate of the current repeater

2) Path Planning Algorithm: The project utilizes a path planning algorithm inspired by the MATLAB Probabilistic Road Map (PRM) approach, which incorporates the A* (A-star) algorithm. The PRM algorithm constructs a graph representation of the environment, while the A* algorithm finds an optimal path between the start and goal configurations within this graph. The A* algorithm combines the strengths of Dijkstra's algorithm [15] and greedy best-first search. It employs a heuristic function, such as the Euclidean distance or Manhattan distance, to estimate the cost from each node to the goal node. This heuristic guides the algorithm to explore nodes that are more likely to lead to the shortest path, enhancing its efficiency.

D. Development of RF-Repeater Planning System(RF-RPS)

After completing the algorithm design, the researcher proceeded to develop an application software that incorporates and utilizes the designed algorithm. This software serves as a practical implementation of the algorithm, providing users with a user-friendly interface and streamlined functionality to interact with and benefit from its capabilities.

The software application includes a graphical representation of repeater locations, allowing users to intuitively visualize the spatial distribution of repeaters within the network. Additionally, the application offers valuable data extraction capabilities, enabling users to obtain crucial information for analysis and optimization purposes.

To initiate the RF-Repeater Planning System(RF-RPS), the user is required to load an OSM file from OpenStreetMap. This file is processed and converted into a Binary Occupancy Map (which will be used for path planning) following the steps outlined in Algorithm 1. Moving forward, the user interacts with the map interface by designating the base transmitter and receiver nodes, which are essential components for path planning. Algorithm 2 effectively searches for paths that fulfill the specified constraints, ensuring optimal connectivity. Finally, to optimize the overall system efficiency, Algorithm 3 merges redundant locations, resulting in an optimal count of transmitters.

Algorithm 1 Loading map from a downloaded .OSM file

```
Data: OSM File
Return: Binary Occupancy Map, will be used for Path Planning.
Load OSM File
Scan OSM Contents
for $i = 1$ to size(OSM Contents) do
    convert OSM Contents to Polyshape
end for
Inflate Polyshapes
Plot( Inflated Polyshapes)
Capture Frame
Convert Frame to Binary Occupancy Map
```

Algorithm 2 Search for Path

```
Data: Transmitter and Receiver Node Coordinates, converted as Start and Goal Nodes
Return: Searched path coordinates
Define Start and Goal Nodes
Find a vertex closest to the goal
Find a vertex closest to the start
Check if the vertices are connected
if connected  then find a path through the graph
    path=aStar(startNode, goalNode)
end if
Get coordinates of the nodes of the path
Return coordinates of the nodes
```

Algorithm 3 Combine Paths

```
Data: Candidate repeater locations from Algorithm 2, Maximum range of repeaters defined as $R_{max}$
Return: Optimized repeater locations
Define arrays that will handle repeater coordinates Global_Path, Path_to_Scan
▷ Check each element of Global_Path with each element of Path_to_Scan
for $i = 1$ to size(Global_Path) do
    for $j = 1$ to size(Path_to_Scan) do
        Check distance (Global_Path[i], Path_to_Scan[j])
        Check obstacle (Global_Path[i], Path_to_Scan[j])
        if distance $< R_{max}$ and Obstacle == $false$ then
            Merge (Path_to_scan , Global_Path)
        else
            continue checks
        end if
    end for
end for
```

V. RESULTS

The following results illustrate the effectiveness of the RF-RPS in improving connectivity within network scenarios. Through the addition of nodes and intelligent optimization, substantial enhancements in signal strengths were achieved, ensuring stable and reliable connections.

A. Run Time of the RF - Repeater Planning System

The execution times are measured using the ”stopwatch time” method implemented in MATLAB through the commands tic and toc. All computations are conducted on a machine equipped with 12th Gen Intel Core$^{\text{TM}}$ i7 CPU clocked at 2.70 GHz and 24.0 GB (nameplate) RAM. The operating system used is Windows® 10 Home Version 10.0 (Build 22621).

Table I shows the run time evaluations of the generated RF-RPS. It encompasses the process of evaluating all feasible combinations of nodes to achieve the minimum total number of nodes based on the specified constraints in Section IV-C1 Based on the results, it is evident that the program’s convergence may be slower when a larger number of nodes is present. This phenomenon can be attributed to the nature of the optimization algorithm employed, which necessitates scanning all possible combinations of nodes. The time required for the program to converge increases as the number of nodes grows, as each additional node introduces more potential combinations to evaluate. Consequently, the algorithm’s computational complexity escalates, resulting in a longer convergence time. It is essential to consider this aspect when working with a substantial number of nodes in the RF-RPS.

TABLE I
RUN TIME EVALUATIONS.

Power Transformer(PT) Nodes	***Search Path Time***	***Optimization Time***	***Total Time***
1 Node	1.407274 sec	1.900211 sec	3.307485 sec
3 Nodes	1.970328 sec	1.148440 sec	3.118768 sec
5 Nodes	3.044875 sec	4.432157 sec	7.477032 sec
7 Nodes	5.245113 sec	26.28258 sec	31.52709 sec
9 Nodes	6.335943 sec	537.0125 sec	543.3485 sec

B. Running RF-RPS in different number of base transmitters

Figure 1 illustrates a scenario on the MSU-IIT map where RF transmitters are positioned at three power transformers(PT) (depicted in blue), along with a receiver at the monitoring station (shown in green). The corresponding signal strengths for each connectivity are listed in Table II. It is worth mentioning that if the receiver used in the setup has low sensitivity (i.e., within the range of -60 dBm to -70 dBm), it may fail to detect the received signals since the readings already in range of -95 dBm to -105 dBm. To address this issue, the RF-RPS has incorporated 2 additional repeater nodes, as illustrated in Figure 2, while taking into account the constraints mentioned in Section IV-C1. This addition of nodes ensures a robust and reliable connectivity across all nodes. Notably, Table III demonstrates significant enhancements in the received signal strengths, indicating a successful and stable connection.

TABLE II
SIMULATED DIRECT PATH ANALYSIS OF A 3-TRANSMITTER NODE NETWORK

Connection	Signal Strength(dBm)
Node 2 to Node 5	–100.903
Node 1 to Node 5	–105.525
Node 6 to Node 5	–95.126

TABLE III
SIMULATION RESULTS FOR A 3 - TRANSMITTER NODE NETWORK WITH ADDED NODES

Connection	Signal Strength(dBm)
Node 4 to Node 5	–51.07
Node 3 to Node 4	–56.997
Node 2 to Node 3	–57.463
Node 1 to Node 2	–55.44
Node 6 to Node 1	–56.787

Another compelling demonstration of the RF-RPS system's capabilities is showcased in Figure 4. In this scenario, the RF-RPS intelligently incorporates 3 new repeater nodes(depicted in red) into the original 5-transmitter setup shown in Figure 3. Initial signal readings from the direct path connections, as outlined in Table IV, exhibited signal strengths ranging from -98 dBm to -105 dBm, with the exception of Node 3 to Node 4. However, thanks to the RF-RPS enhancements, notable improvements in signal strengths can be observed in Table V. These improvements signify the RF-RPS's effectiveness in ensuring reliable and enhanced connectivity within the network.

The results demonstrate the effectiveness of the RF-Repeater Planning System (RF-RPS) in addressing the challenges of optimizing repeater placement and ensuring reliable connectivity in wireless communication networks. The system proves to be a valuable tool for network planners, empowering them to optimize repeater placement and achieve dependable wireless communication in real-world scenarios.

TABLE IV
SIMULATED DIRECT PATH ANALYSIS OF A 5-TRANSMITTER NODE NETWORK

Connection	Signal Strength(dBm)
Node 3 to Node 4	– 55.19
Node 3 to Node 1	– 98.516
Node 3 to Node 9	– 99.301
Node 3 to Node 8	– 104.479
Node 3 to Node 5	– 105.889

TABLE V
SIMULATION RESULTS FOR A 5 - TRANSMITTER NODE NETWORK WITH ADDED NODES

Connection	Signal Strength(dBm)
Node 3 to Node 2	– 53.66
Node 2 to Node 1	– 54.653
Node 2 to Node 7	– 56.997
Node 7 to Node 6	– 56.503
Node 6 to Node 5	– 48.287
Node 7 to Node 8	– 57.956
Node 8 to Node 9	– 56.866

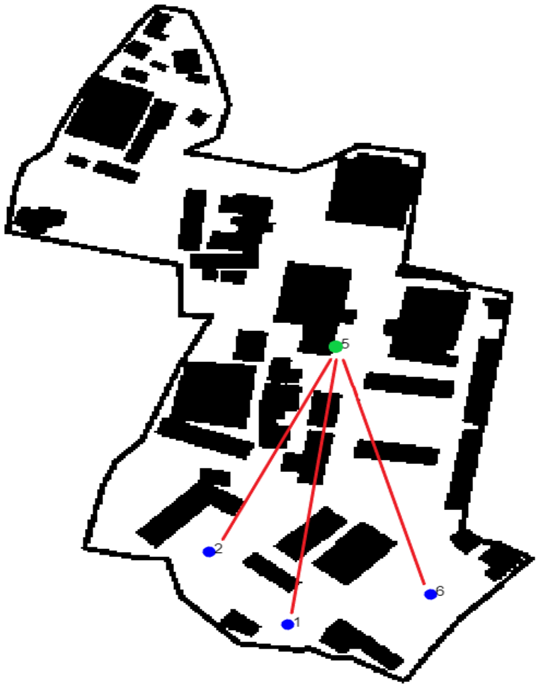

Fig. 1. 3 - Transmitter(blue) and 1 Receiver(green) network scenario

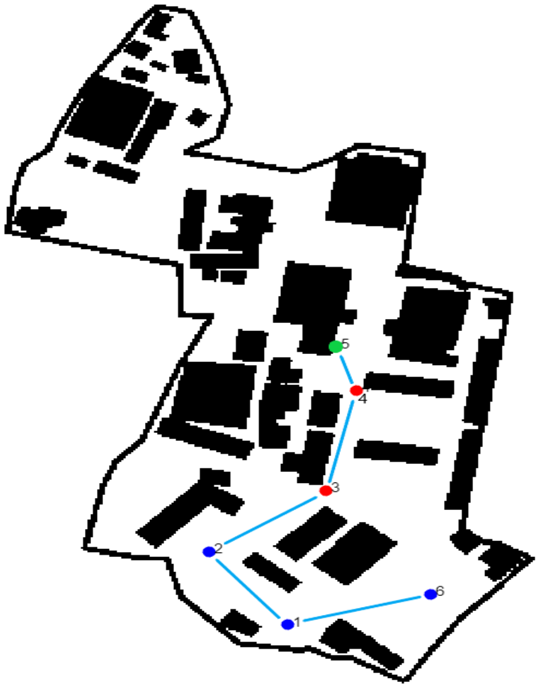

Fig. 2. New Repeater Nodes(red) added by the RF-RPS software

C. Simulations vs Experimental Readings

The experimental readings were conducted utilizing two primary instruments: the Hantek HSA2030 Portable Spectrum Analyzer and the Keysight N5183B Analog Signal Generator.

During the experiment, the Keysight N5183B Analog Signal Generator was set up to generate a signal with a frequency of 900MHz and an output power of +19dBm. On the other hand, the Hantek HSA2030 Portable Spectrum Analyzer was tuned to 900MHz and exhibited a noise floor of approximately -90dBm throughout the testing phase.

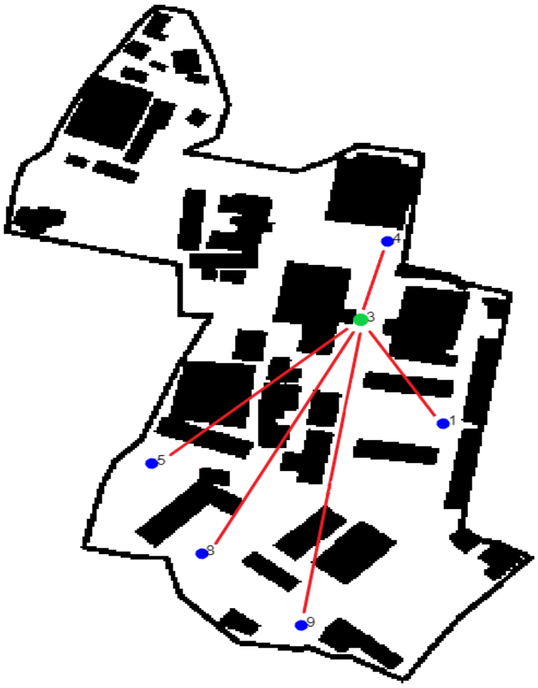

Fig. 3. 5 - Transmitter(blue) and 1 Receiver(green) network scenario

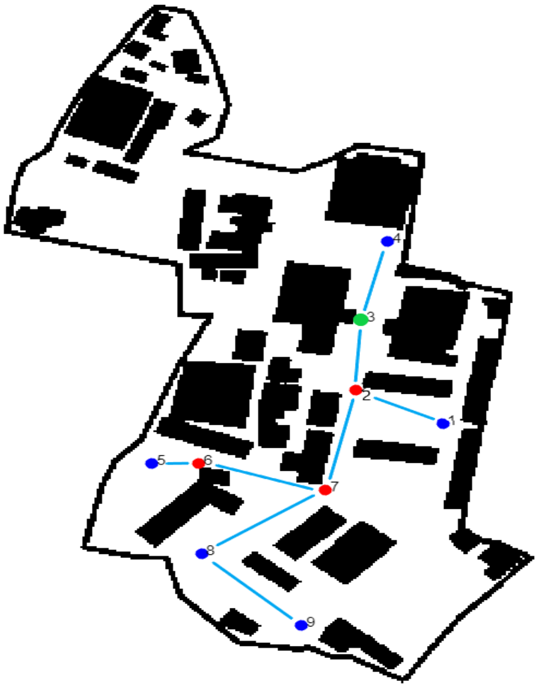

Fig. 4. New Repeater Nodes(red) added by the RF-RPS software

Table VI presents a comparison between the simulation results and experimental readings, revealing an average difference of -25.34 dBm along the obstacle-free path between the ideal simulation and actual measurements. While the simulation's path loss model accounts for certain factors contributing to losses, unconsidered factors such as cable attenuation, impedance mismatches, atmospheric conditions, and interference may have influenced the experimental results. To accommodate these additional losses, the RF-RPS system offers flexibility for users to incorporate them. By integrating the obtained average loss difference of -25.34 dBm into the original simulation values, closer alignment between simulation and experimental results was achieved. Nevertheless, comprehensive data gathering and characterization are recommended to accurately determine the additional losses introduced by the setup. Due to resource and instrument limitations, a thorough characterization of actual loss fell beyond the scope of this study.

For the data points with obstacles in between, the readings from the experimental setup did not reach values near the simulated since the receiver used in the experiment has a noise floor of around -90 dBm, which is the lowest level the receiver can detect as seen on the readings from Table VII.

TABLE VI
COMPARISON OF SIGNAL STRENGTH VALUES(FREE SPACE)

Data Point	*Simulation (Ideal)*	*Simulation (w/ Added Losses)*	*Experimental*
1	-47.78 dBm	-73.12 dBm	-72.799 dBm
2	-47.81 dBm	-73.15 dBm	-72.709 dBm
3	-48.42 dBm	-73.76 dBm	-74.514 dBm

TABLE VII
COMPARISON OF SIGNAL STRENGTH VALUES(OBSTRUCTED)

Data Point	*Simulation (Ideal)*	*Experimental*
1	-106.09 dBm	-90.519 dBm
2	-100.71 dBm	-89.613 dBm
3	-100.75 dBm	-92.440 dBm

VI. CONCLUSION

In conclusion, the RF-Repeater Planning System (RF-RPS) has been successfully developed and demonstrated its effectiveness in facilitating efficient and optimized planning of RF transmission in various scenarios. Through the implementation of advanced algorithms and utilization of Matlab toolboxes, the RF-RPS offers a comprehensive solution for determining optimal transmitter and receiver node locations, considering constraints such as maximum transmitter range, obstacle present in between path, and that locations must not be in designated pathways and roads. The system incorporates user-friendly interfaces, allowing users to input RF parameters, visualize maps, select node locations, and analyze results. The experimental results have shown that the RF-RPS can predict RF performance and provide valuable insights for planning and optimizing RF networks.

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