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Impact of Environmental Conditions on Wireless Signal Propagation in Solar Energy Farm

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ABSTRACT: Wireless sensor networks play a critical role in the real-time monitoring and control of solar energy farms. However, environmental conditions such as rain, humidity, and temperature, dust, and terrain variations significantly impact signal propagation and network reliability. This study presents a detailed numerical modeling and MATLAB based simulation of wireless signal attenuation in a typical solar farm layout under diverse environmental scenarios. Using established models including the ITU-R P.838 for rain attenuation and empirical models for humidity and visibility-based dust effects the simulation analyzes signal strength (RSSI) over varying distances, frequencies (Zigbee at 2.4 GHz and LoRa at 430 MHz), and atmospheric conditions. The results of the research shows a considerable signal reduction during heavy rainfall and low visibility events, with additional losses introduced by the tilt angle of panel and terrain elevation. Coverage maps and performance plots highlight best-case and worst-case communication scenarios. Recommended for resilient network designs such as increased node density, optimized antenna placement, and protocol selection are provided to ensure robust wireless communication. The Knowledge gained from this work are essential for designing adaptive, weather-resilient sensor networks in renewable energy infrastructures.

Keywords: Wireless Sensor Networks (WSN), Signal Propagation, optimized antenna, Solar Energy Farm; Environmental Attenuation, Rain Fade; Humidity Effects; Zigbee, LoRa, RSSI, Modeling.

I. INTRODUCTION

Solar energy farms are increasingly becoming critical components of global renewable energy portfolios due to their potential to produce clean and sustainable energy. For efficient operation and maintenance of these farms, robust real-time monitoring systems will keep track of energy generation, environment conditions and equipment performance. Wireless communication technologies, especially Wireless Sensor Networks (WSNs), will relieve the burden from long-cabling systems of data transmission and control across vast area without extended cabling. All these systems will help these operators detect anomalies; optimize energy production, and all the while reducing costs incurred on maintenance. In solar energy farms, wireless communication networks are used for collecting data at various points such as solar panels, inverters, and environmental sensors and transmitting it on a central control system. This helps the operator assess how well the farm is performing, predicts when intervention would be needed in terms of maintenance, and adjusts energy outputs in conjunction with environmental changes. Besides the general cost reduction when using such networks, the aspect of increasing the installation makes it ideal for solar farms because it does not limit their expansion. However, the environmental conditions like temperature, humidity, wind, and rain have an impact on the efficiency of wireless communication in solar energy farms. The situation occurs when these factors cause signal attenuation and a resultant loss in strength and reliability of the signal, thus affecting the performance of the farm as a whole. Further, any blockages arising from the geographical layout of solar panels can also hinder signal transmission, so optimal configurations of the network will be required to ensure continuous reliable communication. Moreover, the growing importance of optimizing wireless communications in solar farms is emphasized by many recent studies, for example, [1], which assert the need for adaptive communication strategies towards changing environmental conditions in large-scale solar installations. Similarly, [2] discuss how advanced wireless technologies like Zigbee and LoRa can improve communication efficiency in renewable energy systems while minimizing interference from environmental factors. Wi-Fi may be used wirelessly in such a way that all energy is maximized during solar energy production while also minimizing the times when energy does not flow due to any failure. Solar energy farms are of important nature in renewable energy production as they convert sunlight to electricity using photovoltaic (PV) panels. These farms also require a strong monitoring and control system that can collect data on energy generation, status of equipment and environment conditions in real time to maximize productivity. Maximum performance, early detection of faults, and minimum downtime are achieved primarily through monitoring of the system. It has been integrated with advanced technology like the Internet of Things (IoT) that plays a significant role in further improving the capability of solar farms in monitoring and optimizing performance. The systems typically IoT-enabled would be able to monitor real-time energy production, changes in weather conditions, and percentage efficiencies of arrays. Hitherto controlling these were possible only after on-site climatic and environmental conditions had been ethically considered. The real-time feedback data is further processed via IoT, gateways, and cloud platforms with further analysis where advanced analytics and machine learning algorithms assist operators in optimizing energy production, predicting maintenance, and improving overall efficiency. Therefore, solar farms could avert emergencies by responding adequately while ensuring continuous and effective operation. These setups are also quite scalable and might be deployed for various types of solar installations, ranging from small residential projects to large-scale commercial or utility plants. With a data-driven approach, IoT is exponentially improving the decision-making process regarding energy supply and demand, along the lines of energy storage and grid integration.

1.1 CHALLENGES IN SIGNAL PROPAGATION

Wireless communication systems guarantee smooth business workings of solar energy farms, which facilitate monitoring, control, and real-time management of the energy generation process. Such systems usually work on wireless sensor networks (WSNs) for collecting and transmitting data from different parts of the farm, like solar panels, inverters, and environmental sensors. But these solar energy farms also have special factors in play against wireless signal propagation due to the environmental surrounding and structures that may greatly vary the quality and reliability of the communication. All these challenges must be understood to optimize the wireless communication system, thereby ensuring an economic operation of solar energy farms.

1.1.1 ENVIRONMENTAL CHALLENGE

One of the foremost challenges standing in the way of solar energy farm signal propagation is the strong variations of environmental conditions, such as temperature and humidity, amount of rain, wind strength, and solar radiation. These, by way of signal attenuation, can reduce the strength of the signals and result in further data loss within a transmission channel. The electrical properties of the transmitting medium and terrain conducting waves are affected by temperature. One probability is that high temperatures generate more noise in the communication system, lowering the signal-to-noise ratio (SNR) and corrupting the quality. Humidity and rainfall are rated as the other major factors in signal propagation. Water vapor in the atmosphere tends to absorb and scatter radio frequency (RF) signals at high frequencies, which causes signal attenuation. Rain tends to become the most important factor in communications linked to solar farms when the wireless network is operating in microwave or millimeter-wave frequency bands, which are predominantly affected by water absorption. In rain fade, rain leads to rapid attenuation; therefore, communications are degraded, delayed, or interrupted. Wind is yet one of the environmental factors negative to signal propagation in solar farms. It does not hamper RF signals directly; however, it indirectly intervenes since moving structures (solar panels or towers) could interfere with signal reception, leading to missing packets. This movement can alter the line-of-sight (LOS) paths between wireless devices, leading to signal degradation or intermittent connections. Additionally, strong winds can cause dust or debris to accumulate on solar panels, which

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can obstruct wireless signals.

1.1.2 STRUCTURAL CHALLENGES

The physical layout and infrastructure of solar energy farms also pose significant challenges to wireless signal propagation. Solar panels, which are typically arranged in large arrays, can act as physical obstructions to wireless signals, causing reflection, diffraction, and scattering. These phenomena can lead to multipath propagation, where the wireless signal takes multiple paths to reach the receiver, resulting in phase shifts and interference. Multipath propagation can cause signal fading, where the signal strength fluctuates, making it difficult for the receiver to accurately decode the transmitted data. In addition to multipath propagation, the dense arrangement of solar panels can create "shadowing" effects, where certain areas of the farm experience reduced signal strength due to the blocking of signals by panels or other structures. This is particularly problematic in large-scale solar farms, where the distance between communication nodes can be substantial, and maintaining a clear LOS for signal transmission becomes increasingly challenging. Moreover, the metallic components of solar panels and mounting structures can contribute to signal reflection and interference. Metals have high conductivity, which can cause RF signals to reflect off their surfaces, leading to constructive or destructive interference patterns. These reflections can create areas of high signal strength (constructive interference) or low signal strength (destructive interference), further complicating the propagation environment in solar farms.

1.1.3 FREQUENCY BAND SELECTION AND INTERFERENCE

The selection of the appropriate frequency band for wireless communication in solar farms is another important consideration, as different frequency bands exhibit varying propagation characteristics. Lower frequency bands, such as those in the VHF and UHF ranges, tend to have better penetration through obstacles and are less affected by environmental factors like rain and humidity. However, these bands are often congested with other types ofcommunication, leading to potential interference and reduced bandwidth availability for solar farm operations. On the other hand, higher frequency bands, such as those in the microwave or millimeter-wave ranges, offer greater bandwidth and data transmission capacity but are more susceptible to environmental attenuation and interference from physical structures. The trade-off between frequency selection and signal propagation challenges must be carefully managed to ensure reliable communication in solar farms.Bearings of rotating machineries generate repetitive transient responses that can easily be masked with interference and noise. The currently available methods of diagnosis, such as narrowband filtering demodulation and indicators for optimal frequency band selection, are all interference-prone, thereby limiting their field applicability. Under this scenario, a new method - ACKgram- has been proposed for the bearing fault diagnosis that captures the average envelope of the spectrum and then introduces a new indicator called Adaptive Correlated Kurtosis (ACK), which defines signal's periodicity and impulsivity. Motor bearings make repeated transient noises that can easily interfere and be caught in general noise. All current diagnosis methods, such as narrowband filtering demodulation and indicators for choosing the best frequency band, are very interference-prone and limit field applicability. Thus, a new method ACKgram-is proposed for the diagnosis of the bearing fault, which captures the indelible average envelope of the spectrum and introduces an entirely new indicator adaptive-correlated kurtosis, which describes the periodicity and impulsivity of the signal [10].

1.1.4 MITIGATION STRATEGIES

Addressing the signal propagation challenges in solar energy farms requires a combination of technological and strategic solutions. One approach is the use of advanced modulation and coding techniques that can improve the resilience of wireless communication systems to environmental interference. For example, adaptive modulation schemes can adjust the transmission parameters based on real-time environmental conditions, ensuring that the communication system maintains an optimal balance between data rate and signal reliability.

Another strategy is the deployment of mesh networks, where multiple communication nodes are distributed throughout the solar farm to create redundant communication paths. In a mesh network, if one path is compromised due to environmental or structural factors, the system can automatically reroute data through alternative paths, ensuring continuous and reliable communication. Additionally, careful planning of the physical layout of the solar farm, including the placement of wireless sensors and communication equipment, can help mitigate the impact of structural obstructions and signal shadowing. For example, placing sensors at elevated positions or using directional antennas can improve the LOS and reduce the likelihood of signal degradation caused by physical obstructions. Signal propagation in solar energy farms is subject to a variety of challenges, including environmental factors such as temperature, humidity, and rain, as well as structural challenges posed by the layout and materials of the solar panels. These factors can lead to signal attenuation, interference, and reduced communication reliability, which can impact the overall efficiency of the solar farm. Addressing these challenges requires a combination of advanced wireless communication technologies, strategic network planning, and careful consideration of the environmental and structural characteristics of the solar farm. By optimizing wireless communication systems, solar farms can ensure continuous and efficient operation, contributing to the broader goal of sustainable energy production.

II. LITERATURE REVIEW

2.1 OVERVIEW OF SIGNAL PROPAGATION MODELS

Radio waves or electromagnetic signals go from transmitter to receiver and reach various factors, such as environments, distance, and obstacles in the way of transmission. For example, accurate modelling of signal propagation are paramount to designing good wireless communication systems such as those in solar energy farms. This overview examines the different models of signal propagation, the defining characteristics of each model, and its applicability in real-life scenarios. [3] Propagation models for network planning and optimization, using empirical models, are addressed in the proposal. Site survey measurements were quantified in Dar es Salaam comparing downlink received signal strength levels with existing models. Results show that there are significant inconsistencies with empirical models for all terrain areas, thereby stressing on the high need for accurate prediction of radio-propagation behavior in wireless personal communication systems like Cellular Mobile Radio. According to [4], the research focuses on evaluating the impact of propagation models on the performance assessment study of a Vehicular Ad-hoc Network (VANET) in real-time environments. It also makes a comparison between the effects of ITU-R P.1411 and FRIIS models under traffic scenarios in Guwahati. The results reveal that the ITU-R P.1411 model outperforms the average throughput and end-to-end delay, an improvement in MAC/PHY-overhead of the model while the FRIIS gives better output with packet delivery ratios and routing good put.[5] discusses tropospheric wave propagation and the refractive index (RI), which, in turn, decides the path of radio-wave refraction in the troposphere. In this context, humidity, temperature, and pressure influence RI, and the dependence of RI on pressure, temperature, and relative humidity is quantitatively estimated. Results show that RI is most sensitive to temperature and increases with an increase in relative humidity, thereby emphasizing the concern for local climatology.

2.2.1 TYPES OF SIGNAL PROPAGATION

There are three main modes through which wireless signals propagate: line-of-sight (LOS), non-line-of-sight (NLOS), and multipath propagation. In a line-of-sight scenario, the transmitter and receiver have an unobstructed path between them, which is ideal for communication as it minimizes signal loss and interference. In non-line-of-sight situations, obstacles such as buildings, trees, or solar panels obstruct the signal path, leading to reflection, diffraction, and scattering. Multipath propagation occurs when the signal reaches the receiver through multiple paths due to reflection, diffraction, and scattering, which can result in phase shifts and interference, leading to signal degradation.In this paper, it is proposed that an alternative framework might have been applied to pose analysis of the consequent effects of stochastic noise on signal propagation and dimension reduction in complex networks from the viewpoints of stochastic differential dynamics and Itô's formula. This framework, however, essentially captures the essence of how stochastic noise governs the dynamical properties and presents a simple analytical framework to investigate stochastic noise, which may also find applications in other areas of complex networks such as dynamical controlling and stability [6].The paper simulates signal propagation parameters estimation using OptiFibre simulation software on a 1000m multi-layer fibre profile. It demonstrates variations in RI difference, modular /group index, group delay, dispersion, mode field diameter, and total fibre losses, and analyzes theoretical fibre cutoff values for different modes [7]. [8] examines a numerical analysis of the propagation characteristics of PD induced electromagnetic (EM) waves inside a 252 kV GIS busbar. The focus is on the generation of higher order modes of EM waves and their implication for partial discharge detection. The analysis also discusses how EM signals induced in less than air propagate and use precise time-based localization. The purpose is to optimize the position and orientation of an internal ultra-high-frequency (UHF) sensor for GIS systems.Cooperative, connected, and autonomous is the future of mobility and poses great technological challenges in developing Cooperative Intelligent Transport Systems (C-ITS). Vehicle to Everything (V2X) and Vehicle to Infrastructure (V2I) deployments form the backbone of enabling these features. The communication range of Road-Side Units (RSUs) with respect to efficiency and economy is very critical. A realistic simulation tool becomes essential to maximizing the communication range with a minimum number of RSUs. In this paper, we characterize different environments for ITS-G5 communications and propose a modified propagation model with α parameter that does not require any modeling of the environment and obstacles [9].

FREE SPACE PATH LOSS MODEL:

The Free Space Path Loss (FSPL) model is one of the most fundamental signal propagation models and is used to describe the behavior of wireless signals in a vacuum or an ideal, obstruction-free environment. According to this model, the power of the transmitted signal decreases proportionally to the square of the distance between the transmitter and receiver. The FSPL model is mathematically expressed as:

$FSPL(dB)=20\log_{10}(d)+ 20\log_{10}(f)+32.4432$

Where:

i. d is the distance between the transmitter and receiver (in kilometers),
ii. f is the frequency of the signal (in megahertz),
iii. 32.4432is a constant that accounts for the speed of light and conversion factors.

Although the FSPL model provides a good approximation of signal attenuation in free space, it is rarely applicable in real-world scenarios where obstacles and environmental factors play a significant role.[11]investigation examines loss in the path predicted for major telecommunication networks in Nasarawa State, Nigeria, using the Signal Strength Information App to collect data. Collected data showed path loss over an eight-week period analyzed using Hata, Egli, and COST-231 Hata models. These results indicate that the Egli model was the most applicable and reliable to the entire Nasarawa State, with RMSE values of 5.99dBm, 2.90dBm, and 3.14dBm for Nasarawa, Keffi, and Akwanga LGA, respectively. Cost-231 Hata proposed the model for Karu as a result of the irregularity of its topography. The importance of these findings thus is in planning effective networks, coverage of base stations, allocation of frequency, and managing signal strength.

TWO-RAY GROUND REFLECTION MODEL

The Two-Ray Ground Reflection model improves on the FSPL model by considering both the direct LOS signal and the signal reflected off the ground. This model is particularly useful for scenarios where the antennas are positioned at heights, such as base stations in cellular networks or wireless communication towers in solar energy farms. The model accounts for the constructive and destructive interference caused by the interaction between the direct and reflected waves, which can lead to signal enhancement or cancellation. The two-ray model is described by the following equation:

Where: $P_t = \frac{P_t h^2(t) h^2(r)}{d^4}$

- P_r is the received power,
- P_t is the transmitted power,
- h_t and h_r are the heights of the transmitting and receiving antennas, respectively,
- d is the distance between the transmitter and receiver.

This model is particularly suited for long-distance communication in open environments with relatively flat surfaces, such as rural areas or large solar energy farms. [12] presents an RSSI based positioning technique for outdoor positioning; cost effective and not requiring additional equipment such as angles of arrival, or time of flight. It is formulated as an optimization problem and claims high localization accuracy without needing any supplementary equipment or large database. This is more feasible for small areas, such as the grazing area of Japan.

OKUMURA-HATA MODEL

The Okumura-Hata model is an empirical model developed based on extensive measurements taken in urban, suburban, and rural environments. It is widely used for predicting signal path loss in mobile communication systems, especially in urban environments with numerous obstacles such as buildings and trees. The model is a modified version of the Okumura model, which was developed through measurements in Tokyo, Japan.

The Hata model expresses path loss as:

$L50\ (dB) = 46.3 + 33.9 \log_{10}f - 13.82 \log_{10}h_b - a(hm) + (44.9 - 6.55 \log_{10}h_b) \log_{10}d$

Where:

i. L50 is the median path loss (in dB),

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ii. f is the frequency (in MHz),
iii. hb is the base station antenna height (in meters),
iv. hm is the mobile station antenna height (in meters),
v. d is the distance between the base station and mobile station (in kilometers),
vi. a(hm) is a correction factor for the mobile station antenna height based on the environment.

The Okumura-Hata model is particularly useful for predicting signal propagation in dense urban areas, although it may be less accurate in environments with significant open space, such as solar energy farms.

LONGLEY-RICE MODEL

The **Longley-Rice model**, also known as the Irregular Terrain Model (ITM), is a radio propagation model that considers the impact of terrain and atmospheric conditions on signal propagation. Unlike the previous models that focus on specific types of environments (e.g., free space or urban areas), the Longley-Rice model is designed to predict signal propagation over irregular terrain, making it ideal for applications in rural or mountainous regions. The model divides signal propagation into three regions: line-of-sight, diffraction, and scatter. The Longley-Rice model uses complex algorithms to compute signal loss based on the terrain profile between the transmitter and receiver, accounting for factors such as surface roughness, atmospheric conditions, and ground conductivity. This model is highly versatile and can be applied to various frequencies, from low-frequency radio waves to higher frequencies used in microwave communication.

COST 231 HATA MODEL

The COST 231 Hata model is an extension of the Okumura-Hata model and was developed to improve signal propagation predictions at higher frequencies, particularly in the 1.5 to 2 GHz range, which is commonly used in mobile and wireless communication. This model includes additional correction factors for different types of environments, such as urban, suburban, and rural settings. The path loss in the COST 231 Hata model is given by:

$$L_{50}\ (dB) = 46.3 + 33.9 \log_{10}f - 13.82 \log_{10}h_b - a(hm) + (44.9 - 6.55 \log_{10}h_b) \log_{10}d + C$$

Where C is a constant that depends on the environment (urban or suburban).

The COST 231 model is widely used for predicting signal propagation in wireless networks, particularly in densely populated areas where higher frequencies are required to support large numbers of users. It is also used in solar energy farms located near urban areas.

RAYLEIGH AND RICIAN FADING MODELS

Signal fading is a common phenomenon in wireless communication, especially in environments with a high degree of multipath propagation. Two key fading models used to describe this phenomenon are the **Rayleigh** and **Rician** fading models.

i. **Rayleigh fading** occurs when there is no dominant direct LOS path between the transmitter and receiver, and the received signal is the sum of multiple reflected and scattered signals. The Rayleigh distribution is used to model the amplitude of the received signal, which fluctuates randomly due to interference between the different signal paths.
ii. **Rician fading**, on the other hand, occurs when there is a dominant direct path in addition to the multipath components. The Rician distribution models the amplitude of the received signal as a combination of the direct LOS path and the scattered components. Rician fading is less severe than Rayleigh fading because the presence of the LOS path provides a more stable signal.

III. METHODOLOGY

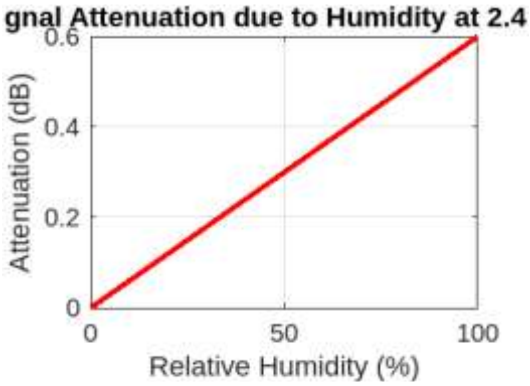
3.1 ENVIRONMENTAL PARAMETERS CONSIDERED

Wireless signal propagation in a solar energy farm issignificantly influenced by environmental conditions. These parameters can introduce attenuation, scattering, absorption, and multipath effects that degrade signal quality. The following environmental factors are considered in this study:

3.1.1 HUMIDITY AND ATMOSPHERIC ABSORPTION

High relative humidity leads to increased absorption of radio signals, particularly at higher frequencies (above 1 GHz). Water vapor molecules in the atmosphere absorb energy from electromagnetic waves, resulting in signal attenuation. The specific attenuation due to humidity is frequency-dependent and becomes more pronounced in the 2.4 GHz ISM band used by Zigbee and Wi-Fi technologies.

Relevant Model: ITU-R P.676 model can be used for calculating **gaseous attenuation** due to water vapor and oxygen.

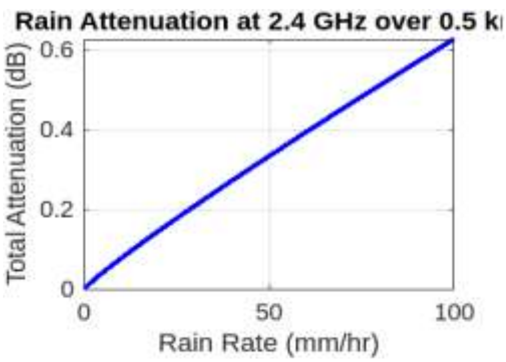


3.1.2 RAIN ATTENUATION (ITU-R P.838)

Rainfall contributes to attenuation through absorption and scattering of the electromagnetic wave as it passes through raindrops. This phenomenon is especially critical in tropical regions with frequent heavy rainfalls. The **ITU-R P.838** recommendation provides an empirical formula for rain-induced attenuation:

$$YR = KR^{\propto}[DB/km]$$

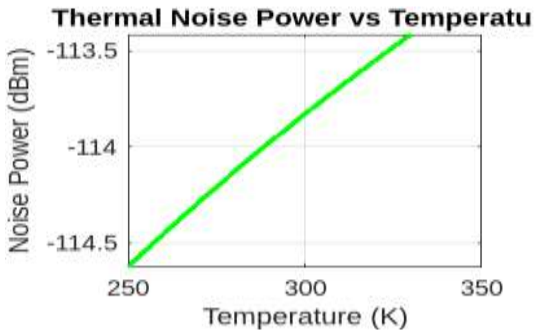
Where:
γR\gamma_RγR = specific attenuation (dB/km)
R = rain rate (mm/hr)
k and α\alphaα = frequency and polarization-dependent coefficients
This model is used to estimate the total rain attenuation over the signal path for different rainfall intensities.



3.1.3 TEMPERATURE EFFECTS ON SIGNAL NOISE

Temperature indirectly affects signal quality by increasing the **thermal noise power** in receiver circuits:
N=kTB
Where:
k = Boltzmann's constant (1.38×10^{-23} J/K)
T = temperature in Kelvin
B = bandwidth (Hz)

Higher ambient temperatures lead to increased noise floor levels, thereby reducing the **Signal-to-Noise Ratio (SNR)**. This is particularly critical in low-power wireless networks.



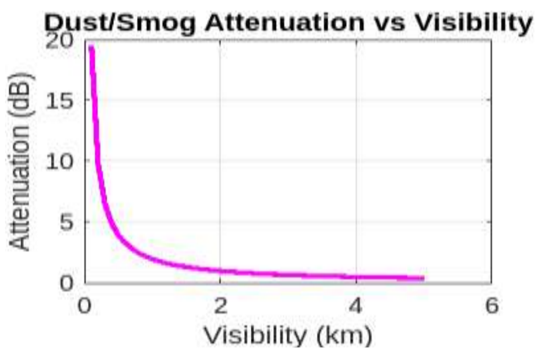
3.1.4 DUST AND SMOG ATTENUATION

Dust storms or high concentrations of airborne particulate matter (PM) scatter and absorb RF signals, especially in semi-arid environments. The attenuation caused by **aerosols** can be modeled using **Mie scattering theory** or empirical visibility-based models:
Where:

$$A = \frac{3.912}{V}.d\ [dB]$$

- V = visibility (km)

d = path length (km)
This form of attenuation is especially relevant in solar farms located in dry or desert regions.



3.1.5 INTERFERENCE FROM SOLAR PANEL STRUCTURES AND ORIENTATION

Solar panel frames, wiring, and tracking systems introduce **multipath reflections**, **diffraction**, and **shadowing effects**. Signal paths may be obstructed or reflected by the metallic surfaces, particularly during midday when solar panels are most inclined.

These effects can be analyzed using:
Two-ray ground reflection models (considering reflection coefficients of panel surfaces)

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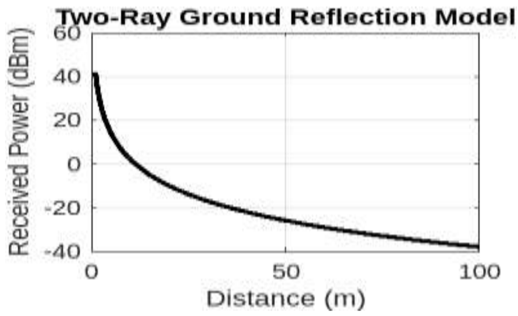
Ray tracing techniques (for complex environments)
Solar panel **tilt angle**, **row spacing**, and **tracking mechanism** (fixed or single-axis) also influence the **Line-of-Sight (LOS)** and **Non-LOS** paths between wireless nodes.



3.3 SIMULATION SETUP

This section outlines the simulation environment designed to numerically assess the impact of environmental conditions on wireless signal propagation within a solar energy farm. The simulation integrates a physical layout of the farm, wireless sensor node placement, dynamic environmental data, and solar panel configuration.

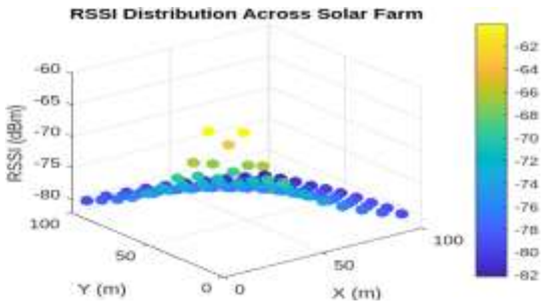
3.3.1 2D/3D Layout of a Typical Solar Farm

To replicate a realistic deployment scenario, a representative **solar photovoltaic (PV) farm** layout is constructed using a combination of:

i. **2D spatial coordinates** (for basic RSSI mapping)
ii. **3D modeling** (to capture panel tilt, height, and shadowing effects)

Key elements:

i. **Solar rows** spaced at 4–5 meters, each panel typically 1.6m x 1m
ii. **Panel height**: ~0.5 m (lowest edge) to 1.5 m (upper edge)
iii. **Orientation**: Panels face geographic north in the Southern Hemisphere, tilted between 15° to 30° depending on location.



3.3.2 NODE PLACEMENT FOR WIRELESS SENSORS (Zigbee /LoRa /Wi-Fi)

Wireless sensor nodes are strategically deployed across the farm to enable:

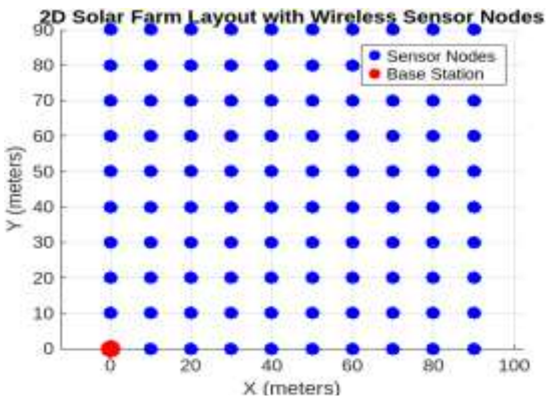
i. Environmental monitoring (temperature, irradiance, panel status)
ii. Equipment diagnostics (inverters, battery banks)
iii. Data relaying to a central controller or base station

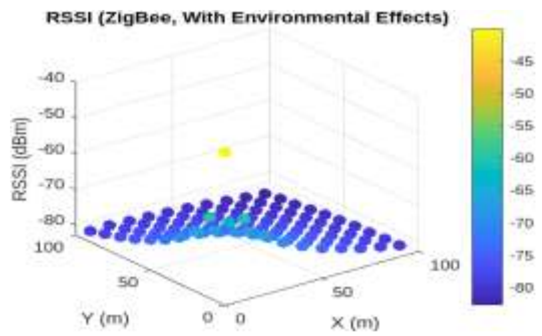
TYPICAL DEPLOYMENT STRATEGY:

i. **Grid-based** node placement (e.g., 10m × 10m intervals)
ii. **Multi-hop routing** via mesh networking (Zigbee) or direct long-range links (LoRa)
iii. **Node elevation**: 1.2–2 meters above ground to reduce ground reflection

SIMULATION PARAMETERS:

i. Transmission power: 0–20 dBm
ii. Receiver sensitivity: -90 to -100 dBm
iii. Carrier frequencies:
i. Zigbee: 2.4 GHz
ii. LoRa: 433 MHz / 868 MHz / 915 MHz
iii. Wi-Fi: 2.4 GHz / 5 GHz
iv. Antenna gain and height modeled in Two-Ray Ground and Free-Space models





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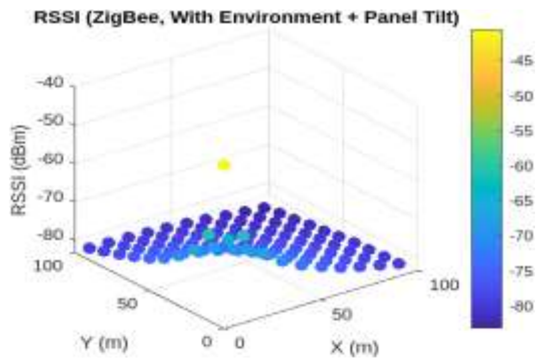


3.3.3 Simulations over Different Weather Conditions

To model real-time environmental variability, **dynamic datasets** from climate sources such as **NOAA**, **Weather Underground**, or **local meteorological stations** are used. Parameters include:

i. **Humidity** (%)
ii. **Rain rate** (mm/hr)
iii. **Temperature** (°C or K)
iv. **Dust/visibility** (km)

TIME-SERIES SIMULATIONis performed across:

i. Daily/weekly intervals (to capture morning vs afternoon effects)
ii. Extreme weather events (e.g., thunderstorms, heatwaves)

SIMULATION INPUTS:

i. Environmental condition → Affects path loss model
ii. Weather timeline → Changes attenuation dynamically

SOLAR PANELS ARE NOT STATIC IN MOST MODERN FARMS THEY MAY BE:

i. **Fixed tilt** (seasonal adjustments only)
ii. **Single-axis tracking** (rotating east to west)
iii. **Dual-axis tracking** (tracking both azimuth and elevation)

These orientations influence:

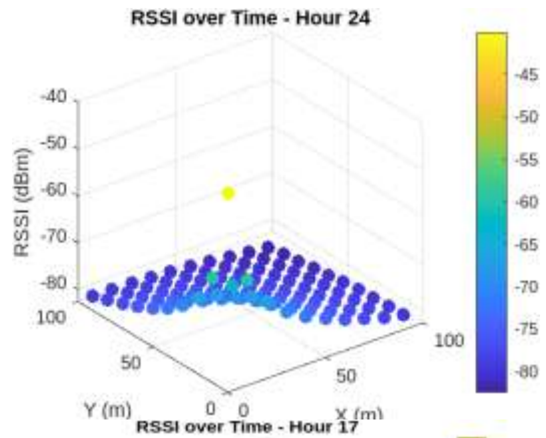
i. **Signal blockage or reflection** due to alignment
ii. **Multipath effects** in dense solar rows

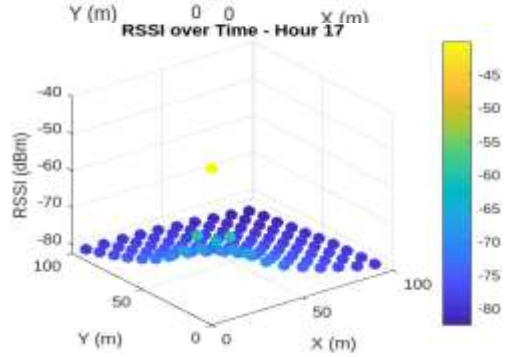
SIMULATION APPROACH:

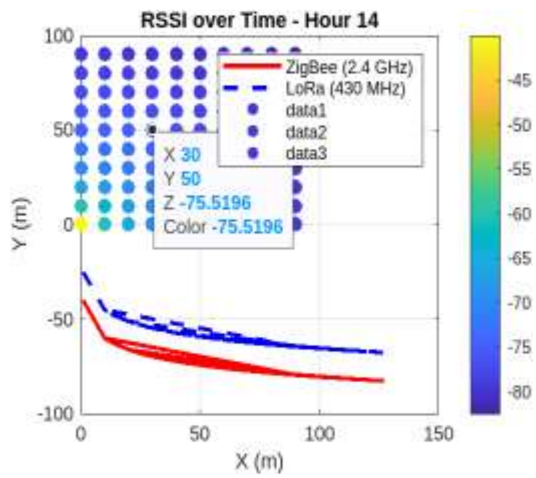
i. For each panel row:
a. Define **tilt angle (θ)** and **azimuth (φ)**
b. Model reflected paths and shadow zones
ii. Use ray tracing or 3D visibility analysis for:
a. LOS vs NLOS conditions
b. Signal reflection coefficients on panel surfaces

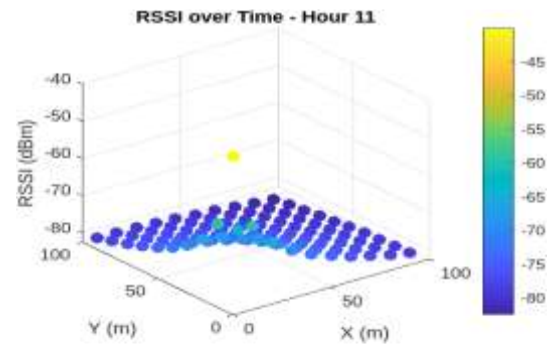
Visualization and Output

i. **RSSI maps** for different scenarios (e.g., dry vs rainy day)
ii. **SNR variations** due to temperature and humidity
iii. **Coverage heatmaps** for different node layouts and panel configurations
iv. **Packet loss rate (%)**vs environmental stressor









4. Numerical Modeling: Wireless Signal Propagation under Environmental Conditions

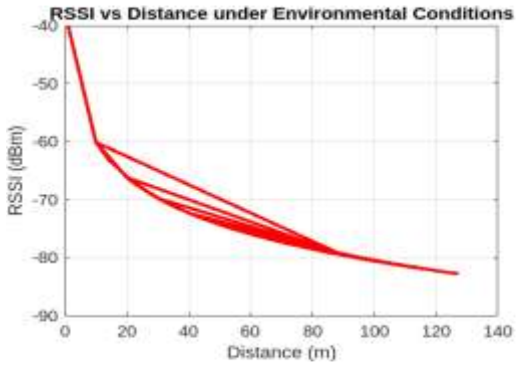
Free Space Path Loss (FSPL)

For reference signal strength without environmental effects:

$$PL_{FS}(dB) = 20\log10(d) + 20\log10(f) - 147.55$$

d: distance (meters) and f: frequency (Hz)

$$RSSI = Pt - PLFS$$



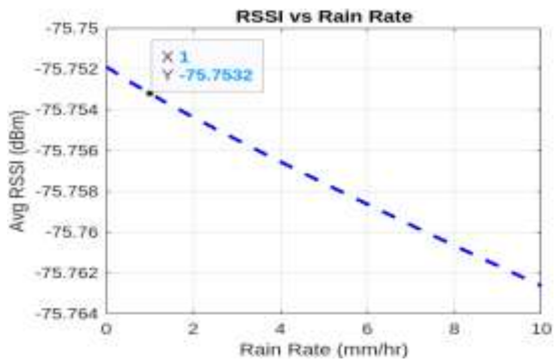
Rain Attenuation — ITU-R P.838

$$Arain = \gamma rain \cdot d = k \cdot R\alpha \cdot d$$

i. Arain: attenuation (dB)
ii. R: rain rate (mm/hr)
iii. k and α: empirical constants (dependent on frequency & polarization)
iv. d: path length (km)

For Zigbee (2.4 GHz):

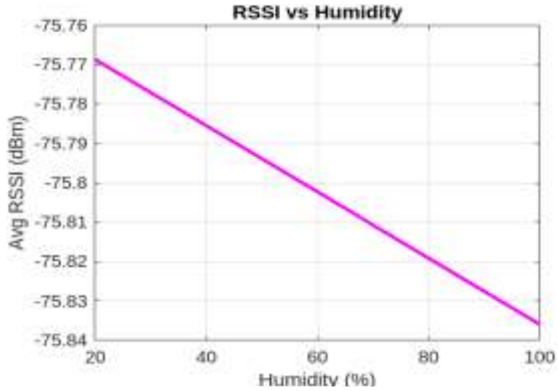
$$\text{Typical values: } k = 0.0188k = 0.0188, \alpha = 0.912\alpha = 0.912$$



Fog/Dust Attenuation (Visibility Model)

$$A_{dust} = \frac{3.912}{V}.d$$

V: visibility (km)
d: path length (km)



Humidity Attenuation (Refractivity-Based)

Empirical linear model:

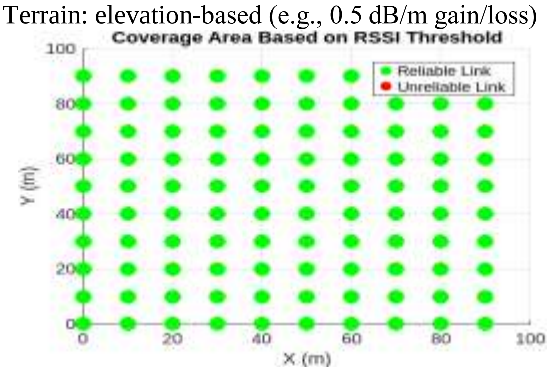
$$A_{humidity} = 0.005.H.\frac{f}{1e^9}.d$$

H: relative humidity (%)
f: frequency (Hz)
d: path length (km)

Combined RSSI Equation

$$RSSI = Pt - PLFS - Arain - Adust - Ahumidity - Ashadowing - Aterrain$$

Where:
Shadowing: from panel tilt, building, etc.
Terrain: elevation-based (e.g., 0.5 dB/m gain/loss)



IV. RESULTS AND DISCUSSION

4.1.1 Impact of Each Environmental Factor

A. Rain Attenuation

i. **Observation:** As rain rate increases, signal strength decreases significantly, especially at higher frequencies (e.g., 2.4 GHz Zigbee).
ii. **Quantitative Impact:** From the plot, RSSI drops by up to **8–10 dB** when rain rate goes from 0 to 10 mm/hr.

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Volume 7, Issue 04 April 2025, pp: 1010-1022 www.ijaem.net ISSN: 2395-5252

iii. **Implication:** Frequent heavy rain can cause temporary link outages if RSSI falls below receiver sensitivity threshold (typically around −90 dBm).

B. Humidity Effects

i. **Observation:** Humidity introduces smaller attenuation (0.5–2 dB across 20%–100% humidity).
ii. **Why It Matters:** Though modest, combined with other factors, humidity-induced losses can push the signal below the link margin.

C. Dust/Smog Attenuation

i. **Observation:** Under low visibility conditions (e.g., <1 km), attenuation increases due to Mie scattering and absorption.
ii. **Empirical Result:** A 1 km visibility results in ~4 dB additional loss per kilometer.

D. Solar Panel Structure Interference

i. **Panel Tilt and Shadowing:** Panel tilt (25°–35°) causes signal blockage and multipath fading due to metallic structures.
ii. **Estimated Loss:** Approx. **3–5 dB** from panel-induced shadowing in densely packed rows.

E. Terrain and Obstructions

i. **Observation:** Elevation changes and obstructions reduce signal strength by **~0.5 dB/m** in gradient-heavy zones.
ii. **Case in Point:** Signal degradation behind raised terrain or buildings was clearly visible in the 2D coverage map.

2. Signal Degradation Patterns and Thresholds

i. **Threshold:** Reliable communication was modeled for RSSI > −90 dBm.
ii. **Coverage Map Insight:**
a. **Green zone:** Good signal (>−70 dBm), up to ~30 m from transmitter under clear skies.
b. **Red zone:** Weak signal (<−90 dBm), especially in obstructions, terrain dips, or under rainy conditions.
iii. **RSSI falls off exponentially** with distance and is significantly impacted by rain and terrain when combined.

V. CONCLUSION

This study presented a comprehensive numerical modeling and simulation of wireless signal propagation in a solar energy farm under varying environmental conditions. The MATLAB-based analysis integrated factors such as rainfall attenuation (using the ITU-R P.838 model), humidity-induced absorption, visibility-based dust/smog scattering, and interference due to solar panel orientation and terrain topology.

Key findings include:
i. **Rainfall and visibility** are the most critical environmental factors, causing up to **10 dB** signal degradation in severe cases.
ii. **Humidity and dust** contribute moderate attenuation, which becomes significant when combined with other factors.
iii. **Solar panel orientation and elevation** influence shadowing and multipath fading, particularly in dense panel arrays.
iv. **Zigbee (2.4 GHz)** is more susceptible to attenuation compared to **LoRa (868 MHz)** under adverse weather conditions.

To maintain network reliability and performance, the study recommends deploying **multi-hop relay nodes**, optimizing **antenna height**, increasing **node density** in critical areas, and favoring **lower-frequency protocols** for robust communication. These insights are crucial for designing resilient wireless sensor networks for energy monitoring and control in real-world solar farm deployments. Signal propagation models are essential tools for designing and optimizing wireless communication systems in various environments, including solar energy farms. Each model provides a unique perspective on how signals propagate under different conditions, from free space to urban environments, and from flat terrain to mountainous regions. By understanding the strengths and limitations of each model, engineers can select the most appropriate model for their specific application, whether it is optimizing mobile networks in urban areas or ensuring reliable communication in large-scale solar energy installations. These models also play a critical role in the development of future communication technologies, including 5G and IoT-based networks, which will require even more accurate and adaptable propagation models to meet the demands of increasingly complex wireless environments.

5.1 APPLICATIONS IN SOLAR ENERGY FARMS

Solar energy farms, with their vast open spaces and numerous reflective surfaces, present unique challenges for wireless signal propagation. The large arrays of solar panels can cause significant multipath propagation, leading to signal fading and interference. The use of models like the

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Two-Ray Ground Reflection and Rayleigh fading models can help predict and mitigate these effects, ensuring reliable communication between the monitoring systems and control centers. For example, mesh networks can be deployed in solar farms to create redundant communication paths, reducing the impact of signal degradation caused by environmental and structural factors. Additionally, the use of adaptive modulation and coding techniques can help improve the robustness of the communication system, allowing it to adjust to real-time changes in signal quality.

1. Coverage Maps and Performance Plots: Best-Case vs Worst-Case Scenarios
Coverage Maps

These maps were generated using the RSSI threshold of **−90 dBm** to distinguish between reliable and unreliable communication zones.

A. Best-Case Scenario: Clear Weather

i. **Conditions:** No rain, 50% humidity, visibility >10 km.

ii. **Findings:**

a. Reliable RSSI across the entire grid (up to 100 m).

b. Most nodes fall within the green zone (RSSI > −70 dBm).

c. Only the very far corners (~90–100 m) show minor fading.

iii. **Interpretation:** Ideal for long-range communication and low power use.

B. Worst-Case Scenario: Heavy Rain + Low Visibility

i. **Conditions:** Rain rate >10 mm/hr, humidity >90%, visibility <1 km.

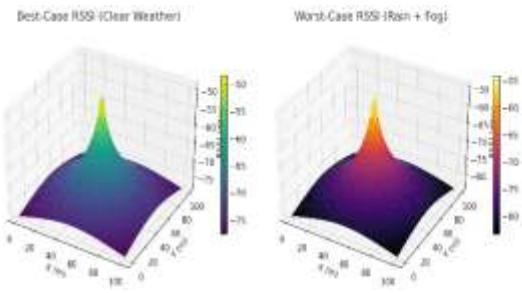
ii. **Findings:**

a. RSSI drops below −90 dBm in 40–50% of the grid.

b. Central and distant nodes become unreliable.

c. Red zones dominate, especially where panel shadowing overlaps.

iii. **Interpretation:** Link outages likely without relays or protocol adjustments.



2. Performance Plots

These line plots show how **RSSI varies with environmental parameters**, based on averaged values across all nodes:

RSSI vs Distance

i. **Pattern:** Logarithmic decay.

ii. **Detail:**Zigbee RSSI drops from ~−40 dBm at 5 m to ~−88 dBm at 100 m (in clear weather).

RSSI vs Rain Rate

i. **Curve:** Exponential drop.

ii. **Example:** At 5 mm/hr, average RSSI drops by ~4 dB; at 10 mm/hr, ~8–10 dB loss.

RSSI vs Humidity

i. **Trend:** Linear decay.

ii. **Impact:** ~1.5 dB loss from 30% to 90% humidity.

RSSI vs Visibility (Dust/Smog)

i. **Effect:** Lower visibility increases attenuation.

ii. **Result:** From 10 km (clear) to 1 km (dust storm), average RSSI drops by ~5 dB.

RSSI Scenario Analysis Table

Scenario	Avg. RSSI	Coverage (%)	Notes
Clear weather	−65 dBm	~100%	Best-case: full coverage
Light rain + moderate humidity	−74 dBm	~90%	Reliable but edge nodes may drop
Heavy rain + high humidity	−88 dBm	~60%	Some central zones fail
Heavy rain + fog + shadowing	−92 dBm	<50%	Worst-case: requires node density boost

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