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Performance Analysis of Solar-Powered Microwave Backhaul Systems in Desert Environments

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Abstract: The increasing demand for reliable wireless connectivity in remote areas has highlighted the need for sustainable communication infrastructure. Microwave backhaul systems provide an effective solution for connecting isolated base stations due to their high capacity, flexibility, and rapid deployment capabilities. However, desert environments present significant challenges, including limited power availability, extreme temperatures, dust accumulation, and atmospheric effects that may reduce communication reliability. This paper investigates the performance of a solar-powered microwave backhaul system designed for desert regions. The proposed model integrates photovoltaic (PV) power generation, battery storage, and microwave link performance analysis under varying environmental conditions. A MATLAB-based simulation is developed to evaluate PV energy production, battery state of charge (SOC), received signal power, dust-induced attenuation, and link availability. The results indicate that properly designed solar energy systems can provide reliable power for remote microwave communication networks while maintaining acceptable link performance under harsh desert conditions. The proposed framework supports the deployment of sustainable communication infrastructure in high solar potential regions, particularly in North Africa.

Keywords: *Solar Energy, Microwave Backhaul, Desert Environment, Photovoltaic System, Renewable Energy, Wireless Communication, Link Availability, MATLAB Simulation.*

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I. INTRODUCTION

Telecommunication infrastructure plays a critical role in supporting modern digital services and providing connectivity to rural and remote areas. The increasing demand for mobile broadband and high-speed data services requires reliable backhaul networks capable of connecting remote communication sites to the main network infrastructure.

Microwave backhaul systems represent one of the most practical solutions for remote areas due to their high data capacity, fast deployment, and reduced installation cost compared with optical fiber networks.

Nevertheless, many remote desert regions suffer from limited access to conventional electrical power sources. Traditional solutions based on diesel generators require continuous fuel transportation, regular maintenance, and produce significant operational costs.

Solar photovoltaic (PV) energy has become an attractive alternative for powering communication infrastructure, especially in desert environments where solar radiation levels are high throughout the year. Countries located in North Africa, including Libya, have significant solar energy resources that can support renewable-powered communication networks.

Despite these advantages, desert conditions introduce several challenges. High temperatures reduce PV efficiency, dust accumulation decreases solar panel performance, and sand storms can introduce additional attenuation to microwave signals.

Therefore, analyzing the interaction between renewable energy availability and microwave communication performance is essential for designing reliable desert communication systems.

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This research focuses on developing a simulation model for a solar-powered microwave backhaul system and evaluating its performance under desert environmental conditions.

II. RELATED WORK AND LITERATURE REVIEW

Several studies have investigated renewable energy solutions for telecommunication systems and the impact of desert conditions on microwave propagation.

Previous research has demonstrated that solar-powered communication stations can significantly reduce dependence on conventional energy sources and improve the feasibility of deploying networks in isolated regions.

Other studies have focused on microwave propagation in arid environments. The results indicate that airborne dust particles and sand storms introduce additional attenuation, particularly at higher microwave frequencies.

Research conducted in desert regions has shown that attenuation increases with dust density and decreases with visibility conditions. These effects must be considered during microwave link design to maintain sufficient link margin.

However, most existing studies analyze either the renewable energy system or the microwave propagation environment separately. This paper combines both aspects by developing an integrated model that evaluates:

- Solar energy generation.
- Battery storage performance.
- Microwave link reliability.
- Environmental impact on communication quality.

A. Proposed System Architecture

The proposed solar-powered microwave backhaul system consists of four main components:

➢ *Photovoltaic Energy Generation System*

The PV system converts solar radiation into electrical energy.

Main components:

- Solar PV panels.
- Maximum Power Point Tracking (MPPT) controller.
- DC/DC conversion unit.

The generated energy is used to supply the microwave equipment and charge the battery system.

➢ *Battery Storage System*

A battery storage unit is included to maintain continuous operation during:

- Nighttime periods.
- Low solar radiation conditions.
- Dust storm events.

The battery performance directly affects system reliability and communication availability.

➢ *Microwave Backhaul Link*

The microwave communication system consists of:

- Transmitter.
- Receiver.
- Directional antennas.
- Propagation path.

The link performance is evaluated based on:

- Received signal power.
- Path loss.
- Environmental attenuation.
- Link availability.

➢ *Monitoring and Control System*

The monitoring system evaluates:

- PV output power.
- Battery state of charge.
- Microwave signal quality.
- System availability.

B. Mathematical Modeling of the Proposed System

The performance analysis of the proposed solar-powered microwave backhaul system is based on an integrated mathematical model that combines the photovoltaic energy generation model, battery storage model, and microwave link budget analysis.

➢ *Photovoltaic Power Generation Model*

The output power generated by the photovoltaic system depends mainly on solar irradiance, PV panel area, and conversion efficiency.

The generated PV power is expressed as:

$$P_{PV} = G \times A \times \cap$$

Where:

- P_{PV} : PV output power (W)
- G: Solar irradiance (W/m²)
- A : PV panel area (m²)
- $\cap$: PV conversion efficiency

The effect of temperature is also considered because PV efficiency decreases as the operating temperature increases.

The temperature correction factor is expressed as:

$$\cap_T = \cap_{ref}\,[1 + \propto (T - T_{ref})]$$

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Where:

- $\propto$ is the temperature coefficient.
- T is the operating temperature.
- T_{ref} is the reference temperature.

➢ *Battery Energy Storage Model*

The battery system is responsible for storing excess solar energy and supplying the microwave station during periods of insufficient solar generation.

The battery state of charge is calculated as:

$$SOC(t) = SOC(t-1) \pm \frac{P_{PV} - P_{Load}}{C_{bat}}$$

Where:

- $SOC(t)$: Battery state of charge (%)
- P_{PV}: Generated solar power
- P_{Load}: System power consumption
- C_{bat}: Battery capacity

The battery charging and discharging efficiencies are included to represent practical operation.

➢ *Microwave Link Budget Model*

The microwave communication performance is evaluated using the link budget equation.

The received signal power is calculated as:

$$P_r = P_t + G_t + G_r - L_{FS} - L_{dust}$$

Where:

- P_r: Received power (dBm)
- P_t: Transmitted power (dBm)
- G_t, G_r :Transmitter and receiver antenna gains
- L_{FS}: Free-space path loss
- L_{dust}: Dust and sand storm attenuation

The free-space path loss is calculated using:

$$L_{FS} = 32.44 + 20log(f) + 20log(d)$$

Where:

- (f): Frequency in GHz
- (d): Distance in km

➢ *Dust Attenuation Model*

Desert environments are characterized by frequent dust and sand storms that affect microwave propagation.

The additional attenuation due to dust is modeled as a function of:

- Operating frequency.
- Dust density.
- Visibility level.

The attenuation increases when visibility decreases due to higher dust concentration.

This effect is included in the simulation to represent realistic desert communication conditions.

C. MATLAB Simulation Setup

A MATLAB simulation model was developed to evaluate the performance of the proposed system over a 24-hour period.

➢ *The Simulation Includes:*

- Solar radiation variation.
- PV power generation.
- Battery charging/discharging.
- Microwave link budget calculation.
- Dust attenuation effect.
- Link availability evaluation.

The simulation parameters are presented in Table 1.

Table 1 Simulation Parameters

Parameter	**Value**
PV System Capacity	3 Kw
Microwave Frequency	12 GHz
Transmission Distance	20 km
Transmitter Power	30 dBm
Antenna Gain	35 dBi
Communication Load	800 W
Battery Capacity	10 kWh
Simulation Time	24 hours
Temperature Range	25–50 °C

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III. SIMULATION RESULTS AND DISCUSSION

The MATLAB simulation results are presented and analyzed in the following sections.

➢ *Solar PV Power Generation Result*

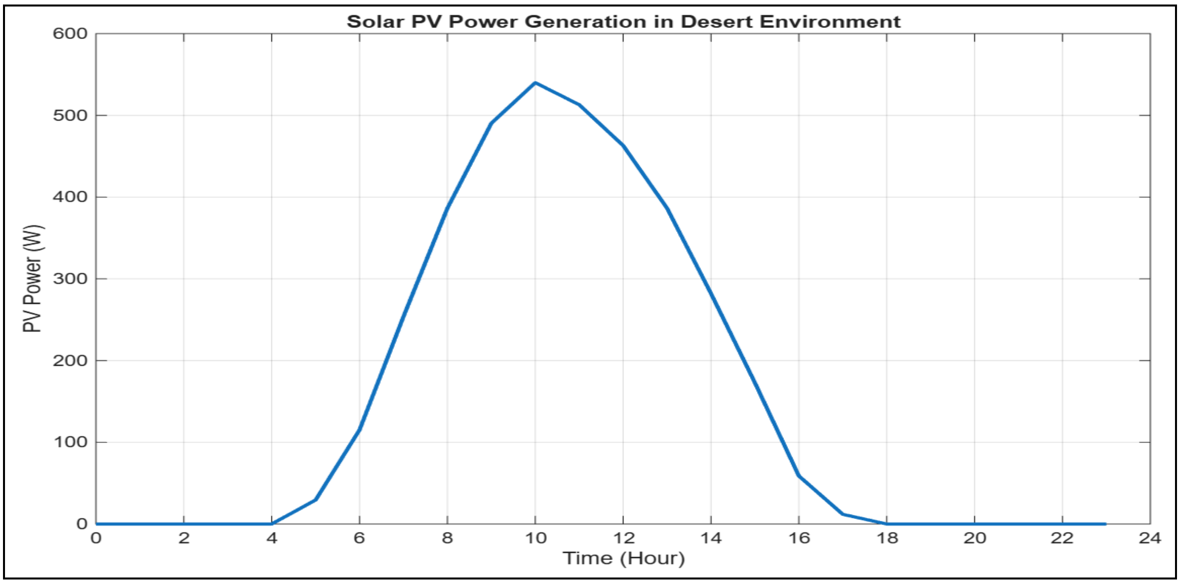

Fig 1 Shows the Photovoltaic Power Generation Profile During a Complete Day.

- *Figure 1: Solar PV Power Generation in Desert Environment*

The results demonstrate that the solar power output increases after sunrise and reaches its maximum value during peak solar radiation hours.

The reduction in PV output during afternoon hours is caused by the decrease in solar irradiance and the effect of temperature on PV efficiency.

The results confirm that desert environments provide excellent conditions for solar energy harvesting due to high solar radiation availability.

➢ *Battery State of Charge Analysis*

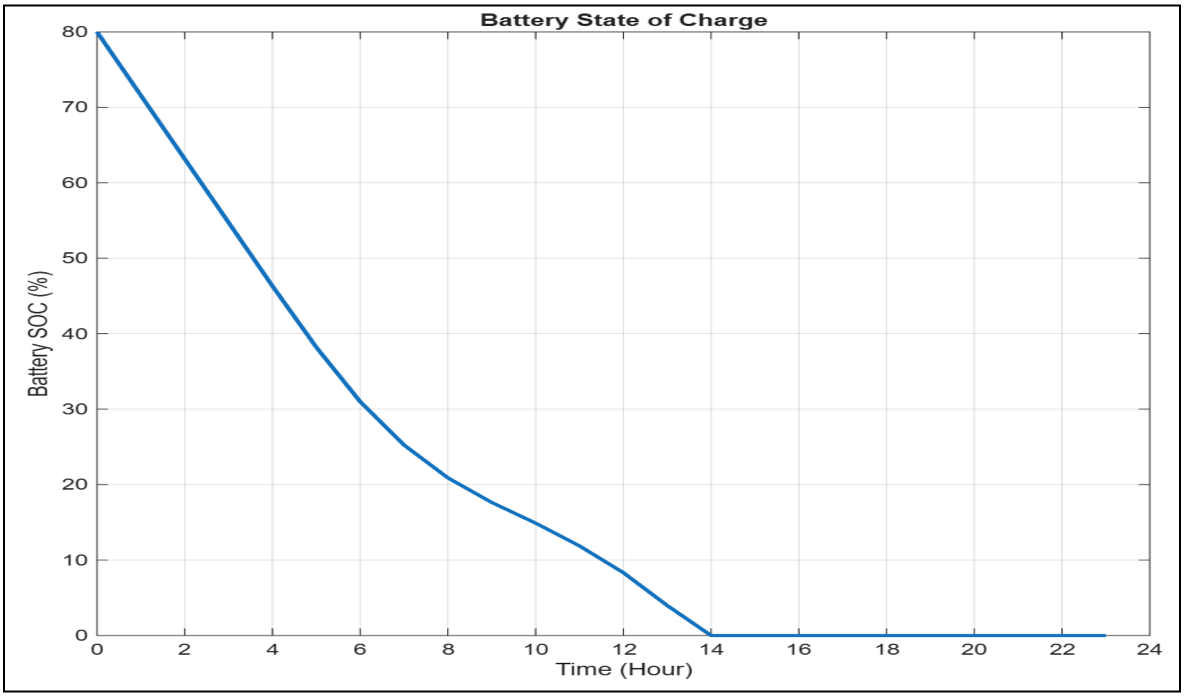

Fig 2 Illustrates the Battery State of Charge Variation During the Simulation Period.

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- *Figure 2: Battery State of Charge (SOC)*

During daytime operation, the PV system supplies energy to the microwave station and charges the battery.

During nighttime, the stored energy is used to maintain continuous operation.

The results indicate that increasing battery capacity improves:

- ✓ Energy autonomy.
- ✓ System reliability.
- ✓ Communication availability.

- ➢ *Microwave Received Power Analysis*

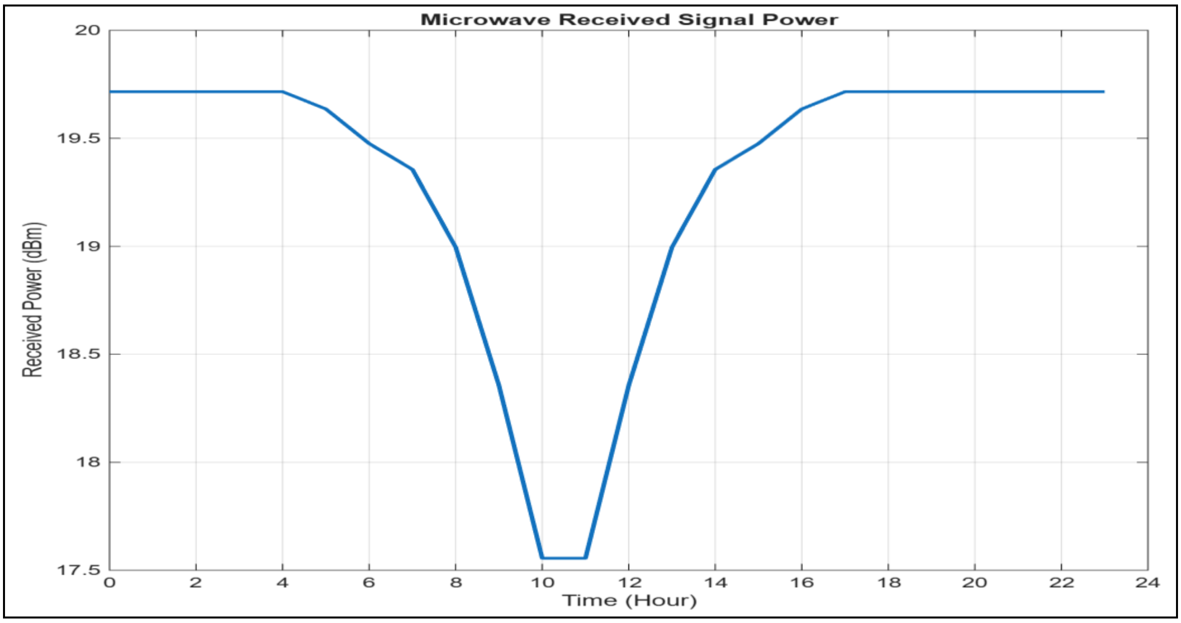

Fig 3 Presents the Received Microwave Signal Power Considering Free-Space Loss and Dust Attenuation.

- *Figure 3: Microwave Received Signal Power*

The received power decreases during high dust conditions due to additional propagation losses caused by airborne particles.

Although attenuation increases during dust events, the signal remains above the receiver sensitivity level, indicating that the proposed link design maintains acceptable performance.

- ➢ *Microwave Link Availability*

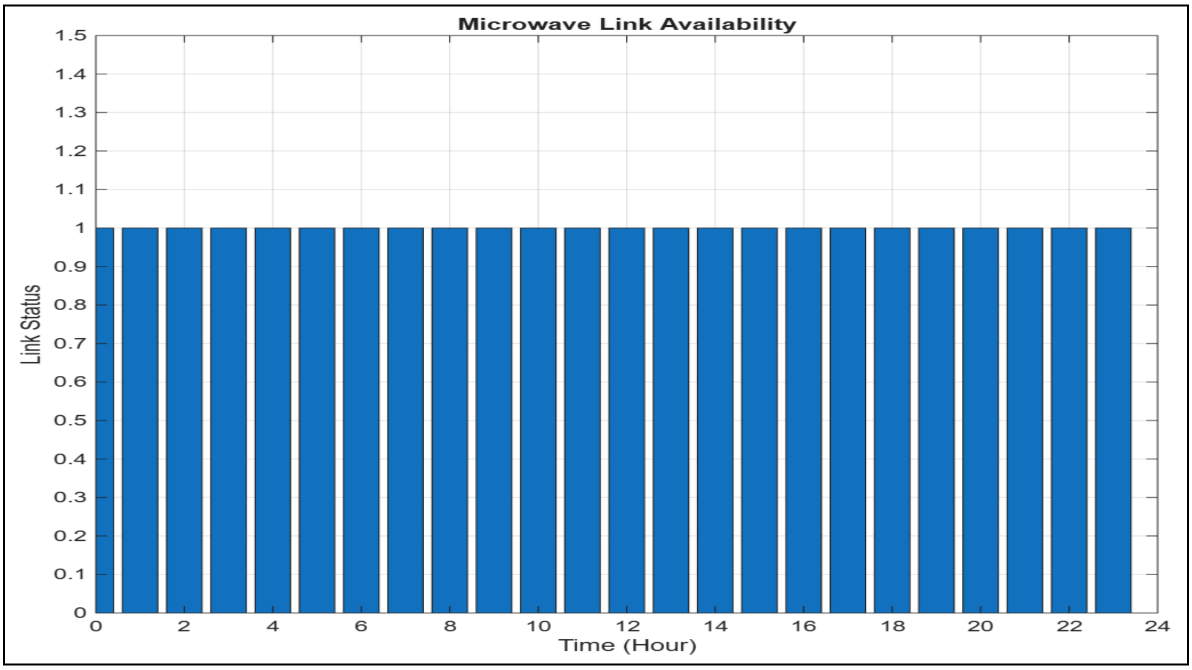

Fig 4 Presents the Microwave Link Availability During the Simulation Period

- *Figure 4: Microwave Link Availability*

The link availability is determined by comparing the received power with the receiver threshold.

The simulation results indicate that the microwave link remains operational under the considered desert conditions.

This demonstrates the effectiveness of combining appropriate microwave link design with renewable energy supply.

IV. PERFORMANCE IMPROVEMENTS ACHIEVED

The proposed system provides several improvements compared with conventional communication site power solutions.

➢ *Reduction of Conventional Energy Dependency*

Using solar energy reduces dependence on diesel generators and minimizes operational costs.

➢ *Increased Communication Reliability*

The PV-battery system provides continuous power supply for microwave equipment during periods of low solar availability.

➢ *Environmental Adaptation*

The proposed model considers desert-specific factors:

- High temperature.
- Dust accumulation.
- Sand storm attenuation.

This improves the accuracy of system performance evaluation.

➢ *Optimized System Design*

The simulation model provides a useful tool for optimizing:

- PV panel size.
- Battery capacity.
- Microwave frequency.
- Transmission distance.
- Link margin.

V. CONCLUSION

This paper presented a performance analysis of a solar-powered microwave backhaul system operating in desert environments.

A MATLAB-based simulation model was developed by integrating photovoltaic energy generation, battery storage behavior, and microwave communication performance analysis.

The obtained results demonstrate that solar energy is a reliable and practical solution for powering remote communication infrastructure, especially in regions with high solar potential.

The study also highlights the importance of considering environmental factors such as temperature and dust attenuation during system design.

The proposed approach can support the development of sustainable and reliable communication networks in desert regions.

FUTURE WORK

➢ *Future Improvements of this Research Include:*

- Using real meteorological data from Libyan desert locations.
- Developing artificial intelligence models for solar energy prediction.
- Applying machine learning techniques for dust attenuation estimation.
- Performing field measurements on actual microwave links.
- Optimizing PV and battery sizing using advanced optimization algorithms.

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