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ENHANCING SUSTAINABILITY AND ENERGY EFFICIENCY IN WIRELESS COMMUNICATION SYSTEMS THROUGH INTEGRATED RENEWABLE-POWERED ANTENNA DESIGN

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Abstract. In the context of wireless communication systems, the integration of renewable energy sources directly into antenna designs has emerged as a promising approach to enhance sustainability and energy efficiency. In order to solve the issue of providing wireless networks with a constant power supply. this research proposes a revolutionary system that combines solar and wind energy collecting with antenna architecture in a seamless manner. The system under consideration comprises several phases, commencing with the collection of energy via photovoltaic cells and small-scale wind turbines that are thoughtfully included into the antenna architecture. Then, using sophisticated energy conversion methods like charge controllers and inverters. these renewable energy sources are transformed into electrical power that may be used. Demand-side management (DSM) and firefly optimisation are used for smart energy management that dynamically allocate power to the antenna based on availability and demand in real-time, optimising energy distribution and utilisation. Additionally. the device has an effective antenna power supply mechanism that seamlessly switches between grid power and renewable energy when needed, utilising stored energy from renewable sources to maintain continuous operation. A site evaluation, advanced control algorithms for energy management, installation, monitoring, and maintenance of renewable energy components integrated with

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the antenna structure are all part of the proposed system flow. This novel method has the potential to improve wireless communication systems' resilience and performance in a variety of environments, paving the way for a more sustainable energy future.

Keywords: energy harvesting, photovoltaic cells, storage, wireless networks, utilisation, environmental sustainability, grid electricity, antenna design.

AIMS AND BACKGROUND

In rural communities of developing countries, access to affordable, reliable, and sustainable energy sources remains a pressing issue. Currently, reliance on diesel and kerosene for meeting energy needs not only poses environmental challenges due to their high pollution levels but also contributes to economic strain[1]. Moreover, the demand for higher power densities in electronic devices, especially those integrated with organisms necessitates the development of advanced power supply solutions[2]. Additionally, the traditional method of farming, while once effective, is now considered outdated and time-consuming. With the global population on the rise, there is a growing need to enhance agricultural productivity without compromising nutrient value, driving the search for innovative farming methods like hydroponics[3]. Furthermore, as the world transitions towards sustainable energy sources, the environmental impact of renewable energy technologies like wind and solar power must be thoroughly understood and addressed. Recycling technologies have advanced, providing valuable insights into the eco-design of modern power generation systems[4]. To sustainably satisfy the world's energy needs, effective energy collecting system development is still essential. In light of this, integrating solar energy with the kinetic energy of footfall offers a viable way to maximise energy conversion and produce sustainable power sources[5]. Furthermore, the problem of frequent charging can be solved by using wireless power transmission technologies, which work similarly to railroad tracks and use renewable resources like solar energy to power gadgets without causing pollution to the environment[6]. In conclusion, the problem statement emphasises the critical need for renewable resources to meet the expanding global energy demands, improve agricultural production, handle energy challenges in rural communities, and power electronic gadgets sustainably.

The fields of wireless communication and renewable energy have benefited from numerous studies. In order to improve system stability and efficiency, a thorough analysis[7] of wind-solar hybrid renewable energy systems (HRES) examines power architectures, converter topologies, and mathematical models. For anyone working in the renewable energy sector researchers, engineers, and policymakers this study provides insightful information. In the field of wireless communications, it was suggested[8] a microstrip patch antenna that is rectangular in shape and intended for 2.4 GHz usage. This design, which targets ISM band applications like Wi-Fi and Bluetooth and offers adaptability and compatibility with microwave integrated circuits, makes use of FR-4 substrate and a Microstrip 50Ω feedline. A tiny microstrip patch antenna that is tailored for ISM 2.4 GHz WBAN applications is also introduced[9], showing good efficiencies and stable radiation characteristics for both on-body and off-body communication. Furthermore, using Rogers RT/Duroid5880 substrate, it was proposed[10] a Microstrip Patch Antenna design suitable for future wireless communication at 2.4 GHz. The CST studio suite was used to model this investigation, which produced reduced return loss, gain, and VSWR. Simulation findings confirmed the improved antenna performance.

EXPERIMENTAL

ENERGY HARVESTING

A crucial part of our renewable-powered antenna design is energy harvesting, which is the targeted use of two main renewable energy sources: small-scale wind turbines for wind energy and photovoltaic cells for solar energy.

Photovoltaic cells. Photovoltaic cells, also referred to as solar panels, are devices that harvest solar energy, which is abundant and sustainable. These solar panels use semiconductors, usually silicon, that are made to absorb photons from sunshine and produce electricity via the process known as photovoltaic effect. Electricity is produced when sunlight reaches the solar panel's surface because it stimulates the electrons in the semiconductor material[11]. Choose areas that receive the most sunshine exposure possible during the day. To maximise energy generation, variables including shading, orientation, and tilt angle are taken into account. Install solar panels firmly on rooftops or in ground-level structures, making sure to align them properly and tilt them at the right angle to get the most sunlight possible. Achieve the desired output of voltage and current by connecting individual solar panels in either series or parallel arrangements. Install inverters to provide alternating current (AC) that can be used in the antenna system from the direct current (DC) produced by the panels. Install monitoring equipment to keep tabs on system performance and energy production. The best performance and longevity are ensured by routine maintenance, which includes cleaning panels and checking electrical connections.

Wind turbines. Small-scale wind turbines are used to absorb wind energy and transform it into electrical power, making wind energy another renewable resource. Usually, these turbines are made up of a tower, a generator, a rotor, and blades.

To guarantee effective energy generation, first locate areas with steady and adequate wind speeds, usually at least 5 to 6 m/s. To reduce turbulence and increase wind exposure, mount the wind turbine on a solid tower and place it above obstructions like trees and structures. Set up the turbine blades to optimally harness wind power. The length, form, and pitch angle of the blade are all tuned for maximum power generation. The wind drives the rotor attached to a generator by causing the turbine blades to revolve. The rotational energy is transformed into electrical power by the generator and supplied to the antenna system. The wind turbine system operates safely and dependably when it receives routine maintenance, which includes lubrication, inspection of the blades and tower, structure, and monitoring of electrical components. Through the efficient utilisation of photovoltaic cells and small-scale wind turbines, our renewable-powered antenna design efficiently captures solar and wind energy, offering wireless networks a dependable and sustainable energy source that lessens dependency on traditional grid electricity and minimises environmental impact[12–15].

ENERGY CONVERSION

An essential part of our renewable-powered antenna design is energy conversion, which uses charge controllers and inverters to effectively convert solar and wind energy into electrical power that can be used.

Inverters. The key component in the energy conversion process is an inverter, which makes it easier to convert the direct current (DC) output from solar panels and wind turbines into alternating current (AC) electricity that meets the needs of the antenna system and the standard electrical grid. To ensure smooth and effective functioning, these devices use complex electrical circuits made up of transistors, capacitors, and transformers to control voltage, frequency, and waveform characteristics. Synchronising the AC output with the frequency and phase of the grid is one of the inverters' most important roles; it allows renewable energy to be seamlessly integrated into the current power infrastructure. Inverters also use sophisticated control algorithms, including maximum power point tracking (MPPT), to maximise power output and optimise energy conversion in a variety of environmental scenarios. The operational conditions of the wind turbines and solar panels are continuously monitored by MPPT algorithms, which then modify the inverter's operating parameters to maximise available electricity. Energy harvesting efficiency and overall system performance are improved by MPPT-enabled inverters, which dynamically adjust to variations in temperature, wind speed, and solar intensity.

Charge controllers. In order to guarantee optimum performance and longevity, charge controllers are essential in controlling the charging process of the batteries used to store the harvested energy. These gadgets control the voltage and current coming from the wind turbines and solar panels to avoid overcharging, which shortens the life of the batteries[16]. Charge controllers maintain the ideal charging voltage of batteries and guard against overvoltage situations by using complex control algorithms like maximum power point tracking (MPPT) and pulse width modulation (PWM). PWM charge controllers effectively control the amount of energy delivered to the batteries by quickly turning on and off the connection between the solar panels or wind turbines and the batteries. This allows them to regulate the charging current. In contrast, MPPT charge controllers optimise energy conversion efficiency and maximise the quantity of energy harvested by dynamically adjusting the charging voltage and current to track the maximum power point of the solar panels or wind turbines.

Additionally, advanced functions like load control and temperature correction can be added to charge controllers to improve battery performance and dependability even more. In order to maintain ideal battery charging and avoid overcharging or undercharging in severe weather, temperature compensation modifies the charging voltage in response to changes in the surrounding air temperature.

With load control features, the charge controller can allocate extra energy to additional storage devices like backup batteries or grid-connected systems, or it can direct excess energy toward powering important loads. Our renewable-powered antenna system ensures a dependable and sustainable energy source for wireless networks, helping to lower energy costs and environmental impact. It does this by effectively converting the acquired solar and wind energy into electrical power utilising inverters and charge controllers[17]. Advanced control features and algorithms are also integrated to improve system resilience and efficiency, allowing for smooth operation in a variety of environmental circumstances.

ENERGY STORAGE

In order to effectively manage and utilise the converted electrical energy obtained from solar panels and wind turbines, energy storage is a crucial part of our renewable-powered antenna design. In order to provide a constant power supply for the antenna system even in the event that renewable energy sources are insufficient or unavailable, this procedure entails storing the excess energy produced during times of high production for later use. A dependable and expandable solution for energy storage requirements is offered by the use of high-capacity and efficient batteries to store the captured energy[18].

Battery sizing and configuration. Based on the estimated energy consumption of the antenna system and the anticipated length of energy storage, determine the necessary battery capacity. To optimise battery sizing, take into account variables such required peak power, desired autonomy, and discharge depth. To attain the required voltage and capacity parameters, put the batteries in series or parallel configurations.

Battery management system (BMS) installation. To ensure the battery bank operates safely and effectively, install a complete battery management system that can monitor and control the charging and draining operations. To maximise battery life and performance, the BMS balances cell voltages, controls voltage levels, guards against overcharging and over-discharging, and offers diagnostic data.

Integration with energy conversion system. To create a smooth interface between renewable energy sources and the energy storage system, connect the batteries to the charge controllers and inverters used in the energy conversion process. Set the inverters' and charge controllers' charging and discharging parameters to maximise energy transfer efficiency and guarantee compatibility with battery technology.

Safety precautions and compliance. To reduce the risk of thermal runaway, fire, and other risks related to battery operation, put in place the necessary safety precautions. Install ventilation systems, heat monitoring equipment, and fire suppression systems to keep the battery bank working safely. Make sure that the installation and use of energy storage devices adhere to all applicable safety requirements and laws.

Monitoring and maintenance. Establish a thorough monitoring and maintenance schedule to guarantee the energy storage system's continuous dependability and efficiency. Make routine maintenance checks for wear, corrosion, and damage on the batteries on a regular basis. Tighten connections, clean the batteries, and replace any worn-out parts. Using diagnostic tools and software keep an eye on battery performance parameters including internal resistance, state of charge, and health to spot possible problems and improve system performance.

Our renewable-powered antenna system ensures a continuous and reliable power supply, minimising the environmental impact and enabling seamless operation of wireless networks while reducing reliance on conventional grid electricity. This is achieved by storing the converted electrical energy in high-capacity, efficient batteries. Advanced battery management systems and safety features work together to improve system resilience and dependability, offering a reliable energy storage solution for a range of settings and applications.

SMART ENERGY MANAGEMENT

Our renewable-powered antenna design relies heavily on smart energy management to maximise wireless network performance and make the best use of stored energy. We use sophisticated algorithms to accomplish this, with the Demand-Side Management (DSM) algorithm being one of the most notable. By utilising the firefly optimisation technique in conjunction with DSM, energy distribution and utilisation are efficiently optimised by dynamically allocating power to the antenna in response to current demand and availability. The DSM algorithm minimises the difference between the intended load curve and actual energy consumption by iteratively modifying the antenna's power allocation in conjunction with firefly optimisation. Inspired by the way fireflies flash, the firefly optimisation technique iteratively updates the attractiveness of prospective solutions to simulate the optimisation process. The objective function aims to minimise the difference between actual energy consumption and the targeted load curve, subject to constraints:

$$\min f(o) = \sum_{t=1}^{T} |P_{\text{actual}}(t) - P_{\text{target}}(t)|, \quad (1)$$

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where $f(o)$ denotes the objective function, $P_{actual}(t)$ and $P_{target}(t)$ refers the actual and targeted energy consumption at time t, respectively, T is total count of time intervals. By iteratively updating potential solutions, the firefly algorithm is used to maximise the objective function. Potential remedies are represented by fireflies, whose brightness or degree of flashing reflects their appeal or level of fitness. As dimmer fireflies are drawn to brighter ones, solutions converge towards the best option. Between two fireflies, j and k, the attraction β is computed as follows:

$$\beta_{ij} = 1/(1 + \gamma D_{jk}^2), \tag{2}$$

where γ denotes attractiveness scaling factor, D_{jk}^2 denotes the Euclidean distance. The attractiveness β_{ij} determines the intensity of attraction between two fireflies, guiding the optimisation process towards the optimal solution. The DSM algorithm dynamically modifies power allocation in response to current availability and demand. It entails planning energy use in accordance with preset load curves and optimising power utilisation to save expenses and increase effectiveness. The firefly optimisation process determines the power allocation $P(t)$ at each time interval, making sure that the actual energy consumption closely resembles the desired load curve. DSM continuously tracks the amount of stored energy and the real-time demand for power from the antenna.

Based on variations in demand, it dynamically modifies power distribution to provide optimal wireless network performance while optimising energy consumption. During the optimisation process, real-time demand $d(t)$ and energy availability $E(t)$ are taken into account to make sure that power allocation satisfies the needs of the network. Restrictions are put in place to make sure power distribution complies with legal and operational standards.

These limitations could include needs for antenna power, battery capacity, and maximum power output limits. These limitations are taken into account during the optimisation process to guarantee that the power allotted satisfies operational and regulatory requirements. Our renewable-powered antenna design maximises the efficiency and sustainability of the wireless network by optimising energy distribution and usage through the integration of DSM and the firefly optimisation technique. By constantly adjusting power distribution in response to current availability and demand, this intelligent energy management strategy ensures optimal performance while minimising costs and environmental effect.

ANTENNA DESIGN

Patch antenna. Patch antenna also called as Microstrip antennas are widely used in wireless communication systems because of their small size, simplicity in integrating into printed circuit boards (PCBs), and adaptability in design. Patch antennas are made up of ground, substrate, patch, and feed components and can be square, elliptical, circular, rectangular, or ring-shaped. Patch antennas for wireless

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communication must be carefully designed and developed, taking into account factors like feed line characteristics, substrate material, and antenna dimensions.

The length and width of the ground, patch, substrate, and feed line, as well as other antenna dimensions, were meticulously chosen for our proposed wireless communication system based on design specifications. Our prototype patch antenna design employed RT/Duroid5880 as the substrate material, which has a thickness of 0.3451 mm and a dielectric constant of 2.2. Several equations were used to determine the microstrip patch antenna's parameters:

$$W_\alpha = \frac{C_0}{2F_\alpha((\varepsilon_\alpha + 1)/2)^{1/2}}. \tag{3}$$

Dielectric constant (ε_α):

$$\varepsilon_{\text{reff}} = (\varepsilon_\alpha + 1)/2 + (\varepsilon_\alpha - 1)/2 \times (1 + 12\, H/W)^{-0.5}. \tag{4}$$

Extended length (E_l):

$$E_l = \frac{C_0}{2F_\alpha((\varepsilon_\alpha + 1)/2)^{1/2}}. \tag{5}$$

Feed line width (W_{fl}):

$$W_{fl} = \frac{7.48H}{\exp(z_0 \times (\varepsilon_\alpha + 1.41)^{1/2}/87)} - 1.25t. \tag{6}$$

These formulas make it possible to calculate the antenna settings precisely, guaranteeing best performance and interoperability with the wireless communication system. The antenna patch width and length W_α and L_α, the substrate height and thickness H_s and t, the feed line width W_{fl}, and the ground width and length W_g and L_g.

DESIGN OF PROPOSED ANTENNA

Enhancing the sustainability and energy efficiency of the antenna system is possible by directly integrating renewable energy sources, such wind and solar power. Our proposed concept, shown in Fig. 1, uses small-scale wind turbines and solar panels to harvest renewable energy from the environment in a seamless manner within the patch antenna structure. The patch antenna's surface is covered with strategically placed solar panels that make use of the available area without adding unnecessary bulk to the system. By absorbing sunlight and converting it into electrical energy, these panels give the antenna system a constant and renewable power supply. In a similar vein, strategically positioned small-scale wind turbines are part of the architecture and efficiently harness wind energy. Because of their ability to function well even in windy situations, these turbines guarantee a consistent flow of clean energy to power the antenna system. Through the direct utilisation of solar and wind energy within the antenna structure, we maximise the system's ability to generate energy while reducing its impact on the environment.

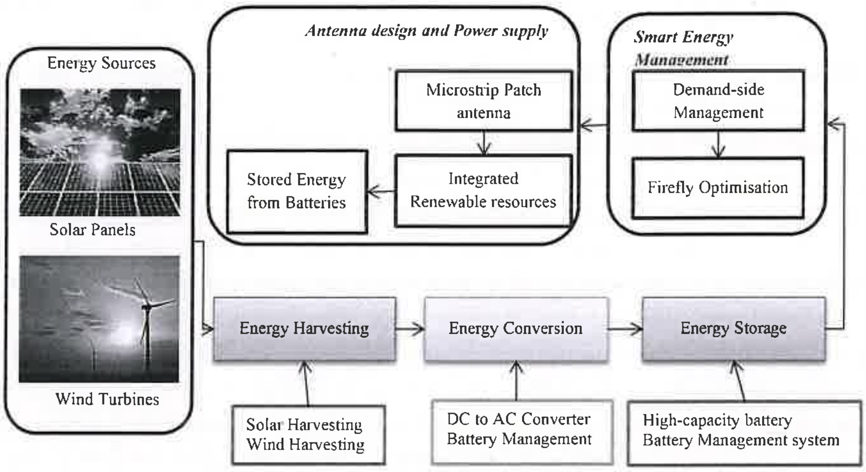

Fig. 1. Block diagram of proposed system

Moreover, the resilience and dependability of the antenna system are improved by the incorporation of renewable energy sources. The antenna system becomes more resilient and able to function independently in isolated or off-grid areas by increasing the variety of energy sources and decreasing dependence on traditional grid power. This is especially helpful in situations when access to conventional electrical infrastructure is few or unstable. The antenna system's effective integration of solar and wind energy also lowers its overall carbon footprint and is in line with larger sustainability objectives. We reduce our negative environmental effects and help the world move toward a more sustainable energy future by using clean and renewable energy sources. Overall, the antenna system's performance, dependability, and environmental sustainability are improved when solar and wind energy are integrated directly into it. This makes it the perfect option for wireless communication applications in a variety of environments.

ANTENNA POWER SUPPLY

The antenna is powered by stored energy from renewable sources, such as solar and wind, in the antenna power supply system, guaranteeing continuous functioning. This energy is stored and can be used as a dependable backup power source, especially when there is less wind or sunlight. The antenna system can store extra energy created during peak production periods for use at a later time when renewable energy generation is insufficient by combining efficient energy storage systems, such as high-capacity batteries.

Furthermore, in order to guarantee steady performance, the antenna system is engineered to smoothly transition between grid power and renewable energy sources as required. To automatically manage this transition based on current energy availability and demand, sophisticated management algorithms and monitoring systems are put in place. The system gives priority to harnessing solar and wind power to decrease grid dependency and lower operational costs during periods of abundant renewable energy output. On the other hand, the system smoothly transitions to grid power to guarantee continuous operation without sacrificing performance when renewable energy output is unable to meet the antenna's power needs.

By enabling the antenna system to adjust to shifting environmental circumstances and energy availability, this dynamic switching capability improves the antenna system's resilience and dependability. The system minimises its impact on the environment and maximises energy efficiency by making optimal use of grid power and renewable energy sources. The effective use of stored energy combined with the smooth transition between grid power and renewable energy sources guarantees dependable and sustainable functioning of the antenna system, satisfying the requirements of contemporary wireless communication networks.

RESULTS AND DISCUSSION

We simulate our proposed Micro Strip Patch Antenna with renewable energy source using simulation tools like NS-3 or MATLAB. Table 1 displays the results of the successful comparison between existing and proposed antenna's directivity gain metrics.

Table 1. Comparison of antenna's directivity gain metrics

Methods	Directivity gain (dBi)
Ref. 8	4.22
Ref. 9	2.05
Ref. 10	6.66
Proposed method	7.43

The directivity gain (dBi) attained by various antenna design techniques is contrasted in Table 1. It was reported[8] a lesser gain of 2.05 dBi, whereas in Ref. 9 was achieved a directivity gain of 4.22 dBi. A greater gain of 6.66 dBi was attained in Ref. 10. On the other hand, the suggested approach outperforms them all with a 7.43 dBi directivity boost, suggesting better performance. This shows that the suggested strategy beats earlier methods in optimising the radiation efficiency and signal strength of the antenna, potentially leading to breakthroughs in wireless communication technology.

CASE STUDY 1: SOLAR-POWERED WIRELESS COMMUNICATION IN RURAL AREAS

In remote regions absent of traditional infrastructure, a wireless mesh network driven by solar energy was established to fill in communication gaps and offer vital services. A self-configuring mesh network was formed by carefully placing solar panels to maximise energy capture and power energy-efficient antennas. Furthermore, base stations powered by renewable energy served as internet connectivity gateways. The technology demonstrated exceptional energy efficiency, guaranteeing dependable connectivity under demanding environmental circumstances. Because of its scalability, coverage may be increased without sacrificing efficiency. Communities were greatly influenced by the deployment because it greatly reduced carbon emissions while providing access to healthcare, education, and employment possibilities.

CASE STUDY 2: WIND-POWERED IOT NETWORK FOR ENVIRONMENTAL MONITORING

An IoT network driven by wind was used for remote environmental monitoring applications, tracking ecological changes in a nature reserve. Data gathering was made easier by the energy-efficient antennas built into sensor nodes, which were powered by small wind turbines. By using LoRaWAN for communication, long-range connectivity was maintained with low energy usage. Effective energy harvesting enabled the system to run continuously and transmit data without interruption. By providing continuous monitoring while minimising operational costs and environmental impact, it provided a substantial contribution to environmental research endeavors.

CHALLENGES

Maintaining a steady power supply for ongoing network operation is difficult when dealing with renewable energy sources' variable output, such as wind and solar power. It is challenging to scale renewable-powered antenna networks while preserving energy efficiency in order to support an increasing number of devices. Integrating diverse renewable energy sources into a cohesive and effective energy-harvesting system is a technical difficulty. In distributed networks fuelled by renewable energy, ensuring secure communication is essential yet difficult. Long-term benefits may be outweighed by high initial implementation costs that could prevent widespread adoption.

CONCLUSIONS

In conclusion, the proposed system effectively combines antenna technology with renewable energy sources, such solar and wind turbines, to produce a wireless communication system in an efficient and sustainable connection. The technology minimises dependency on traditional grid electricity by efficiently powering the antenna through energy collecting, conversion, storage, and intelligent management. Case examples illustrate the system's practicality and advantages in enabling environmental monitoring and bringing connectivity to remote locations. However, effectively scaling networks and regulating variable renewable energy outputs are limited. In the future, efforts should be directed toward improving the efficiency of energy harvesting, maximising network scalability, and resolving issues related to communication security. Furthermore, system performance and dependability may be further enhanced by developments in energy storage technology and intelligent energy management algorithms, opening the door for wider adoption and effect.

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