Off-Grid Wi-Fi Mesh Systems

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***Abstract*— In this paper, an off-grid energy Wi-Fi mesh system for remote areas is proposed. The system is self-powered, and to ensure 24 hours energy production, a hybrid solution of vertical wind turbine and the solar cell is used. Dedicated routers are designed using Raspberry Pi, and other supporting electronic circuitry and results are analyzed. To avoid bandwidth issues, the network off-loading concept is exploited using a novel concept of power used by each node. The proposed system is portable and suitable for remote areas where grid-connected energy availability is an issue.**

***Keywords*— Off-grid, Wi-Fi Mesh, remote, off-loading, hybrid energy**

I. Introduction

In the last decade, the internet is now considered a basic need along with electricity, gas and similar necessities of life. In developing regions across the globe, internet access is still at a moderate level. In rural areas, geographical factors like economy, population, and distance between the urban and rural areas contribute to insufficient internet availability. According to the International Telecommunication Union (ITU), in 2019, 72% of users in urban areas had access to the internet, while only 38% of users in ruler areas had access to the internet. In contrast, look at the statistics of the developed and underdeveloped countries. This ratio is not comparable in either case, which shows that the availability of the internet in the ruler areas is a universal issue irrespective of the development of the nation's [1].

Recently with the help of modern technology, China has brooked the barrier of the urban-rural divide. Now, off-grid Wi-Fi systems for ruler areas are a topic of research, and a lot of research acceleration is evident in this realm. Now many solutions are available which are powered by solar energy [2]. But the fundamental issues with those solutions are that they cannot provide 24 hours operation and the use of batteries have its issues.

Few are using hybrid solutions to power the routers, but they are not efficient as neither source not the routers are designed dedicated for each other [3]. To provide non-stop internet access to remote areas, Solar/wind (hybrid) systems are highly reliable, efficient, and environment friendly, as shown in Fig. 1.

Wi-Fi has undergone a revolutionary transformation during the last two decades. Many companies now provide Wi-Fi networks that go out to remote regions. Powering such wireless networks can be done by grid connected power sources. The challenge arises when the wireless network is deployed in a remote area or designed as a portable node IoT system [4].

In many cases, Wi-Fi coverage is required in remote areas where continuous power sources are not always available. The battery-sourced power system is a solution, but they inherit the high-cost issue and requires power source for charging as well [5].

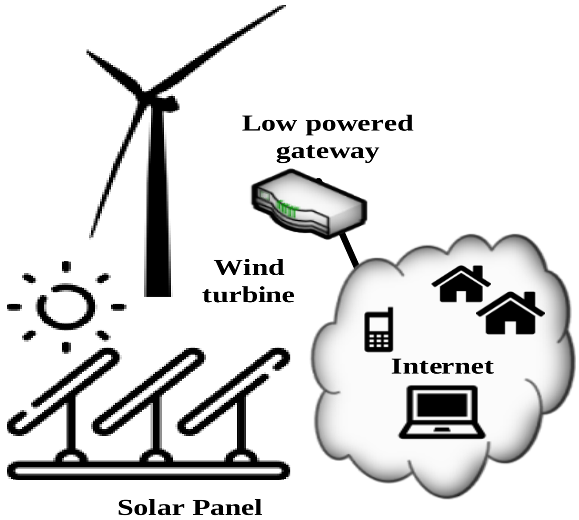


Fig. 1. Architectural view of the self-organizing off-grid wi-fi mesh network

In such situations, the only left solution is to operate the wireless Local Area Network (WLAN) mesh nodes by using a sustainable energy source such as solar or wind power. When the nodes are designed to integrate with renewable solutions, portability is the top-of-the-line benefits along with the low power consumption which one can achieved out of them. Available WLAN mesh networks are frequently set up to offer temporary wireless coverage. Each node in a WLAN mesh network may include one or more IEEE 802.11 radios. As there is just one radio per connection in each node, the power budgeting is considered as a bottleneck especially in transmission mode [6] and hence required continuous sustainable power source.

This study focuses on a sustainable self-organizing Wi-Fi mesh solution to resolve power outages and internet access to remote areas. The paper is formulated such that, in section II, the design methodology is discussed in detail. Section III will discuss prototype testing and iterative system enhancements by tracking the effects of dynamic network traffic on power consumption. Section IV concludes the article.

II. Design Methodology

Fig. 2. illustrates Raspberry Pi Wi-Fi Mesh Node powered by Hybrid Renewable Energy System (HRES). A charge controller of 12V is used for safe battery charging and discharging along with a regulated supply to the attached equipment. The attached node only needs 5V for operation, so a buck converter is used for stepping down voltage without limiting current. The current sensor is used for monitoring load current in real-time. Raspberry Pi only deals with digital data, so an Analog to Digital converter (ADC) is used with the current sensor. The Global Positioning System (GPS) module obtains the location coordinates of the deployed self-organizing mesh nodes.

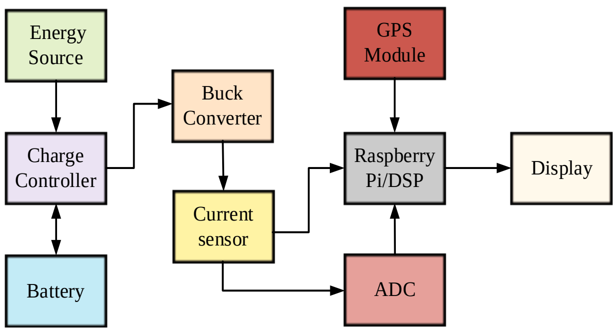


Fig. 2. Proposed System

A. Energy Unit Design

Mostly market available embedded systems and digital electronics are low powered and maximum threshold of 10 W is considered as sufficient to power the small digital systems. Here a source is designed to power a system of 10W.

- Solar Panel Ratings

To design a solar panel for 12.5 W, the PV rating formula is used [7],[8].

$$P_{module} = \frac{Wh_o \times 1.3(loss)}{Sun\ Peak\ Hours} \tag{1}$$

where,

P_{module} = Power rating of the solar panel

W_{ho} = Required output in Watt-hours

$$P_{module} = \frac{12.5 \times 24 \times 1.3}{6} = 65 watts \tag{2}$$

The self-organizing node is active for the day; hence, a three-day battery backup calculation has been performed.

$$B_{cap} = \frac{Wh_o \times 1.3(loss) \times A.days}{Eff \times DoD \times V_{nv}} \tag{3}$$

where,

B_{cap} = Required Battery Capacity,

A. days = Autonomous days when power generation is not possible,

E_{ff} = Efficiency of the battery,

DoD = Depth of discharge means the amount of energy stored and consumed in a cycle,

V_{nv} = Battery nominal voltage

$$B_{cap} = \frac{12.5 \times 24 \times 1.3(loss) \times 3}{0.85 \times 0.8 \times 12} = 143.3 Ah \tag{4}$$

Table I Layout Specification of Wind Turbine

Parameter	**Value**
Diameter of Shaft	1.5 in
Turbine Height	52 in
Turbine Blade Diameter	13 in
Helix Angle	45°
Aspect Ratio	4 cm
Azimuth Angle	135°
Blade Arc Angle	160°

The above calculations will calculate the charge controller, inverters, and backup.

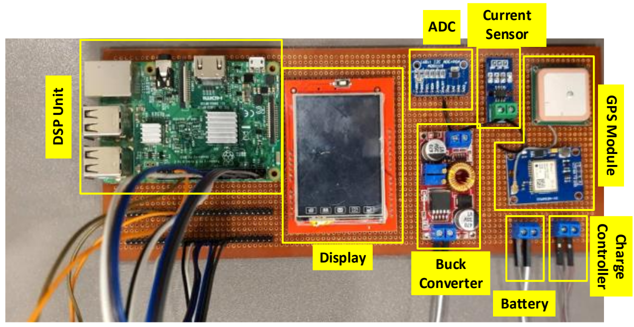


Fig. 3. Prototype Testing

- Wind Turbine Selection

A Savonius wind turbine with a vertical axis and a helical rotor is designed to collect wind energy. This design was selected because it provides higher torque at lower speeds and is best suited to rotate with air drag. The layout specification of the turbine is shown in Table I. The maximum rated power for the generator was 1000W. But the power generation achieved due to Wind and actual electric power was different. Wind power is given by [9]:

$$P_{wind} = (\tfrac{1}{2})\rho \times A \times V^3 \times C_p \tag{5}$$

where,

P_{wind} = Power generated by the wind turbine,

ρ = air density,

A = swept area of blades,

V = Wind velocity of 8 m/s

C_p = Power coefficient of the turbine

Generators and turbines have losses that significantly decrease the total system's Efficiency. The maximum power that can be extracted from the Wind by designing the turbine using the above parameters is 398W.

The Efficiency of the turbine and generator are given below.

$$\eta_T = 55\%$$

$$\eta_G = 90\%$$

The actual electric power generated system is provided by:

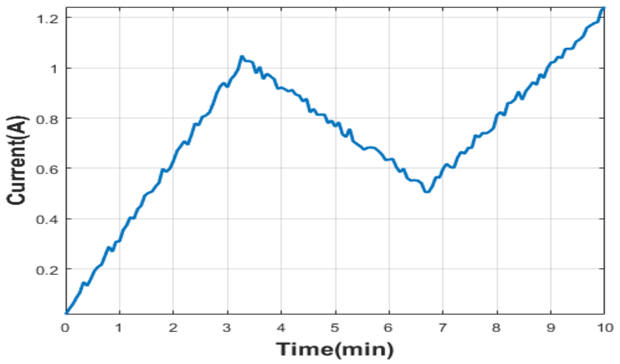
$$P_{electric} = P_{wind} \times \eta_T \times \eta_G \tag{6}$$

The maximum electrical power generated using a designed wind power generator is 197.34W. Upon successful design of energy generating unit that can provide enough power to the node to operate independently. The next step is to design a Power Conditioning and Control (PCC) unit comprising a Raspberry Pi/DSP module interfaced with the sensing unit to take intelligent decisions. Node's performance can be visualized through a user interface. The User-Interface can only be accessed upon request to fulfil the power consumption criteria for a self-organizing node.

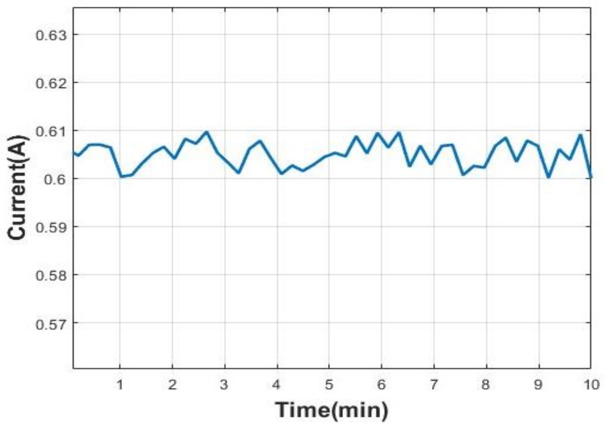
III. Testing and Results

The proposed solution is tested, and measurements are performed in real-time, as shown in Fig. 3. Firstly, the node is empowered and connected to the available gateway for internet access. Current and Voltage readings of the unloaded node (no further clients are connected) are measured. Network parameters like throughput, bandwidth, jitter, or delay are also monitored. When monitoring node performance, the display screen will be activated; otherwise, it will remain OFF.

The Message Queuing Telemetry Transport (MQTT) Protocol defines different QoS levels. Most IoT developers usually consider the appropriate QoS level to achieve better reliability, latency, throughput, and energy needed for communication to minimize energy consumption. Some experimental energy consumption results for different QoS levels are summarized here [10]. At most once (QoS=0) level, the message is sent to the subscriber-only once. At least once (QoS=1) level, the message is sent to the subscriber leastwise one time. At Exactly one (QoS=2) level, the message is sent to the subscriber with complete security in two rounds. So, most energy is consumed at the QoS=2 level, and minor consumption is at the QoS=0 level.



(a)



(b)

Fig. 4.The variation in the power used; (a) Varying number of connected devices, (b) Varying data rate on fixed no. of connected devices

Some equations provide a basic energy model that may be used to estimate how much power a node in a Wireless Sensor Network (WSN) needs to perform its primary functions. The energy model is divided into two sections:(1) packet-dependent and (2) packet-independent [11]. The energy of the node is described as follows.

$$E_i = E_{TXi} + E_{RXi} + E_{switching} + E_A + E_{PIE} \quad (7)$$

where,

E_i= Energy consumed by i^{th} node

E_{TXi}= Energy consumed during Transmission

E_{RXi}=Energy consumed during the reception

$E_{switching}$= Energy consumed during switching between Transmission and Reception.

E_{PIE}=Packet Independent Energy

The energy of Transmission, receiving, switching, and algorithm (CSMA) for communication are packet dependent parameters, while others, like device ON/OFF parameters, are packet independent. Drained current in a wireless Access Point (AP) depends on several factors, including the amount of traffic, transmission power level, modulation, and coding schemes (data rate) [12]. The number of clients will gradually increase with the self-organizing node, and then the V-I characteristics of the node will be monitored accordingly. The current will increase up to the maximum device limit. Different connected devices' effect on current values is shown in Fig. 4.

Moreover, when connected devices to the specific node are fixed, and the data rate (throughput) is increased, the corresponding current rating on the display screen fluctuates minutely without any proper increasing or decreasing trend. So, self-organizing nodes can off-load mesh clients to minimize power consumption and improve network service quality. Off-loading means sending heavy computation to resourceful servers and receiving results from these servers. The algorithmic flowchart of an off-loading solution is summarized in Fig. 5. The self-organizing node will monitor bandwidth and then rationalize bandwidth by the algorithm, which means bandwidth got limited for network operations.

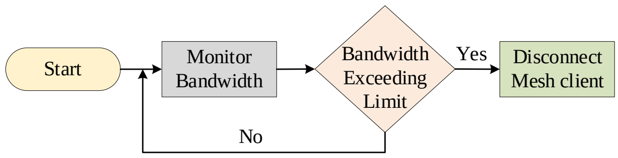


Fig. 5. Flowchart of Network Offloading

Moreover, suppose network traffic exceeds the upper or lower limit of the defined bandwidth. In that case, connected clients will be removed from the self-organizing node, and the whole mesh network will re-organize itself to provide wireless internet service [13]. The Wi-Fi mesh network transmits information from source to destination wirelessly with minimal outer interference. Considering a Wi-Fi mesh network's power consumption, using renewable sources in remote areas is a viable option to expand the internet over rural communities.

The result shows the rise in the server's current with the increased connections while keeping the voltages constant at approx. 5V. The consumption of the server is about 8 watts after connecting six clients, which is a good sign keeping in mind the power rating of Solar panels being used nowadays. Energy-sustainable wireless mesh nodes must be intelligent to organize their power consumption while managing network operations. So, self-organizing nodes can off-load mesh clients to minimize power consumption and improve network service quality.

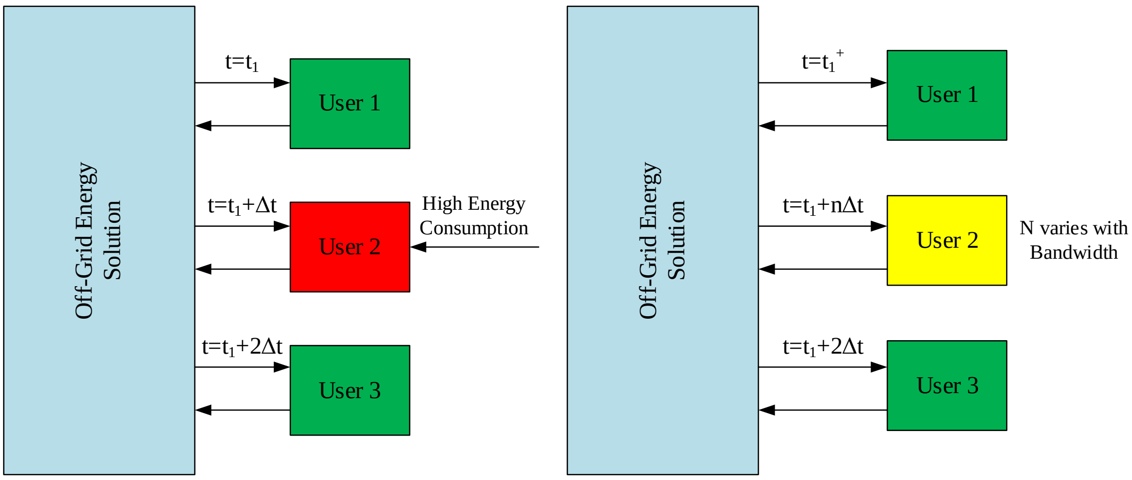


Fig. 6. Network Operation Re-organization

So, the self-organizing node will be optimized accordingly to handle network operations with less power consumption, as shown in Fig. 6. A comparison of different available market solutions is summarized in Table II. All available market solutions cannot perform off-loading in networks; the proposed model is robust enough to perform such optimization decisions. In addition, the self-organizing node is sufficiently efficient regarding decreased power usage.

IV. Conclusion

Electric energy is a primary requirement for all wireless transmission systems. Transmitting information from a source to a destination requires a robust wireless network. The challenge comes when the wireless network is deployed in a remote place or designed as a moving system for sensing analysis. The battery-sourced power system will be better for such a portable wireless system. The suggested system consists of a Raspberry-Pi as a wireless node empowered by a hybrid renewable energy source with a backup of three days without a source. In terms of power consumption and increasing traffic, proposed sustainable nodes are self-organized. Increased traffic ultimately raises the node's current, which raises power consumption. Furthermore, the system can manage network operations by disconnecting the attached clients and re-organizing whole network by performing off-loading. In this way, the whole mesh network will re-organize itself to provide quality internet service.

Table II Comparison of available solutions

Model	**Major Specifications**	**Drawback**	**Advantages**
Mesh++ S618	Range:350m, Backup:7 days, Users: 500	Highly Costly, complex to mount structure	Long backup
ISEMS	Remote monitoring,50 W solar with 12V battery	less range with limited users, Moderate cost	App-based monitoring
Solar Router SCS 01	LiFePo-Battery, Backup: 3.5 days, Users: Router-based	Costly, less range with limited users	Rainproof structure
Current work	65 W Solar module, 3 days backup battery (12V)	better range with limited users	Off-loading, power optimization

V. Acknowledgemt

The work is done under project code CMG054, funded by Africa New Energies Ltd, UK.

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