

“WindFi” - A Renewable Powered Base Station for Rural Broadband

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Abstract—The HopScotch rural wireless broadband access test bed uses a network of low power base stations, powered by renewable energy sources to provide a low-cost rural broadband solution. In this paper we discuss the low power design aspects of the HopScotch base station and the impact on the required generation potential of renewable sources, battery bank sizing and the use of tracking PV arrays.

I. INTRODUCTION

In remote areas many households are located far from an exchange limiting digital subscriber line broadband connectivity with existing copper cabling. Alternatives such as fiber to the home and 3rd generation mobile broadband require substantial capital investment, planning permission and access to the electricity grid or when grid supplied power is either unavailable or unreliable the use of diesel generators. In addition to emitting CO₂, diesel generators can be costly to run due to ever increasing fuel costs and the added expense of fuel transportation to remote areas. The large infrastructure costs and the additional operating expense of electricity and fuel make these standard solutions that have been adopted in urban settings uneconomical for rural deployment without major subsidy.

Renewable energy sources such as wind turbines and photovoltaic (PV) arrays are an attractive alternative for remote telecommunications installations both environmentally and economically. An off-grid renewable power system allows a base station to be placed in the optimum location to serve users, requires no infrastructure to connect to an existing power source and, as no fuel is required, has minimal operating costs. Therefore, using a renewable power system provides an economic as well as environmental justification for the use of low power and energy efficient radios, systems and network designs. As the energy generation and storage system represents a significant proportion of the total cost of a renewable powered base station, minimizing the overall power consumption reduces the required generation potential and storage capacity.

A. Low Power and Renewable Powered Networks and Base Stations

Renewable sources have been suggested to power a number of communications systems. Powering cellular base station with PV has been addressed in [1], [2] but the substantial

power requirements of cellular radio equipment and cooling prohibit the use of purely renewable sources due to the area required for a PV array and the costs involved. The use of low power equipment allows network nodes to be powered either entirely by renewable sources or as a supplement to existing energy sources. In climates where solar radiation is in abundance all year round, solar power has been used effectively to power WiFi rural wireless mesh networks [3]–[5]. A purely solar powered base station is not practical in Scotland due to limited solar irradiation in the winter months. The Tegola mesh network overcomes this by exploiting the inverse relationship between wind speed and solar irradiation throughout the year in Scotland to power nodes with a combination wind and solar sources [6].

Minimizing the power consumption of access points and routers for rural applications is widely acknowledged [7] and is the focus of continued research [8]. This allows the required renewable generation potential and hence cost of a system to be minimized. A number of studies have been undertaken to determine the optimal size of solar and wind sources and battery banks for given loads and conditions. Tanezaki in [9] has simulated various PV array sizes and their effect on battery charge cycles and compared these to recorded values. Panajotovic in [10] focused on sizing energy systems to deal with specific localized weather phenomena.

B. Contribution and Overview of Paper

The HopScotch project [11] provides a green low power solution for rural broadband access that is currently being trialled on the West coast of Scotland. This paper describes the renewable powered “WindFi” base stations which are required to ensure the success of the HopScotch project from both an environmental and economic perspective.

Energy efficient radio technologies allow the HopScotch project to be an economical and environmentally responsible rural broadband solution. Low power radios, systems and network design, and off-grid renewable energy sources are combined to create an affordable yet powerful wireless network capable of delivering high bandwidth content and services. “WindFi” base stations are low power autonomous units, powered by a combination of renewable sources similar to [6] but due to the number of subscribers and selection of radio equipment a larger power consumption is fed by the use of solar tracking and a large 200 W rated wind turbine. Each base station hosts multiple radio interfaces to service different requirements. Standard WiFi access technology similar to systems reviewed in Sec. I-A is used to create an line of sight

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network. However, it also features a digital dividend “white space spectrum” overlay in the 600-800 MHz bands, which serves as a test bed for the development of TV white space (TVWS) links and offers the potential of flexibility offered by cognitive radio techniques as well as a more comprehensive cover than existing fixed wireless bands in rural settings.

This paper is organised as follows. Sec. II introduces the HopScotch project and discusses the requirements of HopScotch base stations. HopScotch is based on a network of “WindFi” base stations, which are described in Sec. III with a particular focus on the green technologies used to reduce power consumption and cost of these devices. Finally, conclusions will be drawn in Sec. IV.

II. HOPSCOTCH NETWORK

A. Network Architecture

Fig. 1 shows how HopScotch could typically connect a remote community to IP-backbone, with point-to-point (PTP) links creating a network backbone between “WindFi” base stations, and point-to-multipoint (PTMP) links illuminating the community. HopScotch uses standard IEEE 802.11n, operating

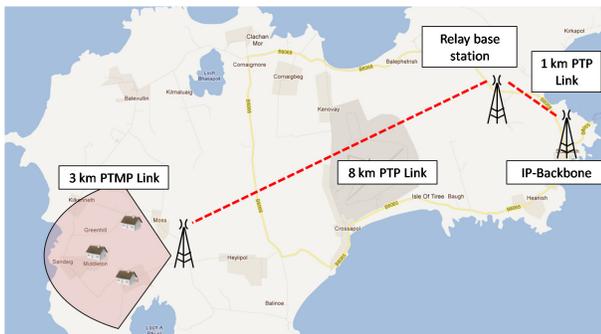


Fig. 1: Example of a HopScotch network connecting a remote community to IP-backbone.

in the 5 GHz spectrum for PTP links and to serve subscribers in close vicinity of the base station. The infrastructure additionally features an overlay “white space” [12] network/testbed in a licensed UHF band, where a modified IEEE 802.11 protocol is utilised for transmission. A combination of spectral bands allow for an optimum trade-off between channel throughput and coverage for different scenarios. The use of licensed and unlicensed spectrum in the 5 GHz band allows off-the-shelf WiFi equipment to use a large channel bandwidth with high throughput. The use of TVWS frequencies allows for greater coverage from the base station, especially in challenging radio terrain at the expense of a reduced channel bandwidth and throughput.

B. Network Requirements on Base Station Design

To serve a community, HopScotch base stations are designed to handle different radio payloads, allowing one base station to best serve a community given the number and location of households, surrounding terrain, throughput requirements and proximity to adjacent base stations.

Households within 3 km LOS of the base station are served using a number of 5 GHz PTMP sectors. Omni-direction coverage around a base station can be created using up to eight partially overlapping sectors, each serving 8 to 10 broadband users on a theoretical 65 Mbps wireless link. Non-LOS coverage up to 6 km from the base station is provided using UHF links. When IP-backbone access is not available at the base station location the base station provides at least one PTP link in the 5 GHz band to obtain connectivity. Relay nodes require two PTP links.

Base stations are designed to be deployed in remote areas of the Highlands and Islands of Scotland therefore are designed to survive high wind speeds up to 45 m/s. “WindFi” base stations are up to 14 m in height and require no permanent foundations and therefore requires no planning permission in the UK to install.

III. “WINDFI” BASE STATION DESIGN

Each HopScotch wireless base station is an ultra-low power autonomous unit, powered by a combination of wind and solar renewable sources as shown in Figure 2. Using renewable energy allows each base station to operate independently of fixed electrical infrastructure, allowing for flexible, optimised placement.

A. Base Station Subsystems

The base station electronics are divided into two subsystems — the renewable power system and the radio payload — which are discussed below.

A typical deployment to serve a medium sized community would provide four radio sectors for PTMP user access and two PTP links for back-haul, requiring a total of six radios. The radios are managed by two single board computers (SBC). The emergence of ultra low voltage yet computationally powerful processors such as the Intel Atom and ARM based embedded processors allow a single processor to manage multiple radio interfaces on a modest power budget. Each SBC operates two PTMP radios and one PTP radio by running a software MAC for each radio and performing packet routing within the mast and network. The use of two SBCs creates redundancy within the base station; if one SBC fails, another PTP link will still be operational and provide back-haul to the unaffected sectors.

To minimize transmission losses between the radios and antennas, the SBCs with attached radios are placed as close to the antennas as possible, allowing the transmit power to be minimised to maintain a desired equivalent isotropically radiated power (EIRP).

A battery bank is used to store energy generated by the wind turbine and PV modules and act as an energy source for the system. A hybrid web-connected charge controller manages charging to prolong battery life and provides resistive loads for the generation units when production is too great. The current status of the wind turbine, PV array, battery bank and loads are monitored remotely in real-time to allow problems to be detected early and corrective action to be taken, minimizing base station downtime. A web interface allows the PV panels to be remotely positioned to facilitate solar tracking and maximise the generation potential of the PV array.



Fig. 2: Prototype “WindFi” base station on the Isle of Bute, Scotland, which has been running since early 2010. The base contains solar panels and batteries, over which a 10 m mast carries the wind turbine with antennas and radio equipment directly beneath.

B. Power System Sizing

For deployment in Scotland, HopScotch uses both wind turbines and PV modules to harvest a combination of wind and solar energy. As discussed in [6], wind and solar energy sources are complementary in Scotland; in the summer months solar energy peaks whilst in the winter months winds prevail. Fig. 3 shows the average daily energy which can be harvested from an 80W PV module and a 200W wind turbine on the Isle of Tiree.

The battery bank in a “WindFi” system is sized to allow for continuous operation without any additional energy input for N_d days and without the capacity dropping below the maximum discharge depth D , where $0 \leq D \leq 1$ with $D = 1$ referring to a full charge, to prolong the battery lifespan. The required battery bank capacity C_b in kWh for a daily energy demand E_d in kWh is given by

$$C_b = \frac{N_d E_d}{D} \quad (1)$$

Two SBCs are used in each base station for redundancy creating a load of up to 10 W. Assuming each radio requires

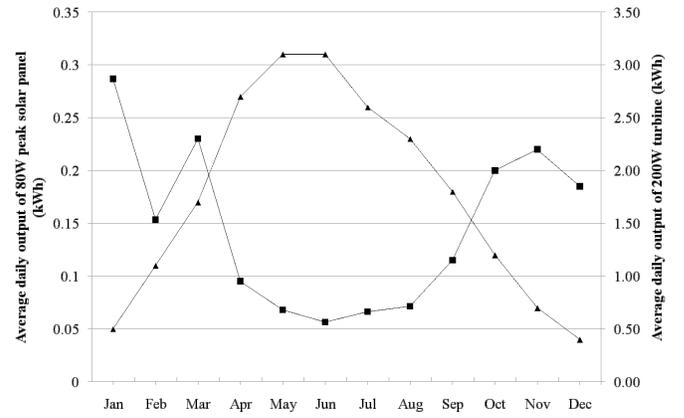


Fig. 3: Average daily power generation from a single 80 W PV module (\blacktriangle) and a 200 W wind turbine (\blacksquare) on the Isle of Tiree, Scotland, based on predicted solar irradiation data from the Photovoltaic Geographical Information System (PVGIS) [13] and averaged wind speeds measured at Tiree Airport between 2008 and 2010 with the wind turbine used for a “WindFi” base station.

up to 5 W the total power requirement of six radios is up to 30 W giving a total base load of 40 W. Due to the additional power requirements for the mast power system, monitoring and control, antenna motorisation and the inclusion of a safety margin for operation whilst testing, a base load of 50 W is used for sizing the power system, creating a maximum daily energy demand of $E_d = 1.2$ kWh assuming a 24h operation under full load.

In our design, the system must remain operational for $N_d = 3$ days without any energy input and without the stored energy dropping below $D = 50\%$ of the total capacity. This mitigates against overcast, wind free days and protects the batteries from over-discharge. Therefore the battery bank must be able to store $C_b = 7.2$ kWh, leading to a required battery bank capacity of 600 Ah when utilising 12 V rated batteries.

The energy production of the mast must be capable of recharging the batteries from the lowest allowed charge depth in N_r days in addition to maintaining the base load. The required energy production per day E_r required to recharge the battery bank over N_r days is

$$E_r = \frac{DC_b}{N_r} \quad (2)$$

Therefore the total energy production required per day, E_p , is the base load energy demand E_d plus the recharge energy demand E_r . When allowing $N_r = 5$ days to recover from a maximum lost charge, an extra energy demand of $E_r = 720$ Wh is required, creating a total daily demand of $E_p = 1.92$ kWh.

In the Highlands and Islands of Scotland the potential of wind energy is greater than that of PV. In the winter months the mean wind turbine output of around 2 kWh per day is sufficient to meet our requirement, while in the summer months the output drops to around 600 Wh per day. To meet the system’s energy demand of $E_p = 1.9$ kWh, the PV must be capable of contributing 1.3 kWh per day assuming an optimal

orientation given by PVGIS, therefore requiring around six 80 W PV units according to the characterisation in Fig. 3.

C. Solar Tracking

Solar tracking increases the output of solar panels by aligning the solar panel with the current position of the sun. Generally three types of solar tracking are used:

- *inclined tracking* rotates the panel around the north/south axis at a fixed inclination;
- *vertical tracking* rotates the panel around a vertical axis at a fixed inclination;
- *two-axis tracking* allows the panel to rotate and incline.

The gain in efficiency of using the above three types of solar tracking for the trial location of the Isle of Tiree is shown in Fig. 4 using PVGIS. During the summer months vertical axis tracking provides roughly a 35% increase in energy taken per day. Therefore with vertical solar tracking, only 0.8 kWh of rated generation potential are required, which allows to reduce the amount of PV units from six to only four. Although two-axis tracking offers the largest efficiency gains, the modest efficiency improvement over single axis tracking, added complexity for motorisation in two planes and the increased risk of failure make it an undesirable solution for HopScotch.

A custom built motorization assembly incurs an additional energy requirement of around 5 Wh per day to re-aligning the PV units once per hour. The added efficiency more than compensates for this penalty. The resulting reduction in the number of PV modules also reduces stresses on the mechanical structure through decreased wind loading, which can be further eased by feathering motorised PV panels during strong winds. The added cost of motorization is proportional to the cost of the saved PV modules.

A web-accessible motor control unit allows for remote control of panel feathering and a solar tracking algorithm based on the latitude and longitude of the installation and current time and date to be run remotely or locally as required.

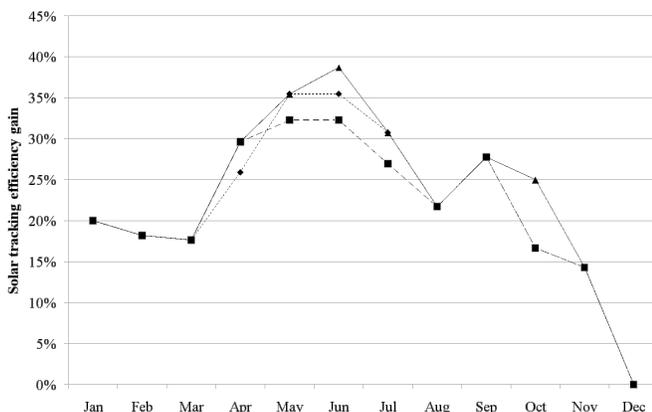


Fig. 4: Average gain in energy generation per day using vertical (♦), inclined (■) and two-axis (▲) solar tracking over a fixed installation on the Isle of Tiree using PVGIS.

IV. CONCLUSION

This paper has discussed how “WindFi” base stations enable HopScotch to be a viable rural broadband solution. Low-power and low-cost WiFi based radio equipment allows “WindFi” base stations to be operated by renewable sources, reducing operating costs, fuel use, and eliminating the requirement of access to the electricity grid. The dimensioning of the system is based on successful initial field results, with further trials on the Scottish Isles of Bute and Tiree planned.

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REFERENCES

- [1] S. Hashimoto, T. Yachi, and T. Tani, “A New Stand-Alone Hybrid Power System with Wind Generator and Photovoltaic Modules for a Radio Base Station,” in *26th Annual International Telecommunications Energy Conference*, pp. 254–259, Sept 2004.
- [2] C. Lubritto, A. Petraglia, C. Vetromile, F. Caterina, A. D’Onofrio, M. Logorelli, G. Marsico, and S. Curcuruto, “Telecommunication Power Systems: Energy Saving, Renewable Sources and Environmental Monitoring,” in *30th International Telecommunications Energy Conference*, San Diego, CA, pp. 1–4, Sept. 2008.
- [3] A. Farbod and T. Todd, “Resource Allocation and Outage Control for Solar-Powered WLAN Mesh Networks,” *IEEE Transactions on Mobile Computing*, 6(8):960–970, Aug. 2007.
- [4] D. Wu, D. Gupta, and P. Mohapatra, “Quail Ridge Wireless Mesh Network: Experiences, Challenges and Findings,” in *3rd International Conference on Testbeds and Research Infrastructure for the Development of Networks and Communities*, Orlando, FL, pp. 1–6, May 2007.
- [5] B. Raman and K. Chebrolu, “Experiences in using wifi for rural internet in india,” *IEEE Communications Magazine*, 45(1):104–110, Jan. 2007.
- [6] G. Bernardi, P. Buneman, and M. K. Marina, “Tegola Tiered Mesh Network Testbed in Rural Scotland,” in *ACM Workshop on Wireless Networks and Systems for Developing Regions*, NY, pp. 9–16, 2008.
- [7] P. Bhagwat, B. Raman, and D. Sanghi, “Turning 802.11 Inside-Out,” in *SIGCOMM*, pp. 33–38, 2003.
- [8] T. Todd, A. Sayegh, M. Smadi, and D. Zhao, “The Need for Access Point Power Saving in Solar Powered WLAN Mesh Networks,” *IEEE Network*, 22(3):4–10, May-June 2008.
- [9] S. Tanezaki, T. Matsushima, and S. Muroyama, “Stand-Alone hybrid power supply system composed of wind turbines and photovoltaic modules for powering radio relay stations,” in *25th International Telecommunications Energy Conference*, pp. 457–462, Oct. 2003.
- [10] B. Panajotovic and B. Odadzic, “Design and Intelligent Control of Hybrid Power System in Telecommunication,” in *15th IEEE Mediterranean Electrotechnical Conference*, pp. 1453–1458, Apr. 2010.
- [11] F. Darbari, M. Brew, S. Weiss, and R. Stewart, “Practical Aspects of Broadband Access for Rural Communities Using a Cost and Power Efficient Multi-Hop/Relay Network,” in *2010 IEEE Global Communications Conference*, Tampa, FL, pp. 731–735, Dec. 2010.
- [12] A. Payne, “Implementation Challenges for UHF White Space Cognitive Systems,” in *IET Seminar on Cognitive Radio and Software Defined Radios: Technologies and Techniques*, London, UK, pp. 1–30, Sept. 2008.
- [13] European Commission, Photovoltaic geographical information system (GVGIS), <http://re.jrc.ec.europa.eu/pvgis/>, 2008. <http://re.jrc.ec.europa.eu/pvgis/>