Multi-Radio Access Network Assignment Using Dynamic Programming

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Abstract—This paper addresses the formulation of an optimisation problem that assigns a user to a multi-network base station for rural broadband access. The base station in this work is a fully off-grid—powered by renewable energy—system with a wireless backhaul link. The solution proposed in this paper relies on a dynamic programming approach, implementing a cost function that balances power consumption and quality of service. The cost is then aggregated using penalties based on the energy harvested and battery charge. The implemented algorithm is demonstrated (in simulations) able to adapt the user assignment to the network load and energy production.

I. Introduction

Information and communications technologies (ICTs) currently represent approximately 10% of the world electricity consumption, and is forecast to reach 50% accounting for 23% of the humans carbon footprint by 2030 [1]. From those figures arises the question of the impact of ICTs on the environment. On the other hand, there is a substantial part of the world population with no or limited access to the internet; this is also true in remote area of economically developed countries such as the United Kingdom (UK) [2].

Typical broadband access solutions use an optical fibre network that is locally distributed to users through the copper twisted-pairs legacy phone network. However, the deployment of optical fibres is a very expensive process, which makes this technology unprofitable for service providers in low density areas. Adding to the network access issues, an unavailable or unreliable power grid at the base station site can represent further challenges and costs.

The suitability of wireless technologies for rural broadband has been studied in developing [3]–[6] and developed countries [7]–[9], both from a technical and economical standpoint. Several wireless technologies were proposed in the context of rural broadband access, including Wireless Fidelity (WiFi) and TV white space (TVWS) approaches. The latter has been strongly motivated by the spectrum release that followed the Digital Television (DTV) switch-over in numerous countries such as the UK [10]. The remoteness of such base stations (BSs) might require the introduction of energy harvesters to supply power [11]–[13]. The introduction of renewable energy harvesting strongly affects the available power, two approaches are then possible to maintain service, either the energy system need to be overdimensioned to guarantee a minimum service [9] or resource management has to be introduced [14].
Previous studies [9] used wireless BSs to provide broadband

in remote areas, which have been successfully combined with various energy harvesters for power supply. Furthermore, the user spacial distribution in rural environments into the form of clusters—villages—surrounded by sporadically placed users renders the rural area well suited for the use of multiple radio access technologies with different propagation characteristics, allowing to serve both the close-by and farther away users to optimise the user data rate [15]. Several studies showed that energy savings are achievable by optimising the user assignment in a heterogeneous network scenarios [16], [17].

In this paper, using the BS design proposed in [9], we present a formulation of an optimisation problem of the user assignment on a base station concurrently employing two radio access technologies to provide broadband in rural area. The problem focussed on the minimisation of the power consumption of the BS under network capacity and harvested power constraints and is expressed to facilitate the use of a dynamic programming (DP) approach.

In Sec. II, we give details on the BS design, while Sec. III focuses on the power consumption and load model for the radio hardware and the energy production from the various renewable energies harvesters. We then describe our formulation of the optimisation problem—based on a DP approach—in Sec. IV and finally provide results and analysis via simulation in Sec. V.

II. Multi-Radio Off-Grid Base Station

A. Radio Systems

In our study we consider a similar design to the one presented in [9]; the BS is equipped with 3 radios; a point to point (PTP) high throughput wireless link provides the backhaul connection to the internet, the service is then redistributed using two point to multi-points (PTMP) radios operating in two different parts of the spectrum. Is selected on one hand a TVWS ultra high frequency (UHF) network for its long-range due to the better propagation characteristics of the lower frequencies [18]. However overcrowding of the TV spectrum [19] limits the achievable throughput, thus restricting the number of users to whom such a network can provide high speed broadband. The TVWS network is then assisted by a 2.4 GHz WiFi network for its high throughput, but limited range reduces the GHz network to solely operate for users within line-of-site. The geographical organisation of rural areas in villages allows to consider a scenario where the WiFi network provides the village with service while the users scattered
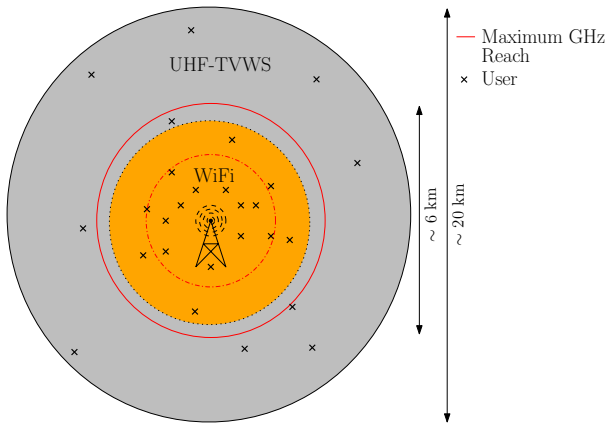
Fig. 1: Multi-radio access network scenario.

Fig. 2: User spatial distribution model.

Fig. 3: Mean load variation throughout the day.

in the countryside are served by the TVWS network. This rural broadband access scenario—proved suitable in previous studies [3], [9], [15]—is presented in Fig. 1.

To optimise the assignment of users to either network, we assume that the users possess radio hardware that can be reconfigured for either the GHz or TVWS transmission channels. The user assignment to either of the TVWS or GHz network is managed by the BS. User radio hardware configurations as well as connection requests are transmitted using a low power, low data rate network covering the community in its entirety.

B. Power Supply and Storage

As in [9], the base station is powered by a single wind turbine (SuperWind SW350) with a peak output power of 350 W and two photovoltaic solar panels producing up to 250 W each. The use of multiple types of renewable energy sources provides the diversity to better safeguard a continuous power supply. In addition to the energy harvesters above, the base station uses a bank of Li-Ion batteries—12 V and 600Ah equivalent to a 7.2 kWh capacity—as an energy buffering and storage system.

III. SYSTEM MODEL

In this section, we present the various models we will be using in the cost and penalty function formulation.

A. Network Model

1) User Spatial Repartition: Rural environment is often composed of clusters of houses (i.e. a village) while other houses are spread sparsely around the community, sometime kilometres away from each other. In this study, we consider a village covering a circular area of 6 km in diameter, surrounded by single users located up to 14 km from the BS. To simplify the system model we place a single BS in the centre of the community and assume similar channel characteristic in all directions. Thus the users' positions can then be simply expressed as their distance relative to the BS. Based on these assumptions, we used the half normal distribution shown in Fig. 2 to generate the position of $N = 30$ users in the community.
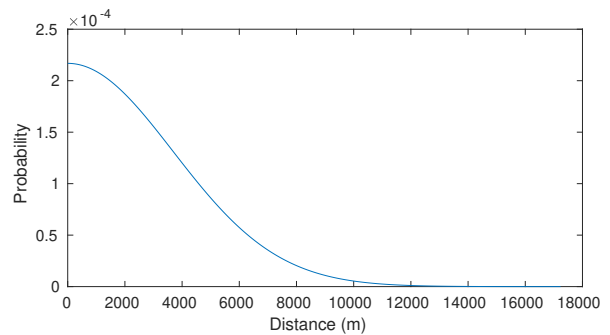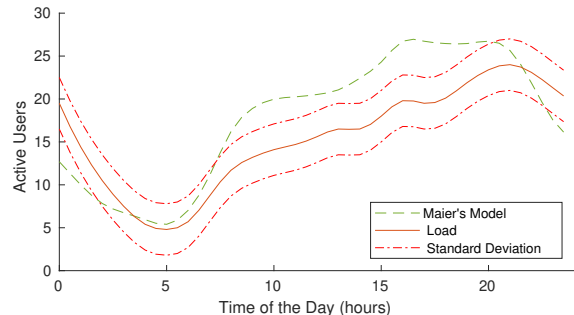
2) Load Model: As with every communication network the number of active users and thus the load on the base station varies, a typical approach would be to use a Maier model [20] to represent the evolution of the traffic over time. However, previously a study [9] of the ADSL traffic on the Isle of Tiree (UK) has shown that the load varied following the model presented in Fig. 3. The variation in the number of active users around the mean is modelled using a normal distribution with a standard deviation of 3 users. We assume however that at least one user is active at all times. This assumption while in theory not perfect represent a good approximation of a practical case in which we would need to keep at least the TVWS radio active to maintain service.

B. Power Consumption Model

In this paper, we used the power consumption model for the PTMP radio presented in [21]. The power consumption P_a (in watts) of the radio system $a \in \{g, u\}$, where g and u refer to the GHz and UHF radio access networks, respectively, can be expressed as follows:

$$P_a(t) = \alpha_a \left(P_a^{tx}(t) - G_a^{tx} \right)^{\beta_a} + \gamma_a, \tag{1}$$

where $\alpha_a, \beta_a, \gamma_a$ are coefficients characterising the radio a power consumption model determined empirically by fitting to power consumption data from the BS in [9], [21]. The parameter G_a^{tx} is the transmitting antenna gain and $P_a^{tx}(t)$ is the minimum transmission power in dB required a the time step t,
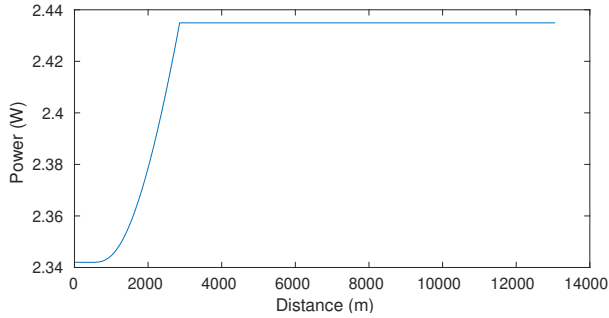
$$P_a^{tx}(t) = L_a(d) + P_a^{rx} - G_a^{rx}, \tag{2}$$

Fig. 4: GHz radio power consumption.

Fig. 5: Average daily energy generation on Tiree, Scotland [9].

where G_a^{rx} the receiving antenna gain, P_a^{rx} the minimum receiving power; d is the distance from the BS, $d = r_{max}$ for the TVWS network ($a = u$), where $r_{\max}$ is the distance to the farthest user and $d = r(t)$ is the reach of the WiFi network at the time step t. The simplified pathloss $L_a(d)$ is

$$L_a(d) = K_a + \eta \times 10 \log(d), \quad (3)$$

as defined by [18]. Values of K_a and η, where determined by pathloss measurement on the Isle of Tiree (UK) [21]. Using the parameters presented in Tab. I, we can then express the power consumption of the GHz radio as a function of the distance reached by the link, as shown in Fig. 4. Due to licensing issues the maximum transmit power for WiFi devices is limited to 30 dBm [22], thus restricting the maximum power consumption of the transmitting hardware.

To guaranty a full coverage of the community at all times the UHF network transmission power is set to reach the farthest user from the base station, we then have $P_u^{tx}(t) = P_u^{tx}(r_{\max})$. In addition to the PTMP radio consumption, the PTP backhaul link and the network equipment is estimated to consume approximately 45 W and 9 W, respectively [9].

C. Power Generation and Storage Models

As with most renewable energy sources, the instantaneous power output of solar panels and wind turbines varies hourly, daily and monthly, thus we need a way to predict the available power at each time-step taking into account the time distribution of each energy source. Our work is based on data for energy harvested on the west coast of Scotland— Isle of Tiree and Bute—as presented in [9] The mean energy production of the two types of harvesters, listed in Sec. II-B, is presented in Fig. 5. These statistics show that the wind represents the main energy source during the winter months and that the increase

in solar energy during the summer counterbalances the lack of wind power.

1) Solar Power: Photovoltaic electricity generation varies according to the weather, the time of the year and the hours of the day. In this work, the hourly energy distribution, as shown in Fig. 6, is estimated from the day length; for simplicity we suppose that the maximum energy can be harvested at midday. The instantaneous power output of a solar panel strongly depends on the amount of sunlight it receives, with its power output dropping down to 10% of its nominal output on a cloudy day. Using both hours of sunshine data [23] and hours of daylight per month, we compute the likelihood of a day to be sunny. This information is then used to randomly select the energy produced by the solar panels each day.

2) Wind Power: To keep the model simple we suppose that the wind is a slow varying resource at a day scale [24] while the solar energy varies greatly depending on the time of the day. However on a larger time-scale the wind is very unsteady and there can be a great difference in generation from one day to the next. Thus, we model the variation of energy in between days using a wide normal distribution with $\sigma_w = \mu_w/2$. After randomly selecting a value for each day, we model the slow hourly variation using interpolation between the produced data points.

3) Energy Storage: In this work we consider batteries with a capacity of 7.2 kWh and a charge/discharge efficiency of 80% [25]. This allows us to model the energy losses within the power management system as well as the natural self-discharge of the battery.

TABLE I: Power Consumption Model Parameters [15].

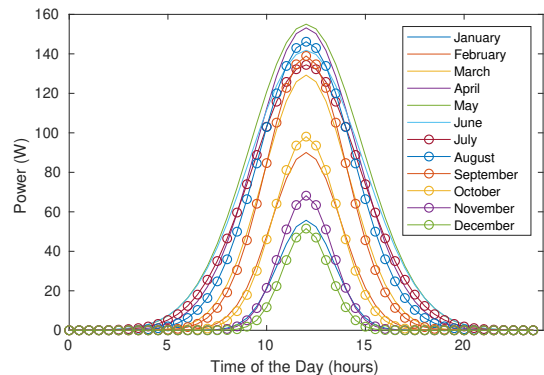| Parameter	GHz	UHF
η	2.39	
α_a	1.135e-7	3.395e-7
β_a	4.545	4.424
γ_a	2.342	2.555
K_a	-47.5dB	-28.43dB
P_a^{rx}	-90dB	-100dB
G_a^{rx}	10dB	10dB

Fig. 6: Sun power generation variation.

IV. ENERGY OPTIMISATION

We assume coverage areas as outlined in Fig.1, and want to determine the boundary between the GHz and UHF networks based on energy optimisation. In the analysis in this section, terms such as E_a, $a = \{b, G, U, BS, \dots\}$, represent an energy amount expressed in Joules (J), obtained from the corresponding power define in the models presented in Sec. III. For this study we discretised the time into 30 minutes time step δ_t, indexed on the variable t.

A. Optimisation Problem

We aim to extract an optimum GHz radio reach $\mathbf{r}_{\mathrm{opt}}(z = t)$ for the current time step t out of the optimal breathing policy over a sliding window of 24 hours centred on the current time t for which we aim to find the best user assignment. This takes into account the current battery level and load, its values for the past 12 hours, and the forecasted energy generation and load for the next 12 hours. This relatively short window, indexed by $z \in [t - 24 \cdot \delta_t; t + 24 \cdot \delta_t[$, is motivated by the limited reliability of forecasting [26]. We formulate the problem to determine the optimum policy $\mathbf{r}_{\mathrm{opt}}$ over the 24-hour window

$$\mathbf{r}_{\mathrm{opt}} = \arg\min_{\mathbf{r}} E(\mathbf{r}) \quad \text{s.t.} \quad E_{\mathrm{b}}(t) > E_{\mathrm{b,min}} , \qquad (4)$$
$$N_{\mathrm{U}} \le N_{\mathrm{U,max}} ,$$

where $E(\mathbf{r})$ is an energy function related to the energy generation and consummation at the BS site over the each of the 24-hour window time steps, under quality of service constraints. The constraints for battery level $E_{\mathrm{b}}(t)$ left after we selected $\mathbf{r}_{\mathrm{opt}}(t)$ and the number of users N_{U} assigned to the TVWS limits the formed to a minimum value $E_{\mathrm{b,min}}$, and the latter to the maximum number of supported users $N_{\mathrm{U,max}}$, at any given time. The vector $\mathbf{r} = [R_{t-24 \cdot \delta_t}, \dots R_{t+24 \cdot \delta_t}]^{\mathrm{T}}$, over which the optimisation is to be performed, contains the range values of the GHz RAN, which for simplicity can take on the discrete distance values of the N users, thus allowing us to index the possible values of R using $n = 1, \dots, N$. There are therefore 30^{49} different ways in which the GHz radio access network can breath, and $\mathbf{r}_{\mathrm{opt}}$ represents the optimum assignment over time.

The problem (4) can be addressed by a DP algorithm [27], which is divided into three steps. First we build a cost space based on the possible values for the reach of the GHz network and the BS load. Secondly, it aggregates the cost using a penalty function related to the harvested energy. Lastly, it generates a cost space were each cost related to a specific $\mathbf{r}$ takes into account the past and future possible states of the network.

B. Cost Function

The cost function for the nth user at time step z

$$C(z, n) = C_{\mathrm{p}}(n) + \mu_{\mathrm{load}} \cdot C_{\mathrm{l}}(z, n) , \qquad (5)$$

is a linear combination of the power consumption $C_{\mathrm{p}}(n)$ of the GHz network and the TVWS network load $C_{\mathrm{l}}(z, n)$, with a control value μ_{load}. We express the power consumption as

$$C_{\mathrm{p}}(n) = \frac{E_{\mathrm{G}}(n) + E_{\mathrm{U}} + E_{\mathrm{BS}} + E_{\mathrm{backhaul}}}{E_{\mathrm{G_{max}}} + E_{\mathrm{U}} + E_{\mathrm{BS}} + E_{\mathrm{backhaul}}} , \qquad (6)$$

i.e. as the ratio between the BS energy consumption associated with $E_{\mathrm{G}}(n)$ and the maximum power consumption of the BS, linked to the maximum GHz radio energy consumption $E_{\mathrm{G_{max}}}$. To balance the energy used by the GHz network to the energy requirements of the rest of the BS, we introduce the energy consumption of the TVWS radio hardware, E_{U}, the energy consumption of the backhaul link radio, E_{backhaul}, and the consumption of other subsystem in the BS, E_{BS}.

While the cost $C_{\mathrm{p}}(n)$ increases with the coverage of the GHz network, the $C_{\mathrm{l}}(z, n)$ decreases. We formulate $C_{\mathrm{l}}(z, n)$ as

$$C_{\mathrm{l}}(z, n) = \begin{cases} \left| \dfrac{N_a(z) - n}{N_a(z) - N} \right| & \text{when } N_a(z) < N \\ \Gamma_{\mathrm{load}} & \text{when } N_a(z) = N \end{cases} , \qquad (7)$$

where $N_a(z)$ is the number of active number in the community at time t. To prevent an infinite cost we introduce Γ_{load} when the number of active users $N_a(z)$ is equal to the total number of users N. The value of Γ_{load} is always set to be greater than any other $C_{\mathrm{l}}(z, n)$.

C. Cost Aggregation

Once the cost space $C(z, n)$ is built, we proceed to the aggregation of the cost in both time directions. The aggregated cost towards negative time can be written as

$$L_{(-)}(z, n) = C(z, n) + \min \Big(\min_{i \le n} \big(P_{\mathrm{up}}(z) + L_{(-)}(z - \delta_t, i) \big),$$
$$\min_{i \ge n} \big(P_{\mathrm{down}}(z) + L_{(-)}(z - \delta_t, i) \big) \Big) \qquad (8)$$

with P_{up} and P_{down} the penalties associated with an increase or decrease, respectively, of the GHz reach, such as $P_{\{\mathrm{up,down}\}}(z) = \mu_{\{\mathrm{up,down}\}}(t) \cdot G(z)$ where $G(z)$ is

$$G(z) = \frac{E_{\mathrm{W}}(z) + E_{\mathrm{S}}(z)}{\max_t \big(E_{\mathrm{W}}(t) + E_{\mathrm{S}}(t) \big)}, \qquad (9)$$

where $E_{\mathrm{W}}(\cdot)$ and $E_{\mathrm{S}}(\cdot)$ are the energy produced by the wind turbine and the solar panels, respectively. To keep the penalty values similar to the cost $C(z, n)$ we normalise $G(z)$ using the maximum energy produced over the entire data. The parameter $\mu_{\{\mathrm{up,down}\}}(t)$, constant over the considered 24-hour window, allows for a finer control of the penalty as well as providing information on whether there is an increase or reduction in reach w.r.t. the previous time step $t - \delta_t$:

$$\mu_{\mathrm{up}}(t) = \max \left(\frac{E_{\mathrm{b}}(t - \delta_t) - E_{\mathrm{b,min}}}{C_{\mathrm{b}}}, 0 \right) \qquad (10)$$
$$\mu_{\mathrm{down}}(t) = 1 - \mu_{\mathrm{up}}(t) , \qquad (11)$$
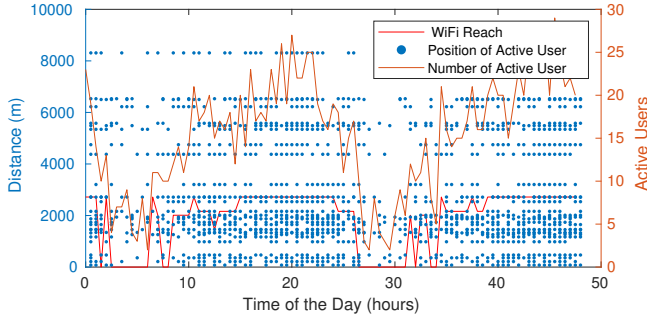
Fig. 7: Two days simulation in January at full harvesting capacity.

Fig. 8: Mean hourly GHz network reach on a day in January and July under full and reduced harvesting capacity.

with C_b the battery energy capacity expressed in Joules and $E_b(t - \delta_t)$ the energy available in the battery at the current time step t on which the considered window is centred. The aggregated costs in each direction are then added together to produce an overall cost

$$L(z,n) = L_{(-)}(z,n) + L_{(+)}(z,n) ; \qquad (12)$$

where $L_{(+)}(z,n)$ represents the aggregation in positive time based on forecasted values. The quantity $L_{(+)}(z,n)$ is define analogously to $L_{(-)}(z,n)$ in (8) by replacing $z - \delta_t$ with $z + \delta_t$.

D. Optimum GHz Range Selection

The optimum reach breathing policy is selected by choosing for each z the value of n which minimises $L(z,n)$, those values can be gathered into a vector $\mathbf{n}_{opt}$ form which we can get the optimal reach values $\mathbf{r}_{opt}$. The minimisation over n is how restricted to users that are reachable by the GHz network. Furthermore, we have to ensure that the number of total active user N_U assigned to the TVWS network is lower than the maximum number of users which the TVWS radio can serve under a quality of service constraint. By extracting the optimum reach policy we can determine the optimum reach for $z = t$ and thus compute a related GHz radio energy consumption $E_G(t)$. We then calculate the energy left in the battery at the end of the time step t, $E_b(t)$ such as

$$E_b(t) = \alpha_b E_b(t - \delta_t) + \eta_{BS}(E_W(t) + E_S(t))$$
$$- \frac{1}{\eta_{BS}}(E_G(t) + E_U + E_{BS} + E_{backhaul}) \qquad (13)$$

the coefficient α_b accounting for the battery self discharge and η_{BS} the efficiency of the power conversion systems. We are then ready to run the algorithm at the time step $t + \delta_t$.

V. RESULTS

In order to test the performances of our algorithm, we ran simulation with a year worth of data randomly generated using the models described in Sec III, under two energy harvesting scenarios. The first considers the harvesting performances described in Secs. II-B and III while the second considers that the BS is equipped with harvesters providing only 25% of the energy output from the first scenario. The value of 25% was chosen empirically to maintain the battery level
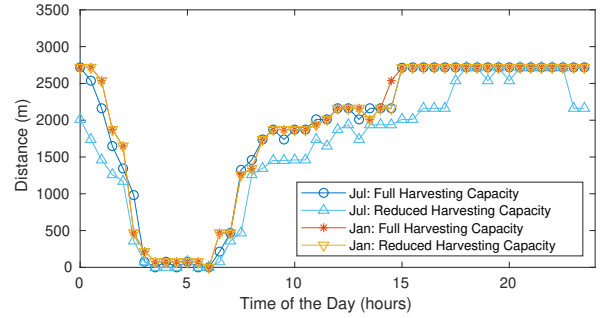
above 10% over the all simulation. This reduced harvesting capacity simulation allows us to get a better understanding of the behaviours of the algorithm and considers the possibility to reduce the harvesting capacity of future BS designs. We used three metrics to judge the algorithm behaviour: the reach variation, the power consumption of the GHz radio as well as the number of users assigned to the TVWS network. We compute those metrics on a monthly basis and draw conclusions on the algorithm behaviours with regards to the mean harvested power presented in Fig. 5

Fig. 7 shows the active users positions as well as the reach for the GHz network selected by the algorithm with respect to those positions over a two-day window. The number of active users confirms that the algorithm behaves as expected by adapting the GHz reach to the user activity, increasing the reach when numerous users are active and reducing it all the way to shutting down the GHz radio when all user can be served by the TVWS network. Fig. 8 presents the hourly average reach of the GHz network of the month of January and July, under the two considered scenario whereby January and July represent month with high and low harvested energy, respectively. The algorithm reduces the reach of the GHz radio in low energy condition, which is especially visible for the month of July under reduced harvesting capacity. This behaviour is corroborated by the reduction in power consumption for the GHz radio in Fig. 9, which is linked to the increase in the number of users assigned to the TVWS network as evident from Fig. 10.
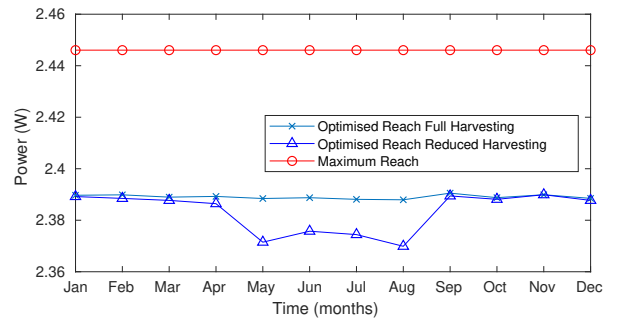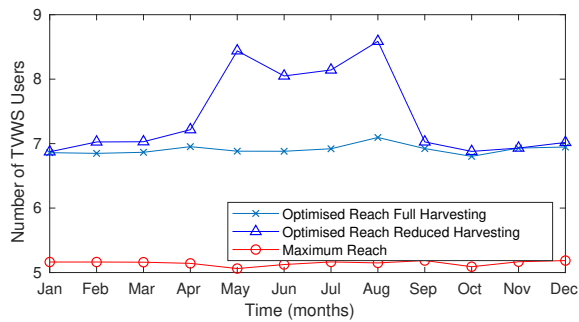

Fig. 9: Mean GHz radio power consumption

Fig. 10: Average numbers of TVWS users

VI. Conclusions

In this paper, we have presented an energy model and optimisation process for the assignment of users in a single base station multi-radio network for rural broadband access. The algorithm uses a dynamic programming approach over a cost function defined as the linear combination of a power consumption and a network load related cost over a 24 hours sliding window.

The algorithm is effective in reducing the power consumption of the GHz PTMP radio, providing up to 3% energy saving against a maximum reach policy. Together with efforts towards a low-power basestation implementation [9], [28], [29], this algorithm can permit a downsizing of the power supply systems (harvesters and batteries), thus reducing the cost of the base station, as demonstrated in simulation by reducing the harvesting capacity of the BS to 25%. Furthermore the algorithm can provide a better balance between the number of users assigned to each of the networks, and is therefore capable of enhancing the quality of service.

Acknowledgement

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