ElasticWISP-NG: Towards Dynamic Resource Provisioning for WISP Access Networks

Duncan E. Cameron, Murugaraj Odiathevar, Alvin C. Valera and Winston K.G. Seah

Abstract *ElasticWISP-NG (Next Generation)* presents an innovative approach to dynamic resource provisioning in Wireless Internet Service Provider (WISP) access networks. This paper introduces the early stages of our novel scheme, which builds upon the foundational concepts of our previous *ElasticWISP* model. We focus on the utilisation (and the implicit constraints) of renewable energy sources, and identify where opportunities to reduce network-wide energy consumption exist. Our findings outline the potential of *ElasticWISP-NG* to transform the accessibility of the Internet in underserved areas, promising significant advances in sustainable and scalable network management.

1 Introduction

The physical growth of the Internet since its inception has been remarkable. By 2025, the number of Internet of Things (IoT) devices alone is expected to exceed 37 billion, far surpassing the human population of our planet [43]. The Internet, through physical telecommunications networks, has brought billions of people across the globe closer together, enabling countless new industries to emerge, consequently changing the way we live forever. As we look to the future, the proliferation of devices connected to the Internet is expected to increase, especially as we enter the IoT and Internet of Vehicles (IoV) era [7].

Today, we collectively take fast and accessible Internet connectivity for granted. It is easy to forget that in remote and rural areas throughout the world, Internet access is not equal and there is an all-too-real digital divide. Even in well-developed nations such as New Zealand, experiencing the displeasure of poor or non-existent connectivity often only requires a short drive out of any major urban centre. Furthermore, during

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the COVID-19 pandemic, we saw that for those living outside of well-connected areas, the ability to work remotely was not always possible, further degrading economic and health outcomes for those with connectivity disadvantage. Although services such as Starlink have since become available in many parts of the world, inequality and cost of service still remain a major concern.

We must also consider that simply having Internet connectivity is no longer enough. Much of the modern Internet is media rich and not built considering remote and rural users with constrained connections. Simply having an Internet connection does not guarantee the ability to benefit from remote work tools such as Zoom, or the ability to stream media through YouTube or Netflix. The promise of telemedicine [33], which arguably benefits remote and rural communities the most, is far from being a reality when many last-mile access networks do not survive beyond their pilot phase [35]. Unfortunately, the path forward to improve remote and rural Internet infrastructure is not definitive throughout much of the world. Despite uncertainty, recent technical innovations, such as the satellite Internet mega-constellation Starlink by SpaceX [22], provide a promising outlook for the future.

In 2019, a study placed the number of people worldwide who lack basic Internet access at 400 million [13], many of whom live outside urban centres. With so many lacking access to basic Internet infrastructure worldwide, it is reasonable to question what is preventing the further expansion of Internet service. From the perspective of an Internet Service Provider (ISP), the density of potential subscribers in remote and rural areas generally means that there is little financial incentive to build infrastructure [16, 42]. The reality is often unfortunate. Without the incumbent and sometimes monopolistic ISPs taking on greater financial risk to build modern Internet infrastructure in these sparsely populated areas, there will be no *modern* infrastructure, if any at all.

The demand for better physical Internet infrastructure, combined with the inaction of slow-moving incumbent ISPs, has led to the development of community networks, often wireless, throughout the world [42]. Sometimes these networks are run entirely by the community, such as Guifi.net [28, 37] and Freifunk [12]. In many other cases, networks are relatively small commercial ventures and are referred to as Wireless Internet Service Providers (WISPs). These wireless networks are of particular interest, as they have the potential to offer high-speed services that can often exceed the commercial offerings of the incumbent ISPs and have been recognised as an important part of remote and rural Internet infrastructure [1, 14, 23, 29, 31, 32, 38]. However, WISPs face challenges, both technical and social, that have seen little improvement over the past decade.

By nature, many of the communities WISPs serve are in remote and rural areas, with limited other connectivity options available [30]. To reduce Capital Expenditure (CAPEX), WISPs deploy infrastructure to high, sometimes mountainous areas to provide the best coverage with the least number of physical sites required, much the same as is done by any Mobile Network Operator (MNO). However, while high ground is typically advantageous for the coverage of wireless networks, being located outside of urban centres often means that there is no electricity grid available [24]. Consequently, renewable energy sources such as solar or wind must be used, which introduce their own challenges, particularly in the area of ensuring network reliability. The possibility of network interruption requires adequate monitoring for fault detection – an area that still requires improvements to be suitable for the particular challenges encountered [9, 27, 34]. The use of renewable energy sources creates a significant cost incentive to minimise the energy consumption of devices where possible [14, 24, 35].

In New Zealand alone, there are more than 30 substantial regional WISP networks – connecting more than 70,000 remote and rural homes and businesses to the Internet [41]. Like New Zealand, WISPs around the world do not always individually operate large networks, but collectively connect millions to the Internet. The next generation of WISP networks will need to be robust, energy efficient, and scalable enough to meet the demands of the future. For WISPs to remain an important part of last-mile Internet access, we **must** determine how we can create affordable, scalable, and maintainable networks. The following sections will introduce our contribution, *ElasticWISP-NG*, which expands on our earlier *ElasticWISP* work, and will enable WISP operators to build energy-efficient and scalable access networks.

2 Related Work and Motivation

Perhaps unsurprisingly, researchers have identified that many WISPs build their networks out of necessity to provide Internet access where connectivity is poor or non-existent, even if they lack background knowledge and experience in operating wireless networks [4, 6, 14, 29, 30, 34]. As a result, many research efforts have focused on improving the outcomes of these wireless networks, often through improved ease of network management [1, 4, 14, 18, 25, 27, 29, 30, 34, 35]. Several important advances have also been made in understanding and monitoring traditional off-grid energy systems used [18, 24, 27, 29, 33]. Despite advances in energy monitoring at the WISP sites and their subsystems, little progress has been made to improve the energy efficiency of these sites [5].

The implications of poor energy efficiency in energy-constrained WISP networks are significant. When microwave radios are used within a wireless network, typically for backhaul, they can be responsible for up to 50% of the energy consumption in the network [11, 36]. In our previous work that aimed to improve energy efficiency within WISP backhaul networks, savings of up to 65% were achieved by turning off redundant backhaul links [5]. Furthermore, designing networks around ever-changing weather conditions can be a challenge. Known weather patterns at particular geographic locations can determine which frequency radios (e.g., mmWave or otherwise) are suitable for use, as well as the type and size of energy harvesting systems that are required. Designing network resource optimisation schemes that can manage high environmental variability first requires appropriate planning and sizing of energy harvesting systems. Underbuilding risks creating unreliable networks that cannot adapt to undesirable conditions. Overbuilding will improve reliability at the potential cost of fewer sites being built due to resource constraints.

2.1 Location

Unfortunately for MNOs and WISPs alike, finding suitable land will always be a challenge. High mountainous areas often provide excellent coverage potential, but come at a price. Take New Zealand WISP Venture Networks as a case study. Venture Networks' Heights site is an example of an all too common situation, especially among WISPs. The lower areas of Tararua Forest Park, a mountain range located around the southern and central north island of New Zealand, are ideal for building wireless infrastructure. Venture Networks, and other MNOs, have built wireless network infrastructure in the lower, more accessible areas of the Tararuas. In any case, grid power in such mountainous terrain is limited almost exclusively to network operators that have the financial ability to invest millions into their most important sites, as power infrastructure must be built to the location.

Consequently, Venture Networks, like many other WISPs around the world, is in a situation where renewable energy sources must be used due to financial constraints. Consequently, planning and maintaining off-grid energy harvesting systems is critical to the long-term success of any wireless network. Although solar and wind systems can be cost-effective compared to installing expensive power cables from the closest source, often kilometres away, building very remote WISP sites means that additional expertise is demanded of network operators. In addition to being able to plan and configure the wireless network infrastructure itself, WISPs also need to be comfortable managing low to medium voltage energy harvesting systems, which in some countries requires certification. In many cases, vehicle access to sites is not viable year-round. Transporting equipment and personnel to new or existing sites can mean using off-road vehicles, hiking, or, in some cases, using a helicopter.

Although MNOs and WISPs do not always face such a difficult terrain, there is a strong motivation to design networks that are robust enough to survive challenging environments. As power systems are a fundamental part of any wireless infrastructure, it is necessary to emphasise energy efficiency. Furthermore, with more energy-efficient wireless infrastructure, greater financial savings can be achieved with reduced spending on energy harvesting and battery systems. In summary, the natural landscape is an invaluable resource, and wireless networks will continue to benefit as technology evolves and energy efficiency increases. However, considering the challenges created by terrain, existing grid-connected structures that can provide reasonable coverage to areas, such as guyed towers or grain silos, are comparatively accessible alternatives.

2.2 Energy Harvesting, Management, and Monitoring

The nature of operating remote and rural access networks often means that renewable energy sources outside the grid, such as solar or wind, must be harvested [5, 18, 24, 26, 27, 33, 35]. Grid electricity in developing nations, where it is available, is often of poor quality, which causes concern about reliability of the network [18, 24, 26, 29, 33, 35].

Despite the fact that energy constraints within wireless access networks are well understood, few research efforts have produced tangible improvements [5]. However, in general, the energy consumption of wireless access networks has been a widely studied area, often with the objective of reducing the operational cost of energy per kWh consumed [2, 17]. Although important research, the fundamental issue of reliably providing power must also be considered.

Additionally, the operational cost of powering remote and rural access networks through renewable sources makes energy efficiency very important, meaning that related cost-reducing initiatives are often applicable. Furthermore, our previous work found that traffic in WISP networks follows diurnal patterns [5]. Importantly, our findings are consistent with related work [15, 21]. The distribution of daily traffic, as seen in Fig. 1, means that intelligent use of network resources, namely access radios, is possible. Our *ElasticWISP* scheme is one of such examples, but it is limited to point-to-point backhaul networks. Related research has identified that point-to-multipoint Long-Term Evolution (LTE) cellular base stations can almost halve their otherwise normal off-grid energy harvesting and storage requirements by implementing a sleep mode during low-traffic periods [21]. For WISPs, we found no comparable point-to-multipoint energy conservation schemes, presenting an important opportunity for the development of our *ElasticWISP-NG* scheme.

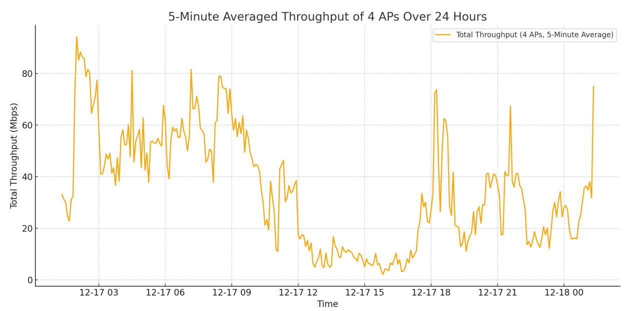

Fig. 1 Access Network Traffic (4 x Access Points).

Planning off-grid energy systems and properly sizing them is another important task that can be exacerbated by weather variations [3]. Solar Photovoltaic (PV) systems are widely used, but limited sunlight hours during the winter months mean that energy harvesting and storage capacity planning must be carried out carefully. Unfortunately, there is no “one-size-fits-all” approach for capacity planning. The daytime hours of sunshine vary depending on the geographic location and the intensity of the solar radiation. Even with an appropriately sized off-grid energy system in place, monitoring and ensuring year-round availability is critical. In support of this, our earlier work studied the automatic monitoring of off-grid energy systems and preemptively detecting power system faults before they occur [27]. Fig. 2 shows the degradation of the battery bank at the Venture Networks Heights site during an extreme weather event.

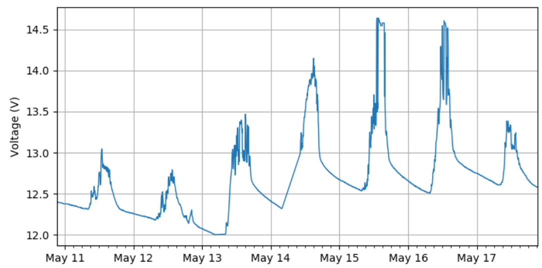

Fig. 2 Battery degradation and recovery during a storm.

3 Design

We have argued why energy efficiency in WISP networks is of utmost importance. Operators face challenges that we are not familiar with in daily life, even as engineers, and every incremental step we can make towards alleviating these pains is a major benefit. The following subsections describe the high-level formulation of our *ElasticWISP-NG* scheme. Although we are in the early stages of fully implementing *ElasticWISP-NG*, and seeing it through to becoming a production ready system, we believe it is important to highlight our contribution and what the next key steps are in our journey.

3.1 Model Formulation (Original)

Let us first review our *ElasticWISP* [5] model formulation, which is an adaptation of the *ElasticTree* [15] formulation. We define a flow network $G = (V, E)$ with edges $(u, v) \in E$ and with capacity $c(u, v)$. We have k different commodities $K_1, K_2, ..., K_k$, where $K_i = (s_i, t_i, d_i)$. For commodity i, s_i is the source, t_i is the sink, and d_i is the demand. We establish that the flow of commodity i along the edge (u, v) is $f_i(u, v)$. We add standard multi-commodity flow constraints and find a flow assignment that can satisfy them [8, 10]:

Edge capacity: Ensure that all flows over each link do not exceed the available capacity, that is, $\forall (u, v) \in V$,

$$\sum_{i=1}^{k} f_i(u, v) \leq c(u, v). \tag{1}$$

Flow conservation: Intermediary nodes cannot create or destroy commodities. That is, $\forall i \in [1, k]$,

$$\sum_{w \in V} f_i(u, w) = 0, \text{ when } u \neq s_i \text{ and } u \neq t_i. \quad (2)$$

Demand satisfaction: Every source and sink must send or receive an amount of flow equal to its demand. We have $\forall i \in [1, k]$,

$$\sum_{w \in V} f_i(s_i, w) = \sum_{w \in V} f_i(w, t_i) = d_i. \quad (3)$$

3.2 Energy Minimisation Constraints

We now add energy-saving constraints to the multi-commodity flow formulation. We use the notation listed in Table 1 to describe the energy minimisation constraints [15].

Table 1 PTP energy minimisation notation.

Notation	*Definition*
$a(u, v)$	Power cost of the link (u, v)
$X_{u,v}$	Binary decision variable for the power state of link (u, v)
$r_i(u, v)$	Binary decision variable for indicating if commodity i uses link (u, v)

Deactivated links. Ensure that flows are restricted to only links (and radios) that are powered on. For all links (u, v) used by a given commodity i, $f_i(u, v) = 0$ when $X_{u,v} = 0$. The flow variable f will always be positive in our formulation, and thus we can write the linear constraint as

$$\sum_{i=1}^{k} f_i(u, v) \leq c(u, v) \times X_{u,v}, \quad (4)$$

$\forall i \in [1, k], \forall (u, v) \in E$.

Bidirectional power. On a radio pair, both radios must be turned on, irrespective of which direction network traffic is flowing, hence, we have

$$X_{u,v} = X_{v,u}, \quad \forall (u, v) \in E. \quad (5)$$

Flow splitting. Finally, as we target OSPF, a single-path routing protocol, we also add a constraint to prevent flow splitting. Additionally, we acknowledge that flow splitting is generally undesired due to the effects of TCP packet reordering [19]. We constrain the flow of commodity i over link (u, v) to either the full demand or zero. Hence, $\forall i, \forall (u, v) \in E$,

$$f_i(u, v) = d_i \times r_i(u, v). \quad (6)$$

Objective function. Now that the appropriate constraints have been added, we define the objective function, which is to minimise the overall network energy consumption:

$$\textbf{minimise} \sum_{(u,v)\in E} X_{u,v} \times a(u,v). \tag{7}$$

3.3 Extended Notation for PTMP Access Networks (New)

We now extend our original *ElasticWISP* formulation by adding constraints that consider the network beyond simple Point to Point (PTP) backhauls, as well as including an updated objective function.

Table 2 PTMP energy minimisation notation.

Notation	*Definition*
A	Set of access points
S	Set of subscribers
$P(u)$	Set of subscribers connected to access point u
Y_u	Binary decision variable for the power state of access point u
$L_{u,s}$	Binary decision variable indicating if subscriber s is connected to access point u
g_s	Demand of subscriber s
$b(u)$	Power cost of access point u

Access Point-Subscriber Assignment. Ensure that each subscriber is assigned to one and only one powered-on access point. For each subscriber s,

$$\sum_{u\in A} L_{u,s} = 1, \tag{8}$$

and to ensure that the access point u is on if subscriber s is connected to it, we have

$$L_{u,s} \leq Y_u, \quad \forall s \in S, \forall u \in A. \tag{9}$$

Access Point Capacity. The total demand of all subscribers connected to an access point must not exceed its capacity.

$$\sum_{s\in P(u)} g_s \times L_{u,s} \leq c(u), \quad \forall u \in A. \tag{10}$$

Updated objective function. In addition to the original *ElasticWISP* objective function, during low load periods, ensure that only the minimum set of access points necessary to serve all subscribers is powered on. This can be viewed as a Steiner Tree problem, where Steiner points are the access points, and terminals are the subscribers:

$$\textbf{minimize} \sum_{(u,v)\in E} X_{u,v} \times a(u,v) + \sum_{u\in A} Y_u \times b(u). \tag{11}$$

As with our *ElasticWISP* model, solvers such as Gurobi can be used to find solutions. For reference, we have uploaded an example using Gurobipy [40]. Note that a licence is required. Heuristics for our model are currently in development.

4 Proof of Concept

Steiner Tree problems have long been known to be NP-Complete [20], as are multi-commodity flow problems, such as our original *ElasticWISP* [10] scheme. While we continue to work on the evaluation of *ElasticWISP-NG* against larger network topologies, we should first consider the possible energy reduction possible with the scheme under worst-case conditions. Fig. 3 and Fig. 4 demonstrate how *ElasticWISP-NG* could save energy over a 24-hour period, using real-world data from our experimental testbed. In this case, we consider 4 access points, each of which consume at most 15 W of energy. For our Proof of Concept (PoC), we add a fifth access point, which is used to offload traffic from the other four access points during periods of low network load.

The process for identifying the energy saving potential in Figs. 3 and 4 is as follows. We denote the energy saving potential as $E_{savings}$. First, we set a safe capacity threshold, $C_{threshold} = C_{AP5} \cdot U_{threshold}$, where C_{AP5} is the capacity of the fifth access point, and $U_{threshold}$ is the utilisation threshold (85% in this context). The utilisation threshold should be set appropriately to avoid saturating queues and inducing unnecessary queueing delay, or "bufferbloat". We then calculate the rolling average of the total throughput, $T_{rolling}(t)$, over time t and identify the points, P_i, that offloading is possible. Functionally, this means whenever $T_{rolling}(t_i) \leq C_{threshold}$, subject to constraints such as radio boot time. In our case, we considered 5-minute rolling averages. The offloading period extends from each P_i to the subsequent time where the rolling average exceeds $C_{threshold}$. Finally, we give the total offloading time as $T_{offload}$, which is aggregated across all the recorded periods. We then use $T_{offload}$ to quantify the energy saving potential, as a percentage:

$$E_{savings} = \left(\frac{E_{main} - E_{5th}}{E_{main}} \right) \cdot \left(\frac{T_{offload}}{T_{total}} \cdot 100 \right), \tag{12}$$

where E_{main} and E_{5th} are the energy consumption metrics of the main four access points and the fifth access point, respectively, and T_{total} is the total observed time.

Fig. 3 shows the potential energy savings of offloading the 4 access points when their cumulative throughput drops below 50 Mbps of downstream traffic. Network resources (access points) will begin to scale up when we reach 85% of the maximum offloading capacity, to avoid introducing excessive queueing delays when running too close to the capacity ceiling of the single access point. The percentage of time during which the offloading to the fifth access point is active is approximately 70% of the total observed time during this 24-hour period. The energy savings achieved under these conditions are approximately 53% of the total energy that would have been consumed if the four main access points had run simultaneously.

This is the worst-case scenario; as we know, we could save more energy by considering offloading as few as two or more access points during low load. With that said, considering clusters of access points is not foolish, as high cumulative traffic across them is a better indicator of increased demand than from a single access point alone. Offloading is also not initiated until we fall below 85% of the target offload capacity, to prevent undesirable situations from occurring where excessive load is forced onto the single access point. The events highlighted in green indicate periods when only the fifth access point is operational, offering substantial energy savings, although less than with the higher capacity threshold shown next in Fig. 4.

Fig. 4 shows the same approach, with the fifth access point supporting 75 Mbps of offload capacity. The percentage of time during which the offloading to the fifth access point is active is now approximately 93%. This indicates that most of the time, the network conditions are suitable for offloading to the fifth access point, and we only need to scale up resources under peak load. The energy savings achieved under these conditions are approximately 70% of the total energy that would otherwise have been consumed. Effectively, these results demonstrate that *ElasticWISP-NG* can enable network operators to run a reduced capacity access network, with a minimal power footprint, and scale resources up to support peak demand, allowing better energy consumption today and scalability for the demands of tomorrow.

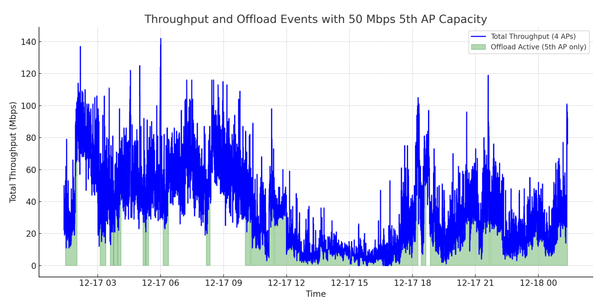

Fig. 3 Offloading at less than 50 Mbps of throughput.

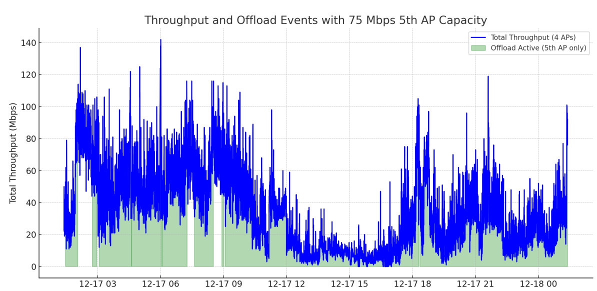

Fig. 4 Offloading at less than 75 Mbps of throughput.

5 Future Work

Our contribution goes beyond an updated *ElasticWISP* model. We have designed hardware to enable the real-world deployment of *ElasticWISP* and *ElasticWISP-NG*, and we are pleased to announce that we will make it open source for all [39]. Fig. 5 shows an ultrawide voltage input power control platform that we developed as part of this work. The platform accepts 9-75 VDC in with a fixed 24 VDC output, supplying a load of up to 150W. The system can currently be adapted to operate at 9-75 VDC in with a fixed 48 VDC output by swapping the power supply module. We intend to extend this in the future to support both output voltages simultaneously. The platform has integrated management via Ethernet and has an affordable bill of materials.

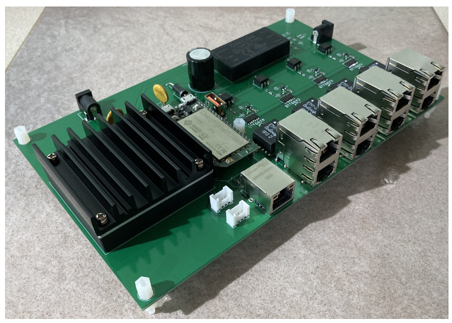

Fig. 5 Radio Power Control Platform.

Another important consideration for *ElasticWISP-NG* is how to react to, or preempt, network-wide subscriber demand. *ElasticTree* took a preemptive approach, using an autoregressive model to predict demand days ahead. *ElasticWISP* took a reactive approach, only powering up additional backhaul radios when there was a consistent increase in demand. Future work will look at how we can best anticipate and manage demand in the combined context of PTP backhaul and Point to Multi Point (PTMP) access networks. We know from our *ElasticWISP-NG* PoC that a reactive approach would still save a substantial amount of energy, although we also know that we can push this limit even further.

Furthermore, we know that flexible traffic engineering is mandatory to experience the full benefits of a scheme such as *ElasticWISP-NG*. Intelligent routing decisions within dynamic WISP access networks will help ensure that Quality of Service (QoS) remains acceptable and that network subscribers remain satisfied. However, we know that traditional shortest-path routing protocols are not, at least on their own, suitable for traffic engineering [5]. During our original *ElasticWISP* work, we encountered this very problem: steering specific flows over specific links was not easily achievable using traditional shortest-path routing protocols such as Open Shortest Path First (OSPF).

6 Conclusion

Our preliminary findings show great promise for dynamic resource provisioning in WISP access networks. Although still in the early stages of development, our PoC shows that there is a great opportunity to improve the energy efficiency of access networks at low load or idle. Our next steps will dive deeper into refining our formal model, as well as proposing less computationally complex heuristics. We must also assess the challenges of real-world implementation on a wider scale, as well as considering a broader dataset for evaluation. Practical deployment will help validate the effectiveness of the scheme and reveal any unforeseen challenges that we are yet to encounter. When completed, we can fully realise the path to more sustainable, energy efficient, and inclusive remote and rural connectivity solutions. Finally, to allow other researchers to build on our work, we have released real-world subscriber throughput data from our wireless testbed that can be used to assess how similar schemes could perform [39].

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