

ElasticWISP: Energy-Proportional WISP Networks

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Abstract—The provision of rural broadband infrastructure is a challenge for network operators across the globe, irrespective of their size. Wireless Internet Service Providers (WISPs) have shown that the small scale deployment of wireless broadband infrastructure is a viable alternative to relying on cellular network providers for remote coverage. However, out of concern for excessive energy consumption WISPs must often resort to using off-grid renewable energy sources such as solar energy for powering network sites, often resulting in undesirable, low-performance backhaul radios being used between sites. To encourage the development of high-performance, sustainable WISP networks, we present *ElasticWISP*, a backhaul optimisation architecture. *ElasticWISP* dynamically controls the configuration of backhaul radios based on bandwidth demands and the network-wide energy consumption of these radios. Through simulations driven by real WISP topology and data traffic, we show that *ElasticWISP* can offer energy savings of approximately 65% when following our design methodology.

Index Terms—Wireless, WISP, Backhaul, OSPF, Rural, Broadband, Network Operations

I. INTRODUCTION

Wireless Internet Service Provider (WISP) networks play an important role in connecting rural and underserved areas to the Internet [1]–[5]. Amongst various operational challenges, researchers have identified that many WISP operators build their networks out of necessity in order to provide faster connectivity to deprived communities, even if they lack strong knowledge to design and maintain wireless networks [2], [3], [6]. While efforts have been made to lower the barrier to entry for such WISPs to successfully operate networks [1]–[3], [7], we identify little has been accomplished to overcome one of the greatest operational challenges: off-grid network energy consumption [2], [7], [8].

To gain a better understanding of why energy consumption is important to WISPs, their target markets must be considered. By nature, underserved remote and rural communities often lack ubiquitous deployment of other infrastructure, e.g. power networks. Where a WISP builds Internet infrastructure in an unconnected frontier, there is often an assumption that grid-power will not be available, or will, at a minimum, be unreliable [3]. To power network equipment such as radios and routers, an appropriate energy harvesting system must be designed, taking into consideration the business case and cost of the entire system. As WISP markets are typically remote and rural with low subscriber density, budgets are often limited.

WISPs are then presented with a dilemma: either build low-cost, low-performance infrastructure to offer basic internet

connectivity, or build high-cost, high-performance infrastructure to offer services competitive to those found in cities. The latter may not be sustainable, however we find that this is not due to prohibitively expensive radios, but rather prohibitively expensive energy harvesting systems responsible for providing power to remote sites, or Points-of-Presence (PoPs). Therefore it is in a WISP's best interest to conserve as much energy as possible in order to maintain a sustainable balance between network performance and capital expenditure.

A. About WISPs

A WISP network typically consists of a combination of point-to-multipoint customer access radios, and point-to-point backhaul radios. The former is used for distribution of internet access to end-users, and the latter is used for backhaul, or connecting edge routers to the network core. While access radios have a low energy footprint, high-performance backhaul radios typically use substantially more energy. This led us to consider how we could make a meaningful contribution for WISPs. We know from past experience that WISPs can adapt network site configurations to use less energy, such as using less radios for customer access purposes, often at the sacrifice of performance. However, we considered that most access radios available to WISPs have a low energy footprint. Next we considered backhaul radios. In evident contrast, one backhaul radio could use as much energy as five access radios. Dedicated point-to-point backhaul radios are also typically much less flexible in deployment, unless a network operator sacrifices throughput for lower energy consumption. With this in mind, we considered how we could improve the sustainability of WISP backhaul networks through reducing their energy consumption.

Companies such as Ubiquiti Networks [9] have pioneered inexpensive, low-power radios that have enabled low-cost development of Internet access infrastructure in remote and rural communities [6]. The majority of these radios operate in unlicensed frequency bands in all but few countries, typically subjecting them low power budgets and interference from other unlicensed devices operating within the same frequency range. These factors result in unpredictable network performance, impairing even well-established WISP operators [6]. Where high-performance radios are available, WISPs must account for their substantially higher power consumption [1]. The considerable energy consumption of high-performance backhaul radios makes them unsuitable for many WISPs with a limited budget. Another drawback of these high-performance radios is that they are typically not *energy-proportional*, mean-

ing that they consume a nearly constant amount of energy irrespective of the throughput over them [1].

B. Our Architecture

In this paper, we present *ElasticWISP*, an architecture to enable WISP operators constrained to using off-grid energy systems to operate high-performance, energy-proportional backhaul networks. *ElasticWISP* is designed to promote *energy-proportionality* in WISP networks, while working in unison with a range of topologies and with commonly used routing protocols. *ElasticWISP* operates without the need for additional control protocols such as OpenFlow [10], avoiding potentially expensive hardware upgrades and staff retraining.

Unlike the on-grid powered data centre networks targeted by ElasticTree [11], WISPs must often construct sites that are located in remote, off-grid locations. Consequently, WISPs are often constrained to using off-grid energy harvesting systems, commonly being solar and, less frequently, wind. Using a real-world WISP network topology, and utilising recorded traffic from the same network, we were able to reduce network-wide energy consumption to a lean 35% of the original over a 7-day period. We observed regular diurnal traffic patterns, allowing us to keep high-power, high-performance radios turned off for up to ≈ 20 hours in a 24-hour period throughout most days of the week, substantially reducing overall network energy consumption while preserving Quality of Service (QoS).

C. Organisation

We first discuss in Section II the related work, followed by the motivation for *ElasticWISP* in Section III. We then describe the design of our *ElasticWISP* architecture in Section IV, and discuss the energy consumption of several key backhaul radios available to WISPs. We also describe our formal model, which is based on a standard multi-commodity flow formulation enhanced with energy minimisation and radio configuration constraints. Next, we detail our evaluation using a real WISP network topology, and present the energy minimisation potential of *ElasticWISP* in Section V. Finally, we discuss some implementation considerations of *ElasticWISP* in Section VII and describe our planned future work in Section VIII.

II. RELATED WORK

Several related efforts have addressed lowering the cost of expensive off-grid energy systems used by WISPs [7], [8]. These offer important contributions, however they do not address the energy-proportionality issues faced by WISPs that desire to build higher-performance networks. We believe the globally recognised viability of WISP networks relies on them being seen as sustainable. For a WISP to be sustainable and compete with other commercial network operators, they must be able to provide a competitive service. Where off-grid energy must be harvested, it is critical that the total network energy consumption is kept at a minimum. Ideally, not at the expense of network QoS and negligent over-subscription ratios.

Previous research showed us that energy consumption is one of the biggest challenges faced by WISPs that rely on

renewable energy sources [6]. Pragmatic research by UC Berkeley and the Google-sponsored FurtherReach network discusses the challenges involved with operating solar energy systems and power-hungry backhaul radios [1]. Overall, the challenges involved with using renewable energy harvesting for WISP networks are well understood [2], [3], [7], [8], [12]–[14]. Despite the existence of a well-grounded understanding, we acknowledge little research has been carried out to find an immediate means of addressing these energy-related network operational difficulties.

Closely related to WISP backhaul networks are microwave backhaul networks. In some cases, especially where energy is not constrained, WISPs will use microwave backhaul radios for high-performance links. It has been found that microwave backhaul networks can account for approximately 50% of overall network energy consumption [15], [16], showing the importance of designing energy efficient network architectures. In a similar effort focused on mmWave backhaul networks for omnipresent 5G deployment, energy savings of up to 65% were achieved through turning off both backhaul links and small cells [17].

Numerous general efforts to reduce network wide energy consumption have been made. GreenTE [18] utilises both Open Shortest Path First (OSPF) routing and Multiprotocol Label Switching (MPLS), and places line-cards into a sleep-state, reducing their energy consumption by 27%–42%. The GreenTE approach is similar to ours, but actively avoids triggering OSPF Link State Advertisements (LSAs) when links are sleeping. While useful for avoiding full network reconvergence, this approach requires either OSPF implementation modification or amendments to the OSPF protocol specification. ElasticTree [11] is another example, reducing energy consumption in data centre networks by up to 60%. Unlike GreenTE, ElasticTree utilises OpenFlow for network traffic forwarding, allowing for explicit enforcement of optimal flow paths.

III. THE NEED FOR ENERGY-PROPORTIONAL WISP BACKHAUL NETWORKS

In this section, we motivate energy-proportionality by showing that traffic patterns in WISP networks provide opportunities for reduction in energy consumption through the use of radios that consume lower power while satisfying traffic demand from subscribers.

To understand the potential benefits of energy-proportional operation in WISP backhaul networks, we studied the energy consumption of several backhaul radios targeted at the WISP market. Table I provides the energy consumption of five radios as reported in datasheets and from our own measurements using a Netonix [19] Power-over-Ethernet (PoE) switch that reports energy draw per PoE port.

Fig. 1 shows the daily traffic bandwidth, averaged in 20-second intervals, between two sites (Able and Heights) of a WISP backhaul network. The daily traffic peaks at around 400 Mbps of TX traffic. Both sites use full-duplex airFiber 5 radios to support the peaks. From Table I, we know that

TABLE I
WISP BACKHAUL RADIO ENERGY CONSUMPTION

Radio	Max power draw (W) ^a	Low load (W) ^b	Heavy load (W) ^b	Aggregate throughput (Mbps) ^c
PowerBeam5AC G2	8.5	≈ 4	≈ 6	≈ 200
Rocket5AC Prism G2	9.5	≈ 6	≈ 8	≈ 300
airFiber5	50	≈ 40	≈ 40	≈ 1000

^aFrom radio datasheets.

^bFrom our measurements. Results may vary.

^cThroughput depends on external factors.

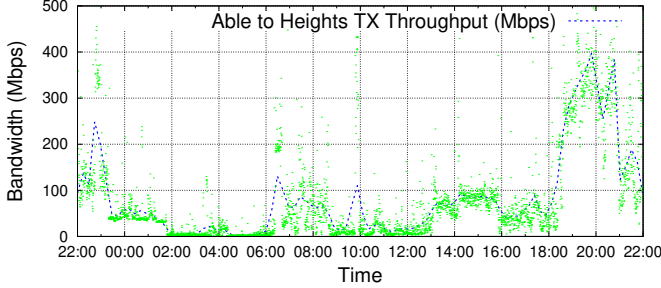


Fig. 1. Able to Heights TX Traffic (with Bézier curve).

airFiber 5 uses significantly more energy than the lower-power Rocket Prism, or PowerBeam radios. The most notable aspect of this data is that regardless of the traffic, the energy consumption of the airFiber 5 would remain consistently high at approximately 40 W.

Although there are numerous intervals during the day when the traffic is relatively low (even going less than 20 Mbps), the radios still operate at maximum power consumption. There is clearly a need to enable energy-proportional operation of the radios, i.e., the dynamic selection of radios such that energy consumption is minimised while maintaining data rate that is sufficient enough to meet traffic requirements. This requires each site to be equipped with low throughput but low power radios.

In the case of Fig. 1, the high-power airFiber 5 radio would need to be turned on for approximately six hours, depending on link-capacity safety margins set by the network operator. For regular periods of low throughput, even the inexpensive PowerBeam 5AC G2 radio meets the traffic requirements.

A. WISP Backhaul Energy Consumption

To draw comparisons about how energy is used by WISP backhaul sites, we consider the energy harvesting and storage requirements of a basic relay site with two backhaul radios operating 24 hours a day. For Tables II, III, and IV, we make a rudimentary assumption that the battery bank will be capable of powering the site for two days with severely impaired energy harvesting capability. As the battery banks are lead-acid, they should not be discharged below 50% of their overall capacity.



Fig. 2. Heights Road Battery Bank.

We include an example of the battery bank used at the Heights Road site in Fig. 2. This battery bank contains several Absorbent Glass Mat (AGM) lead-acid batteries, totalling 600 Ah of storage capacity. The battery bank is charged by a 1200 W solar array using a commercially available Maximum Power Point Tracking (MPPT) solar charge controller.

Firstly, in Table II, we consider a relay site that uses two high-power, high-performance backhaul radios. Secondly, in Table III, we consider a relay site where two low-power, low-performance backhaul radios are used. Finally, in Table IV, we consider a relay site that uses a combination of the two radio types described; high and low power.

We make an optimistic assumption that each low and high power radio pair will operate for 12 hours each. Table IV shows that even if both radios operated for 12 hours each per day, the energy reduction is approximately 40% of the highest-consumption configuration shown in Table II.

B. Benefits of Energy-Proportional WISP Backhaul

The energy and traffic bandwidth measurements show that we could enable WISP operators to benefit from energy-proportional operation in two ways. Firstly, being able to turn off idle resources when they are not needed will make off-grid energy constrained sites more sustainable. For example, where redundant backhauls exist, we can disable and power down one radio pair to conserve energy.

Secondly, we can encourage WISPs to design networks that have better energy-proportionality. This is a key benefit, as WISPs can use high-power, high-throughput radios only as they are needed. In practice, better energy-proportionality requires us to deploy backhauls that include both high and low power radio pairs. Based on our earlier measurements, we know that designing backhaul links in this way is achievable and will reduce energy consumption should link utilisation not be persistently high.

IV. ElasticWISP DESIGN

We now present the design of *ElasticWISP*. At the core of *ElasticWISP* is a network flow model formulated as a multi-commodity flow problem enhanced with energy minimisation constraints. To make *ElasticWISP* useful on real WISP backhaul networks, we design a control mechanism that

TABLE II
WISP RELAY SITE (2 X AIRFIBER5)

Component	Minimum value
Daily consumption (Wh)	2400
Battery bank size (Ah)	800
Solar array capacity (W)	750

TABLE III
WISP RELAY SITE (2 X RADIO
POWERBEAM5AC G2)

Component	Minimum value
Daily consumption (Wh)	408
Battery bank size (Ah)	140
Solar array capacity (W)	150

TABLE IV
WISP RELAY SITE (2 X AIRFIBER5 AND
POWERBEAM5AC G2)

Component	Minimum value ^a
Daily consumption (Wh)	1404
Battery bank size (Ah)	470
Solar array capacity (W)	450

^aWe assume each radio will operate for 12 hours per day.

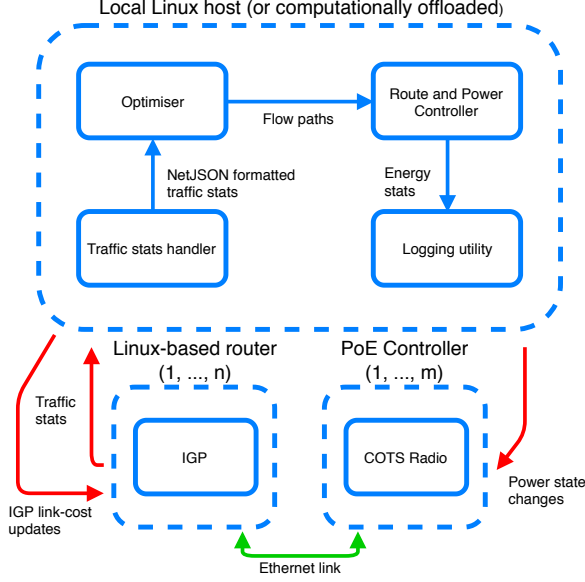


Fig. 3. Simplified *ElasticWISP* system overview.

integrates *ElasticWISP* with OSPF routers. OSPF was selected as previous work showed that it is the routing protocol of choice for most WISPs [6].

Fig. 3 illustrates a high-level, Interior Gateway Protocol (IGP) independent overview of the *ElasticWISP* architecture.

A. Model 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 $K_1, K_2, \dots, K_k$, 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 [20], [21]:

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

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

TABLE V
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)

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 $\forall i \in [1, k]$,

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

B. Energy Minimisation Constraints

We now add energy-saving constraints to the multi-commodity flow formulation. We use the notation listed in Table V to describe the energy minimisation constraints [11].

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 [22]. We

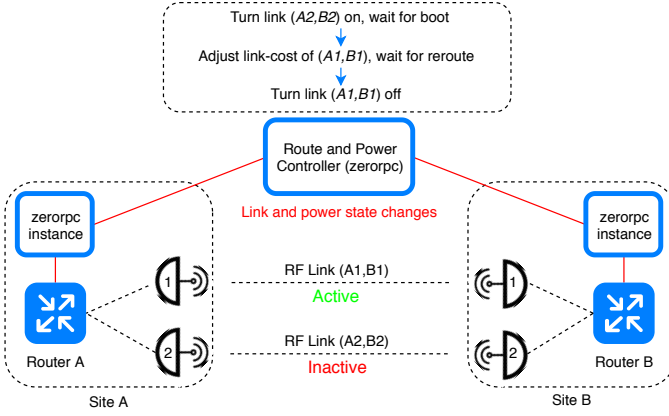


Fig. 4. Simplified link-cost and power control mechanism.

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:

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

C. Routing Protocol Integration and Control

We approach the integration with routing protocols pragmatically. The OSPF routing daemon Quagga supports gracefully rerouting traffic when an OSPF link-cost is increased. Other OSPF and non-OSPF routing protocols generally function in this way, however we chose Quagga due to its stability and mature codebase. We designed a reliable in-band control mechanism (see Fig. 4) for adjusting the OSPF link-costs of routers running the Quagga OSPF daemon using ZeroMQ [23] and MessagePack [24] based zerorpc [25].

When the optimiser outputs a subset of links, the zerorpc based route and power controller determines which radio pairs need their link-cost and power-state changing. If radios need to be booted prior to link-costs being adjusted, the controller will do this first. Power-state changes can happen through the use of a compatible PoE switch or through a custom PoE control unit. The controller then connects to zerorpc instances running on each router in the network, and adjusts the link-costs per radio as required. Following the completion of these state changes, traffic is rerouted.

D. Practical Considerations

For *ElasticWISP* to become a viable architecture for use on real WISP networks, we had to ensure that no substantial packet loss or latency was introduced when a backhaul changeover or reroute of traffic occurs. As desired, when gracefully adjusting the OSPF link-cost of a given radio pair, no additional packet loss or latency is introduced in our implementation. While appropriate for production deployment,

this approach does come at a cost; *ElasticWISP* staggers link-cost adjustments to avoid excessive OSPF LSAs occurring at once, and to enable OSPF to reroute traffic over paths that will remain online. Consequently, *ElasticWISP* incurs a delay when switching the power state of radio pairs. It is worth noting that even in a large WISP topology with 16+ OSPF routers operating, this time is under three seconds for each radio pair. When you consider the radio boot and reassociation delay, this time can become ≈ 60 -180 seconds per radio pair. Boot times must be carefully managed to prevent traffic being routed over radio pairs that have not completed reassociation. Neglecting these delays results in packet loss and service degradation.

V. EVALUATION

In this section we discuss and evaluate aspects of *ElasticWISP*'s design. We begin by discussing our model implementation, followed by the different modes of traffic generation used in the evaluation. We then investigate whether *ElasticWISP* can preserve the network QoS; and finally, we evaluate and compare its energy consumption.

A. Model Implementation

We implemented the model presented in Section IV-A using Gurobi [26]. For Gurobi to solve the optimisation problem, we must input a network topology, the capacity and energy consumption of links, and a traffic matrix. We start by defining a network topology using NetJSON [27]. We add radio capacity and power consumption as attributes to the NetJSON formatted network topology, and interpret it into a format appropriate for Gurobi using a parser we wrote in Python. The Gurobi optimiser runs on a host, and in our case on the same device that is responsible for traffic matrix generation. Alternatively, Gurobi supports computational offloading [28].

The output of Gurobi is a subset of the original network topology. The topology subset is passed to the zerorpc based link-cost and power controller which subsequently turns on and off links as appropriate. The time it takes Gurobi to output a subset of a given topology depends on the size of that topology. In our experience, most WISP topologies contain less than 50 nodes, meaning subsets can be computed rapidly even on low-end hardware.

B. Traffic Generation

We evaluate *ElasticWISP* through playing back captured network traffic. To use *ElasticWISP*, a network operator must first specify a link-saturation threshold for backhaul links. This can be per link, or on a network-wide basis. If the traffic passing over a link exceeds a threshold for more than a given number of consecutive periods, the “safe capacity” of a given link will be used for solving the optimisation problem. Where faster links are available, this will result in them being turned on as the sum of all measured flows across the link will exceed what the optimiser knows the active link can provide. Although this approach is naive and cannot ascertain the actual demand, it is an effective operator-tunable means of powering up higher-capacity radios when they are most likely needed.

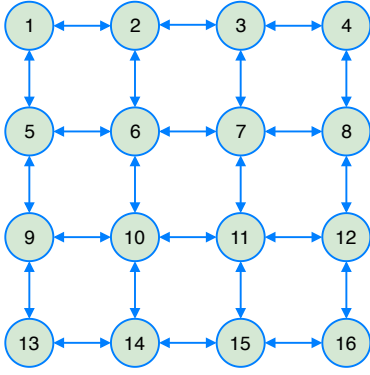


Fig. 5. 4x4 grid topology used to evaluate impact on QoS.

Next, from reading the packet capture, our evaluation computes how many times the optimiser will need to run in a given period and thus runs the optimiser with appropriate traffic demands, and then calculates the sum of network-wide energy consumption. The responsiveness of *ElasticWISP* to network demand and change is dependent on the operator specified configuration. In our case, a Simple Moving Average (SMA) was used to determine when to invoke the optimiser.

C. QoS Preservation Performance

One of the most important considerations for the design of *ElasticWISP* was ensuring QoS preservation. More than anything else, we aim to avoid packet loss, latency spikes, and excessive jitter. From previous practical work, we were aware that when the OSPF link-costs are adjusted, Quagga will reroute traffic to the next shortest path without disrupting network performance. To determine the impact on QoS of the rerouting process, we emulated the operation of a 4x4 grid topology (see Fig. 5) in the CORE [29] network emulator.

A set of QoS samples were taken over consecutive 30 second periods. RTT samples were taken at the same time as TCP traffic was being generated and used to saturate the links. Datagram loss and jitter was measured using a UDP traffic generator and collector. Fig. 6–8 shows the RTT, jitter, and datagram loss of two different route changeover techniques, including the case where there is no changeover (reference). The results show that over all sampling intervals, our staggered cost-adjustment approach does not result in any noticeable change in RTT, jitter and datagram loss as compared to the reference. Whereas, the simple approach of switching off the links for route changeover results in substantial datagram loss.

D. Energy Consumption Performance

Next we evaluate the performance of *ElasticWISP* in terms of energy consumption. Like ElasticTree, the most important metric we are concerned with is the energy consumption of the reduced topology as a percentage of the original energy consumption:

$$\frac{\text{Energy consumed by ElasticWISP}}{\text{Energy consumed by original WISP topology}} \times 100 \quad (8)$$

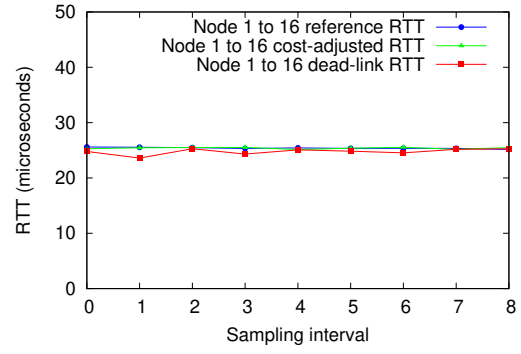


Fig. 6. Node 1 to node 16 RTT.

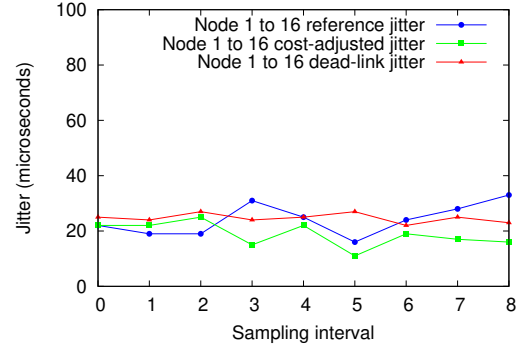


Fig. 7. Node 1 to node 16 jitter.

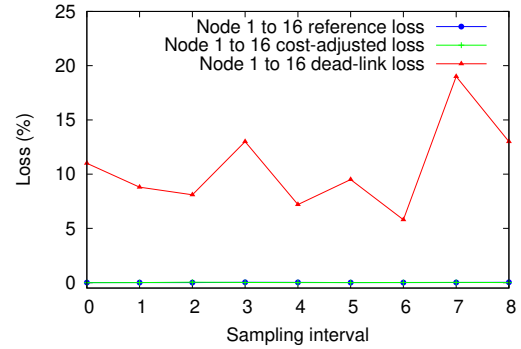


Fig. 8. Node 1 to node 16 datagram loss.

1) *Setup*: We evaluate the performance of *ElasticWISP* using a network topology and traffic capture dataset provided by Venture Networks [30]. The dataset contains two weeks of network traffic, split into numerous small captures for manageability. We use the network topology shown in Fig. 9 for evaluation. Every node in the network is equipped with two different radio types per node: (i) a high-power, high-throughput radio (airFiber 5); and (ii) a low-power, low-throughput radio (PowerBeam 5AC G2).

It should be noted that the energy saving potential of *ElasticWISP* is much greater where a meshed or partially meshed topology is used. In our evaluation topology, no redundant links between sites exist. If the topology had redundant

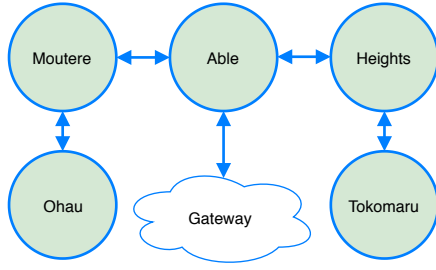


Fig. 9. Evaluation topology.

links, e.g., between Ohau-Able, *ElasticWISP* would reduce the topology further, forming a "minimum power tree" where constraints are satisfied.

From the traffic capture, we select and evaluate a one week period using *ElasticWISP*. We evaluate how many times the optimiser produces a different subset of the original topology, and record the energy used during each period. The network traffic from all nodes of the topology follows a predictable diurnal pattern, with little variation across days of the week. We establish that the power consumption of the network topology running entirely with high-performance airFiber 5 radios (50 W) is a maximum of 9600 Watt-hours (Wh) per day.

If the network were to run entirely on low-performance PowerBeam 5AC G2 radios (8.5 W), the maximum consumption would be 1632 Wh. We assume that each site will be interconnected to each neighbouring site using two radios: an airFiber 5, and a PowerBeam 5AC G2. Other than during radio boot time, SSID reassociation, and the subsequent rerouting of traffic, only one of the two radios will be active at a time. Radios that are inactive will be powered off to conserve energy.

We conservatively estimate that the low-performance radio can support a maximum of 100 Mbps of capacity when transmitting or receiving. We assume the high-performance radio can support up to 500 Mbps while transmitting or receiving. We know in reality these values will be different. The performance of unlicensed radios is challenging to accurately predict, and is subject to factors such as external interference, rain fade, and obstructions in the line of sight and Fresnel zone. Lastly, in this topology we expect that distant links will offer the best potential for energy conservation as they carry the least amount of transient traffic from other nodes.

2) *Results*: Upon running our evaluation of *ElasticWISP* we discovered promising results. We assume that using a straw man configuration with only high-power airFiber 5 radios, the evaluation topology would consume approximately:

$$50W \times 8 \text{ radios} \times 24 \text{ hours per day} \times 7 \text{ days of the week} \quad (9)$$

Overall, the weekly consumption should be approximately 67,200 Wh (67.2 kWh). Utilising *ElasticWISP* and the provided dataset with a combination of airFiber 5 and PowerBeam 5AC G2 radios, we were able to reduce the consumption for a given week to 23,765 Wh (≈ 23.8 kWh). Overall, this saves 65% of network-wide energy, a significant reduction. Of course, this figure uses the maximum power consumption of the radios. In practice, the energy reduction may in fact

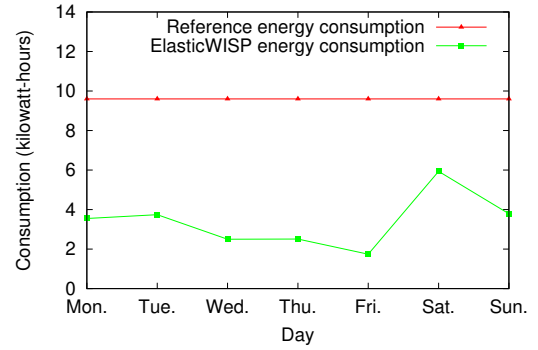


Fig. 10. Energy consumption over a 7-day period.

TABLE VI
COMPARISONS - THE STATE-OF-THE-ART

Platform	Flow path enforcement	Energy saving	Approach
<i>ElasticWISP</i>	IGP best-path	$\approx 65\%$	Radio changeover, turning off links
Routing on Demand [31]	IGP best-path (with optimal link-weights)	$\approx 43\%$	Turning off links
Energy Efficient Backbone Networks [32]	Explicit (Segment Routing)	$\approx 44\%$	Turning off links

be greater, as we know that low-power backhaul radios (such as the PowerBeam 5AC G2) available to WISPs typically use much less than their design maximum, whereas high-power, full-duplex radios (such as the AirFiber 5) use near their maximum consumption continuously.

Fig. 10 shows that network-wide energy consumption throughout the week is substantially reduced. On most days, *ElasticWISP* will turn on high-power radios for less than four hours. The exception to this is the weekend, where traffic demand is far less predictable. Unexpectedly, we see that network-wide energy is lower on Friday than any other day throughout this week, likely due to social factors.

VI. STATE-OF-THE-ART COMPARISONS

Table VI compares *ElasticWISP* to other state-of-the-art schemes, such as OSPF-based Routing on Demand [31] and segment routing-based Energy Efficient Backbone Networks [32]. Both competitor schemes are formulated as multi-commodity flow problems, and are focused toward wired service provider backbone networks.

A key advantage *ElasticWISP* has over competitor schemes, and specifically for WISP (and perhaps microwave) use, is the ability to perform radio changeover based on traffic demand. Practically, this is similar to approaches that turn off links in a bundle to conserve energy for wired service provider networks. However, *ElasticWISP*'s energy saving potential is high due to the disparity of energy consumption between the backhaul radios we studied. As a result, in comparison to other schemes,

ElasticWISP can conserve more energy in WISP networks where both high and low power backhaul radios are used.

Of course, *ElasticWISP* is formally similar to ElasticTree. As *ElasticWISP* uses a subset of the energy minimisation constraints proposed by ElasticTree, the performance difference between the two platforms will be negligible for any given test topology. However, unlike ElasticTree, we do not consider turning off switches, or in our case, nodes at each network site. As a result, ElasticTree can conserve energy where it is able to turn off redundant switches.

Functionally, *ElasticWISP* is very different to ElasticTree. The use of OSPF as opposed to OpenFlow introduces its own unique challenges, as does dealing with the unpredictable nature of radio links. Additionally, ElasticTree deals with links that can be brought up and down very quickly, whereas radio links will always have comparatively expensive boot and reassociation times. In addition to this, practical deployment of *ElasticWISP* itself required a new architecture of remotely managed PoE devices to be designed.

VII. IMPLEMENTATION CONSIDERATIONS

While the OSPF-based implementation of *ElasticWISP* can help WISP operators realise substantial energy savings, it is not without caveats. The time taken for traffic to be rerouted is not instantaneous; the OSPF link-costs of a given link (radio pair) must be adjusted prior to powering them down. The time it takes for traffic to be routed over a lower-cost path is OSPF implementation-specific. While these changeover times were consistently low in our implementation, there is no guarantee that other configurations will perform in the same way. With an appropriate traffic engineering mechanism, this problem could be eliminated.

Additionally, the performance of *ElasticWISP* will vary between network topologies. Unlike ElasticTree which uses OpenFlow for controlling the path of individual flows, *ElasticWISP* runs alongside OSPF routers and therefore will always use the OSPF-determined best path for routing. In most WISP topologies we observed this to not be problematic, as none were fully meshed, and traffic typically always had to flow over a limited set of links. In a topology that has meshed segments, there is no discernible solution for flow-level path enforcement alongside *ElasticWISP* instances; although Fibbing [33] is a promising solution for centralised control over unmodified OSPF routers. Furthermore, flow-level path enforcement would ensure that optimal flow-paths computed using Gurobi are always taken.

Lastly, *ElasticWISP* is designed for the optimisation of backhaul links on WISP networks. While we showed that full-duplex backhaul radios used by WISPs account for a significant portion of energy consumption per site, we must also consider the point-to-multipoint radios that are used for customer access purposes. Much like their point-to-point counterparts, customer access radios typically used by WISPs have very little variation in energy consumption, irrespective of how much traffic is being passed over them. Typically these access radios are connected to sector antennas that distribute

internet access to customers. Sector antennas used will have a manufacturer specified azimuth and elevation radiation pattern. In a high-capacity configuration, a WISP may have numerous sector antennas with a 30 degree azimuth radiation pattern serving a collection of customers.

During off-peak periods of network consumption we propose that WISP operators could offload traffic from numerous high-capacity radios onto a lesser number of radios that have antennas that cover a wider azimuth. This approach has similarities to historical work proposed for energy conservation [34]. While existing equipment from the likes of Ubiquiti Networks enables WISPs to set a fallback SSID, there is currently no way of carrying out a graceful transition between access radios. Recent research has shown that DFS Channel Switch Announcement Information Elements (CSA-IE) can be used as a seamless infrastructure initiated handover mechanism between access points [35]. Unfortunately for WISPs, BigAP relies on radios being compliant with the 802.11n/ac standard, which includes the IEEE 802.11h amendment. Radios from the likes of Ubiquiti Networks et al. make no claim to be compliant with such standards, and often use custom fabricated radio chipsets.

VIII. CONCLUSION AND FUTURE WORK

We have presented *ElasticWISP*, a practical architecture to enable the design of high-performance, energy-proportional WISP networks. Through “playing back” daily network traffic, we have shown that it is possible to employ high-performance radios on demand while maintaining energy-proportionality during off-peak periods, reducing overall network energy consumption by around 65%. Given our findings, we hope that *ElasticWISP* will help enable WISPs around the world to build faster, robust wireless internet infrastructure even to the most remote frontiers. To support improving internet access in remote communities, we would like to call other research institutions to action. As our society further builds a dependence on the internet, there are digital voids across the world that have no, or very poor, connectivity. Through technical innovation we can help to close this digital divide.

Based on the limitations encountered with flow path enforcement, traffic reroute times, and being able to guarantee QoS metrics, the future development of *ElasticWISP* will involve overcoming these issues. It should be noted that segment routing [36] may be a viable scheme to leverage in order to overcome the limitations described. Segment routing utilises the source routing paradigm and can be deployed on an MPLS or native IPv6 dataplane. When deployed, segment routing allows network operators to steer packets across an ordered list of segments with arbitrary precision, making it an ideal fit for *ElasticWISP*. Additionally, as we know that the energy consumption of many wireless radios used by WISPs increases under load, segment routing may also enable us to optimise sending traffic through nodes that have more battery capacity available, or are currently harvesting more energy than others.

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