

Reliability Analysis of Wireless Backhaul for Rural Wireless ISP

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Abstract—In this paper, we propose a model to improve the reliability of a mesh-based last-mile replacement for broadband connectivity in rural and underserved areas. Using open data from ten such regions, we analyze representative demand scenarios and focus on enhancing the robustness of the corresponding wireless backhaul design. We introduce graph-partitioning methodologies to construct mesh clusters with multiple gateways and increased vertex-connectivity, ensuring stronger resilience to radio and node failures. To capture the stochastic behavior of device outages, we model radio failures through a Markov-chain formulation and derive metrics such as failure probability and expected time to disconnection. Through numerical evaluation, we show that incorporating multi-gateway structures and reliability-aware topology constraints can significantly improve the resilience of rural mesh networks with only modest additional infrastructure requirements.

I. INTRODUCTION AND RELATED WORKS

Wireless ISPs (WISPs) have become a practical alternative for providing broadband connectivity in regions where large telecommunications operators have not deployed wired access networks. These providers typically operate with small teams, limited capital, and thin profit margins. As a result, designing cost-efficient backhaul and last-mile infrastructure—both in terms of the wireless equipment mounted on rooftops and the limited fiber connectivity available for upstream—is a central challenge. Ensuring that such networks remain reliable despite equipment failures or harsh deployment environments is equally critical, yet often constrained by budget and sparse infrastructure.

Most existing work on WISP deployments focuses on characterizing practical roll-outs in the field [1], [2], [3], [4], [5] and their economic analysis [6], [7]. On the technical side, the research community has extensively analyzed topology design for 5G/6G cellular systems (see e.g. [8] and references therein), where the deployment environment, equipment reliability, and resource budgets differ substantially from those of rural WISPs. Work on community-driven mesh networks provides useful insights for multi-hop wireless topologies [9], [10], but these designs typically aim at maximizing coverage or flexibility rather than providing quantifiable guarantees on reliability or gateway survivability. Overall, although the literature provides valuable building blocks, few studies have examined how to jointly design cost-constrained and reliability-aware wireless backhaul topologies tailored to rural last-mile scenarios.

We base our work on the data produced by a previous work by the same authors [6]. That paper proposes a network

design based on a mesh network, evaluated using extremely realistic assumptions. The authors start from the real 3D data describing 10 regions in Italy in which the wired infrastructure has very low penetration (digitally-divided areas), and using the real distribution of households, they generate a set of houses containing potential subscribers. The design process produces a network connecting all the houses made of wireless mesh clusters connected to a core backbone through optical fiber. The authors show that such a design is technically and economically sustainable.

In this paper, we thus focus on extending the design to increase the reliability of each cluster, modifying the original design to support more than one gateway per cluster, and designing the network around this constraint. Our solution is general; it can be adopted in any network scenario in which a set of nodes must be interconnected to a number of gateways, providing resistance to failures.

II. WIRELESS BACKHAUL DESIGN

Here we briefly recall the design proposed by us [6], in order to describe our improved design.

a) Network Graph Definition: The process starts from an estimation of the demand for the areas under analysis. This initial step identifies a set \mathcal{V} of buildings that need to be connected. Using a socio-economic metrics from a public dataset, we estimate the probability p_i of having a WISP subscriber in the building. This probability is then be used in Monte Carlo simulation to extract multiple random set of buildings for an area, with a given penetration rate. Using Graphics Processing Units (GPUs) for ray-tracing, line-of-sight between every couple of nodes is evaluated. If the two nodes are in LoS, then the edge is added to \mathcal{E} . With realistic assumptions on the radio technology, each link is also annotated with a value for the its capacity in b/s. This process yields the visibility graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$.

b) Graph Partitioning: For scalability reasons, the network can not be made of only one giant component and needs to be partitioned into clusters, each with one gateway node. The well-known *METIS* graph partitioner is used to produce clusters of the same (or at least similar) size. This produces a list of subsets $\mathcal{V}_i \subset \mathcal{V}$, and their associated subgraph $\mathcal{G}_i = (\mathcal{V}_i, \mathcal{E}_i)$, in which $\mathcal{E}_i = \{(v_j, v_k) \in \mathcal{E} \mid v_j, v_k \in \mathcal{V}_i\}$.

c) Gateway Selection: Given \mathcal{V}_i we must identify a group of nodes \bar{D}_i , that are in the best position for being the gateways

of the cluster. In the original design, there is only one gateway, so $|\bar{D}_i| = 1$. Since the hop-count from a node to the gateway influences the end-to-end delay, the single gateway is chosen as the node that minimizes the distance to all nodes in \mathcal{V}_i .

d) Distribution Tree Design: To connect each node of a cluster to its gateway, a subset of the available edges of \mathcal{G}_i is sufficient, forming a tree to the gateway. The optimal tree is the Shortest Path Tree (SPT) computed with Dijkstra's algorithm, using link length as the link weight (as it influences capacity). Using the bit-rate from the data-sheets or real wireless outdoor devices, the tree is designed to guarantee at least 20 Mb/s per subscriber. At the end of this step, we have a set of graphs $\bar{\mathcal{G}}_i = (\mathcal{V}_i, \bar{\mathcal{E}}_i)$ with $\bar{\mathcal{E}}_i \subseteq \mathcal{E}_i$. Note that with this design, the SPT tends to have many nodes that directly connect to the gateway.

e) Graph Augmentation: The previous step produces a backhaul network using the minimal number of edges (a tree) in which every node has a path to one gateway. In a tree, the loss of a link partitions the network. The design then takes the *core* of the tree (defined as the subset of \mathcal{V}_i made of all non-leaf nodes) and makes it 2-edge connected. A 2-edge-connected graph tolerates the failure of 1 edge without disconnecting any node. As the problem of finding the minimum augmentation is NP-hard, a heuristic is used.

III. THE MULTI-GATEWAY BACKHAUL DESIGN

In this section, we report the steps needed to obtain a multi-gateway design that is resistant to the failure of one of the gateways. The proposed design leaves untouched the initial two steps described in Sect. II and modifies the following 3 steps, so the next paragraphs use the same numbering of the corresponding ones in Sect. II.

c) Gateway Selection: We want to find the set \bar{D}_i of nodes in \mathcal{V}_i that minimizes the distance to any node in the cluster. Given a node $y \in \mathcal{V}_i$, the distance of a candidate group D of nodes to y is defined as follows:

$$d(y, D) = \min_{n \in D} d(y, n)$$

Since in our problem each node can connect multiple subscribers in the same building, we weigh the distance with the number of subscribers $s(m)$ associated with it, and we use the concept of Centrality [11], and in particular of *group closeness centrality*. The set \bar{D}_i with the highest group closeness centrality is the group (among all groups D of the chosen dimension) that maximizes the inverse of the sum of the weighted distance to all the other nodes of the network, as follows:

$$\bar{D}_i = \operatorname{argmax}_D \frac{1}{\sum_{m \in \mathcal{V}_i} s(m)d(m, D)}$$

If we want only one gateway per cluster ($|\bar{D}_i| = 1$), computing centrality requires computing the shortest path between any couple of nodes, so it has polynomial complexity with the size of \mathcal{V}_i , and it takes negligible time with thousands of nodes. When $|\bar{D}_i| > 1$ the problem becomes combinatorial and NP, but with two gateways, we can still find the optimal solution in minutes.

d) Tree Design with Multiple Gateways per Cluster:

The straightforward extension of the previous design would be to compute a multi-rooted SPT, with roots corresponding to the gateways. However, this would not fully exploit the presence of multiple gateways. The failure of a gateway, in fact, would disconnect the leaf nodes attached to it from the wireless backhaul and thus, from the other gateway.

Thus, we use the multi-rooted SPT approach as a benchmark, but we propose a multi-gateway design that avoids leaf nodes directly attached to the gateways named Shortest Path without Attached Leaves (SPAL). Given \mathcal{V}_i , and a choice of gateways \bar{D}_i we search for a forest $F(\mathcal{V}_i, \bar{\mathcal{E}}_i)$ that minimizes the distance between each node and one gateway, where no edge directly connects leaf nodes to gateways. More formally, we call $\delta(n)$ the degree of node n , which is one for leaf nodes, and we search for $\bar{\mathcal{E}}_i$ that minimizes:

$$\min \sum_{n \in \mathcal{V}_i} d(n, \bar{D}_i) \quad (1)$$

constrained to:

$$(n, g) \notin \bar{\mathcal{E}}_i \quad \forall n \in \mathcal{V}_i \mid \delta(n) = 1, \quad \forall g \in \bar{D}_i \quad (2)$$

As a result, every node that is not directly connected to the gateway is not a leaf node, but is part of the core of the network. As the network core is 2-edge connected via augmentation (see next paragraph), the failure of one link in the core does not partition the cluster.

Through graph manipulations, SPAL can be reduced to the class of known Shortest Path with Forbidden Paths (SPFP) [12] problems, specifically to Elementary SPFP (ESFP), which does not allow cycles and produces a tree topology [13].

Our solution is inspired to the work by Elkael et al. [14] that solves the generic ESFP problem, defining a function $\text{ESFP}(\mathcal{V}_i, d, P)$. The function takes as input a graph $\bar{\mathcal{G}}_i = (\mathcal{V}_i, \bar{\mathcal{E}}_i)$, a destination node d , and the set of forbidden paths P and yields the set of edges $\bar{\mathcal{E}}_i \subseteq \mathcal{E}_i$ that defines the tree topology. The algorithm we use is reported in Algorithm 1 and described hereafter.

We first add to the graph a fictitious destination d^* connected to each gateway $d \in \bar{D}_i$ (Algorithm 1), so the result will be a single tree we can map to a forest of trees in our graph. Then for each node n , we introduce a fictitious leaf node called n^* connected to n (Lines 7,8). We add to the list of forbidden paths P the paths $\{n^*, n, d, d^*\} \forall d \in \bar{D}_i, \forall n \in \mathcal{V}_i$ (Algorithm 1). We can then apply ESFP to this manipulated graph, remove all the fictitious edges from the solution, and obtain the solution to our problem (Algorithm 1).

e) Graph Augmentation: ESFP creates two trees made of a separate partition of nodes in \mathcal{V}_i , so the failure of a link can still disconnect subscribers. We then augment the core of each tree as in the original design to make it 2-edge connected. Finally, we connect the two partitions with the shortest link between relay nodes if available, or the shortest link between any two types of nodes if not.

Algorithm 1: Reduction from SPAL to SPFP

Require: $\mathcal{G}_i(\mathcal{V}_i, \mathcal{E}_i)$ (Visibility Graph), \bar{D}_i (Gateway Nodes)

- 1: **procedure** SPAL(\mathcal{G}_i, \bar{D}_i)
- 2: $F = \{\}$
- 3: $\mathcal{V}_i = \mathcal{V}_i \cup d^*$ ▷ Create and add the fictitious gateway
- 4: **for** $d \in \bar{D}_i$ **do**
- 5: $\mathcal{E}_i = \mathcal{E}_i \cup (d, d^*)$
- 6: **for** $n \in V$ **do**
- 7: $\mathcal{V}_i = \mathcal{V}_i \cup n^*$ ▷ Create and add the fict. node
- 8: $\mathcal{E}_i = \mathcal{E}_i \cup (n, n^*)$
- 9: **for** $d \in \bar{D}_i$ **do**
- 10: $F = F \cup \{n^*, n, d, d^*\}$
- 11: $\bar{\mathcal{E}}_i = \text{ESFPF}(G, d^*, F)$ ▷ Solve ESFPF
- 12: **for** $d \in \bar{D}_i$ **do**
- 13: $\bar{\mathcal{E}}_i = \bar{\mathcal{E}}_i \setminus \{(d, d^*)\}$ ▷ Remove the fict. gateway
- 14: **for** $n \in V$ **do**
- 15: $\bar{\mathcal{E}}_i = \bar{\mathcal{E}}_i \setminus \{(n, n^*)\}$ ▷ Remove the fict. source
- 16: **return** $\bar{\mathcal{E}}_i$

A. Features of the Generated Graphs

To test our approach, we perform Monte-Carlo sampling to extract 10 different random graphs as described in Sect. IIa. Then, for each of them, we build three network backhauls using the spanning tree with only one gateway (SPT-1), the variant with 2 gateways (SPT-2), and ESFPF¹. The whole process returns the number of clusters, the network topology, and, as in the original design, an estimation of the number of radio devices needed to build the topology and satisfy the capacity constraint.

TABLE I: Data describing the features of the generated graphs: number of subscribers, number of clusters, nodes, leaf nodes, radios, radios in the core network only, total edges. Values are averaged and rounded to the closest integer.

	subs.	clusters	nodes	dev.	leaves	core radios	edges
SPT-1	742	8	475	630	354	275	546
SPT-2	742	8	475	642	341	300	528
ESFPF	742	8	475	773	257	516	630

Table I shows a summary of the properties of the graphs. The number of subscribers and of nodes are input parameters, clustering is the same, ESFPF produces graphs with roughly 15% more edges and 22% more radio radios compared to the two approaches based on Dijkstra. The network core is larger as the network becomes more robust.

IV. BACKHAUL NETWORK RELIABILITY

The final network graph is not two-edge connected in a strict sense (there are still leaf nodes), but every node has two paths to reach the two gateways. However, more than one link can fail simultaneously when a single radio fails, and thus, we need an analysis of the graph's robustness. As a first step, we evaluate the probability of j simultaneous radio failures, using as an input parameter the minimum number of radios reported in Tab. I, and estimations for the *mean time to failure* (mttf)

¹With reference to the parameters used in [6] we set penetration to 50% and target cluster to 100.

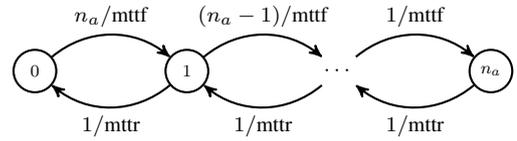


Fig. 1: Markov Chain whose state variable j represents the number of failed radios, and n_a the total number of radios.

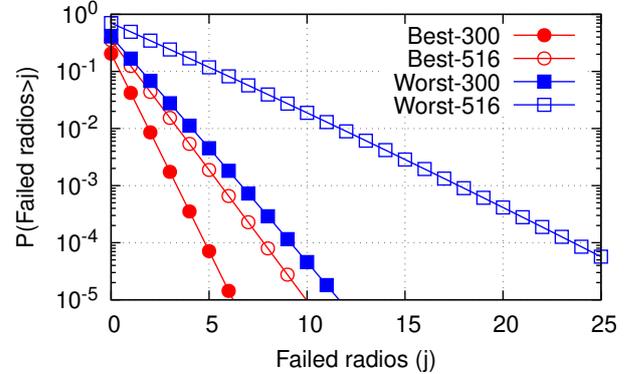


Fig. 2: Failure probability of radios in a cluster.

and the *mean time to repair* (mtrr) of antennas. Assuming the time to fail and to repair are exponentially distributed random variables with exponent $\frac{1}{mttf}$ and $\frac{1}{mtrr}$, the probability of being in state j (having j failed radios), π_j , can be computed as the stationary distribution of the birth/death process in Fig. 1, given by:

$$\pi_j = \frac{\alpha^j}{\sum_{k=0}^{n_a} \frac{\alpha^k}{(n_a-k)!}}, \quad j = 0, \dots, n_a \quad (3)$$

where $\alpha = \frac{mtrr}{mttf}$. We consider two scenarios, in both we assume mttf = 4 years, in the best one we assume a mtrr of 24 hours, in the worst one a mtrr of 48 hours.

Fig. 2 reports the probability of being in a state with more than j failures in a network made of 300 and 516 radios, which correspond to the number of radios in the core network with SPT-2 and ESFPF. A probability lower than 10⁻⁴ means roughly less than 52 minutes per year, and we consider it acceptable. In the non-acceptable range, we have:

Best: 5+ for SPT-2, 8+ for ESFPF

Worst: 10+ failures for SPT-2, 24+ for ESFPF

Clearly, increasing the number of radios in the core increases the probability of being in a state with a larger number of failures. However, a more robust network will be more resistant to the failures of the radios. This analysis guides our choice for testing the network robustness in the next section.

A. Impact on the Network Connectivity

Given the bi-connected relay graph of a single cluster \mathcal{G}_i^* we test what fraction of nodes are disconnected when j radios fail, among the core nodes (the failure of a radio in a leaf node simply disconnects the leaf and is not relevant for the rest of the network). Note, however, that the design process does not

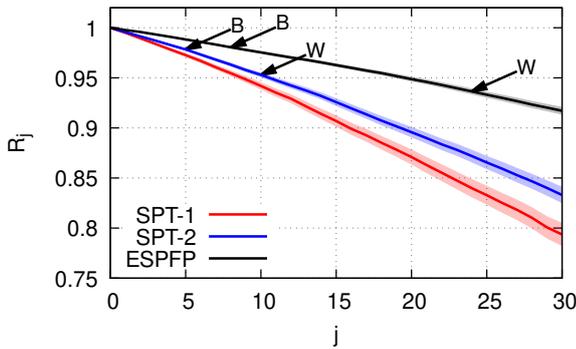


Fig. 3: R_j : ratio of connected subscribers w.r.t. the number of failed radios, computed on the whole network.

return an allocation of links for each radio; it generates the number of radios per node $n_a(n)$ needed to support a minimum desired throughput (more details in the original paper). To make a robustness test, we choose j radios at random among the nodes in the core. We then remove from the affected relays $\lceil \frac{\delta(n)}{n_a(n)} \rceil$ edges at random for each failed radio, and we compute R_j : the fraction of subscribers that still have a multi-hop path to one gateway after j failures.

Fig. 3 then reports R_j averaged on all clusters after 100 repetitions (10 runs for 10 areas), the solid line shows the average, and the shading shows the confidence intervals at the 95th percentile with arrows pointing to the limits of the acceptable range defined in the previous section for the best and worst cases. Comparing SPT-2 to ESPFP, we see that the former performs slightly worse in the worst case and slightly better in the best case, but the difference is minimal. Also, SPT is very close, which indicates that the augmentation of the core in the original design already protects the subscribers from the failure of edges. Overall, ESPFP reduces the leaves (thus the network is more robust) but increases the radios that can fail, and the two effects even out. Note that some subscribers can be allocated to the gateway itself, so even with ESPFP the failure of one single gateway produces a small decrease of R_j .

Fig. 4 reports R_j when we force the failure of a number j of gateways in the whole network. Recall from Tab. I that we have an average between 8 and 9 clusters. In the case of SPT, the failure of a gateway automatically disconnects the cluster, so R_j has a steep decrease as a function of j . When a gateway fails in SPT-2, the leaves that are directly connected to it will also disconnect, while with ESPFP, this does not happen. As a result, in both cases the decrease is smoother than with SPT, and ESPFP is stably above SPT-2, guaranteeing on average 8.3% more connected subscribers.

V. CONCLUSIONS

We proposed a methodology to design reliable wireless backhaul networks for rural WISPs. The network is partitioned into clusters with strategically placed gateways, and a multi-gateway design ensures core nodes remain connected even if a gateway fails. Using a Markov chain model, we quantified the impact of radio failures on subscriber connectivity. Results

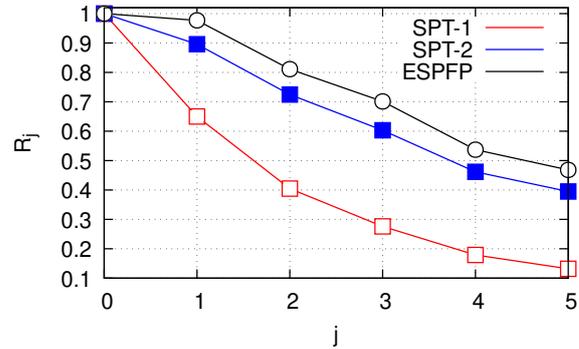


Fig. 4: R_j : ratio of connected subscribers w.r.t. the number of failed gateways, computed on the whole network.

show that the ESPFP-based design provides the highest reliability with a modest increase in radios. The approach offers a practical, scalable framework for resilient backhaul design in rural environments.

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