DrWSpahn

How to protect critical network infrastructure against sabotage?

use optimal network planning to build resilient networks

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Recent events have highlighted the vulnerability of critical infrastructure by exploiting local points of attack, but with a global impact. A realistic resilience plan must identify these points of attack, quickly eliminate them and avoid them in the future. Today's 'fibre first, paths and services second' design approach does not address this properly. It accumulates vulnerabilities in the late stages of network deployment as new services compete with those already in service. Network resilience to sabotage is not optimized. The attack angles of a potential saboteur with global impact remain hidden.

Figure 1: Uninterrupted evening services for DB trains (Foto by Stefan Gabriel)

Only by analysing all levels of the network - under all constraints for a complete build - can you get a true understanding of how to protect networks against sabotage. This approach has been known for some time, but has been considered too difficult and complex to put into practice.

In this article, I show that with today's hardware and recent advances in linear programming, end-2-end analysis becomes feasible. It paves the way for practical end-2-end planning and analysis of optimal resilient networks that can be applied to existing and newly planned networks.

1 Introduction

In October 2022, the northern part of Deutsche Bahn's (DB) GSM-R communications network was completely sabotaged by just two cuts in its fiber optic cables at two distant locations[1]. All trains

stopped. Thousands of passengers were unable to reach their destinations. The depth of insight into DB's fiber topology and the simplicity of the attack raise great concern. It drastically illustrates the importance and vulnerability of digital communications to critical infrastructure.

What can be done? The obvious is not possible: Just to increase the surveillance, isolation and protection of the entire infrastructure along the 34,000 km of German railroad tracks is far too difficult. A realistic plan must focus on the most critical elements. But where are these angles of attack. What additional redundancy and protection need to be applied?

Today's design approach is not helpful in this situation, as current network planning defines optimal paths in a local context, which leaves quite a room for improvement.

2 Network Planning

Communication networks are built on a hierarchical technology stack. Users or their applications define data transport by specifying source-to-destination forwarding [1], which is sent along paths that span multiple fiber links that carry packets from node to node. Clearly, the attack space is large, diverse, and heavily influenced by the flow capabilities predefined by the network design. It is difficult for the operations team to determine, where the fiber layout has opened up inherent vulnerabilities[2].

Just to name a few examples where we might suffer:

- Fiber redundancy layout may not be robust. Redundant paths run over different fibers, but are inadvertently bundled in the same cable or duct. Thus, destruction of one cable or duct segment will also cut the redundant path. Not good!
- The timing may change too drastically after the redundancy switch over, so the real-time service cannot handle this change in characteristics and will not survive the event.
- Congestion may occur after traffic is rerouted, which degrades the quality of service, which again does not ensure the service.

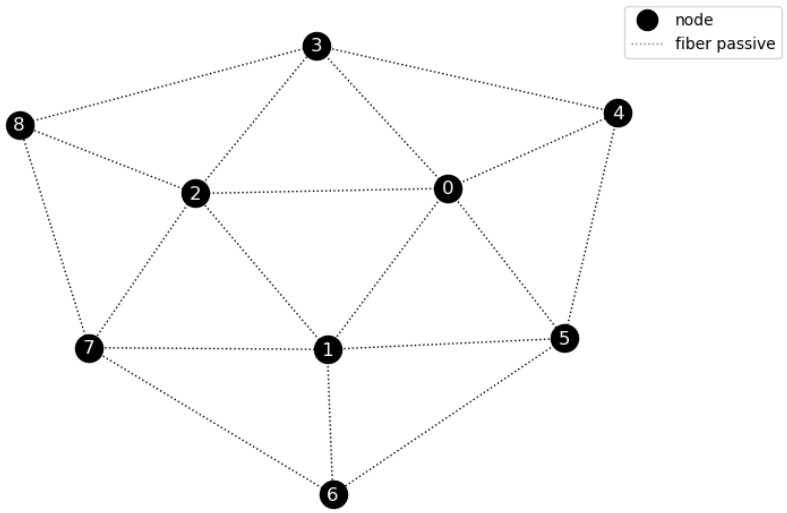


Figure 2: An example infrastructure: 9 nodes and 18 fiber are available to setup the network.

To complicate matters, modern networks use a wide range of technologies. (OTN,Ethernet/RSTP, MPLS-TP, IP, IP/MPLS, TSN, SDN, to name a few) to build the network topology.

[1] In some sort, heavily depending on the technology used.
[2] Maybe even better known to potential attackers!

Sure, they all define traffic in very different ways, but they all ultimately define, over what path and fiber, and with what characteristics, quality and protection, data will flow through the network. So the question, "Do we have a proper network design to support the specification, in the current setup, for future build outs?" remains a constant:

- Have we chosen the right fiber layout that will protect us and gives the traffic characteristics we want?
- Have we avoided easy angles of attack?
- Does critical data travel through protected paths that are free of congestion?
- Can a path be completely taken over by a well-separated, protecting equivalent?

To give a practical example to shed light on this challenge please have a look into figure 2.

We just consider a small core segment of 3 nodes 0, 1, 2, which are connected any to any, and which shall serve 6 access nodes 3, 4, 5, 6, 7 and 8. For connectivity there are 18 fiber links available.

3 Multi level Constraints

To reflect real complexity, we consider multiple layers, but with only a few constraints to keep it digestible[3]. We first define rules in English to later translate them into mathematical formulas.

3.1 Constraints

Since devices are limited in fiber ports (or SFPs), we have to choose which fiber can be served.

- **Rule1:** *Each node can only support up to 4 SFPs: so not all fiber links can be served! Choose the best ones!*

We consider an end-to-end communication service that spans multiple nodes: A real-time critical application where server needs to talk to a number of clients and vice versa without interruption:

- **Rule2:** *Nodes 3,4..8 connect to node 0 redundantly. A protecting path can take over with the least change in characteristics.*

Connecting two nodes in critical situations means relying on a path from source to destination that is kept alive under all circumstances, even if some fiber links [4] stop working. In order to protect against failure, an alternate path must be able to take over[5].

- **Rule3:** *There is one working and one protected path. These two pathes are disjunct (don't share any link or intermediate node).*

To respect real-time, switch over has to be fast[6] and protecting path needs to mirror working paths' characteristics as close as possible.

- **Rule4:** *To assure similar timing there should be not more than 1 hop difference between working and protecting path*[7].

Finally, we have cost as a competing requirement. Together with all the technical constraints we want to find a global optimum:

- Avoid costs of optical fiber connection modules (small formfactor plugable SFP)

  Rule5: *Use as little fiber as possible. Core node SFPs are more expensive than aggregation SFPs, so avoid SFPs at [0,1,2].*

[3] For real networks there are much more rules to be considered.

[4] In a more complete pictures we have to consider as well the nodes explictly, which we will fail to do in some of our ad hoc examples. You see it?

[5] We name them working and protecting paths.

[6] That's the job of the node, the similarity has to be secured by the network!

[7] When network load is low difference in hop count determines mainly the real-time behaviour. By applying different kinds of traffic shaping and priority methods, all protocols try that high prio traffic sees a nearly empty network, where frames don't disturb each other. So the influence of number of hops asymmetry will stay, and needs to be managed

- But if invested, expensive optics must be used:

  Rule6: *Core hops are preferred over aggregation hops. Keep traffic on the inner ring [0,1,2].*

4 Tradional network design

In traditional design approaches, you start with an ad hoc fiber layout that satisfies the physical constraints. It is based on the assumption that this layout will provide a path routing that meets the specifications. Let's see if this is justified.

4.1 Ad hoc fibre layout assumptions

With a little experience and intuition, we get three obvious starting points[8].

In a first attempt, we work with two rings (see figure [3]), a core ring [1,2,3] and an outer access ring [4,5,6,7,8] and connect them with three joints. In a sense, our design will consist of three rings[9].

Rings are good for redundant design because they naturally provide two paths to each node. The use of SFPs at the core nodes is optimal. We only need 3.

On the other hand, the long distance from 0 to 3 - neglecting the direct path - shows the disadvantage of this layout. Clearly, we will never get similar characteristics for the working and protecting paths. This gives us a first heuristic rule: pay attention to the size of your rings.

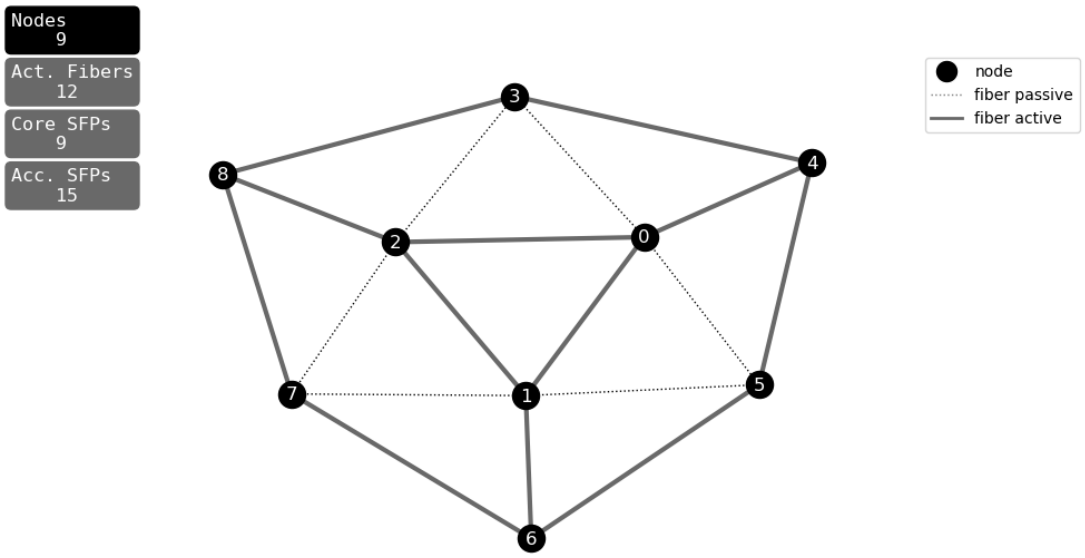


Figure 3: Adhoc1 - Fibre and node layout with only 3 SFPs needed per core node.

Since ring size is an issue, let's make the rings smaller (see figure [4]), which gives better length differences. But still for connection (0,3) a delta between working and protecting path of only 1 is not possible!

[8] Be symmetrical, as humans think in symmetry!

[9] the nodes 0,3,4,5 and 1 would represent such a subring. There are two others of the same type.

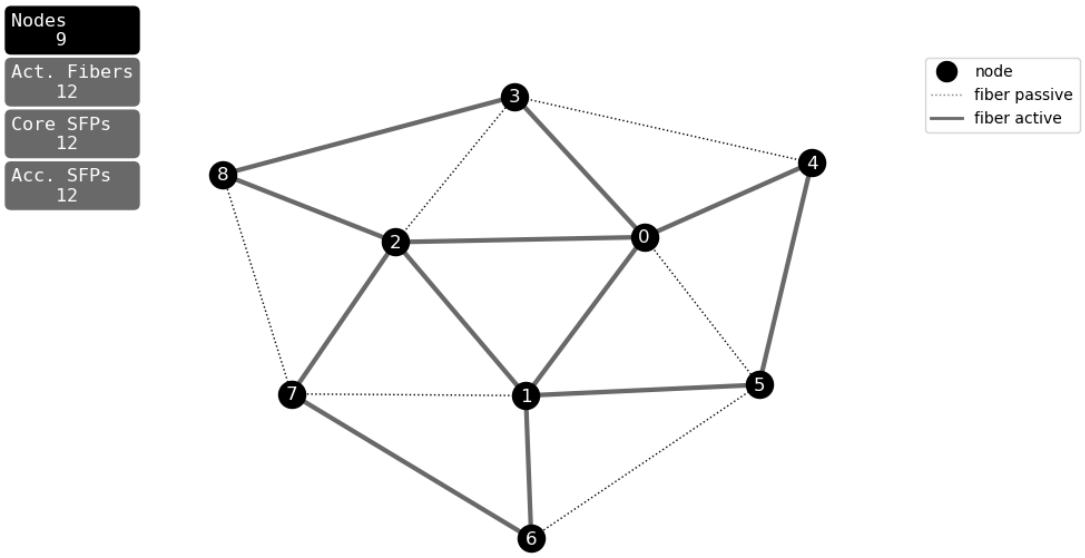


Figure 4: Adhoc2 - Fibre and node layout with 4 SFP core count(g).

So let's reduce the ring size even further. We arrive at the design shown in Figure[5]. Cores [0,1,2] are now single point of failure, But for the time, would this do it? We will see.

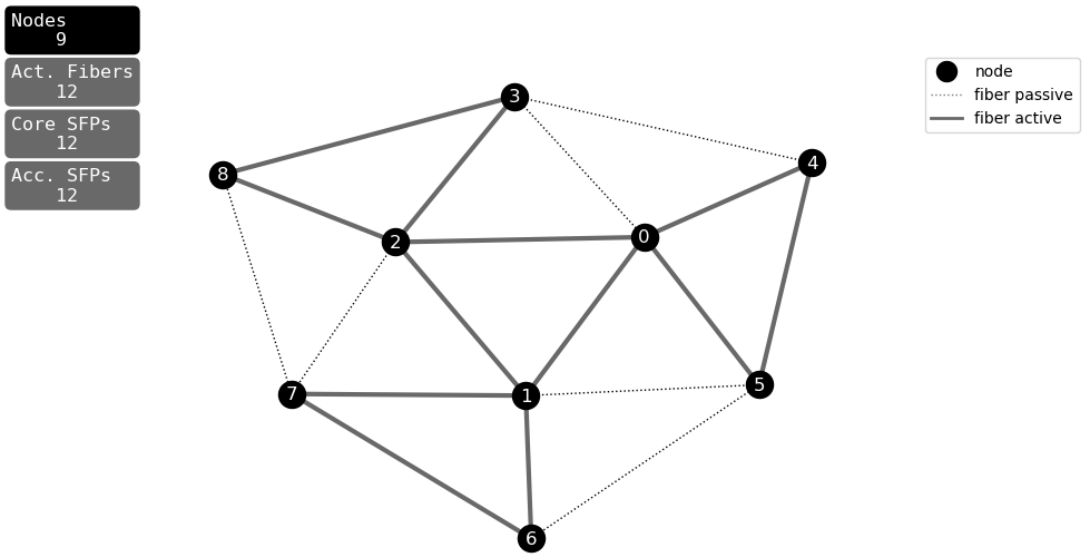


Figure 5: Adhoc3 - Another fiber and node layout with 4 SFP core count(b).

4.2 Find the best path

Once the fiber layout is established, network routing protocols, topology protocols, orchestrators or managers can do their work.

Whatever technology is used, they all look for the best path [10] from source to destination. The more

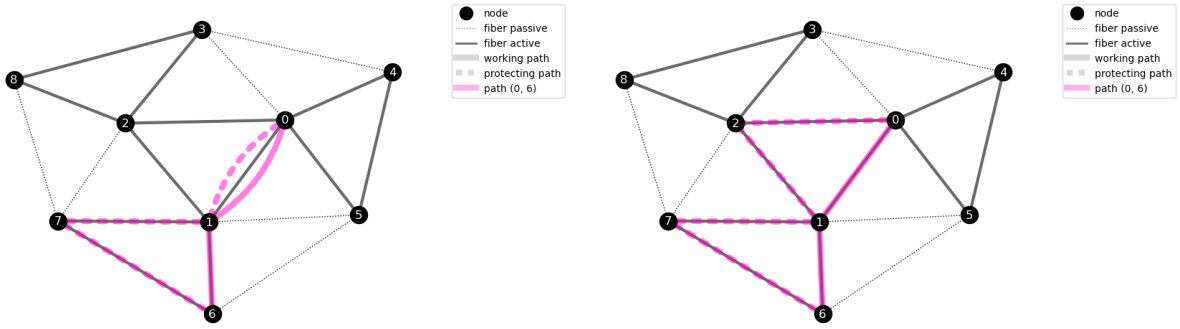
[10]You may have trouble imagining that traffic in Ethernet/RSTP switched networks is routed along routed paths. Yes, there is no explicit path. We are on a switched network where each node does MAC-based forwarding. But think about it. Once the RSTP tree is set up and MAC learning is done, there is only one way to get from source to destination. That's equivalent to our path. If a link fails, the RSTP topology will change to provide an alternate tree, which in turn provides a

advanced approaches are aware of protection needs, so they will optimize working and protecting paths together to ensure that they are disjunctive.

More ambitious algorithms will even try to optimize link capacities. They will create new paths along underutilized links to distribute bandwidth more evenly[11]. This is good for capacity constraints but creates a natural bias toward increasing complexity. More and more difficult compromises come later in the build.

In short, we can conclude, there is not an optimal network planned.

Let's look at our example. When routing our ad hoc option shown in the figure 5, the paths for connection (0-4) and (0-5) come out fine. Not much of a delta. They are disjunct and well separated. Good job, router! But for connection (0-6) we cannot find a protected pair, that satisfies all the rules, either the difference in hops between the working and protected paths is too high or they are not separated. Not good!



(a) **(b)**

Figure 6: Adhoc3 - Connection 0-6 can not be routed fulfilling the specification. Node 1 is a single point of failure. Link paths are not compliant: Either the difference in hops of working [0,1,6] and protected [0,2,1,7,6] paths is too high (3 hops versus 5) (a) or they are not separated (both run over the 0-1 link) (b).

As we have already seen, the other two options are even worse, timing wise. Neither can make the difference in hop count equal to or less than 1.

As you can imagine. This can quickly become very frustrating and complex. Do we need core routers with 6 SFP ports? Or should we just try a different choice of active fiber? Should we go back to the drawing board and start over again, or should we invest in more hardware? It's a quite an effort and there is no guarantee that it will work this time.

Is there a better way? Let's see.

5 Multi-level optimal solution using linear programming.

The industry has known for a long time that current approaches to network planning do not give us an optimal solution. We would have to optimize all levels and constraints at the same time. The method of choice is linear programming, a mathematical optimization scheme, that is well suited to this task, but has long been considered too difficult and too machine-intensive.

But times are changing. Methods and algorithms that have been dormant for many years due to lack of computing power and reluctance to dive into mathematics, are finally shining[2]. The current success in AI is a very prominent example.

new path. This will create what we call a protection path. Of course, in the context of RSTP, paths are a rather verbose concept.

[11] Since packet traffic varies, this can only be done statistically.

With today's laptops, our small problem can be solved in milliseconds. For realistic networks, such as the German mobile backhaul and FFTH network, optimal solutions were computed as early as ten years ago. These models were huge, but could be solved in minutes to hours. [3]

5.1 Optimal Solution

Transformed into standard form our problem can be solved by, for example, COIN|OR [4]. This gives us the solution, a optimal network topology as shown in figures 7 and 8 [12]

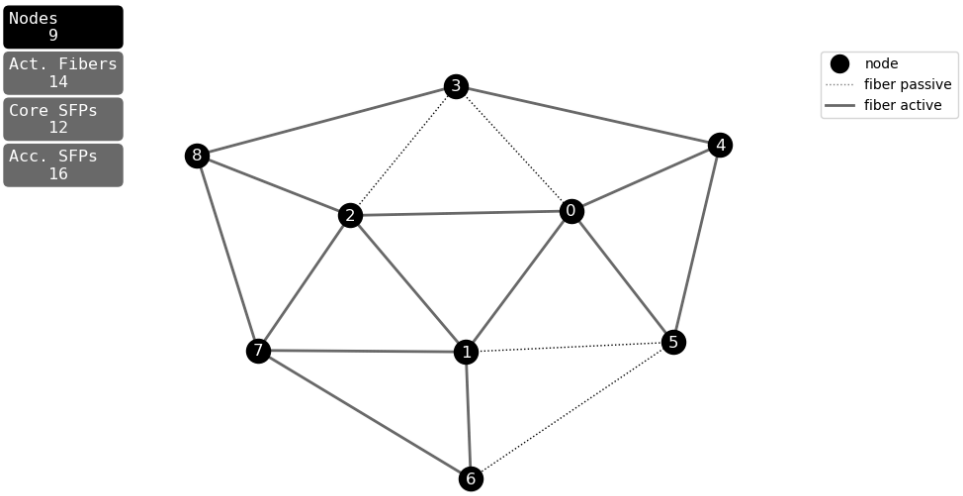


Figure 7: Optimal Solution: Fiber layout and respective metric.

The optimal network is asymmetric and uses 2 more fibers than our ad hoc trials before. Nonetheless, the resource utilization is well within the limits.

You can convince yourself that all constraints are fulfilled at all levels. Paths are disjunct and number of hops differ by at most 1.

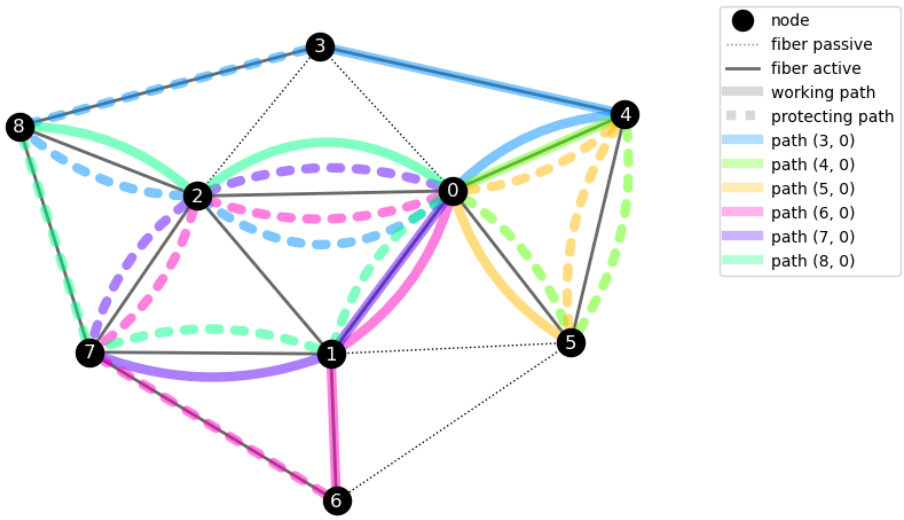


Figure 8: Optimal Solution: All protected paths fulfill the constrains.

[12] Link (2-3) comes out as not needed, but is drawn as active, as we want and any-to-any connected core.

Have you seen this option? If not, don't worry, the solution is not symmetric, so it's difficult to find. In more realistic scenarios we would have many more parameters and no chance to find the optimum by hand anyway.

Not only when starting from scratch, but also for already deployed situations, this method helps to get a transparent view on what is installed. Formulating constraints in hard mathematical facts gives us an objective measure and its deviation from optimal. In my opinion, this is a proper and transparent way to identify angles of attack and ultimately we can plan our defense.

6 Conclusion

Recent events have demonstrated the vulnerability of critical infrastructure. Any realistic protection plan needs to prioritize and identify low hanging fruit.

I hope I have shown how holistic network planning can help. How we can avoid easy points of attack. How to increase the robustness of the network design.

Doing this at all levels and under all constraints -instead of relying on an ad hoc initial assumption on fiber layout- has been too difficult in the past. Computational requirements and complexity of the tools had been too high.

I think that recent advances in usability, algorithms, and computing power will help to approach this in a new complete way. Currently, there is no plug-and-play software available. Formulating the model and defining the mathematical constraints requires a background in network engineering, requirements management, and mathematical optimization. But it worth the effort.

References

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[4] "COIN|OR : Open source for the operations research community." https://www.coin-or.org/, 2022.