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Availability optimization in a ring-based network topology

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ABSTRACT

Cellular networks are nowadays considered as a major critical infrastructure. Resiliency to failure due to disasters, weather based disruptions or malicious activities is essential. In the case of ring topology, because of delay and availability requirements, a wireless network connected to an aggregation node must sometimes be split into several rings. In this paper, we study the availability optimization in a ring-based network topology for a given number of cellular sites and a given size of rings. We prove that if each ring includes 3 nodes, the problem can be solved in a polynomial time, while for bigger rings, the problem is NP-hard. In this latter case, we provide approximation methods based on linear programming in order to converge to the solution.

1. Introduction

The choice of a network technology is mainly a matter of cost, availability and resiliency. For a given technology, these parameters will also impact the choice of the topology.

While fiber is capital intensive (cost function of distance) and offers limited availability, wireless is highly cost effective and flexible [1]. Besides, fiber is more expensive in urban areas. The choice of fiber in urban areas may be cost-effective for very short distances only. However, this comparison must be considered cautiously: a large part of capex expenses for fiber is civil engineering. Civil engineering costs can represent up to 80% of total cost, especially in urban areas. In many cases and particularly in developing areas, these civil engineering expenses must be done anyway for infrastructure investment (road, rail, pipeline, electricity). Therefore, the relevant parameter which has to be taken into consideration for the fiber/wireless cost comparison is the additional cost generated by the fiber.

Availability is a key parameter which quantifies network performance. This parameter is closely related to reliability. The difference between these two concepts is that reliability refers to failure-free operation during an interval, while availability refers to failure-free operation at a given instant of time [2].

Unavailability is generally defined as the sum of the unavailabilities of the network nodes [3]. According to this definition, an unavailability which impacts a great number of nodes in the network gets a higher ponderation than an unavailability which impacts a small number of nodes. However, this definition may lead to unavailabilities greater than 100%. For this reason, in this paper, we define the unavailability as the percentage of time for which all or part of the network is down.

While the availability of an optical fiber connection is all or nothing, line-of-sight and propagation considerations must be taken into account in wireless links. Automatic Coding Modulation enables a microwave link to use lower modulations in degraded conditions. This difference has an impact on the network resiliency, which is the ability of the network to provide and maintain an acceptable level of service in the face of faults and challenges to normal operations [4].

In the case of a radio network, the main parameters which come into account are propagation factors and infrastructural considerations. The most common topologies used in radio backhaul networks are trees and rings or a combination of both. Since tree topology generally offers shorter paths and lower costs, while ring topology generally ensures a better availability, a ring-tree combination can be an efficient solution to cumulate the advantages of both technologies [5].

Various causes of a network failure are identified in [4]: unusual traffic load, accidents and human mistakes, large-scale disasters, malicious attacks, environmental challenges and failures at a lower layer. A relevant network availability strategy must reduce as much as possible the failure probability of any link in the network and add redundancy in order to minimize the impact of a single link failure on the availability of the network nodes.

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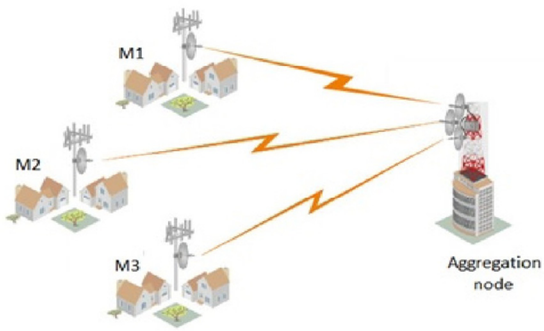

Fig. 1. Backhaul network. The aggregation node handles all the traffic produced by and to nodes M1, M2, M3.

Statistical approaches have been proposed in order to optimize availability [6,7] for systems subject to random failures. These approaches are based upon maintenance considerations for a partially observable system.

Backhaul can be made of fiber or microwave radio. In both cases, the goal is to connect the base stations (BS) to the core network. In some cases, when the gateway to the core is not far, this can be performed in one hop. But in rural areas or in Ultra Dense Networks, where there are a huge number of small BS to connect, this can require multiple hops. In this paper, we consider the Microwave Radio technology as the medium to perform the backhaul. We assume that we have a large number of BS to be connected to a single aggregation node which itself will be connected to the core network (Fig. 1). This latter connection is assumed to be wired and therefore out of the scope of this paper. Making a single large ring raises serious delay issues since the Backhaul for a BS might require several hops. In addition, it might raise serious availability issues since the disconnection of two links can affect a large number of BS. Therefore, it could be preferable to split the network into several rings.

In this paper, we will study the question of topology optimization from the point of view of availability maximization. Given an aggregation node and n cellular sites, what is the best topology based on rings, each one of them including the aggregation node, which maximizes availability?

The paper is organized as follows: we first build a simplified model in Section 2 which provides a basic understanding regarding the relation between ring size and availability. In Section 3, we use existing results from graph theory in order to discuss the general model. Approximation methods based on linear programming are proposed in Section 4. Concluding remarks are given in Section 5.

2. Simplified model

In a first step, we build a simplified model, based on the following five assumptions. Though the last two assumptions of this model are not realistic, this simplified approach will enable us to draw basic conclusions regarding backhaul network topologies.

Assumptions:

- the network includes n cellular sites (in addition to the aggregation node);
- the network topology is made of k rings;
- for $1 \leq i \leq k$ ring i includes n_i cellular sites and the aggregation node; $n_1 \geq n_2 \geq \cdots \geq n_k \geq 2$;
- same failure probability for all links: p;
- failure events are uncorrelated.

n and n_i are related by the following equation:

$$n = \sum_{i=1}^{k} n_i \tag{1}$$

Availability: the condition for availability is that all cellular sites are connected to the aggregation node. This condition is fulfilled if there is no more than one failure in each ring.

$$A = \prod_{i=1}^{k} \left((1-p)^{n_i+1} + (n_i+1)p(1-p)^{n_i}\right) \tag{2}$$

If $p \ll 1$, this expression can be approximated by its second-order Taylor development:

$$A = 1 - n\frac{p^2}{2} - \frac{p^2}{2}\sum_{i=1}^{k} {n_i}^2 + o(p^2) \tag{3}$$

Therefore,

$$A = 1 - n\frac{p^2}{2} - \frac{p^2}{2}\left(kV(n_i) + \frac{n^2}{k}\right) + o(p^2) \tag{4}$$

where $V(n_i)$ is the empirical variance of the n_i distribution:

$$V(n_i) = \frac{1}{k}\sum_{i=1}^{k}\left(n_i - \frac{n}{k}\right)^2 = \frac{1}{k}\sum_{i=1}^{k} {n_i}^2 - \left(\frac{n}{k}\right)^2 \tag{5}$$

Therefore, increasing the number of rings reduces the maximum path length and unavailability. On the other hand, it requires more antennas. In any case, given the number of rings, it is preferable that the empirical variance of the ring size distribution be as small as possible.

For a given number of rings k, the maximum availability is obtained when the empirical variance is minimized, which means when the numbers of cellular sites in the rings are as close as possible to $\frac{n}{k}$. Let q and r be the quotient and the remainder of the Euclidean division of n by k:

$$n = qk + r;\ 0 \leq r \leq k-1 \tag{6}$$

Then, $n_1 = \cdots = n_r = q+1$ and $n_{r+1} = \cdots = n_k = q$.

Therefore, the best availability is:

$$A_{k,p} = \left((1-p)^{q+2} + (q+2)p(1-p)^{q+1}\right)^r \left((1-p)^{q+1} + (q+1)p(1-p)^q\right)^{k-r} \tag{7}$$

$$A_{k,p} = 1 - n\frac{p^2}{2} - \frac{p^2}{2}\left(r(q+1)^2 + (k-r)q^2\right) + o(p^2) \tag{8}$$

$$A_{k,p} = 1 - \frac{p^2}{2}(n + kq^2 + 2rq + r) + o(p^2) \tag{9}$$

$A_{k,\,p}$ is an increasing function of k and a decreasing function of p. Of course, since the total number of antennas is $2n + 2k$, increasing k increases the cost.

The results above are illustrated with the following numerical application:

$p = 0.01$
$n = 100$
$2 \leq k \leq 50$

The cost and the availability are growing functions of the number of rings k. This defines a curve of feasible. According to the price the operator is ready to pay for a given level of availability, it is possible to define an acceptable set. Any point of the feasible curve which is inside the acceptable set is a relevant choice for the operator (Fig. 2).

It should be noted that this conclusion cannot be generalized to n rings, each one of them including one cellular node: in this case,