

3RIS for 4G: A New Approach for Increasing Availability and Reducing Costs for LTE Networks

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Abstract— The evolution of mobile communications systems leading to technologies like 4G-LTE is expected to substantiate high bandwidth applications, seamlessly. The necessity to connect the switches and gateways of these systems through microwave backhaul links to serve remote locations is inevitable. These links are not 100% reliable since the transmission path may be disconnected due to bad weather or equipment failures. Taking this premise as our starting point, in this paper, we propose a novel solution for increasing availability and reducing network costs of 4G-LTE mobile networks. This new concept that we have termed as Resiliency, Reliability, Redundancy by Infrastructure Sharing (3RIS) provides a solution to improve availability without additional cost investments, by sharing another operator's microwave backhaul. A proof of concept for the proposed solution has been evaluated by an analytical model that has been developed to show the advantages of infrastructure sharing.

Keywords—Infrastructure Sharing, Link Failure, Microwave Backhaul, Resiliency Mechanisms, Theory and Modelling.

I. INTRODUCTION

The curiosity of any smart phone user lies in the fact of exploiting the multitudinous of the services that the device has to offer. However, the eccentricity of using a smart phone lies in the fact how capable the network operator is able to offer those services, seamlessly. Perfectly consistent and coherent connectivity in today's communication world is considered to be one of the most challenging tasks for operation and maintenance engineers and researchers. When it comes to high availability requirements, mobile backhaul networks are exceptional, as they are a key element in providing high-revenue mobile services that relays upon the traffic between the radio base stations and the core network. Today, in most cases, the preferred connectivity for backhaul networks are microwave links, especially in Europe and Africa [1]. The provisioned connectivity services represent a significant part of a core network operator's revenues and a good way to increase them is by improving the connection availability. This connection availability is improved in communication networks by implementing protection through redundancy. The cost of adding redundancy is always expensive. Thus said, in this paper we propose a novel concept of infrastructure

sharing considering sharing the microwave backhaul links with other operators under link failure conditions. This new concept that we have termed as Resiliency, Reliability, Redundancy by Infrastructure Sharing (3RIS) provides a solution to improve availability without additional cost invested for redundancy.

The rest of the paper is structured as follows. Section II elaborates our motivation to carry out research within this area with a very brief state of the art in existing resiliency mechanisms. With the results of the cost-based evaluation in section III, we evaluate our proposed solution by an analytical model where we have detailed with an architectural model for infrastructure sharing. Finally, we present the opportunities and challenges towards realising this in real time which concludes the paper.

II. MOTIVATION

A. Concept Visualization

In recent years, considerable attention has been given by research community to the design of resilient networks and technologies [2]-[4]. A variety of measures for network reliability and availability has been proposed [5], [6]. These may be classified broadly into three categories: network survivability, network vulnerability, and network availability. The former two measures are limited to the concept of graph theory, but have penetrated into telecommunication systems. The third one not only concerns the various failure modes of network elements, but also the degraded performance of a network due to faults in network elements. This paper deals with the network design of resource-sharing that is extended to the next level where network operators share backhaul link resources for reducing the unavailability time as a result of link or node failures.

B. Evaluating Approach

Approaches to evaluate a system's availability can be broadly categorised as measurement-based and model-based. Our results in this paper are evaluated based on both of them. In the first part of the paper, statistical analysis of the costs that are associated with the microwave backhaul solution for real Orange 3G networks, especially for the last mile and middle mile are evaluated and presented. By this, we

demonstrate the impact of high cost investments for improving availability on the backhaul links. Thus pointed out the measurement-based results, we proceed further with the model-based approach to evaluate our proposal of infrastructure sharing in the second part of the paper. The proposed solution has been evaluated by analytical model that has been developed to show the advantages of infrastructure sharing. We adapted to analytical models as they are more of an abstraction of the real system than a discrete-event simulation model that require tight confidence bounds in the solutions obtained. The evaluation of this measure is presented here by the use of State-Space based Markov Chain Model [7], [8]. Fault Tree (FT) [9] or Reliability Block Diagram (RBD) [9], [10] cannot used to model our case, since it is not possible to model reliability-with-repair using such models and these models cannot represent the system dependency occurring in real systems. Instead, we need to resort to Markov chains. By doing so, we conclude that when backhaul links are shared between operators instead of investing for an additional back up path by themselves, each operator could still be able to gain an increase in the mean life of each intermediate link by a factor $\mu/3\lambda$ where μ represents single repair rate and λ is the failure rate of an intermediate link.

III. SYSTEM MODELLING

A. Formal definitions

- Resiliency is defined as the ability of a system to withstand a number of sub-system and components failures while continuing to operate normally [11].
- Reliability is defined as the ability of an item to perform a required function under given conditions for a given time interval [11]. It is the conditional probability at a given confidence level that a system will perform its intended function properly without failure and satisfy specified performance requirements during a given time interval $[0, t]$ when used in the manner and for the purpose intended while operating under the specified application and operation environment stress levels. Let the random variable X be the time to failure of the system. Then, reliability $R(t)$ is given by,

$$R(t) = P(X > t) = 1 - F(t) \quad (1)$$

where X is time to failure, $F(t)$ is the distribution function of the item's lifetime, and $P(X > t)$ is the probability that the time to failure is greater than time " t ".

- In practice, Mean Time Between Failure (MTBF) is used as a measure of reliability [11]. It is the expected value of the time between two consecutive failures. The MTBF and reliability are related mathematically as follows:

$$MTBF = \int_0^{\infty} R(t) dt \quad (2)$$

- Availability is defined as the ability of a component to be in a state to perform a required function at a given instant of time or at any instant of time within a given time interval, assuming that the external resources, if required, are provided [11]. Considering microwave backhaul links, availability depends on the nodes and links reliability, maintenance logistic. The maintenance logistic is characterized by the parameter Mean Time to Repair (MTTR), which represents the average time needed to repair/restore a failure and bring it back into operation. The availability at any point " t " in time, denoted by $A(t)$, is called point-wise availability, instantaneous availability, or transient availability. However, in practice, the steady state availability denoted by " A " is often used and is given by

$$A = \frac{MTBF}{MTTR + MTBF} \quad (3)$$

An important difference between reliability and availability is that reliability refers to failure-free operation during an interval, while availability refers to failure-free operation at a given instant of time, and usually, at the time when a device or system is first accessed to provide a required function or service. MTBF gives a measure of reliability, while MTBF and MTTR together provide a measure of availability.

- A discrete-state continuous-time stochastic process $\{X(t) | t \geq 0\}$ is called a Markov chain if, for $t_0 < t_1 < \dots < t_n < t$, the Conditional Probability Mass Function satisfies the following Markov property [7]:

$$P(X(t) = x | X(t_n) = x_n, X(t_{n-1}) = x_{n-1}, \dots, X(t_0) = x_0) = P(X(t) = x | X(t_n) = x_n) \quad (4)$$

- A Continuous Time Markov Chain is characterized by state changes that can occur at any arbitrary time [7]. A Continuous Time Markov Chain can be completely described by:
-Initial state probability vector for $X(t_0)$:

$$P(X(t_0) = k), \text{ where, } k = 0, 1, 2, \dots \quad (5)$$

-Transition probability functions (over an interval)

$$p_{ij}(v, t) = P(X(t) = j | X(v) = i), \text{ for } 0 \leq v \leq t, \text{ and } i, j = 0, 1, 2, \dots$$

$$p_{ij}(v, t) = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{Otherwise} \end{cases}, \text{ and} \quad (6)$$

$$\sum_{j \in I} p_{ij}(v, t) = 1, \forall i, 0 \leq v \leq t \quad (7)$$

Now, the probability mass function of $X(t)$,

$$\pi_j(t) = P(X(t) = j) \quad (8)$$

Using the theorem of total probability,

$$\pi_j(t) = \sum_{i \in I} P(X(t) = j | X(v) = i) P(X(v) = i) \quad (9)$$

If $v = 0$ in the above equation, we get,

$$\pi_j(t) = \sum_{i \in I} p_{ij}(0, t) \pi_i(0) \quad (10)$$

B. Statistical Analysis based on Real Measurement Model

Developing the “cost of availability” relationship will give the engineer an understanding of how to best concentrate the effort and allocate resources. The first step is to determine the relationship between the cost of improvement and availability. The preferred approach would be to formulate the cost function from actual cost data by estimating the different costs associated with different vendors or different component models a function of availability. The costs associated with each stage of improvement could be quantified if a reliability growth program is in place. We adopted the same approach in quantifying our results. Therefore, here, a cost-based evaluation associated with the microwave backhaul solution for Orange 3G networks, especially for the last mile and middle mile were evaluated. Even if we are conscious that the figures here refers to a given system with specific reliability figures and politics of maintenance, the evaluations that were made for the results of this paper are concrete examples of the availability results that could be transposable for any network design.

Considering the evaluated results concluded by evidence from the real network, the results below show that in a microwave backhaul, there are always downtimes by default system configurations, be it chain or ring topologies, without any redundant links already existing. Although, the values vary widely between chain and ring topologies, there is atleast a minimum downtime of 56 min/year for both of them. Unavailability results as a function of number of hops from 1 to 6 hops and E1 interfaces are reported for all the microwave scenarios in Figure 1.

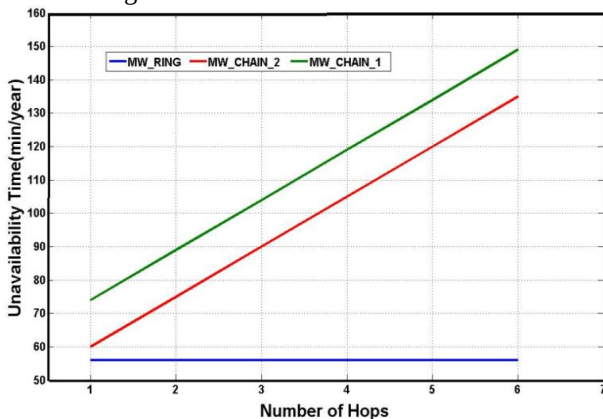


Figure 1. Unavailability results of the MW scenarios as a function of the number of hop

In Figure 1, MW_CHAIN_1 is chain topology with low protection, i.e. N+1 protection and similarly MW_CHAIN_2 is chain topology with high protection, i.e. N+2 protection. Addition of hop leads to an additional increase of 16 min/year downtime in case of the microwave chain topology scenarios. The ring topology is hop number independent with a constant downtime value around 56 min/year. Thus evident of having respective downtimes for any kind of topological configuration, it therefore necessitates the need to add more redundant links. Hence, the next step led to the evaluation of the cost that each operator invested for the sake of adding redundancy to improve the reliability and thus, availability of their microwave backhaul.

Figure 2 shows the analysed results incurred out of the cost evaluation. For the sake of company confidentiality and business reasons, we have not represented the actual figures of costs. Instead, we defined a new term called Cost Enhancement Co-efficient. This term is defined as follows:

$$CEC = \frac{C_{max} - C_{min}}{C_{min}} \quad (11)$$

where,

- CEC stands for Cost Enhancement Co-efficient.
- C_{max} is the maximum cost invested to bring down the unavailability time (in minutes per year) to a minimum value by adding the highest possible redundancy.
- C_{min} is the minimum cost invested to bring down the unavailability time (in minutes per year) to a minimum value by adding the least possible redundancy.

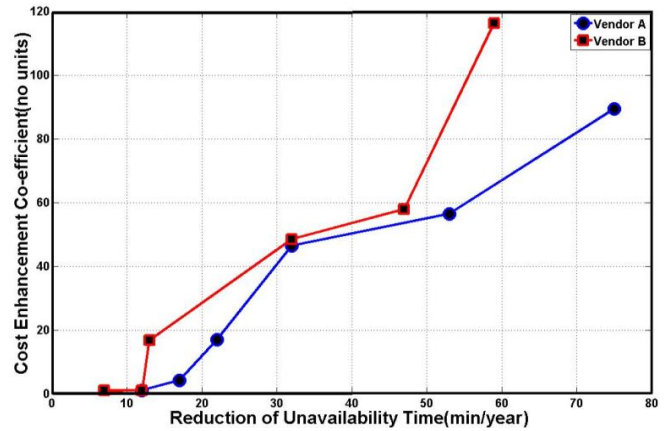


Figure 2. Cost Enhancement Coefficient as a function of unavailability results of the MW scenarios

We evaluated the results for two different network equipment vendors who play a major role in the telecommunication world in Europe and Asia. From the curves, it is observable that in order to bring down the unavailability time from 20 min/year to 10 min/year, the operator has to invest atleast 10 times higher cost than the initial cost. To be more decipherable, let us consider the performance of the equipment of the vendor A in Figure 2. By default, the equipment is expected to have downtime value of

117 min/year without any redundant links. In order to bring the downtime to (117-75) min/year, (the last point in the curve), i.e. 42 min/year, the minimum achievable value for downtime, the cost that would incur for the operator is 88 times higher than the initial cost that the operator would have invested to bring down the unavailability time reduced to (117-10) min/year, i.e. 107 min/year. This amount that the operator had to invest to bring down their downtimes is enormously high. If this is the case for improving reliability at only a particular destination in the backhaul network, then the cost investment for the complete backhaul network is myriad.

Proceeding further, to emphasize more on the cost investments that incur for the network operators, we continued to analyse the cost increment as a function of percentage. This is depicted in Figure 3. We could infer that even to reduce the unavailability value by a small fraction, the percentage increase in cost is extraordinarily tremendous. For e.g. looking at performance of vendor A, there is an increment of almost 100% in cost to bring down the network unavailability time to a minimum of 56 min/year from the original unavailable time value of 117 min/year. To elaborate it on a more perceivable way, let us say that an operator uses equipments supplied by vendor A, that has a default downtime of 117 min/year without adding any redundant links. In order to improve the availability of the network, the operator must add redundancy. For this, in order to bring the downtime from 117 min/year to 107 min/year, i.e. to achieve a reduction of downtime of 10 min/year, the operator has to invest atleast 20% more than the initial cost that he would invest. Eventually, to obtain satisfactory results in reducing downtimes, the operator is forced to invest almost 100% more than the cost of the initial investments.

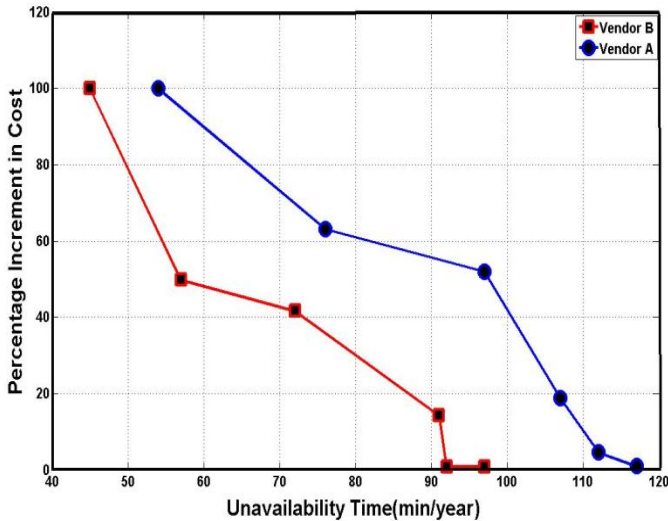


Figure 3. Percentage increment in cost as a function of unavailability results of the MW scenarios

This basically lead to the idea of backhaul infrastructure sharing, where two operators share their backhaul architecture for the purpose of increased availability without investing additional costs.

C. State Space Analytical Model for Infrastructure Sharing

The mathematical equations for the availability model were derived on the basis of Continuous-Time Markov Chains developed by [7]. Our model assumes two parallel paths with each path belonging to one operator. Fundamentally, each of the two operators provisions their own network with only one path and shares the back-up the path with another operator. One path serves as working path (primary path) and the other path serves as the protection light path (backup path) and vice versa for each of the two operators who decide to share their backhaul. For our model, we assumed that these two paths exist in parallel for the sake of redundancy and this is true for the most of the cases in backhaul topologies connecting till the last mile. This is illustrated below.

Each path has a failure rate of λ . The repair rate is μ . For the availability analysis, the state space is shown as follows.

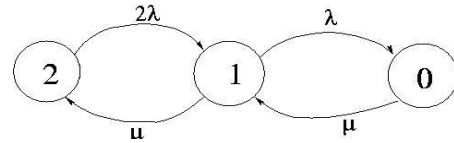


Figure 4. State diagram for availability analysis of a parallel redundant system

For reliability analysis, since we do not consider the repair once the system is in down state, all the down states will be considered as "absorbing" states, in a reliability model. Hence in our model we get,

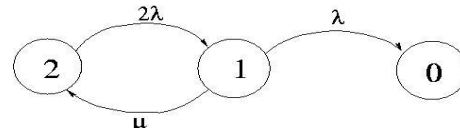


Figure 5. State diagram for reliability analysis of a parallel redundant system

Note that the above Markov chain is a reliability model with repair since component repair is allowed if the system has not failed. It is also possible to construct a reliability model without repair. When both paths, i.e. primary path and the backup paths, have failed the system is considered to have failed and no recovery is possible. Let the number of properly functioning components be the state of the system. The state space is $\{0, 1, 2\}$, where 0 is the absorbing state. The state diagram is given in Figure 5.

Assume that the initial state of the Markov chain is 2; that is,

$$\pi_2(0) = 1, \pi_k(0) = 0, \text{ for } k = 0, 1, \text{ then} \quad (12)$$

$$\pi_j(t) = p_{2j}(t), \quad (13)$$

And the system of differential equations is written based on the rule:

$$\text{Rate of build-up} = \text{Rate of flow IN} - \text{Rate of flow OUT}$$

Thus the system of differential equations are given by,

$$\frac{d\pi_2(t)}{dt} = -2\lambda\pi_2(t) + \mu\pi_1(t),$$

$$\frac{d\pi_1(t)}{dt} = 2\lambda\pi_2(t) - (\lambda + \mu)\pi_1(t),$$

$$\frac{d\pi_0(t)}{dt} = \lambda\pi_1(t).$$

Applying Laplace transform to the above set of equations, we can reduce this system to:

$$s\overline{\pi_2}(s) - 1 = -2\lambda\overline{\pi_2}(s) + \mu\overline{\pi_1}(s),$$

$$s\overline{\pi_1}(s) = 2\lambda\overline{\pi_2}(s) - (\lambda + \mu)\overline{\pi_1}(s),$$

$$s\overline{\pi_0}(s) = \lambda\overline{\pi_1}(s). \quad (15)$$

Solving the above equation for $\overline{\pi_0}(s)$, we get,

$$\overline{\pi_0}(s) = \frac{2\lambda^2}{s[s^2 + (3\lambda + \mu)s + 2\lambda^2]} \quad (16)$$

After an inversion, we can obtain $\pi_0(t)$, the probability that no components are operating at time $t \leq 0$. Let Y be the time to failure of the system; then $\pi_0(t)$ is the probability that the system has failed at or before time t . Thus the reliability of the system is,

$$R(t) = 1 - \pi_0(t) \quad (17)$$

The Laplace transform of the failure density function

$$f_Y(t) = -\frac{dR}{dt} = \frac{d\pi_0(t)}{dt}, \text{ is given by}$$

$$L_Y(s) = \overline{f_Y}(s) = s\overline{\pi_0}(s) - \pi_2(0) \quad (18)$$

$$L_Y(s) = \frac{2\lambda^2}{[s^2 + (3\lambda + \mu)s + 2\lambda^2]} \quad (19)$$

The denominator can be factored so that,

$$s^2 + (3\lambda + \mu)s + 2\lambda^2 = (s + \alpha_1)(s + \alpha_2) \quad (20)$$

and the preceding expression can be rearranged so that

$$L_Y(s) = \frac{2\lambda^2}{\alpha_1 - \alpha_2} \left(\frac{1}{s + \alpha_2} - \frac{1}{s + \alpha_1} \right), \text{ where} \quad (21)$$

$$\alpha_1, \alpha_2 = \frac{(3\lambda + \mu) \pm \sqrt{\lambda^2 + 6\lambda\mu + \mu^2}}{2} \quad (22)$$

Inverting the transform in $L_Y(s)$, we get,

$$f_Y(t) = \frac{2\lambda^2}{\alpha_1 - \alpha_2} (e^{-\alpha_2 t} - e^{-\alpha_1 t}) \quad (23)$$

and hence the reliability becomes,

$$R(t) = \int_t^\infty f_Y(x) dx = \frac{2\lambda^2}{\alpha_1 - \alpha_2} \left(\frac{e^{-\alpha_2 t}}{\alpha_2} - \frac{e^{-\alpha_1 t}}{\alpha_1} \right) \quad (24)$$

As per eq. (2), the MTBF of the system is given by,

$$\begin{aligned} E|Y| &= \int_0^\infty R(t) dt \\ &= \frac{2\lambda^2}{\alpha_1 - \alpha_2} \left(\frac{1}{\alpha_2^2} - \frac{1}{\alpha_1^2} \right) = \frac{2\lambda^2(\alpha_1 + \alpha_2)}{\alpha_1^2 \alpha_2^2} \\ &= \frac{2\lambda^2(3\lambda + \mu)}{(2\lambda^2)^2} = \frac{3}{2\lambda} + \frac{\mu}{2\lambda^2} \end{aligned} \quad (25)$$

From the above equation, it is evident that the MTBF of an intermediate microwave link that comprises of an additional backup path in parallel shared with another operator, for the sake of redundancy, increases by a mean life of $\mu/2\lambda^2$, or by a factor:

$$1 + \frac{\mu/2\lambda^2}{3/2\lambda} = \frac{\mu}{3\lambda} + 1 \quad (26)$$

The same equation, while in the absence of an additional backup path, (i.e., $\mu = 0$), would be equal to the first term, $3/2\lambda$ in expression (25). Therefore, from the above analytical evaluation, it is evident that sharing an additional link with another operator instead of having to invest one by themselves, will increase of reliability of each intermediate link, for every operator who agree to share the links and thus availability increases which also depends on MTBF.

IV. PROPOSED ARCHITECTURE MODEL

With this in mind, as a next step, we propose a basic model on the architectural design of networks by infrastructure sharing. Before to proceed, the question that very often engineers have to answer is related to the selection of the best and most reliable network topology. It has been proved from the prospective of the individual microwave path availability/reliability analysis of [4] for a linear topology of the five cell-site network, the average unavailability per BTS is 0.003% (availability = 99.997%); for the star/hub topology, the average unavailability per BTS is 0.0018% (availability = 99.9982 %), and for the ring topology, 0.00000007% (availability = 99.99999993%). Therefore, the resulting topology arising out of microwave backhaul network infrastructure sharing between two operators has to result in a ring topology that will result in minimum CAPEX, thus providing superior availability and resiliency. For this, we choose a real topology of Orange networks. Again, for confidentiality reasons, the geographical location of this topology is unrevealed. The topology below represents a chain

topology till the last mile. Since, this is a chain topology every intermediate link has a double protection, i.e. a primary path and backup path. However, the last mile is never protected and the failures accounting in the last mile are not avoided at all.

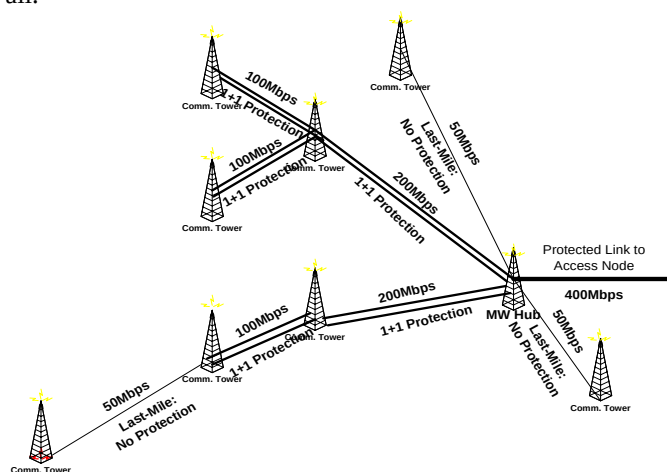


Figure 6. Last mile chain topology with redundant links.

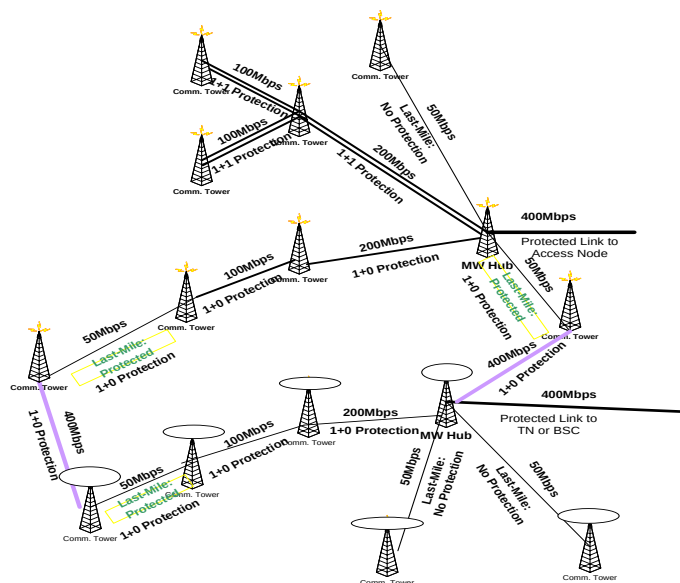


Figure 7. Resiliency design flow using infrastructure sharing

Figure 7 shows the topological evolution of a chain topology into a ring topology, which results in the protection of a last mile link as well as cost reduction due to elimination of an extra backup link for both the operators. In Figure 7, there are two operators who share the backhaul links. The one at the top of the figure is the initial topology that we represented in Figure 6. The one below with circles on the top is the topology of another operator. When the last miles of these two operators are connected by just another additional link, we observe that even the last miles could be efficiently protected. Besides protecting the last mile link, the other advantage is that the sharing operators need not invest for another additional link for redundancy in their chain topology.

V. CONCLUSION

Wireless standards such as the 4G-LTE keep on evolving but the backhaul architecture remain the same. A first thought and a simple solution to enable quick roll-out of new technologies like the 4G-LTE without having to invest more for backhaul is presented in this paper. We evaluated our results by a simple 2-path parallel system using State Space Markov Chain model. The advantage of the model is that it can be applied to any system with high complexities. The technique is effective for small and large-scale systems. As long as the system's reliability equation can be derived analytically, the model can be used to solve the reliability allocation problem. By adopting the proposed solution to achieve backhaul infrastructure sharing, networks operators could decrease their unavailability time without having to invest more for adding redundancy. Henceforth, the cost reductions will lead to a reduction of business risk for the involved operators. The cost and energy reduction in this scenario is of a similar magnitude, since more traffic can be served with the same links before additional sites are needed. With all these in mind, backhaul infrastructure sharing could be one of the problem solvers to tackle the issue of restoring network failures or undermining peak traffic problems.

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