Give and Take: Characterization of Availability of Multi-State Wireless Backhaul Networks

VENMANI Daniel Philip*†, Yvon GOURHANT*, Djamal ZEGHLACHE†
*Orange Labs, France Telecom R&D, Lannion, France
†Institut Mines-Télécom, TELECOM SudParis & CNRS, SAMOVAR / UMR 5157, Evry, France
{danielphilip.venmani, yvon.gourhant}@orange.com, djamal.zeghlache@it-sudparis.eu

***Abstract*—In this paper, we provide a new availability analysis of backhaul wireless communication networks which are supported by microwave links which evolved out of sharing between two different mobile network operators (MNOs) based on the Multi-State System (MSS) approach using Discrete-state Continuous-time Markov chain model. Our results show that such a jointly-constructed network was available to meet the required demand of the total system more than 99.8 % of the time.**

Keywords- Backhaul Networks; Infrastructure Sharing; Theory and Modeling; Multi-State Systems; 4G-LTE.

I. INTRODUCTION

Mobile Network operators (MNOs) such as Orange, Vodafone no longer adapt to the classical approach of having an exclusive use of the wireless network resources such as spectrum, sites, transmission lines, core networks, etc. Cell site sharing which evolved mostly due to the lack of site locations and environmental aspects has been widely adopted as the most common and the most prevailing form of "Resource sharing". However, recent developments show further expansion towards the concept of resource sharing i.e. wider network infrastructure sharing, technically termed as "Active sharing". The 3GPP specifications of multi-carrier options in advanced wireless access systems (e.g. HSPA+, LTE-Advanced) and the fragmented spectrum bands owned by different MNOs pushes infrastructure sharing farther from its demarcations. The drivers to expand the area of infrastructure sharing can be (1) cost-oriented -e.g. lower CAPEX and OPEX, (2) tackling network failure conditions, (3) customer-oriented -e.g. maintaining constant throughput, higher capacity, coverage, end-user quality, (4) regulatory-oriented -e.g. satisfying licensing agreements, (5) environmental-oriented e.g. reduced number of sites, power consumption and even more. Now within this context, focusing towards emerging economies, enhancing reach through the creation of infrastructure is the need of the hour. To maintain increased growth levels, MNOs need to push out to rural and remote areas. However the capital costs for this are very formidable and are simply not addressable through the revenues currently generated. Under these circumstances, the concept of infrastructure sharing between MNOs assumes crucial importance. This will allow MNOs to leverage on existing infrastructure to provide affordable services to rural consumers. In a low-income country like India or Kenya or Nigeria, it is also undesirable for each MNO even if they were able to afford it, to replicate expensive telecom infrastructure to reach the subscribers in rural / remote areas. Infrastructure sharing is equally important in the urban areas where the presence of two or three MNOs and a rapidly increasing mobile subscriber base, is resulting in more and more cell-sites being put up by each MNO to cater to higher traffic requirements. This results in separate individual high costs for each MNO. With all this in mind, as a next step, we bring forward the next feasible approach in infrastructure sharing where MNOs share their backhaul architecture. With Radio Access Network (RAN) sharing being a great success within MNOs especially in Europe, our approach to share backhaul links also seems to acceptable from a political point of view of MNOs and regulators. Thus, this paper considers measures of availability and reliability analysis for wireless backhaul architecture that is evolved out of sharing between two different MNOs, within the context of multi-state systems (MSS) theory [1] where each of the MNOs' backhaul can have different performance levels ranging from perfect functioning to complete failure. Our approach presents a model representing demand as a continuous-time Markov chain [2], [3] with four different logical state spaces. We propose a general approach to describe, model and evaluate the availability characteristics of the microwave backhaul systems with various types of failures and repair scenarios. Such failures may change the state of the backhaul system and the quality of its operation, but do not necessarily lead to complete system failure.

The rest of the paper is organized in the following order and we thus enunciate this here to give the reader a quick overview of our work in this paper. In what follows next is the Section II that describes our adapted approach of MSS theory with a very brief description. For readers who might require an initial clear understanding on MSS theory, reading [1] is strongly encouraged. In Section III, we have given an overview of our architectural design. The evolution of the design itself is not the main scope of this article while it still necessitates a very brief description for a better understanding of this analysis. Section IV gets deeper into the subject with a formal introduction to the preliminaries and then directly into the analysis. Here, we have supported our approach based on MSS theory analytically. A general model for describing reliability process in backhaul systems while being shared among MNOs with gradual failures is proposed. Section V illustrates the numerical results showing its support to the theory. Finally, Section VI gives the concluding remarks for the paper with our claim to support backhaul link sharing under link failure situations.

II. EVALUATING APPROACH

Approaches to evaluate a system's availability studies are common by two main characteristics: the life-time of the

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system and its steady state characteristics under some assumptions about repair process. The ways to evaluate these characteristics depend on the approach to the following two aspects: probabilistic and structural. Probabilistic aspect deals with calculation of the system states probabilities, and uses them in availability calculations. The structural aspect considers kind of direct evaluation of reliability characteristics for any given structure of a particular system. In this paper we deal with probabilistic aspect of modeling system availability and focus on both of its common characteristics. While the probabilistic aspect of modeling system availability is being considered, it can be further categorized as the binary state and multi-state models. Traditional binary-state availability models allow only two possible states for a system and its components: perfect functioning (up or 1) and complete failure (down or 0). However, many real-world complex systems have different levels of performances for which one cannot formulate an "all or nothing" type of availability criterion, especially when the performance of one component is affected by the performance of another component. Such systems are defined as the Multi-State Systems (MSS). Estimation of the availability and optimizing the design of the MSS is gaining popularity and has been widely studied in literature [4], [5]. MSS availability and reliability evaluation can be carried out based on three different approaches [6], namely the stochastic process that mainly deals with the Markov Model (MM) approach; the structure function approach, where Boolean models are extended for the multi-valued case; and Monte Carlo simulation. Our proposed solution has been evaluated by the stochastic model approach for the MSS. The proposed model has been developed to show the advantages of sharing backhaul links between two or more different network operators to enable quick roll-out of new technologies and to improve the overall network resource utilization capacity. Our present work in this paper elicits the architectural design of our previous work [7] but provides a completely new availability analysis to illustrate our design. Furthermore, to the best of our knowledge, no previous work analyzes resource sharing in wireless backhaul architecture between different MNOs within the context of the MSS theory.

Our proposed solution in this paper has been evaluated by the stochastic model approach that has been developed to show the advantages of backhaul link sharing between two different MNOs to improve the overall capacity. We adapted to stochastic 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. Furthermore, our results in this paper are evaluated based on the Markov chain method, also for the following reasons: it is appropriate for quantitative analysis of availability and reliability of systems; it can be used with large, complex systems; it is not only useful, but often irreplaceable, for assessing repairable systems. Therefore, this paper adopts Markov Model approach that considers of multi- state model to analyze the availability of microwave links when shared.

III. Architectural Design

Here, we describe very briefly our architectural design that we had proposed earlier in [7], since it is inevitable for the better understanding of our work here [1]. According to our architecture, each network operator shares another operator's working path as their backup path. This provides a solution for network operators to reduce the total cost of building a backhaul network since they obviate the need for an additional backup path. Besides, our solution could be one of problem solvers for situations such as disaster recovery, like the tsunami and earthquake affected Japan, where operators are willing to share and invest to bring back the technology as soon as possible. As it can be seen in Fig.1, there are two different operators who share the microwave backhaul links. The one at the top of the figure (in the north of the country) is the topology of operator A. The one below with circles (in the south of the country) is the topology of another operator who agrees to share the backhaul links. When the last miles of both the operators are connected by another additional link (green colour thick link), we observe that the ring topology network that has evolved, provides more protection including the last miles compared to a microwave chain topology. In addition to offering more protection, the other advantage is that the sharing operators need not invest for another additional link to include redundancy across their entire chain topology.

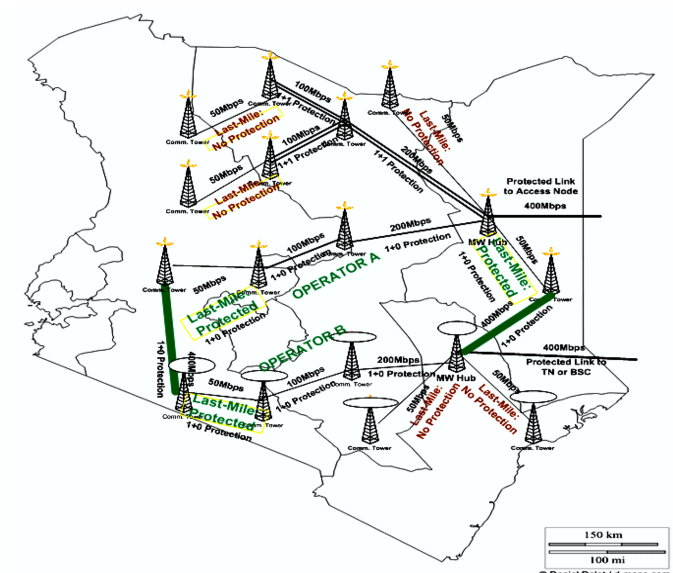


Figure 1. An illustrative example network topology portraying resiliency design flow using infrastructure sharing within the country Kenya.

Now, in this paper, we provide an availability analysis to illustrate the availability within network operators' backhaul at times when a path is blocked due to link/node failure and/or when resource utilization exceeds a threshold and/or when the network state changes to achieve better resource utilization. We call it "Give and Take" here, because network operators "give" a part of their working path bandwidth to another network operator with whom the Service Level Agreement (SLA) is concluded, without jeopardizing their own availability requirements. This working path is used by another operator as their backup path. At the same time, operators also "take" bandwidth from the sharing operators if there is a surge for more bandwidth within their own backhaul.

[1] For more details on the evolution of architectural design, please refer [7].

IV. Multi-State System Availability Analysis

A. Formal Definitions

To define systems with degrading components in the MSS availability analysis model, we assume that the system under consideration has the reliability state set denoted as s can have $\{0,1,,2,\ldots z\}$ different states, where the state 0 is the worst state and the state z is the best state, for any system element j, where $j = \{1,2,\ldots n\}$. The system reliability states degrade with time t without repair. The above assumptions mean that the system states degrade in time only from better to worse, corresponding to the performance rates, represented by the set $g_j = \{g_{j1}, g_{j2}, \ldots g_{js}\}$ where g_{js} is the performance rate of element j in the state s.The performance rate $G_j(t)$ of element j at any instant $t \geq 0$ is a discrete-state continuous-time stochastic process that takes its values from g_j: $G_j(t) \varepsilon\, g_j$. The system structure function $G(t) = \Phi(G_1(t), \ldots . G_n(t))$ produces the stochastic process corresponding to the output performance of the entire MSS. In practice, a desired level of system performance (demand $W(t)$) also can be represented by a discrete-state continuous-time stochastic process. For reliability assessment, MSS output performance and the desired performance level ($W(t)$) are often assumed to be independent stochastic processes. The desired relation between the system performance and the demand at any time instant t can be expressed by the acceptability function $\Phi(G(t), W(t))$. In many practical cases, the MSS performance should be equal to or exceed the demand. So, in such cases, the acceptability function takes the following form:

$$\Phi(G(t), W(t)) = G(t) - W(t) \qquad (1)$$

and the criterion of state acceptability can be expressed as

$$\Phi(G(t), W(t)) \geq 0 \qquad (2)$$

A general expression defining MSS reliability measures can be written in the following form:

$$R = E\{\mathcal{F}[\Phi(G(t), W(t))]\} \qquad (3)$$

where E denotes the expectation symbol, $\mathcal{F}$ is the function that determines corresponding type of reliability measure, and Φ, the acceptability function. Many important MSS reliability measures can be derived from the expression (3) depending on the functional $\mathcal{F}$ that may be determined in different ways. For example, it may be a probability $\Pr\{\Phi(G(t), W(t))\} \geq 0$ throughout a specified time interval $[0, t]$ and the acceptability function (1) will be non negative. In this case, this probability characterizes MSS availability. It may be also an expectation of an appropriate function up to the time of the MSS, s initial entrance into the set of unacceptable states, where $\Phi(G(t), W(t)) < 0$ is the number of such entrances within time interval $[0, t]$ and so on. For a wireless backhaul system where the available capacity at time instant t is $G(t)$ and the corresponding load demand is $W(t)$, if the acceptability function is defined as:

$$\Phi(G(t), W(t)) = \begin{cases} W(t) - G(t), & \text{if } W(t) > G(t) \\ 0, & \text{if } W(t) \leq G(t) \end{cases} \qquad (4)$$

B. Multi-State Wireless Backhaul Networks Availability Analysis with Sharing between Different MNOs

The following assumptions and conditions are adapted for our model, thus making it as a MSS with four different logical state spaces:

1) Assumptions and Conditions:

a) Assumption 1: Our model assumes that there are only two operators (MNO A and MNO B) who agree to share their backhaul. However, our solution can be practically possible allowing any number of MNOs to share, provided they are all within the same geographical zone, i.e. within one country.

b) Assumption 2: For obtaining system performance values $\Phi(G_1(t), G_2(t))$, we set each MNO's backhaul bandwidth to 200Mbps link. Taking advantage of the now available granularity features, e.g. MPLS-TE, OpenFlow [8], MNOs "split" capacity according to the sharing MNO's requirements. For our simplification, we assume that each MNO allows the sharing MNO to "give and take" up to a maximum of 75Mbps of their link bandwidth for the sake of resiliency and redundancy and also for over-provisioning.

2) Four States (Multi-State) while MNOs Share:

a) State 1- Both UP (Normal Operating State (NOS)): The working paths (primary path) of both the MNOs utilize their bandwidth capacity fully, i.e. no failure encountered by any of the MNOs and hence sharing backhaul link bandwidth becomes unnecessary. We call this as *NOS*.

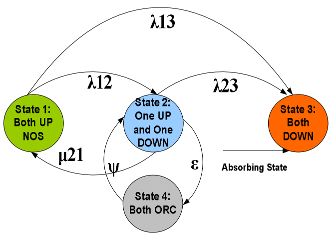
b) State 2- One UP and One DOWN: One operator (MNO A) is faced with a link failure in its own backhaul and thus down, whereas the sharing operator (MNO B) functions under normal operating conditions, i.e. no failures.

c) State 3- Both DOWN: Both of the MNOs have encountered network outage due to failures at the same time and hence they are down at the same time. This is defined as the *Absorbing State* where resource sharing between MNOs becomes void and necessitates manual intervention.

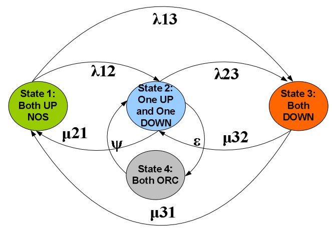
d) State 4- Both ORC (Operating at Reduced Capacity): This is a special case, which categorizes our model as a multi-state system, since there is no absolute "UP or DOWN" state. As per our assumption, when there is a link failure in MNO A backhaul, the MNO B shares the reserved bandwidth with MNO A and thus the state of MNO A changes from state "DOWN" to "UP". However, both the MNOs can not utilize their fullest bandwidth capacity now, since they are allowing the other MNO to take a part of their bandwidth. It is an intermediate state that is not categorized into a complete failure or a perfect functioning. This state is the state that we define as the *Operating at Reduced Capacity* state. At this state, MNOs decide which kind of their traffic (high revenue generating premium customers' traffic and/or delay sensitive voice call customers' traffic) must be given more priority than the rest due to the limited available *shared* bandwidth.

3) State Space Diagram and State Probabilities:

Our model encompasses all the transitions caused by the each element's failures and repairs that correspond to the transition intensities which are expressed by the element's failure and repair rates. Each path that encounters a failure has a failure rate of λ. The repair rate is μ. Also, the transition to the intermediate ORC state is represented as ε and the transition from the intermediate ORC state is ψ. Failure and repairs cause element transition from one state to another state.



(2)



(3)

Figure 2. Multi-state system reliability analysis diagram for wireless backhaul network with infrastructure sharing

Figure 3. Multi-state system availability analysis diagram for wireless backhaul network with infrastructure sharing

From the state space diagrams seen in Fig. 2 and Fig. 3, with assumption that the state 1 is the best state of our system under analysis, there is a transition from the state 1 to the state 2 if failure (λ_{12}) occurs in the state 1; then if the repair (μ_{21}) will be completed, the system will be back to the previous highest state 1. Similarly, there is a transition from the state 2 to the state 3 if failure (λ_{23}) occurs in the state 2; however, the state does not return back to the previous highest state since there is no repair under reliability analysis, as in Fig. 2. In addition, there is a transition to the state 4 with transition intensity rate ε and back to the state 2 with transition intensity rate ψ when there is a failure or demand variation when the system is in the state 2. The corresponding performance $g_s$is associated with each state transition. Table I indicates the system states and the corresponding performances calculated based on our assumed values from Section IV (B).

TABLE I. SYSTEM STATE AND PERFORMANCE

System States	**State of the elements**	**System Performance $\boldsymbol{\Phi(G_1(t), G_2(t)) = G_1(t) + G_2(t)}$**
1	$\{g_{11}, g_{22}\} = \{200, 200\}$	$g_1 = 400$ Mbps
2	$\{g_{12}, g_{22}\} = \{0, 200\}$	$g_2 = 200$ Mbps
3	$\{g_{13}, g_{23}\} = \{0, 0\}$	$g_3 = 0$ Mbps
4	$\{g_{14}, g_{24}\} = \{75,125\}$	$g_4 = 200$Mbps

From the table, it can be observed that the performance of the system in the state 1 achieves the best performance with $g_1 = 400$ Mbps, where both of the MNOs demands could be met satisfactorily. Without doubt, the performance of the system in the state 3 is the worst, where both of the MNOs demands could not be satisfied at all due to link failure situation. Now, observing the state 2 and the state 4, they both show the same system performance with $g_2 = 200$ Mbps and $g_4 = 200$Mbps respectively. Nevertheless, what is interesting is that with the state 2 system performance, only MNO B demands are satisfied while MNO A demands are not. With our solution through sharing the backhaul links, analyzing the state 4 system performance, what could be deduced is that both MNO A as well as MNO Bs demands (if not completely) could be satisfied, since they both have atleast limited shared-bandwidth available.

The next step is to determine the state probabilities $P_s(t)$ of the element's performance process $G_j(t)$ at time t. Formally,

$$P_s(t) = \Pr\{G_j(t) \varepsilon\, g_{js}\} \text{ where } s = \{0,1,,2,\ldots z\}: t \geq 0 \quad (5)$$

Accordingly, the Kolgomorov's system of differential equations for finding the state probabilities $P_s(t)$ for the homogeneous Markov process is:

$$\frac{dP_s(t)}{dt} = P_s(t)\, V(t) \quad (6)$$

where, $P_s(t)$ indicates the system-state probability vector at time t, whose entries are the system state probabilities at t and $V(t)$ denotes the transition-rate matrix, whose entries are the component failure, repair and intensity rate. Based on the developed multi-state system space diagram, the mathematical equations using Markov chain were developed and therefore, the corresponding system of differential equations is written as:

$$\frac{dP_s(t)}{dt} = P_s(t)\begin{bmatrix} -(\lambda_{12}+\lambda_{13}) & \mu_{21} & \mu_{31} & 0 \\ \lambda_{12} & -(\lambda_{23}+\mu_{21}+\varepsilon) & \mu_{32} & \psi \\ \lambda_{13} & \lambda_{23} & -(\mu_{32}+\mu_{31}) & 0 \\ 0 & \varepsilon & 0 & -\psi \end{bmatrix} \quad (7)$$

4) Estimation of Transition Probabilities:

Failure and repairs cause element transition from one state to another state. The estimation of transition probabilities are calculated on assumptions based on the real-world performance data. Table II shows the values that were used for the numerical illustrations. To know how the values were obtained, please refer [7]. Transition values λ and μ considered here represents the failure and repair rate for a microwave chain topology.

TABLE II. TRANSITION RATES OF ALL STATES

	System States			
System States	1	2	3	4
1	0.0	0.017241	0.034482	0.0
2	0.022777	0.0	0.017241	0.00002
3	0.001388	0.022777	0.0	0.0
4	0.0	0.00002	0.0	0.0

As we know that the initial state of the Markov chain, i.e. state 1 gives the best performance, $P_1(0) = 1$, and for the rest $s = 2,3,4$, $P_s(0) = 0$. Therefore, solving (7) using Laplace transformation under the initial conditions, we determine the state probabilities $P_s(t)$. Fig. 4 illustrates this graphically.

5) Multi-State System Availability and its Demand:

Based on the state probabilities which are determined from the Markov model for all the system elements, we define the availability of the entire shared backhaul architecture, as a measure which indicates the probability of the network to work normally under determinate time t and demand $W(t)$, where $W(t)$ is a random process that can take discrete values from the set $W = \{W_1, \ldots, W_M\}$. Therefore, the MSS availability $A\left(t, W(t)\right)$ at instant $t > 0$ for random constant demand $W(t)$for the wireless backhaul when shared is written as:

$$A\left(t, W(t)\right) = \sum_{i=1}^{k} \left[\!\left[\mathrm{P_s(t)}.\left(\mathrm{g_{js}} - \mathrm{W(t)}\right) \right]\!\right] \ \forall\, k \leq n \tag{8}$$

V. ILLUSTRATIVE NUMERICAL EVALUATION

A. Estimation of State Probabilities from the Markov Model

As a first step, we determine the probability of each system state defined earlier, with the corresponding system performance. This enables us to evaluate the availability of the entire backhaul architecture evolved out of sharing between MNOs. Fig. 4 shows the evaluated system state probabilities as function of time obtained by solving (7). The probability that each element provides a performance rate is based on each value of system performance and the values of failure and repair rates. It can be observed that the state 1, which is the best state of the system with no failures at all has the highest probability to satisfy the demand $W(t)$ during the operation days. On the other hand, the state having the next highest probability to meet the demand is the state 4. This is due to the very low transition rate from the state 2 to the state 4. This implies that when MNOs share their link bandwidth, the overall performance is nearly as good as they operate without any failures at all.

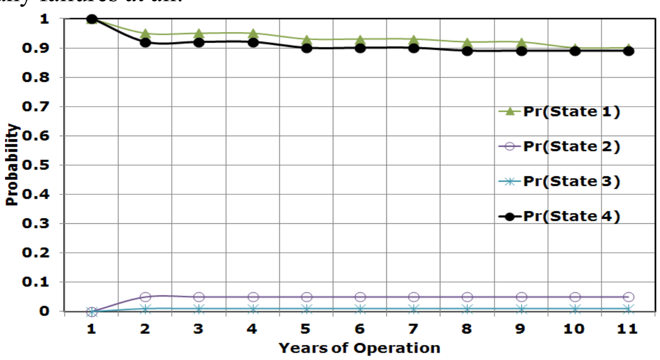


Figure 4. Estimation of state probablities of wireless backhaul network with infrastructure sharing

B. MSS Average Availability of the Wireless Backhaul when Shared

Based on the state probabilities, we now measure the availability. From the state diagrams, each state represents the set of acceptable states based on the required demand $W(t)$. We use (8) to calculate the average availability. This is obtained by the summation of the calculated state probability values of only the acceptable states, i.e. states 1, 2 and 4.

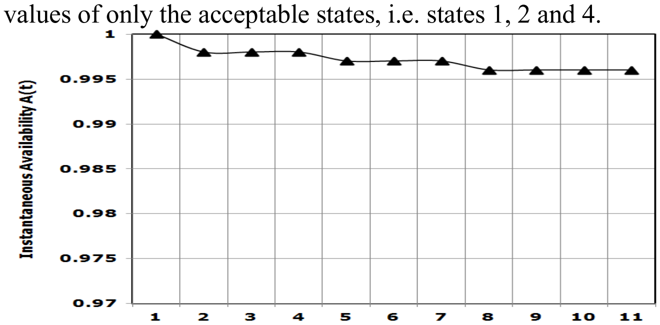


Figure 5. Multi-State system availability for wireless backhaul network with infrastructure sharing

The availability of entire backhaul architecture evolved out of sharing between MNOs is shown in Fig. 5. We observe that total system availability is greater than 99. 8%. If the required demand is within the limits of the allocated bandwidth capacity, then we observe that all the states satisfied the required availability requirement except state 3, which is the absorbing state. In this case, the state 3 would be an unacceptable state which is not considered for the calculation of the system availability. We also notice that the availability decreases through time anyway. This is only due to the performance degradation that arises due to wear and tear effects.

VI. DISCUSSIONS

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. As discussed in the paper, we have presented a novel resource sharing framework which can cost-effectively provide protection services without jeopardizing guaranteed availability requirements for the MNOs. Our approach here is to define which type of traffic needs to be protected all the time, and which can have a lower level of protection. True, the above scenario does not offer a 100% protection scheme like in the SDH world. It does however offer 100% protection level for the premium (i.e. revenue generating) traffic during partial network downtime, while leaving some headroom for low priority service so as to avoid starvation. From a first glance it may seem like we have reduced availability, but in truth, the system ensures that premium types of service never fail and have a guaranteed channel regardless of any other traffic. Thus, MNOs improve the availability of their revenue generating services to ensure high-quality, uninterrupted user experience, and increase link capacity to offer more data services.

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