Availability improvement schemes for multi-carrier optical transmission systems

Hiroshi Yamamoto\textsuperscript{a),} Kei Kitamura, Masahiro Yokota, Shohei Kamamura, Rie Hayashi, and Yoshihiko Uematsu
NTT Network Service Systems Laboratories, NTT Corporation, 3–9–11 Midori-cho, Musashino, Tokyo 180–8585, Japan
\textsuperscript{a)} yamamoto.hiroshi@lab.ntt.co.jp

Abstract: In multi-carrier optical transmission systems, availability of a transponder decreases in accordance with the increase in the number of optical modules comprising the transponder. In this paper, we clarify promising schemes to improve availability by comprehensively comparing them. We first clarify the condition under which availability problems become apparent by analyzing the basic trend in availability. Then, we compare the improvement in availability and difficulty in transmission system development. As a result, we showed that the Pool scheme, where the small amount of shared backup optical modules are implemented to avoid transponder failure, is promising since it effectively increases availability with a small amount of additional optical modules and has enough feasibility.

Keywords: multi-carrier optical transmission, availability improvement

Classification: Transmission Systems and Transmission Equipment for Communications

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1 Introduction

Multi-carrier transmission technology, with which a large amount of client traffic is transmitted using multiple channels called sub-carriers, is regarded as promising to
accommodate continuously growing traffic demand [1]. In multi-carrier transmission systems, a transponder is composed of a number of optical modules equal to that of sub-carriers. Assuming that each optical module fails at a certain probability, availability of a transponder decreases in accordance with the increase in the number of optical modules comprising the transponder.

In this paper, we clarify promising schemes to improve availability of multi-carrier transmission systems by comprehensively comparing them. We first clarify the condition under which availability problems become apparent by analyzing the basic trend in availability of multi-carrier transmission systems. Then, we compare the improvement in availability and difficulty in transmission system development based on two major schemes: (a) client traffic is continuously transmitted using only non-failed sub-carriers (Polishing scheme) and (b) the small amount of shared backup optical modules are implemented to avoid transponder failure (Pool scheme). As a result, we showed that the Pool scheme is promising since it effectively increases availability with a small amount of additional optical modules and has enough feasibility.

2 Availability of multi-carrier optical transmission systems

In a multi-carrier transmission system, client traffic is transmitted at $X \times n$ Gbps using $n$ sub-carriers, each of which transmits the signal at $X$ Gbps. The structures of a multi-carrier transmission systems and transponders are illustrated in Fig. 1(a). A transponder is composed of a framer and $n$ optical modules. Client traffic is divided into $n$ signals by a framer on the sender side. Each divided signal is transmitted through an optical module. Note that the standardization discussion of beyond 100G OTN (Optical Transport Network) in ITU-T has currently proceeded according to the policy where partial failure in a transponder is treated as failure of the entire transponder. Thus, in Normal scheme, communication between a pair of transponders becomes completely unavailable if any of optical modules fails.

Assuming that each optical module fails at a certain probability, unavailability of communication between a pair of transponders is formulated with the following equation.

$$P_{normal} = 1 - ((1 - a)^n) \cdot (1 - a_F)^n,$$

$$a = \frac{MTTR}{MTBF + MTTR}, \quad a_F = \frac{MTTR}{MTBF_F + MTTR}$$

(a) Structure of multi-carrier optical transmission systems (b) Unavailability and number of sub-carriers

Fig. 1. Multi-carrier optical transmission systems (Normal)
Here, \( a, a_F, n, MTBF \) and \( MTBF_F \) correspond to unavailability of an optical module, that of a framer, the number of optical modules, mean time between failure of an optical module, and that of a framer, respectively. \( MTTR \) corresponds to the mean time to repairer of both of an optical module and a framer.

If two systems are operated under the redundant mode as shown in Fig. 1(a), unavailability is the square of \( P_{\text{normal}} \) in Eq. (1). The redundancy can be achieved by OTN/ODU (Optical channel Data Unit) protection switching or IP rerouting.

Fig. 1(b) illustrates unavailability and number of sub-carriers. In the case of two sub-carriers, the increase in unavailability does not cause a serious problem since unavailability is only twice as large as that in a single carrier for non-redundant. However, unavailability increases along with an increase in the number of sub-carriers. For example, in the case of 5 sub-carriers, unavailability becomes 5 times as large as that for non-redundant and 25 times as large as that for redundant.

Thus, a countermeasure against increasing unavailability due to the number of sub-carriers has become essential to keep unavailability as small as that of current single carrier transmission system at least.

3 Schemes to improve availability of multi-carrier optical transmission system

Assuming that optical modules, the number of which in a transponder is large, form a bottleneck in availability of a multi-carrier transmission system, there are two schemes for improving such availability: (a) client traffic is continuously transmitted using only non-failed sub-carriers (Polishing scheme) and (b) the small amount of shared backup optical modules are implemented to avoid transponder failure (Pool scheme).

Fig. 2(a) illustrates the Polishing scheme. This scheme uses \( n \) optical modules to transmit client traffic at \( X \times n \) Gbps. When \( m \) \((m < n)\) optical modules fail, \( X \times (n - m) \) Gbps of client traffic is continuously transmitted using available optical modules, while the rest is discarded.

In the Polishing scheme, unavailability, where more than \( X \times m \) Gbps are discarded, is the probability that more than \( m \) sub-carriers are unavailable. This probability is formulated with the following equation.
\[ P_{\text{polishing}}(\frac{m}{n}) = \sum_{i=m}^{n} a_i \cdot (1 - (1 - \alpha)^2)^i \cdot ((1 - \alpha)^{n-i} \cdot (1 - \alpha_F)^2 + (1 - (1 - \alpha_F)^2) \quad (2) \]

Fig. 2(b) illustrates the Pool scheme. This scheme uses additional \( \Delta n \) shared backup optical modules in addition to \( n \) working optical modules to transmit client traffic at \( X \times n \) Gbps. When the optical module \( i \) fails at one side of a pair of transponders, all client traffic is transmitted continuously by assigning the signal that is originally assigned to optical module \( i \) to one of the shared backup optical modules in the transponder. Note that all client traffic is discarded if \( \Delta n + 1 \) optical modules fail at either side of a pair of transponders. Several detailed schemes of the Pool scheme have been proposed by Tanaka et al. [2] and Hirano et al. [3].

In the Pool scheme, unavailability is formulated with the following equation.

\[ P_{\text{pool}} = 1 - \left( \sum_{i=0}^{\Delta n} a_i \cdot (1 - \alpha)^{i+\Delta n-i} \cdot (1 - \alpha_F)^2 \right)^2 \quad (3) \]

### 4 Analysis on effectiveness and difficulty in transmission system development

First, we evaluated availability. In the evaluation, \( n, \Delta n, \text{MTBF}, \) and \( \text{MTTR} \) were set to 5, 1, 20,000 hours, and 2 hours, respectively. We first focused on failure of optical modules, and we set \( \alpha_F \) at 0. Fig. 3(a) shows the number of optical modules and unavailability. The horizontal broken lines show unavailability for a single carrier \( (n = 1) \). In the case of non-redundant mode, unavailability for Normal becomes higher than that for a single carrier. Fig. 3(b) shows the scale of failure, which is defined by \( m/n \) as described in Eq. (2), and unavailability. With the Polishing scheme, unavailability varies in accordance with the scale of failure. In Fig. 3(a), the possible range of unavailability with the Polishing scheme is shown with a red arrow. Unavailability for small failure \( (m/n = 1/5) \), where one of optical modules in a transponder fails, remains as high as that for Normal and becomes higher than that for a single carrier, while unavailability for large failure decreases greatly since multiple failure scarcely happens. For these reasons, improvement in availability with the Polishing scheme is limited. In contrast, with the Pool scheme, unavailability decreases drastically and remains significantly lower than that for a single carrier, though the number of optical modules increases slightly due to additional shared backup. Fig. 3(c) shows unavailability and the ratio of framer’s MTBF to optical module’s MTBF. Regardless of the ratio of framer’s MTBF to optical module’s MTBF, with the Pool scheme, unavailability decreases almost constantly compared to other schemes. Due to the limitation of space, although we showed results only for 5 sub-carriers, with the Pool scheme, unavailability decreases, regardless of the number of sub-carriers. Note that the trend in availability in the case of redundant mode is the same as that in the case of non-redundant mode.

We then discuss difficulty in transmission system development. In the recommendation ITU-T G.709, a client signal is mapped into an ODU. This ODU signal
is mapped into an OTU. Since an OTU can accommodate multiple ODU signals, we consider two cases: (1) client traffic is transmitted at $X \times n$ Gbps using an ODU, and an OTU accommodates the only one ODU signal (single ODU case), (2) multiple groups of client traffic, each of which is transmitted at less than or equal to $X$ Gbps, are transmitted using their dedicated ODUs, and an OTU accommodates multiple ODU signals (multiple ODU case). For the Polishing scheme, in the single ODU case, the establishment of operations, administration, and maintenance (OAM) and alarm transfer methods for variable bandwidth links are required. In addition, the management of traffic priority and the functionality to distribute traffic based on the priority considering the structure of data packets accommodated in the payload of the traffic are also required to select some client traffic to discard in the case of failure. In the multiple ODU case, the management of the priority of ODU signals and the functionality to re-assign ODU signals are still required to select some ODU signals to discard in the case of failure, although the management of the traffic priority considering the structure of data packets is no longer required.

In contrast, the Pool scheme requires only the implementation of the functionality to switch over from the failed optical module to the shared backup optical module regardless of the above-mentioned cases.

As a result, the Pool scheme is promising to improve availability of multi-carrier transmission systems since the scheme effectively increases availability with a small amount of additional optical modules and has enough feasibility.

![Graphs showing availability and number of optical modules, availability and failure scale, and availability and ratio of framer's MTBF to optical module's MTBF](https://example.com/graphs.png)

**Fig. 3.** Numerical example

### 5 Conclusion

In multi-carrier transmission systems, availability of a transponder decreases in accordance with the increase in the number of optical modules comprising the
transponder. In this paper, to clarify the promising schemes of improving availability, we comprehensively compared them based on the trend in availability and difficulty in transmission system development. As a result, we showed that the Pool scheme is promising since it increases availability more than that for a single carrier with only one additional shared backup optical module in each transponder and has enough feasibility.