Monitoring of Linearly Accumulated Optical Impairments in All-Optical Networks

Siu-Ting Ho and Lian-Kuan Chen

***Abstract*—Optical performance monitoring covers a very wide range of measurements intended to help ensure network performance and is essential for service providers. We address the problem of solving the linearly accumulated end-to-end impairments of a special set of paths of interest in a reconfigurable all-optical network. This set of paths of interest may include all the paths between any two communicating nodes. The main focus is on the minimization of the number of monitoring devices that are required. A set of channels is injected into the network and monitored. By using the correlation in the channel quality between injected channels, a framework of algebraic performance monitoring is proposed to derive the channel quality of the paths of interest from the linear combination of the monitoring results of the injected channel. The upper bounds on the minimum number of monitoring devices required are derived and constructively achieved for a general network. For a special network in which all nodes are capable of initiating and dropping the monitoring channels, the fundamental limit on the minimum number of monitoring devices is also achieved. The proposed monitoring scheme for this kind of network can also locate at least one fault, even if multiple faults occur. We reduce the cost of monitoring by utilizing the information from the monitoring results and minimizing the number of monitoring devices.**

***Index Terms*—All-optical networks; Fiber optics communications; Networks; Optical communications**.

I. Introduction

Optical performance monitoring (OPM) covers a very wide range of measurements intended to help ensure network performance. It is used for various applications, including signal quality characterization, fault management, active compensation, and quality of service provisioning. All-optical reconfigurable mesh networks impose great challenges on OPM because of the signal transparency and nonstatic configuration for different channels. Optical signals propagate through an all-optical network without optical-electrical-optical conversions at intermediate nodes. Thus, noise and signal distortions accumulate along the entire channel paths. Monitoring devices are usually installed to monitor the degraded signal and feed back the results of monitoring for adaptive impairment compensation. Many promising OPM techniques [1–4] for different kinds of impairments have been proposed, such as optical signal-to-noise ratio (OSNR) monitoring [5–9], chromatic dispersion (CD) monitoring [10–12], and polarization mode dispersion (PMD) monitoring [13,14]. On the other hand, data channels are set up and torn off dynamically in a reconfigurable network. It will be beneficial to optical network management that the quality of the data channels can be estimated before they are established. This provides some network management functions, such as channel setup, control, and optimization. With this prior performance information, network operators can estimate the quality of different channel paths and regard it as a metric for path computation in the network layer [15]. However, it is impractical to measure the performance of all possible paths individually to obtain this prior performance information because the connectivity of the modern backbone network is high to provide high fault tolerance, and the number of possible paths between any two communicating nodes is large. It is of great interest to network operators to find an efficient way of estimating the end-to-end quality of the paths without probing them individually. At the same time, the number of monitoring devices should be small in order to minimize the cost of monitoring.

A novel efficient algebraic approach is proposed here to derive the linearly accumulated end-to-end impairment of a special set of paths. This set of paths of interest may include all the paths between any two communicating nodes. In the proposed approach, a set of channels, called "probing channels," are generated

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by probing modules and are injected into the network. Their accumulated impairments are measured by the monitoring devices, called "monitoring modules," and the results of monitoring are used to derive the linearly accumulated impairments of the paths of interest. The paths of interest and the paths of probing channels may not be the same. This study focuses on the minimization of the number of monitoring modules that are necessary to monitor all the paths of interest. The upper bounds on the minimum number of monitoring modules required are derived for a general network, and the corresponding monitoring scheme is proposed. For a special network in which all nodes are capable of initiating and dropping (not necessarily of monitoring) the probing channels, a monitoring scheme that achieves the fundamental limit on the minimum number of monitoring modules is also introduced. The monitoring scheme proposed for this kind of network is also applicable for fault localization in a network. At least one fault can be located, even if multiple faults occur, when the proposed monitoring scheme is applied.

The paper is organized as follows: the network model and the mathematical formulation are presented in Section II. Section III discusses the proposed monitoring schemes for the networks with and without nodes that can only route channels. Section IV discusses the fault localization ability of the probing scheme proposed in Section III. Section V concludes this paper. The proofs of two main theorems are given in Appendix A, and examples are given to illustrate the theorems.

II. Network Model and Problem Formulation

A. Network Model

The network is modeled as an undirected graph G with the total number of links L. The terms "graph" and "network" are used interchangeably hereafter. No link connects a node to itself, but multiple links between nodes are allowed. Every link consists of a pair of fiber links that carry traffic for the two opposite directions. It is assumed that any traffic path cannot traverse the same link twice. Every node is classified into two kinds: "terminal" and "routing." Both kinds of node can route channels, including both data and probing channels, from the incoming ports to the outgoing ports. However, only terminal nodes can initiate and drop the channels, while routing nodes cannot. Therefore, any communicating node is assumed to be a terminal node. For example, an optical add–drop multiplexer can be regarded as a terminal node, whereas an amplifier can be regarded as a routing node. When a probing module or a monitoring module is installed at a node, the ways of installation are summarized in the following table. When a monitoring module is installed in a routing node, the probing channels monitored at the node are not dropped; they continue to propagate until they meet a terminal node to drop them.

How is a module installed at a node?	**Terminal node (e.g., an add-multiplexer)**	**Routing node (e.g., an amplifier)**
Probing module (e.g., a light source)	**YES**: attached to the add-port to inject the probing channels to the network.	**NO:** installing a probing module at a routing node is NOT allowed.
Monitoring module (e.g., an OSNR monitor)	**YES**: attached to the drop-port to monitor and terminate the probing channels.	**YES:** probing channels are tapped off by a coupler to the monitoring module.

Networks are classified into two kinds according to the existence of a routing node. The discussions in Section III are divided into two parts accordingly, one on the general networks with routing nodes and one on the special case of networks without routing nodes.

The paper considers a generic impairment that accumulates additively in the reconfigurable all-optical network. The impairment is assumed to be induced in the links. Any impairment induced in the incoming port or outgoing port of a node is aggregated to the corresponding link impairment. Thus, node impairment is not considered. Since two separate sets of optical devices are used for the two opposite directions along the link, the impairments induced in these two directions are assumed to be independent. Two impairment variables are assigned to each link to represent the impairment levels induced in both directions. There are a total of $2L$ impairment variables, labeled x_j for $j \in [1, 2L]$. Designate l_j as the link associated with the impairment variable x_j. Thus the accumulated impairment of a path p is expressed as follows:

$$\text{accumulated impairment of a path } p = \sum_{l_i \text{ is a link in } p} x_i. \tag{1}$$

For example, the noise figure, CD per unit spectral width, and the square of the PMD can be modeled, respectively, as follows.

The OSNR is a significant indicator for optical noise; the accumulated noise figure $\mathrm{NF}_{\mathrm{acc}}$ along the channel path with k hops can be expressed as [16]

$$\mathrm{NF}_{\mathrm{acc}} = \mathrm{NF}_1 + \frac{\mathrm{NF}_2}{G_2} + \frac{\mathrm{NF}_3}{G_3} + \cdots + \frac{\mathrm{NF}_k}{G_k},$$

where NF_i is the individual noise figure of the ith hop, for $i \in [i,k]$. All noise figures NF_i and $\mathrm{NF}_{\mathrm{acc}}$ are expressed in log scale. The variable G_i is the cumulative gain up to the ith hop. If each hop is fully compensated, i.e., all $G_i = 1$, the accumulated noise figure $\mathrm{NF}_{\mathrm{acc}}$ can be expressed as a sum of noise figures in each hop:

$$\mathrm{NF}_{\mathrm{acc}} = \mathrm{NF}_1 + \mathrm{NF}_2 + \mathrm{NF}_3 + \cdots + \mathrm{NF}_k.$$

The CD in single-mode fiber is equal to the product of the dispersion parameter, the path length, and the spectral width of the light source, i.e., $\Delta T_{\mathrm{CD}} = DL\Delta\lambda$, where ΔT_{CD} is the CD, D is the dispersion parameter in picoseconds per nanometer per kilometer, L is the length of the path in kilometers, and $\Delta\lambda$ is the spectral width of the light source in nanometers. Assume that the nonlinear effects of the fiber are negligible. The spectral width is expected to be constant along the path; thus the accumulated CD per unit spectral width $\Delta T_{\mathrm{CD}}/\Delta\lambda$ (in picoseconds per nanometer) along the channel path with k hops can be expressed as the sum of the CD per unit spectral width $\Delta T_i/\Delta\lambda$ (in picoseconds per nanometer), for $i \in [i,k]$, in each hop:

$$\Delta T_{\mathrm{CD}}/\Delta\lambda = (\Delta T_1 + \Delta T_2 + \Delta T_3 + \cdots + \Delta T_k)/\Delta\lambda.$$

The statistical mean of the accumulated PMD along a path is a root-mean-square of the sum of the PMD along the path. Thus, the square of the accumulated PMD of a path, $\mathrm{PMD}^2_{\mathrm{acc}}$, is the sum of the square of the PMD in each fiber hop, $(\mathrm{PMD}_{\mathrm{fiber}})^2$, and the square of the PMD in each component, $(\mathrm{PMD}_{\mathrm{component}})^2$, along the path:

$$\mathrm{PMD}^2_{\mathrm{acc}} = \sum \mathrm{PMD}^2_{\mathrm{fiber}} + \sum \mathrm{PMD}^2_{\mathrm{component}}.$$

In this case, take PMD^2 as the impairment variable x_i in Eq. (1). The squares of the PMD induced in the components are aggregated in the square of the PMD of the links.

Let the impairment variable x'_j be the alias of the impairment variable for the direction opposite that of x_j; i.e., two impairment variables x_j and x'_j are assigned to the same link for the two opposite directions. When the link is denoted l'_j (l_j), it means that the link is propagated through in the direction with impairment variable x'_j (x_j). As an example, Fig. 1 depicts an exemplifying network that consists of $L=5$ links. There are a total of 10 impairment variables assigned to the 5 links, labeled from x_1 to x_{10}. The impairment variables x_1 and x_2 refer to the same link but indicate the impairment level in both directions. The alias of x_1 is x'_2, and the alias of x_2 is x'_1. The link from node a to node b is l_1, and the reverse link is l'_1 or is denoted l_2. Similarly, the alias of x_3 is x'_4, and the reverse link of l_3 is $l'_3 = l_4$, etc. In the rest of the paper, the prime is regarded as a reverse operator, i.e., path p' is the reverse of path p.

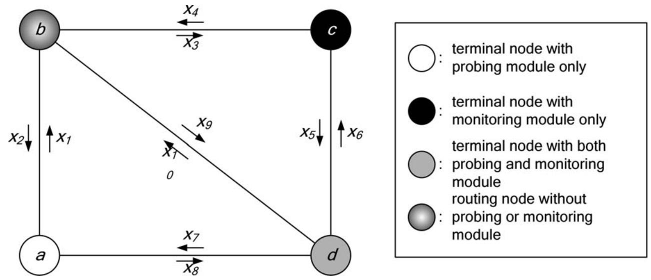

Fig. 1. Sample network for the illustration of the terminology in the paper.

Network operators specify the paths whose linearly accumulated end-to-end impairments are going to be derived. Let this set of paths of interest be Q. Three assumptions are made for Q:

Assumption 1. The set Q is assumed to contain at least a path connecting each ordered pair of any two terminal nodes. The assumption comes from the fact that network operators are interested in the end-to-end communications quality between any two communicating nodes.

Assumption 2. If the two terminal nodes in the pair are adjacent, the incident links between them must be in Q. This is because the links between two adjacent terminal nodes are the most direct paths connecting these two nodes.

Assumption 3. Any path of interest should be a subpath of a path connecting two terminal nodes. A path that can never be a subpath of a data channel path is, of course, not of interest. In practice, this assumption is always satisfied, as routing nodes are the intermediate nodes to some destined terminal nodes.

It is worth noting that the paths of interest and the paths of probing channels may not be the same. According to the level of network monitoring requirement, it is possible to include all possible paths between any ordered pair of terminal nodes in Q. For example, suppose the accumulated impairment of all possible paths between the two terminal nodes in Fig. 1 has to be derived. The set Q of paths contains 12 paths of interest:

$$q_1 : a \to b \to c,$$

$$q_2 : c \to b \to a,$$

$$q_3 : a \to b \to d \to c,$$

$$q_4 : c \to d \to b \to a,$$

$$q_5 : a \to d \to b \to c,$$

$$q_6{:}c \to b \to d \to a,$$

$$q_7{:}a \to d \to c,$$

$$q_8{:}c \to d \to a,$$

$$q_9{:}a \to d,$$

$$q_{10}{:}d \to a,$$

$$q_{11}{:}c \to d,$$

$$q_{12}{:}d \to c.$$

In order to retrieve the accumulated impairment of the paths in Q, a set of channels, called "probing channels," are injected for monitoring. The accumulated impairments of these probing channels are measured, and the results are used to derive the accumulated impairment of the paths in Q algebraically. The paths of the probing channels are not freely defined unless they fulfill the following three conditions:

Condition 1. Probing channels should be originated and terminated at terminal nodes.

Condition 2. The source nodes of the probing channels should be installed with probing modules in order to generate the probing channels.

Condition 3. The probing channels should propagate through or be terminated at a node with a monitoring module so that it can be monitored.

Note that the paths of probing channels may not be the same as the paths of interest, and the paths of interest may not satisfy the above conditions. For example, one possible set of paths of probing channels for the example in Fig. 1 is

$$p_1{:}a \to b \to c,$$

$$p_2{:}d \to c,$$

$$p_3{:}a \to d,$$

$$p_4{:}a \to b \to d,$$

$$p_5{:}d \to b \to a \to d,$$

$$p_6{:}d \to b \to c,$$

$$p_7{:}d \to c \to b \to d,$$

$$p_8{:}a \to b \to c \to d,$$

$$p_9{:}d \to a \to b \to c.$$

Each probing channel is assigned a unique index. Probing modules can generate multiple probing channels with different indices; meanwhile, monitoring modules can monitor and identify all probing channels that propagate through or terminate at them. The OPM results in that the monitoring modules, together with the corresponding indices, are assumed to be collected to a monitoring center through a separate error-free network. The monitoring center stores the paths of each probing channel and processes performance information from the monitoring modules to derive the accumulated impairment of the path of interest.

B. Mathematical Formulation

The accumulated impairment, denoted z_i, of the path q_i in $\boldsymbol{Q}$ can be expressed by $z_i = \mathrm{init}(q_i) + \Sigma_{\{j:l_j \in q_i\}} x_j$, where $\mathrm{init}(z_i)$ is the initial impairment of q_i induced in the transmitter module and is expected to be known from the module specification. The accumulated impairments of all q_i in $\boldsymbol{Q}$ can be expressed in matrix form: $z - \mathrm{init}(z) = \boldsymbol{Zx}$ where $z = [z_1 z_2 z_3 \ldots z_{|Q|}]^{\mathrm{T}}$ and $\mathrm{init}(z) = [\mathrm{init}(q_1)\mathrm{init}(q_2)\mathrm{init}(q_3)\ldots\mathrm{init}(q_{|Q|})]^{\mathrm{T}}$. The matrix $\boldsymbol{Z}$ is $|Q| \times 2L$ matrix with entry $m_{ij} = 1$ if q_i contains the link l_j; otherwise, $m_{ij} = 0$ and $x = [x_1 x_2 x_3 \ldots x_{2L}]^{\mathrm{T}}$. On the other hand, the ith probing channel gives a linear equation, $y_i = \mathrm{init}(p_i) + \Sigma_{\{j:l_j \in p_i\}} x_j$, where p_i is the subpath, from the originating node to the node at which the probing channel is monitored, of the ith probing channel; $\mathrm{init}(p_i)$ is the initial impairment of p_i induced in the transmitter module; and y_i is the OPM result. Let P denote the set of all these subpaths of probing channels; then $\boldsymbol{y} - \mathrm{init}(\boldsymbol{y}) = \boldsymbol{Yx}$, where $y = [y_1 y_2 y_3 \ldots y_{|P|}]^{\mathrm{T}}$and $\mathrm{init}(\boldsymbol{y}) = [\mathrm{init}(p_1)\mathrm{init}(p_2)\mathrm{init}(p_3)\ldots\mathrm{init}(p_{|p|})]^{\mathrm{T}}$. The matrix $\boldsymbol{Y}$ is a $|P| \times 2L$ matrix with entry $n_{ij} = 1$ if p_i contains the link l_j; otherwise, $n_{ij} = 0$. In order to simplify the notation, all $\mathrm{init}(q_i)$ and $\mathrm{init}(p_i)$ are assumed to be 0 throughout the paper.

Let $\langle \boldsymbol{M} \rangle$ be the space spanned by the row vectors of any matrix $\boldsymbol{M}$. When $\langle \boldsymbol{Y} \rangle \supseteq \langle \boldsymbol{Z} \rangle$, there is a $|Q| \times |P|$ matrix $\boldsymbol{K}$ such that $\boldsymbol{Z} = \boldsymbol{KY}$. The entries in the matrix $\boldsymbol{K}$ are the coefficients used in generating the row vectors in $\boldsymbol{Z}$ from the row vectors in $\boldsymbol{Y}$, and they can be solved by Gaussian elimination. Then $z = \boldsymbol{Zx} = \boldsymbol{KYx} = \boldsymbol{y}$. Thus, the paper aims at finding a valid set of probing channels that satisfies the three conditions in the network model part such that $\langle \boldsymbol{Y} \rangle \supseteq \langle \boldsymbol{Z} \rangle$. In view of this, the number of probing channels is lower bounded by the rank of $\boldsymbol{Z}$ and upper bounded by $2L$. The vector space spanned $\boldsymbol{Y}$ is determined by the locations of probing modules, monitoring modules, and probing channel paths. Let N_p be the set of nodes that are installed with probing modules, and N_m be the set of nodes installed with monitoring modules. A probing scheme exists if there is a collection of the set N_p, N_m, and P such that $\langle \boldsymbol{Y} \rangle \supseteq \langle \boldsymbol{Z} \rangle$. The corresponding set P is sometimes referred to as the probing scheme for simplicity.

Example. The corresponding matrix $\boldsymbol{Z}$ of the set Q in the previous example for Fig. 1 is a 12×10 matrix:

$$Z = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

Although the total number of paths needed is 12 and the total number of links is 10, the rank of the matrix is only 9. To solve the accumulated impairments, it is not necessary to solve all (total of 10) impairment variables. It is possible to solve all the accumulated impairments of all possible paths between terminal nodes by using only nine probing channels. This is achieved by the set of probing channels stated in the previous example. The corresponding matrix $\boldsymbol{Y}$ is a 9×10 matrix. $\langle \boldsymbol{Y} \rangle = \langle \boldsymbol{Z} \rangle$:

$$Y = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}.$$

III. Probing Scheme

This section constructively proves the existence of probing schemes by properly choosing the locations of probing and monitoring modules. First a necessary condition for the locations of probing and monitoring modules is provided in Theorem 1 such that a probing scheme exists. This necessary condition is assumed to be fulfilled in the proofs of the following Theorem 2 and Theorem 3. The corresponding sufficient condition is stated in Theorem 2. The number of monitoring modules required in the sufficient condition in Theorem 2 is highly related to the existence of a cut node, where a cut node is a node whose removal disconnects the remaining network. Implicitly, the fewer cut nodes there are, the fewer monitoring modules are required. In the special of case of a network without routing nodes, a less restrictive sufficient condition is stated in Theorem 3. Similar to Theorem 2, the sufficient condition is related to the existence of a bridge, where a bridge is a link whose removal disconnects the remaining network. The fewer bridges there are, the fewer monitoring modules are required. Fortunately, the optical backbone networks are usually highly connected mesh networks in order to provide fault-tolerant service. For example, the National Science Foundation (NSF) backbone network (Fig. 2) is a two-node-connected network without a cut node or bridge. Thus the number of monitoring modules needed in both Theorem 2 and Theorem 3 is small.

Theorem 1 states a necessary condition for the sets N_p and N_m such that a probing scheme exists. The proof is by contradiction. It considers a node that is a source node or a destination node of the paths of interest. If the node is out of $N_p \cup N_m$, all probing channels should route through the node without monitoring. Thus, either none or an even number of impairment variables associated with the incident links of the node are involved in the row vectors in matrix $\boldsymbol{Y}$. This restricts the vector space spanned by $\boldsymbol{Y}$ and eventually leads to the contradiction $\langle \boldsymbol{Y} \rangle \supseteq \langle \boldsymbol{Z} \rangle$.

Theorem 1. Let $\mathrm{src}(p)$ and $\mathrm{dst}(p)$ denote the originating node and terminating node of any path p, respectively. Let N denote the set $\mathrm{src}(Q) \cup \mathrm{dst}(Q)$. If a probing scheme exists, all nodes in the set $N \subseteq N_P \cup N_m$.

Proof. The theorem is proved by contradiction. Let $J \subseteq [1, 2L]$ be an index set. For any matrix $\boldsymbol{M}$ with $2L$ column vectors, denote $\boldsymbol{M}|_J$ as a matrix such that the jth column vector of $\boldsymbol{M}|_J$ equals the jth column vector of $\boldsymbol{M}$ if $j \in J$. All other column vectors in $\boldsymbol{M}|_J$ are zero vectors. The existence of a probing scheme implies $\langle \boldsymbol{Y} \rangle \supseteq \langle \boldsymbol{Z} \rangle$. Consider a row vector u in $\boldsymbol{Z}$ such that $u = k_1 v_1 + k_2 v_2 + \ldots + k_{|\mathbf{Y}|} v_{|\mathbf{Y}|}$, where v_i is the ith row vector in $\boldsymbol{Y}$ for all $1 \leqslant i \leqslant |\boldsymbol{Y}|$. For all $k \notin J$, masking all the kth components of all the vectors in the equation to zero keeps the equality. Thus $\langle \boldsymbol{Y}|_J \rangle \supseteq \langle \boldsymbol{Z}|_J \rangle$. The proof is divided into three cases for any node $n \in N$ with different degrees d.

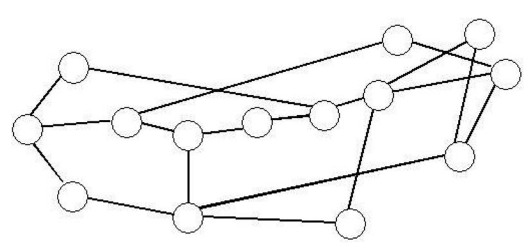

Fig. 2. The National Science Foundation (NSF) backbone network is a two-node-connected network without cut nodes and bridges.

Case 1: $d=1$. The node n should be a terminal node; otherwise, it is a redundant node, as there is no data channel route through it. Let the impairment variables assigned to the only incident link be x_1 and x_2. In order to derive x_1 and x_2, n should be the originating node and the terminating node for at least one probing channel. Therefore, it should be in $N_p \cap N_m$.

Case 2: $d=2$. Refer to Fig. 3(a). Without loss of generality, let $\{x_1,x_3\}$ and $\{x_2,x_4\}$ be the impairment variables for the two incident links, where $\mathrm{dst}(l_1)=\mathrm{dst}(l_2)=n=\mathrm{src}(l_3)=\mathrm{src}(l_4)$. Let $J=[1,4]$. Suppose $n \notin N_P \cup N_m$. The only two possible nonzero row vectors in $\boldsymbol{Y}|_J$ are [1 0 0 1 0…0] and [0 1 1 0 0…0]. In contrast, [1 0 0 0 0…0], [0 1 0 0 0…0], [0 0 1 0 0…0], or [0 0 0 1 0…0] is one of the row vectors in $\boldsymbol{Z}|_J$ by the definition of N. This contradicts $\langle \boldsymbol{Y}|_J \rangle \supseteq \langle \boldsymbol{Z}|_J \rangle$.

Case 3: $d \geqslant 3$. Let $\{x_j,x_{d+j}\}$, $j \in [1,d]$, be the impairment variables for the jth incident link of n such that $\mathrm{dst}(l_1)=\mathrm{dst}(l_2)=\mathrm{dst}(l_3)=\ldots=\mathrm{dst}(l_d)=n=\mathrm{src}(l_{d+1})=\mathrm{src}(l_{d+2})=\mathrm{src}(l_{d+3})=\ldots=\mathrm{src}(l_{2d})$. Figure 3(b) shows the case of $d=4$. Let $J=[1,2d]$. Similar to Case 2, suppose $n \notin N_P \cup N_m$. Assume that the ith probing channel propagates through n from the first link to the $(i+1)$th link for $i \in [1,d-1]$, the $(d+i-1)$th probing channel propagates through n from the $(i+1)$th link to the first link for $i \in [1,d-1]$, and the $(2d-1)$th probing channel propagates through n from the rth link to the sth link for some $r \neq 1$ and some $s \neq 1$. Let $\boldsymbol{w}_i$ be the ith row vector of $\boldsymbol{Y}|_J$ and $\boldsymbol{w}=-\boldsymbol{w}_{s-1}-\boldsymbol{w}_{d+r-2}+\boldsymbol{w}_{2d-1}$. Note that $\boldsymbol{w}$ is a $1 \times 2L$ row vector with only the first and $(d+1)$th components equal to -1 and others equal to 0. Suppose the $2d$th probing channel propagates through n from the gth incident link to the hth incident link. If $g=1$ or $h=1$, $\boldsymbol{w}_{2d} \in \{\boldsymbol{w}_1,\boldsymbol{w}_2,\boldsymbol{w}_3,\ldots,\boldsymbol{w}_{2d-1}\}$; otherwise, $\boldsymbol{w}_{2d}=\boldsymbol{w}_{d+g-2}+\boldsymbol{w}_{h-1}+\boldsymbol{w}$. Therefore, the rank of $\boldsymbol{Y}|_J \leqslant 2d-1$ if no probing channel is originated or terminated at node n. Let $\boldsymbol{e}_k$ denote the $1 \times 2L$ row vectors with only the kth component equal to 1 and all other components equal to 0. The matrix $\boldsymbol{Z}|_J$ should contain a row vector $\boldsymbol{e}_k$ for some $1 \leqslant k \leqslant 2d$ by the definition of N. Suppose $k \leqslant d$; then $\boldsymbol{e}_{d+1}=w_{d+k-2}-\boldsymbol{e}_k$ and $\boldsymbol{e}_1=-\boldsymbol{e}_{d+1}-\boldsymbol{w}$. In contrast, suppose $k \geqslant d+1$; then $\boldsymbol{e}_1=\boldsymbol{w}_{k-d-1}-\boldsymbol{e}_k$ and $\boldsymbol{e}_{d+1}=-\boldsymbol{e}_1-\boldsymbol{w}$. In both cases, $\boldsymbol{e}_j=\boldsymbol{w}_{d+j-2}-\boldsymbol{e}_{d+1}$ and $\boldsymbol{e}_{d+j}=\boldsymbol{w}_{j-1}-\boldsymbol{e}_1$ for $2 \leqslant j \leqslant d$, which implies that the rank of $\{\boldsymbol{w}_1,\boldsymbol{w}_2,\boldsymbol{w}_3,\ldots,\boldsymbol{w}_{2d-1},\boldsymbol{e}_k\}=2d > 2d-1 \geqslant$ rank of $\boldsymbol{Y}|_J$. Thus, the row vector $\boldsymbol{e}_k \notin \langle \boldsymbol{Y}|_J \rangle$, which contradicts $\langle \boldsymbol{Y}|_J \rangle \supseteq \langle \boldsymbol{Z}|_J \rangle$. The theorem is proved.

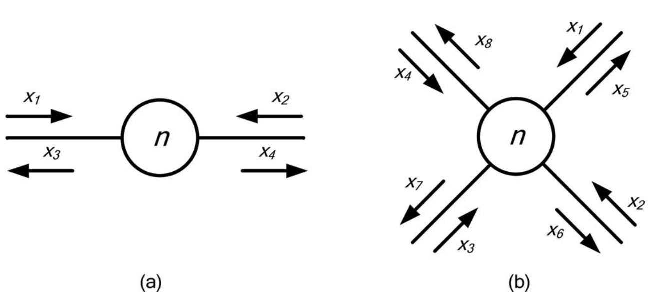

Fig. 3. (a) Impairment variables for a node with degree 2. (b) Impairment variables for a node with degree $d=4$.

The following lemma states a sufficient condition for N_p and N_m such that the accumulated impairment of a path of interest q can be derived from a linear combination of the OPM results of a few probing channels. The existence of the probing schemes stated in Theorem 2 and Theorem 3 is proved by choosing N_p and N_m appropriately so that the sufficient condition in Lemma 1 is satisfied.

Lemma 1. Let the operator + denote the concatenation operator of paths. Consider a path $p=p_m+p_t$ such that p_m contains a subpath q, while $\mathrm{src}(p_m) \in N_p$, $\mathrm{dst}(p_m) \in N_m$, and $\mathrm{dst}(p_t)$ is a terminal node. If both $\mathrm{src}(q)$ and $\mathrm{dst}(q)$ are elements of $N_p \cup N_m$, there exist a set of probing channels along the subpaths of p such that the linear combination of their monitoring results derives the accumulated impairment of the path q.

Proof. According to the property of $\mathrm{src}(q)$ and $\mathrm{dst}(q)$, the proof can be divided into four cases:

Case 1: Both $\mathrm{src}(q)$ and $\mathrm{dst}(q)$ are elements of N_p. In this case, $\mathrm{src}(q)=\mathrm{src}(p_m)$.

Case 2: Both $\mathrm{src}(q)$ and $\mathrm{dst}(q)$ are elements of N_m. In this case, $\mathrm{dst}(q)=\mathrm{dst}(p_m)$.

Case 3: The node $\mathrm{src}(q) \in N_p$ and $\mathrm{dst}(q) \in N_m$. In this case, the path $q=p_{\mathrm{m}}$.

Case 4: The node $\mathrm{src}(q) \in N_m$ and $\mathrm{dst}(q) \in N_p$.

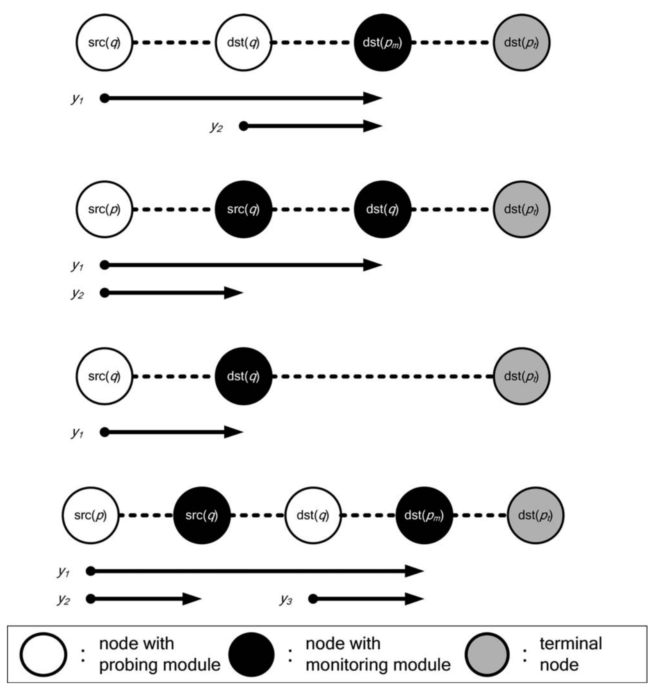

Fig. 4. Probing channels for four cases.

Refer to Fig. 4; the accumulated impairment of the path q can be solved by

Case 1: $z = y_1 - y_2$.

Case 2: $z = y_1 - y_2$.

Case 3: $z = y_1$.

Case 4: $z = y_1 - y_2 - y_3$.

The dotted lines in the figure represent the subpaths between nodes. The subpaths between the node $\mathrm{dst}(p_m)$ and the node $\mathrm{dst}(p_t)$ can be a null path if $\mathrm{dst}(p_m)$ is a terminal node. The terminal node $\mathrm{dst}(p_t)$ is used to terminate the probing channels only if the nodes at which the probing channels are monitored cannot terminate them, i.e., if the nodes are routing nodes. This proof is complete.

A. General Networks With Routing Nodes

1) Network Transformation: Recall that N is the set $\mathrm{src}(Q) \cup \mathrm{dst}(Q)$. Any path in Q can always be divided into subpaths at every node in N. According to this division, if the segment contains only a single link, both end nodes of the link are in N. This kind of segment is called a "short segment." If the segment contains multiple links, the originating node and the terminating node of the segment are in N, while all intermediate nodes are out of N. This kind of segment is called a "long segment." To derive the accumulated impairment of the paths in Q, it suffices to derive the accumulated impairment of all short segments and long segments. Again, the necessary condition stated in Theorem 1 is assumed to be fulfilled. To facilitate the analysis, the network G is contracted and then decomposed into maximal two-node-connected networks. The details of contraction and decomposition are discussed in the following.

Contraction of link between a node in N and a node out of N. All links in the network G can be classified into three kinds: both end nodes are in N, both end nodes are out of N, and exactly one of the end nodes is in N while the other is out of N. Here "contraction" means the contraction of links of the second kind: both end nodes are out of N.

Refer to Fig. 5. Note that, by contraction, all the short segments are kept unchanged, while the long segments are contracted to two-hop paths. In each of these two-hop paths, both end nodes are nodes in N. The middle node is obtained by contracting all the intermediate nodes of the long segment. This middle node is called a "supernode." The set of supernodes is denoted S. Since there is at least a path between any ordered pair of terminal nodes in Q, the set N contains all terminal nodes, and thus no terminal node is contracted into a supernode in S. If multiple long segments have intermediate nodes in common, all the intermediate nodes of these long segments are contracted into one supernode. The contraction certainly hides the complex topology among the intermediate nodes. This simplification does not negate Theorem 2 below, as a probing scheme on this contracted network implies a probing scheme in the original network. This will be discussed after the theorem is introduced.

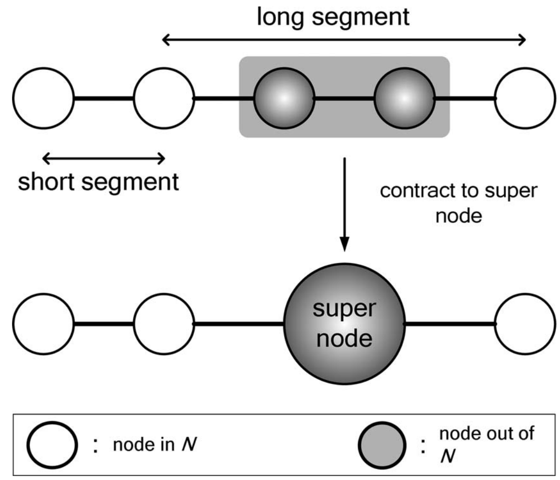

Fig. 5. Contraction of link between nodes out of N. A short segment is a link between nodes in N. A long segment is the segment that contains multiple links, and the originating node and the terminating node of the segment are in N, while all intermediate nodes are out of N. The middle nodes in the long segment are contracted into a supernode; thus the long segment becomes a two-hop path after contraction.

Decomposition into maximal two-node-connected subnetworks. A two-node-connected network is a network without a cut node. A single-node or a single-link network is a two-node-connected network by definition. A two-node-connected network is "proper" if it is not a single-node or single-link network, otherwise it is "improper." Any network can be uniquely decomposed into maximal two-node-connected subnetworks by the equivalent relation in Proposition 1 below. The proof is based mainly on the fact that if two two-node-connected networks have more than a node in common, the union of these two network forms a larger two-node-connected network. Moreover, by Proposition 2, a node is a cut node if and only if it belongs to multiple maximal two-node-connected subnetworks. Both directions of the proof are by contradiction.

Proposition 1. Define $l_a \sim l_b$ if and only if there is a two-node-connected subnetwork containing both link l_a and l_b. The relation "$\sim$" in the link set is a well-defined equivalence relation. Since the equivalence relation above induces a partitioning on the set of links, the two-node-connection subnetwork induced by a partition of links is maximal.

Proof. Since every link, together with its end nodes, defines a two-node-connected network, the reflectivity $l_a \sim l_a$ is fulfilled. Obviously, the symmetry $l_a \sim l_b \Rightarrow l_b$

$\sim l_a$ is naturally satisfied. In order to show that the equivalence relation is well defined, the transitivity $l_a \sim l_b$ and $l_b \sim l_c \Rightarrow l_a \sim l_c$ has to be shown for any links l_a, l_b, and l_c.

Let O_a be the two-node-connected subnetwork that contains links l_a and l_b. Similarly, let O_c be the two-node-connected subnetwork that contains links l_c and l_b. Thus O_a and O_c have two nodes, src(l_b) and dst(l_b), in common. The subnetwork $O_a \cup O_c$ is the two-node-connected network that contains both links l_a and l_c. Therefore, the equivalence relation is well defined.

Proposition 2. According the equivalent relation in Proposition 1, decompose the network into maximal two-node-connected subnetworks. A node is a cut node if and only if it belongs to multiple maximal two-node-connected subnetworks.

Proof. Let n be a cut node in the network G. Each adjacent node of n, together with n and the link between, forms a two-node-connected network. If all the adjacent nodes of n belong to the same two-node-connected subnetwork, these adjacent nodes are still connected even if the node n is removed. This contradicts that n is a cut node. Therefore, any cut node belongs to multiple maximal two-node-connected subnetworks.

On the other hand, suppose n is not a cut node but belongs to two maximal two-node-connected subnetworks. The node n should be the only node in common; otherwise, the union of these two-node-connected subnetworks forms a larger two-node-connected subnetwork. The nodes, except n, in these two subnetworks are connected by some paths without the node n, as n is not a cut node. Each of these paths induces a ring of maximal two-node-connected subnetworks. This ring of subnetworks forms a two-node-connected network, as no node in these subnetworks is a cut node. This contradicts that the two-node-connected subnetwork that the node n belongs to is maximal. The proof is complete.

2) Probing Scheme After Network Transformation: Define H as the network obtained after the contraction of network G. The analysis of the existence of a probing scheme in network G is divided into several cases that depend on the topology of network H. Recall that N includes all terminal nodes and also routing nodes that are originating nodes or terminating nodes of some paths considered in the set Q. Four trivial cases are first excluded before the detailed discussion.

Case 1. If H has only one node, then the original network G is a network with a single terminal node or a network of routing nodes, with no need for monitoring.

Case 2. If H has two nodes such that one is in N and one is in S, there is only one terminal node in the whole network. There is no need for monitoring.

Case 3. If H has two nodes such that both are in N but one of them is a routing node, there is still only one terminal node. There is no need for monitoring.

Case 4. If H has only a single link such that both end nodes are terminal nodes, certainly they are in N; both nodes should be in $N_p \cap N_m$. The probing scheme for this case is trivial.

Case 5. For all other situations, refer to Theorem 2.

Theorem 2. When H is a proper two-node-connected network, a probing scheme exists if there is a node in $N_p \cap N_m$. Otherwise, H contains cut nodes. Suppose H is decomposed into maximal two-node-connected subnetworks. Consider the two-node-connected subnetworks that contain exactly one cut node of the whole network H. If there is a node in $N_p \cap N_m$ in each of these subnetworks, a probing scheme exists.

Proof. See Appendix A. The proof is divided into four cases. The first case considers short segments in a proper two-node-connected network. The second and third cases consider long segments in a proper two-node-connected network. Both the first and the second cases involve finding a ring subnetwork that covers the short and the long segment, respectively. The existence of a node in $N_p \cap N_m$ in this ring subnetwork implies the solvability of the segment by Lemma 1. The third case considers the situation when there is no such ring subnetwork that covers the long segment and the node in $N_p \cap N_m$. The last case artificially creates a proper two-node-connected network in a general network with cut nodes so that every short segment and long segment can be solved by the methods in the first three cases.

Recall that the paths of interest in the set Q are divided into long segments and short segments at the nodes in N. Originally, the long segments contain multiple links; after contraction of links whose end nodes are out of N, the long segments become two-hop paths. Therefore, each long segment in network G maps to a two-hop path in network H or, equivalently, maps to an input–output port pair of a supernode in H. This port pair corresponds to an ingress–egress node pair in the subnetwork in G that contracts to the supernode. First assume that each input–output port pair maps to at most only one long segment. In the proof of Theorem 2, the accumulated impairment of the two-hop path is derived. The derived accumulated impairment is regarded as the accumulated impairment of the original long segment. This implication is valid only if whenever the probing channel transverses the two-hop path in H, the probing channel transverses the corresponding long segment in G. Explicitly, in order to use Theorem 2 to derive the accumulated impairment of the short and long segments, there are two rules to follow. Whenever a probing channel is routed through an input–output port pair of a supernode,

i. the corresponding long segment is routed through if the port pair corresponds to the long segment; otherwise,
ii. an arbitrary fixed subpath that connects the corresponding ingress–egress node pair in the contracted subnetwork is routed through.

Rule i raises a problem when there are multiple long segments that correspond to the same input-output port pair of a supernode. The probing channels in the proposed probing scheme solve only one of the long segments. In order to solve all of these long segments, multiple sets of probing channels have to be used, one set for each of the long segments. The redundancy can be removed by the linear dependency.

B. Networks Without Routing Nodes

In the special case of a network with only terminal nodes, the set N contains all the nodes in the network and no supernodes in the set S. All links have both end nodes in N; therefore no contraction is required, i.e., $H=G$. Moreover, every link connects two adjacent terminal nodes; thus every link is in the set Q. It suffices to consider the set Q containing all the links, as the accumulated impairment of any path of interest can be derived once the impairment variables of all the links are known. The probing scheme in Theorem 2 certainly applies to this special case. However, the nonexistence of a routing node offers advantages in reducing the number of monitoring modules and shortening the length of probing channel paths. A less restrictive sufficient condition such that a probing scheme exists is stated in Theorem 3, which requires fewer monitoring modules. This reduces the capital expenditure, whereas the reduction of the length of probing channels by Theorem 4 reduces the operational expenditure.

Similar to the analysis for the general network with routing nodes, the network G is first decomposed into two separate maximal two-link-connected networks. The decomposition is described in the following.

Decomposition into maximal two-link-connected subnetworks. A two-link-connected network is a network without a bridge, where a bridge is a link whose removal disconnects the remaining network. Any network can be decomposed into maximal two-link-connected subnetworks and bridges by the following proposition.

Proposition 3. Any network can be decomposed into maximal two-link-connected subnetworks and bridges. Also, the two-link-connected subnetworks are interconnected by the bridges of the whole network. Moreover, a link is a bridge if and only if it connects two maximal two-link-connected networks. Furthermore, the decomposition is unique.

Proof. Let T denote the network obtained by contracting all links except bridges of network G. Claim that the network T is a tree network. Let B denote the set of bridges in G. The link set of T is exactly the set B by definition. Remove a link l_b in T, and suppose that T is still connected. This implies that the network G remains connected after the removal of the link l_b, too. This is because any node in T is obtained by contracting a connected subnetwork in G. This leads to a contradiction. Thus T is a tree network. This completes the claim.

Every node in T comes from a connected subnetwork in G. Let one of these subnetworks be O, and it is contracted to a node n_T in T. Claim that O is two-link connected. Suppose that the removal of a link l in O disconnects its end nodes src(l) and dst(l) in O. Since l is contained in O, it should not be a bridge. So, src(l) and dst(l) should be connected in the original network G through a path that does not contain l. This path should contain some links in G that are not in O, as l disconnects src(l) and dst(l) in O. This implies that there is a ring subnetwork that contains n_T in T, as both src(l) and dst(l) are contracted into the node n_T in T. This contradicts that T is a tree network. This completes the claim and the proof is completed.

Theorem 3. When G is a two-link-connected network, a probing scheme exists if there is a node in $N_p \cap N_m$. Otherwise, suppose that the network G is decomposed into maximal two-link-connected subnetworks. Consider the two-link-connected subnetworks that are attached to exactly one bridge of the whole network. If there is a node in $N_p \cap N_m$ in each of these subnetworks, a probing scheme exists.

Proof. See Appendix A. The proof is divided into two cases. The first case considers a two-link-connected network. The second case considers a network with bridges. The first case involves finding an Eulerian cycle that covers the short segment and the node in $N_p \cap N_m$. The existence of such an Eulerian cycle implies the solvability of the short segment by Lemma 1. The second case artificially creates a two-link-connected network in the general network with bridges so that every short segment can be solved by the method in the first case.

Since probing channels cannot propagate through a link twice, each of the two subnetworks that are disconnected by a bridge should contain a node in N_p and a node in N_m. Therefore, the proposed probing scheme uses the lowest number of monitoring modules.

A two-node-connected network is two-link-connected, except in the special case of the single-link network. Also, both end nodes of a bridge are cut nodes. Therefore, no proper two-node-connected network contains bridges; any bridge should belong to its own single-link, improper two-node-connected subnetwork. In contrast, a two-link-connected subnetwork may be further decomposed into two-node-connected subnetworks if it contains cut nodes. In particular, the maximal two-link-connected subnetworks described in Theorem 4 may be further decomposed into two-node-connected subnetworks. Thus, the number of maximal two-node-connected subnetworks that contain exactly one cut node of the whole network must not be less than the number of maximal two-link-connected subnetworks that are attached to exactly one bridge of the whole network. Figure 6 shows an example to illustrate the concept. In Fig. 6, there is only a single two-link-connected network, but it has three two-node-connected subnetworks, and two of them contain exactly one cut node. This confirms that the number of nodes in $N_p \cap N_m$ stated in Theorem 2 must not be less than that stated in Theorem 3. Actually, Theorem 2 minimizes the total number of monitoring modules.

Besides the constructive proof in Theorem 3, the next theorem shows that the set of minimum-length probing channel paths suffices to give a probing scheme when all nodes in the network are terminal nodes. This is becauset, by proper indexing of these minimum-length probing channel paths, they induce a triangular matrix $\boldsymbol{Y}$, and thus it spans the whole vector space.

Theorem 4. Whenever a probing scheme exists, every link in the network must be contained in some paths from a node in N_p to a node in N_m. For any link l_j, $j \in [1,2L]$, where L is the total number of links, let p_j denote the minimum-length path that contains the link l_j such that $\mathrm{src}(p_j) \in N_p$ and $\mathrm{dst}(p_j) \in N_m$. Probing channels along the paths p_j, for all $j \in [1,2L]$, give a probing scheme. The total length of probing channels in this probing scheme is automatically a minimum.

Proof. For any $j \in [1,2L]$, there should be a probing channel that propagates through the link l_j in order to derive x_j. Therefore, there should be a path from a node in N_p to a node in N_m that contains l_j if a probing scheme exists. It is also a sufficient condition under which a probing scheme exists as stated in Lemma 1.

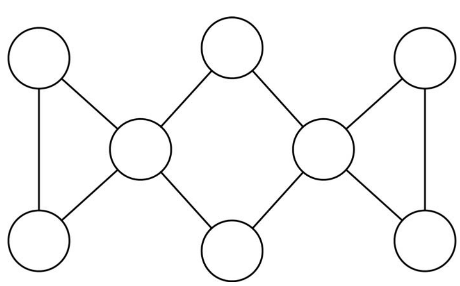

Fig. 6. Single two-link-connected network that can be decomposed into three two-node-connected networks.

Let p_j denote the minimum-length path that contains the link l_j such that $\mathrm{src}(p_j) \in N_p$ and $\mathrm{dst}(p_j) \in N_m$. Index the link l_j so that $\mathrm{len}(p_1) \leqslant \mathrm{len}(p_2) \leqslant \mathrm{len}(p_3) \leqslant \ldots \leqslant \mathrm{len}(p_{2L})$. Claim that $\{p_1, p_2, p_3, \ldots, p_j\}$ do not contain l_{j+1}.

Assume that the claim is true for $j=k$, where $k \geqslant 2$. Suppose there exists an $i \in [1,k]$ such that p_i contains l_{k+1}. It is worth noting that $\mathrm{src}(l_i)=\mathrm{src}(p_i)$ if $\mathrm{src}(l_i) \in N_p$ and $\mathrm{dst}(l_i)=\mathrm{dst}(p_i)$ if $\mathrm{dst}(l_i) \in N_m$, as p_i is the minimum-length path. Remember that the necessary condition in Theorem 1 is assumed to be satisfied. The proof is divided into four cases, according to the property of the nodes $\mathrm{src}(l_i)$ and $\mathrm{src}(l_{k+1})$.

Case 1: Both $\mathrm{src}(l_i)$ and $\mathrm{src}(l_{k+1})$ are elements in N_p. There should be no monitoring module along the subpath from $\mathrm{dst}(l_i)$ to $\mathrm{src}(l_{k+1})$ of p_i; otherwise, $\mathrm{len}(p_i)$ is not minimum. In particular, the node $\mathrm{dst}(l_i) \in N_p$ by the necessary condition stated in Theorem 1. The subpath of p_i, from node $\mathrm{dst}(l_i)$ to the node $\mathrm{dst}(p_i)$ is denoted p_s, which contains l_{k+1}. It is true that $\mathrm{len}(p_i) \leqslant \mathrm{len}(p_{k+1}) \leqslant \mathrm{len}(p_s)$ by definition. However, $\mathrm{len}(p_s) < \mathrm{len}(p_i)$. This leads to a contradiction.

Case 2: The node $\mathrm{src}(l_i) \in N_p$ while $\mathrm{src}(l_{k+1}) \in N_m$. Therefore, path p_i can be shortened by removing the subsequent links after $\mathrm{src}(l_{k+1})$. This contradicts that $\mathrm{len}(p_i)$ is minimum.

Case 3: The node $\mathrm{src}(l_i) \in N_m$ while $\mathrm{src}(l_{k+1}) \in N_p$. If l_{k+1} is visited before l_i in p_i, the subpath of p_i, from $\mathrm{src}(l_{k+1})$ to $\mathrm{dst}(l_i)$ is denoted p_{bef} and contains l_{k+1}. Then $\mathrm{len}(p_i) \leqslant \mathrm{len}(p_{k+1}) \leqslant \mathrm{len}(p_{\mathrm{bef}})$ by definition. However, $\mathrm{len}(p_{\mathrm{bef}}) < \mathrm{len}(p_i)$. This leads to a contradiction. In contrast, if l_{k+1} is visited after l_i, the subpath of p_i, from $\mathrm{src}(l_{k+1})$ to $\mathrm{dst}(p_i)$, is denoted p_{aft} and contains l_{k+1}. Similarly, $\mathrm{len}(p_i) \leqslant \mathrm{len}(p_{k+1}) \leqslant \mathrm{len}(p_{\mathrm{aft}})$ by definition. However, $\mathrm{len}(p_{\mathrm{aft}}) < \mathrm{len}(p_i)$. This leads to a contradiction.

Case 4: Both $\mathrm{src}(l_i)$ and $\mathrm{src}(l_{k+1})$ are elements in N_m. If l_{k+1} is visited before l_i in p_i, the subpath of p_i, from $\mathrm{src}(p_i)$ to $\mathrm{src}(l_i)$, is denoted p_{bef} and contains l_{k+1}. Then $\mathrm{len}(p_i) \leqslant \mathrm{len}(p_{k+1}) \leqslant \mathrm{len}(p_{\mathrm{bef}})$ by definition. However, $\mathrm{len}(p_{\mathrm{bef}}) < \mathrm{len}(p_i)$. This leads to a contradiction. In contrast, if l_{k+1} is visited after l_i, the subpath of p_i from $\mathrm{src}(p_i)$ to $\mathrm{src}(l_{k+1})$ is denoted p_s and contains l_i. But then $\mathrm{len}(p_s) < \mathrm{len}(p_i)$, which is a contradiction. This proves the claim.

Suppose a set of probing channels is injected along the paths $\{p_1, p_2, p_3, \ldots, p_{2L}\}$. The $(k+1)$th component of the first k row vectors in the corresponding matrix Y should be 0, as all the paths $\{p_1, p_2, p_3, \ldots, p_k\}$ do not contain l_{k+1}. On the other hand, the $(k+1)$th component of the $(k+1)$th row vector is 1 by definition. By induction, all the row vectors in Y are linearly independent, which implies that Y is invertible and the set P of paths gives a probing scheme. This completes the proof.

IV. Fault Localization in Networks Without a Routing Node

Fault localization [17–19] is a special kind of performance monitoring. The performance of a network component has only two levels: "on" or "off." It is natural to consider a channel as off whenever a link along the channel path is off. For both channels and links, this performance information can be represented as a binary failure indicator: failure indicator=1 means off, while failure indicator=0 means on. An adaptive technique for fault diagnosis using probes has been presented [18]. In [18], probes are established sequentially, and the paths of the probes depend on the results of the already established probes. The total number of probes used asymptotically achieves the information theoretical limit of retrieving all the statuses of the links. However, the technique assumes that a probe can originate and terminate at any location. In the worst case, all the nodes in the network need to have monitors. Another approach to fault localization was advocated in [19]. In [19] only a few nodes in the network are equipped with monitors, referred to as monitoring locations. The failures may be uniquely localized by using monitoring paths and monitoring cycles. The total number of failures that can be localized is bounded by a number chosen by the network operator. The higher the bound, the more monitoring paths and cycles are required; thus more nodes should be equipped with monitors. No localization ability is guaranteed if the total number of failures exceeds the bound. The probing scheme discussed in the present paper installs monitoring modules at some determined nodes. It can locate at least one fault even if multiple faults occur, and subsequently all the other faults can be identified iteratively.

The failure indicators of probing channels and the failure indicators of links are related by logical OR instead of addition, which makes the proposed probing scheme unable to retrieve the fault indicators of all links. However, Theorem 5 below shows that at least one fault can be located if the minimum-length approach in Theorem 4 is applied for probing channels. This is because the corresponding matrix $\boldsymbol{Y}$ is triangular. Note that Theorem 4 applies only to the networks without a routing node; the fault localization ability is thus restricted to networks without a routing node.

Theorem 5. If the minimum-length path approach in Theorem 4 is used for probing channels, at least one fault can be located even if multiple faults occur.

Proof. The impairment variable x_j is interpreted as the fault indictor of the link l_j. That is, $x_j=1$ if there is fault in the link l_j; otherwise, $x_j=0$. Similarly, the fault indicator y_j for the jth probing channel along the path p_j is set to 0 if there is no fault along the path p_j; otherwise, it is set to 1. Let $\boldsymbol{y}=[y_1\, y_2\, y_3 \ldots y_{2L}]^{\mathrm{T}}$. Without loss of generality, index the paths p_j, for $j\in[1,2L]$, according to their length as in Theorem 4. Let W be the index set such that the wth components in $\boldsymbol{y}=1$ if and only if $w\in W$. Let s be the smallest number in W. Since $s\in W$, $y_s=1$; there should be at least one fault along path p_s. Since p_s does not contain any link with an index larger than s, as shown in Theorem 4, the potential failed links should have indices $t\leqslant s$. On the other hand, $y_t=1$, as p_t contains l_t. Since s is the smallest number in W, $t\geqslant s$ which concludes that $t=s$. The proof is complete.

Theorem 5 induces a fault localization algorithm. Upon receiving the failure indicator vector $\boldsymbol{y}$, the failed link with the smallest index can be located by Theorem 5. Any other failed link, if it exists, can be located iteratively after the repair of the located fault. The following table compares the fault location schemes in [18,19] and this paper.

Fault Location Scheme	Ref. [18]	Ref. [19]	This Paper
Monitoring module location	Not fixed; may be installed in all nodes.	Fixed; installed in only some determined nodes.	Fixed; installed in only some determined nodes.
Number of probing channels	Depends on the failure probability; asymptotically approaches the information theoretic limit.	About 2 probing channels per link	About 1 probing channel per link
Fault location ability	Can locate all faults	Can locate fault only up to a number designed by the network operator. The larger the number, the more monitoring modules. If the number of faults exceeds the number, no guarantee of localization ability.	Can locate at least one fault occurrence. Any other failed links, if they exist, can be located iteratively after the repair of the located fault.

V. Conclusion

Although it is uncertain how much monitoring is needed, OPM is clearly indispensable for future high-capacity transparent mesh optical networks. All-optical reconfigurable mesh networks impose great challenges for OPM because of the signal transparency and nonstatic configuration for different channels. In the existing OPM schemes, performance monitoring is always done on a channel basis. The channel qualities are monitored separately. The correlation in channel quality between different channels is ignored. These performance monitoring schemes are usually applied to measure the existing data channels for adaptive compensation of degraded signal quality. However, data channels are set up and torn off dynamically in reconfigurable networks. The path of data channels changes from time to time. It is beneficial to have an estimation of the quality of a path before a data channel is established along it. This quality estimation provides some network management functions, such as channel setup, control, and optimization. Network operators can also regard the estimations as a metric for path computation.

In this paper, a novel algebraic approach provides a systematic method for OPM in reconfigurable all-optical networks. The proposed approach provides an efficient way to derive the accumulated impairment of all possible paths between any two communicating nodes. The channel quality can be estimated before it is established. In addition, the end-to-end performance, subpaths of any data channel paths can also be monitored. On the other hand, if it is not necessary to estimate the quality of all paths, the redundant paths can be excluded, which may reduce the number of monitoring modules required. By using the correlation in the channel quality between different channels, the total number of channels injected for monitoring is always bounded by the number of links in the network, which is much less than the number of all possible paths. Furthermore, the bounds on the number of monitoring modules required are derived, and the corresponding monitoring scheme is proposed. For a special network in which all nodes can originate and terminate channels, a monitoring scheme that achieves the fundamental limit on the number of monitoring modules is introduced. The monitoring scheme proposed for this kind of network can also be used to locate faults. At least one fault can be located even if multiple faults occur. Any other failed links, if they exist, can be located iteratively after the repair of the located fault.

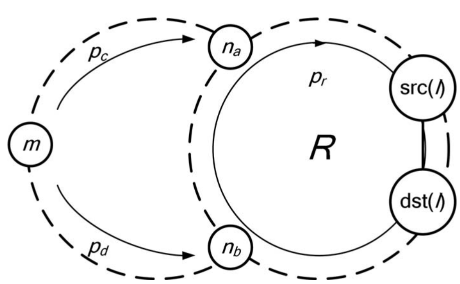

Fig. 7. Left, ring subnetwork in a two-node-connected network. Right, a Eulerian cycle in a two-link-connected network. If $n_a \neq n_b$, the Eulerian cycle is a ring subnetwork.

Appendix A

Theorem 2. When H is a proper two-node-connected network, a probing scheme exists if there is a node in $N_p \cap N_m$. Otherwise, H contains cut nodes. Suppose H is decomposed into maximal two-node-connected subnetworks. Consider the two-node-connected subnetworks that contain exactly one cut node of the whole network H. If there is a node in $N_p \cap N_m$ in each of these subnetworks, a probing scheme exists.

Proof. The nodes in $N_p \cap N_m$ are called "fully equipped nodes." The proof is divided into four cases. The first case considers short segments in a proper two-node-connected network. The second and third cases consider long segments in a proper two-node-connected network. The last case artificially creates a proper two-node-connected network in a general network with cut nodes so that every short segment and long segment can be solved by the methods in the first three cases.

Case 1. Suppose H is a proper two-node-connected network and the accumulated impairment z of a short segment, i.e., a single link l, has to be derived. Let m denote the fully equipped node. Refer to Fig. 7. There should be a ring subnetwork R containing the nodes src(l) and dst(l), as the whole network is two-node connected. Suppose m is not in R. As a two-node-connected network, there are two node-disjoint paths p_a and p_b from m to src(l). Let the first node [in the direction from m to src(l)] in which p_a and p_b meet R be n_a and n_b, respectively. Let p_c and p_d be the subpath of p_a and p_b from m to n_a and n_b, respectively. Since the path p_c and p_d are node disjoint, $n_a \neq n_b$. Without loss of generality, let p_r be the subpath, from n_a to src(l) to dst(l) to n_b of R. The path $p = p_c + p_r + p_d'$ forms a ring subnetwork that contains the nodes m, src(l), and dst(l). Therefore, there is always a ring subnetwork containing all the nodes m, src(l), and dst(l). The cyclic path along the ring subnetwork from m to itself is sufficient to derive the impairment variable of the link l by Lemma 1.

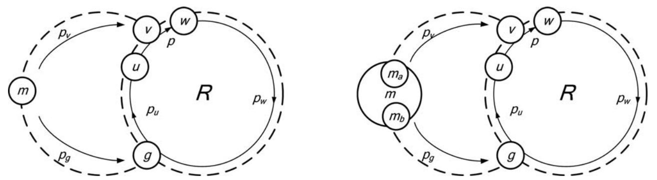

Fig. 8. Left, a figure for the proof of the Case 3 of Theorem 2. Important nodes and paths in the proof are labeled. Right, in the proof of Case 4 of Theorem 2, the merged node m can be restored into the two fully equipped nodes m_a and m_b.

Case 2. Suppose H is a proper two-node-connected network and that the accumulated impairment z of a long segment has to be derived. Designate the fully equipped node as m. Let the long segment be the path $p = u \rightarrow v \rightarrow w$, where u and w are nodes in N while v is a supernode in S. Similar to Case 1, there should be a ring subnetwork R containing path p, as the whole network is two-node-connected. If m is contained in R, the accumulated impairment z can be derived by Lemma 1 along the cyclic path in R. The next case considers the situation that the node m is not included in any ring subnetwork.

Case 3. Suppose H is a proper two-node-connected network and that the accumulated impairment z of a long segment has to be derived. Recall the notation in Case 2. Suppose there is no ring subnetwork that contains the fully equipped node m and the path p. But there should be a ring subnetwork R that contains the path p, as the whole network is two-node connected. Refer to Fig. 8 (left). As a two-node-connected network, there are two node-disjoint paths, labeled p_v and p_g, from m to u. Let the first node [in the direction from m to src(l)] in which p_a and p_b meet R be v and g. Let p_v and p_g be the subpath of p_a and p_b from m to v and g, respectively. Note that one of the paths p_a and p_b, assumed to be p_a in the analysis, should meet the ring subnetwork R at v; otherwise there is a ring subnetwork that contains both the node m and the path p. Define p_w and p_u as the subpath from the node w to the node g and the subpath from the node g to the node u, along the cyclic path in R, respectively. Case 3 is further divided into three cases.

Case 3a. Suppose the node $u \in N_p$; the path $p + p_w + p'_g$ is a path that suffices to derive z by Lemma 1.

Case 3b. Suppose $u \in N_m$ while $w \in N_p$. Let l_u and l_w be the link from u to v and v to w, and x_u and x_w be the impairment variables for them, respectively. Then impairment variable $z = x_u + x_w$. Let z_v (z'_v) be the accumulated impairment along path p_v (p'_v). Consider the five paths $p_1 = p_g + p_u + l_u + p'_v$, $p_2 = p_v + l'_u + p'_u + p'_g$, $p_3 = p_g + p'_w + l'_w + p'_v$, $p_4 = p_v + l_w + p_w + p'_g$, and $p_5 = p' + p'_u + p'_g$. Path p_1 suffices to derive $x_u + z'_v$ by Lemma 1. Similarly, path p_2 suffices to derive $x'_u + z_v$, path p_3 suffices to derive $x'_w + z'_v$, path p_4 suffices to derive $x_w + z_v$, and path p_5 suffices to derive $x'_u + x'_w$. The accumulated impairment $z = x_u + x_w = (x_u + z'_v) + (x_w + z_v) - (x'_w + z'_v) - (x'_u + z_v) + (x'_u + x'_w)$ can then be derived.

Case 3c. Suppose both node u and w are elements in N_m. Recall the notation in Case 3b. Paths p_1, p_2, p_3, and p_4 let us derive $x_u + z'_v$, $x'_u + z_v$, $x'_w + z'_v$, and $x_w + z_v$, respectively. However, path p_5 may not be a valid path for a probing channel, as w may not be installed with probing. The accumulated impairment along p', i.e., $x'_u + x'_w$, is derived in another way. Since path p is a subpath of some paths of interest in Q, there should be a path p_t, between two terminal nodes, that contains the path p, according to the property of the paths of interest in Q. Refer to Fig. 9(a). Let t_1 and t_2 denote the nodes of src(p_t) and dst(p_t), respectively. Consider the path p_t as $p_{\mathrm{bef}} + p + p_{\mathrm{aft}}$. Note that path p_{bef} is a null path if the node u is a terminal node. Similarly, path p_{aft} is null if the node w is a terminal node. As a two-node-connected network, there should be two node-disjoint paths from m to u. The two paths should not meet p_t at the same node. Therefore, one of these two paths meets p_t as a node, labeled f, which is not node v. Let p_f denote the path from m to f, along the path from m to u, which is mentioned above. If f is a node in p_{aft} or $f = w$, the path p_f concatenated with the path from f to t_1 along the reverse path p'_t suffices to derive the accumulated impairment along p', i.e., $x'_u + x'_w$. Otherwise [refer to Fig. 9(b)], if f is a node in p_{bef} or $f = u$, the path p_f concatenated with the path from f to t_2 suffices to derive accumulated impairment along p directly by Lemma 1.

Case 4. The network H contains cut nodes. Consider that the network H is decomposed into maximal two-node-connected subnetworks. The interconnection between the maximal two-node-connected networks is like a tree network. To see that, create a node for each cut node and create a node for each maximal two-node-connected subnetwork. Let A and B be the set of nodes created from the cut nodes and the maximal two-node-connected subnetworks, respectively. Add a link between a node in A and a node in B if and only if the cut node that comes from A is a node in the corresponding maximal two-node-connected subnetwork that comes from B. Let T denote the resultant network. There is no ring subnetwork in T; otherwise, this ring subnetwork induces a ring of maximal two-node-connected subnetworks. This ring of maximal two-node-connected subnetworks forms a larger two-node-connected subnetwork, which contradicts the fact that each two-node-connected subnetwork is maximal. Therefore, T is a tree network.

The maximal two-node-connected subnetworks contain exactly one cut node of the whole network H if and only if they come from the leave nodes in T. These subnetworks are called "leave subnetworks." To make use of the analysis in the first three cases of the proof, two fully equipped nodes in two separate leave sub-

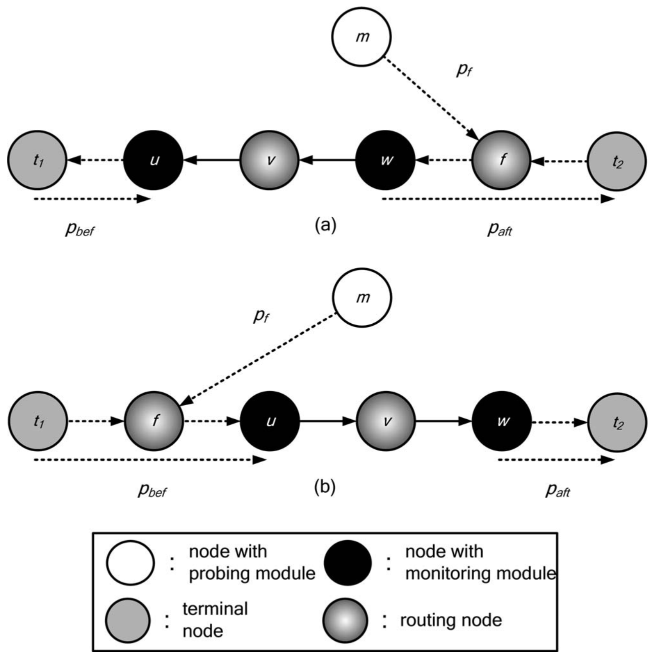

Fig. 9. (a) Paths to derive the accumulated impairment in the path p'. (b) The accumulated impairment along the long segment p can be derived directly by Lemma 1.

networks are merged to artificially create two-node-connected subnetworks. Suppose two fully equipped nodes, called m_a and m_b, in two separate leave subnetworks are merged into one node, called m. This induces a ring subnetwork in T. Equivalently, the merging induces a ring of two-node-connected subnetworks that are interconnected through cut nodes and the node m. This ring of subnetwork is a two-node-connected subnetwork as a whole. Note that any short segment or long segment can be included in an artificial two-node-connected subnetwork if the fully equipped nodes to be emerged are chosen properly. Then the segments can be solved by the analysis in the first three cases. The merged node m plays the role of the fully equipped node in the three cases of the recent discussion. Refer to Fig. 8 (right); restoring m into m_a and m_b does not violate the existence of the solution for both short and long segments. The proof is completed.

Example. Figure 10 shows a sample network. The

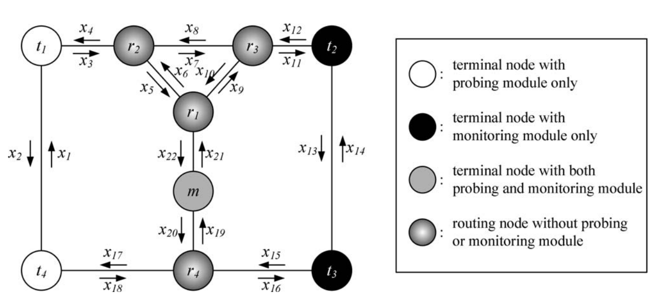

Fig. 10. Sample network to illustrate the application of Theorem 2.

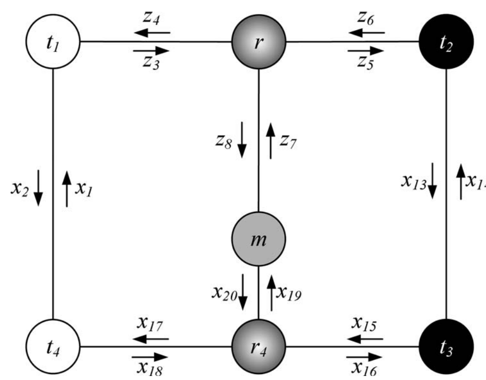

Fig. 11. Routing nodes contracted by contracting links between two routing nodes.

node $m \in N_p \cap N_m$. Other terminal nodes are labeled t with indices, while routing nodes are labeled r with indices. Figure 10 becomes Fig. 11 after the contraction of links between two routing nodes. The routing nodes r_1, r_2, and r_3 are contracted into a node r. Suppose that all possible paths between terminal nodes are in Q. There are a total of 4 short segments and 12 long segments that have to be solved. Obviously, the network is two-node connected; thus the fully equipped node m suffices to solve the long and short segments.

Long segments are solved first. The following set of paths suffices to solve the long segments involving the contracted routing node r:

$$z_3 + z_8 : t_1 \to r \to m,$$

$$z_7 + z_4 : m \to r \to t_1 \to t_2 \to r_4 \to m$$

and $t_1 \to t_2 \to r_4 \to m$ (by Lemma 1),

$$z_7 + z_5 : m \to r_4 \to t_3,$$

$$z_6 + z_8 : t_4 \to r_4 \to t_3 \to t_2 \to r \to m$$

and $t_4 \to r_4 \to t_3 \to t_2$ (by Lemma 1),

$$z_3 + z_5 : t_1 \to r \to t_2,$$

$$z_6 + z_4 = (z_6 + z_8) + (z_7 + z_4) - (z_3 + z_8) - (z_3 + z_8) + (z_3 + z_5) \text{ (by Case 3b of Theorem 2)}.$$

The following set of path suffices to solve the long segments involving the routing node r_4:

$$z_{18} + z_{19} : t_4 \to r_4 \to m,$$

$$z_{20} + z_{17} : m \to r_4 \to t_4 \to t_1 \to r \to m$$

and $t_4 \to t_1 \to r \to m$ (by Lemma 1),

$z_{20}+z_{16}$: $m \rightarrow r_4 \rightarrow t_2$,

$z_{15}+z_{19}$: $t_1 \rightarrow r \rightarrow t_2 \rightarrow t_3 \rightarrow r_4 \rightarrow m$,

and $t_1 \rightarrow r \rightarrow t_2 \rightarrow t_3$ (by Lemma 1),

$z_{18}+z_{16}$: $t_4 \rightarrow r_4 \rightarrow t_3$,

$$z_{15}+z_{17}=(z_{15}+z_{19})+(z_{20}+z_{17})-(z_{18}+z_{19})-(z_{20}+z_{16}) + (z_{18}+z_{16}) \text{ (by Case 3b of Theorem 2).}$$

After all long segments are solved, the accumulated impairment induced in them can be subtracted directly from the OPM results of the paths that involve them. This, equivalently, contracts all the long segments. In this example, the contraction of all long segments eventually gives a network without routing nodes. Therefore, the short segments can be solved by the minimum-length path approach stated in Theorem 4:

x_1: $t_4 \rightarrow t_1 \rightarrow r \rightarrow t_2$ (by the minimum-length path approach in Theorem 4),

x_2: $t_1 \rightarrow t_4 \rightarrow r_4 \rightarrow t_3$ (by the minimum-length path approach in Theorem 4),

x_{13}: $t_1 \rightarrow r \rightarrow t_2 \rightarrow t_3$ (by the minimum-length path approach in Theorem 4),

x_{14}: $t_2 \rightarrow r_4 \rightarrow t_3 \rightarrow t_2$ (by the minimum-length path approach in Theorem 4).

Theorem 3. When G is a two-link-connected network, a probing scheme exists if there is a node in $N_p \cap N_m$. Otherwise, suppose that the network G is decomposed into maximal two-link-connected subnetworks. Consider the two-link-connected subnetworks that are attached to exactly one bridge of the whole network. If there is a node in $N_p \cap N_m$ in each of these subnetworks, a probing scheme exists.

Proof. The nodes in $N_p \cap N_m$ are called "fully equipped nodes." The proof is divided into two cases. The operator + denotes the concatenation operator of paths.

Case 1. The network G is two-link-connected. Let m denote the fully equipped node in G. Refer to Fig. 7 (left) (proof of Theorem 2). There should be a ring subnetwork R that contains src(l) and dst(l), as the whole network is two-link connected. If m is contained in R, the cyclic path from the node m to itself along the ring R is sufficient to derive the impairment variable in the link l by Lemma 1. Suppose m is not in R. As a two-link-connected network, there are two link-disjoint paths p_a and p_b from m to src(l). Let the first node [in the direction from m to src(l)] where p_a and p_b meet R be n_a and n_b, respectively. Let p_c and p_d be the subpath of p_a and p_b from m to n_a and n_b, respectively. Without loss of generality, let p_r be the subpath from n_a to src(l) to dst(l) to n_b of R. The path $p=p_c+p_r+p_d'$ forms an Eulerian cycle subnetwork that contains m, src(l), and dst(l). This Eulerian path, from the node m to itself, is sufficient to derive the impairment variable of the link l by Lemma 1.

Case 2. The network G contains bridges. Consider that network G is decomposed into maximal two-link-connected networks and bridges. As mentioned in the discussion of the decomposition, the contraction of these maximal two-link-connected networks gives a tree network, denoted T. The maximal two-link-connected subnetworks are connected to exactly one bridge of the whole network if and only if they are contracted into the leave nodes in T. These subnetworks are called "leave subnetworks."

To make use of the analysis in the first case of the proof, virtual links are inserted to the network G to artificially create two-link-connected subnetworks. Suppose a virtual link is inserted between two fully equipped nodes, called m_a and m_b, in two separate leave subnetworks. This virtual link induces a ring subnetwork in T. Equivalently, the virtual link induces a ring of two-link-connected subnetworks that are interconnected by bridges and the virtual link. This ring of subnetworks is a two-link-connected network as a whole. Note that any link in the network G can be included in the artificial two-link-connected network if the two leave subnetworks are properly chosen. Denote a link, except the virtual link, in the artificial two-link-connected network by l. From Case 1, there is a ring subnetwork or an Eulerian cycle containing the node m_a, src(l), and dst(l). Either one of the situations gives a cyclic path that is sufficient to derive the impairment variable of the link l by Lemma 1. If the cyclic path, along the ring subnetwork or an Eulerian cycle, does not contain the virtual link inserted, the impairment variable can be derived in the original network without the virtual link. Otherwise, the removal of the inserted virtual link disconnects

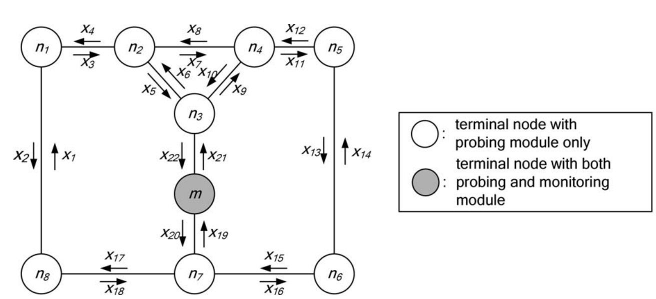

Fig. 12. Sample network to illustrate application of Theorems 3 and 4.

the cyclic path into a path from the node m_a to m_b but still contains the link l. This path is also sufficient to derive the impairment variable of l by Lemma 1. The proof is complete.

Example. Figure 12 shows a sample network. The node $m \in N_p \cap N_m$. There are total of 22 short segments that have to be solved. Obviously, the network is two-link-connected; thus the fully equipped node m suffices to solve all the short segments. Applying Theorem 4, the minimum-length paths for each link are listed below. The paths on the right are the minimum-length path that the link associated with the impairment variables on the left:

x_1:$n_8 \to n_1 \to n_2 \to n_3 \to m$,

x_2:$n_1 \to n_8 \to n_7 \to m$,

x_3:$n_1 \to n_2 \to n_3 \to m$,

x_4:$n_2 \to n_1 \to n_8 \to n_7 \to m$,

x_5:$n_2 \to n_3 \to m$,

x_6:$n_3 \to n_2 \to n_1 \to n_8 \to n_7 \to m$,

x_7:$n_2 \to n_4 \to n_3 \to m$,

x_8:$n_4 \to n_2 \to n_3 \to m$,

x_9:$n_3 \to n_4 \to n_5 \to n_6 \to n_7 \to m$,

x_{10}:$n_4 \to n_3 \to m$,

x_{11}:$n_4 \to n_5 \to n_6 \to n_7 \to m$,

x_{12}:$n_5 \to n_4 \to n_3 \to m$,

x_{13}:$n_5 \to n_6 \to n_7 \to m$,

x_{14}:$n_6 \to n_5 \to n_4 \to n_3 \to m$,

x_{15}:$n_6 \to n_7 \to m$,

x_{16}:$n_7 \to n_6 \to n_5 \to n_4 \to n_3 \to m$,

x_{17}:$n_7 \to n_8 \to n_1 \to n_2 \to n_3 \to m$,

x_{18}:$n_8 \to n_7 \to m$,

x_{19}:$n_7 \to m$,

x_{20}:$m \to n_7 \to n_8 \to n_1 \to n_2 \to n_3 \to m$,

x_{21}:$m \to n_3 \to n_4 \to n_5 \to n_6 \to n_7 \to m$,

x_{22}:$n_3 \to m$.

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