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NETWORK RELIABILITY EVALUATION FOR COMPUTER NETWORKS: A CASE OF THE TAIWAN ADVANCED RESEARCH AND EDUCATION NETWORK

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Abstract. *Due to the unrealistic definition for paths of network models in previous literature, existing models are not appropriate for real-world computer networks. This paper proposes a modified stochastic-flow network model to evaluate the network reliability of computer networks where data are transmitted through a light path (LP). We focus on a practical computer network, the Taiwan Advanced Research and Education Network (TWAREN). Network reliability is defined as the probability of delivering a maximal flow of no less than a specified requirement from source to sink. It is taken as a performance index to measure the service level of TWAREN. This paper studies the network reliability of the international portion of TWAREN from Taipei to New York that goes through the submarine and the land surface cable between Taiwan and the United States.*
Keywords: Network reliability, Stochastic-flow network, Light path (LP), Submarine cable, Minimal light path (MLP)

1. **Introduction.** Performance evaluation is an important method to understand the efficiency of real-world computer networks, especially regarding quality of service (QoS) [1]. QoS refers to the ability to provide a predictable, consistent data transferring services, and the ability to satisfy customers' application needs while maximizing the use of network resource. The Taiwan Advanced Research and Education Network (TWAREN) [2] is Taiwan's academic research network that mainly provides network communication services for Taiwan's research and academic society. It also offers a tunnel between Taiwan and the United States to connect the global research network through a land surface line and the Asia Pacific region's submarine cable. Since TWAREN's resources (i.e., bandwidth) are limited, it is a critical issue to find a technique to optimize its utility. Using efficient evaluation tools to understand TWAREN's performance in order to improve its infrastructure and network management skills is the major task of Taiwan's National High Performance Computing Center (NCHC). Helping NCHC's managers to coordinate the related network providers for improving its efficiency and to supervise the whole project, we propose a new algorithm to evaluate the whole performance of TWAREN.

To measure TWAREN's capability, network analysis is a useful tool. For a practical computer network, transmission media (physical lines such as fiber optics or coaxial cables) may be modeled as arcs, while transmission facilities (switches or routers) may be modeled as nodes. In particular, the capacity of each arc should be stochastic due to the possibility of failure, partial failure, or maintenance. Thus, the computer network characterized by such arcs also has stochastic capacities and it is a typical stochastic-flow network [3-16]. Network reliability evaluation of a stochastic-flow network has been studied as a performance index for decades [3-16]. Most studies have examined the network reliability from the source node s to the sink node t in terms of minimal paths (MPs), in which an MP is a path without cycles [3-5,7-10]. This implies that an MP is a set that connects a (s, t) pair without any surplus arcs from the perspective of the network topology.

Those previous studies assume that data can be sent through all possible MPs from s to t according to the network topology, where each MP is composed of some physical lines (arcs). However, in a real computer system, data can only be sent through some unique light paths (LPs) between specific node pairs, where an LP is a virtual tunnel between two end-to-end nodes which are combined by some segments (i.e., arcs or lines) and nodes; however, an MP is a path that connects a specific source and a specific sink, while an LP can be a link between any two nodes (not limited to source and sink pair). That is, data may be transmitted from source node s to sink node t via more than one LP. In particular, any segments that LP goes through cannot be divided during transmission. Therefore, the previous studies [3-5,7-10] based on MPs to transmit data are not appropriate for TWAREN which is constructed by LPs. In TWAREN, each LP is composed of a set of light path segments (LPSs) linking two different nodes. In particular, each physical line can be divided into several LPSs, and each LPS belongs to only one LP. Since TWAREN involves the LP, which cannot be divided through any part of its nodes or arcs during data transmission, this kind of network model is different from the MP concept described in [3-5,7-10]. Therefore, we implement a minimal light path (MLP) concept to find all LPs to evaluate TWAREN's network reliability. MLP is a core new technique in this paper that makes the real system performance analysis more efficient. In this paper, the MLP is defined as a series of nodes and LPSs, from source node to sink node, which contains no cycle.

In order to evaluate TWAREN's performance, we construct a revised stochastic-flow network. Furthermore, we convert TWAREN's physical network topology into a virtual network in terms of LPs. Then we can evaluate the network reliability for the international part of TWAREN whose tunnel mainly connects to the global academic research network, especially the Internet2 Network [17]. Taiwan's largest network service provider (NSP), Chunghwa Telecom (CHT) [18], integrates those NSPs that the lines pass through to organize the whole portion of TWAREN's international infrastructure in two areas: on the land surface of both Taiwan and the United States; and in the under-sea areas of the Asia Pacific, including the Japan-US submarine cable that disconnected when it was hit by the earthquake and tsunami in Japan on March 11$^{\text{th}}$ 2011. Nakagawa [19] has mentioned the influence of that earthquake regarding reliability, so we study this disaster's effect as well. In fact, when a line breaks, the NSPs of these pass-through lines will offer serviceable lines as backups; therefore, they offer some degree of the network reliability. However, in this study, we only concentrate on the portion that includes the regular lines to determine the factors that affect TWAREN's network reliability, as the NCHC's prime task, aside from improving TWAREN's overall performance, is to anticipate major factors which could fail the regular lines. The issue of the network reliability of the backup line [20-24] has not been considered yet.

This paper mainly emphasizes the probability that the network can send a specified unit of data from the source node in Taipei to the sink node in New York through TWAREN's light path. The remainder of this paper is organized as follows. The TWAREN network is introduced in Section 2. The research scope, problem formulation, the concept of the minimal light path and the evaluation technique, recursive sum of disjoint of products, (RSDP [10]) are described in Section 3. Network reliability of TWAREN is discussed in Section 4. A summary and conclusion are presented in Section 5.

2. TWAREN Network.

2.1. Introduction to TWAREN.

TWAREN has been funded by the National Science Council of Taiwan since 1998 and was built by the NCHC. Construction was completed at the end of 2003 and service and operation started in 2004. Today, more than 100 academic and research institutions connect with TWAREN in Taiwan and this number is increasing continuously. As well, since 2005, over 1,000 elementary schools and junior and senior high schools have been using TWAREN's internal backbone. TWAREN provides network infrastructure for general use but is also an integrated platform for network research. For instance, TWAREN was instrumental in developing applications and network technology such as IPv6, MPLS, VoIP, e-learning, multicast, multimedia and performance measurement, and has supported GRID computing applications such as e-Learning Grid, Medical Grid, and EcoGrid. As promoting Taiwan as an international R&D center is one of NCHC's objectives, a stable and reliable TWAREN is the foundation to achieve this goal.

Many countries fund national research and education network (NREN) infrastructure. TWAREN, Taiwan's NREN, connects to the international research community through global advanced networks, specifically the Internet2 Network [17] of the United States, the major NREN in the world. Therefore, network reliability analyses of TWAREN will help to continuously improve its infrastructure so it can continue to cooperate and connect globally.

2.2. TWAREN's light path.

TWAREN is network that connects to the world-wide research network through light path international tunnel. TWAREN's physical topology is an optical infrastructure and its virtual topology is constructed by connecting light paths and routers. A light path is a tunnel between two sites connected by various cables and is an end-to-end, pre-allocated optical network resource, according to users' needs. It allows signals to be delivered sequentially without jitters and congestion. Each light path is generally a 155 Mbps $\sim$ 10 Gbps dedicated channel that transports various applications.

Figure 1 is the light path international infrastructure that TWAREN leases from CHT, including major sites located at Taipei and Hsinchu in Taiwan, and Los Angeles, Chicago, and New York in the United States. This infrastructure contains the land surface and submarine cable between these cities. Each light path is denoted by LP_i where i is the light path number, $i = 1, 2, \ldots, l$ with l being the number of light path.

Most of these city sites connect to each other with 2.5 Gbps physical line connections, divided into four light path channels at 622 Mb bandwidths. The research scope of this paper is to study the network reliability of the transmission from the source node (Taipei) to the sink node (New York) by means of the light path tunnel.

3. Problem Description and Model Formulation.

3.1. Problem description.

This paper describes how the probability that a specified amount of data can be sent from Taipei to New York via TWAREN is measured. This is referred to as network reliability. By deleting those light paths not used between Taipei and New York, we transform Figure 1 into Figure 2 which is constructed by the light path segments and nodes.

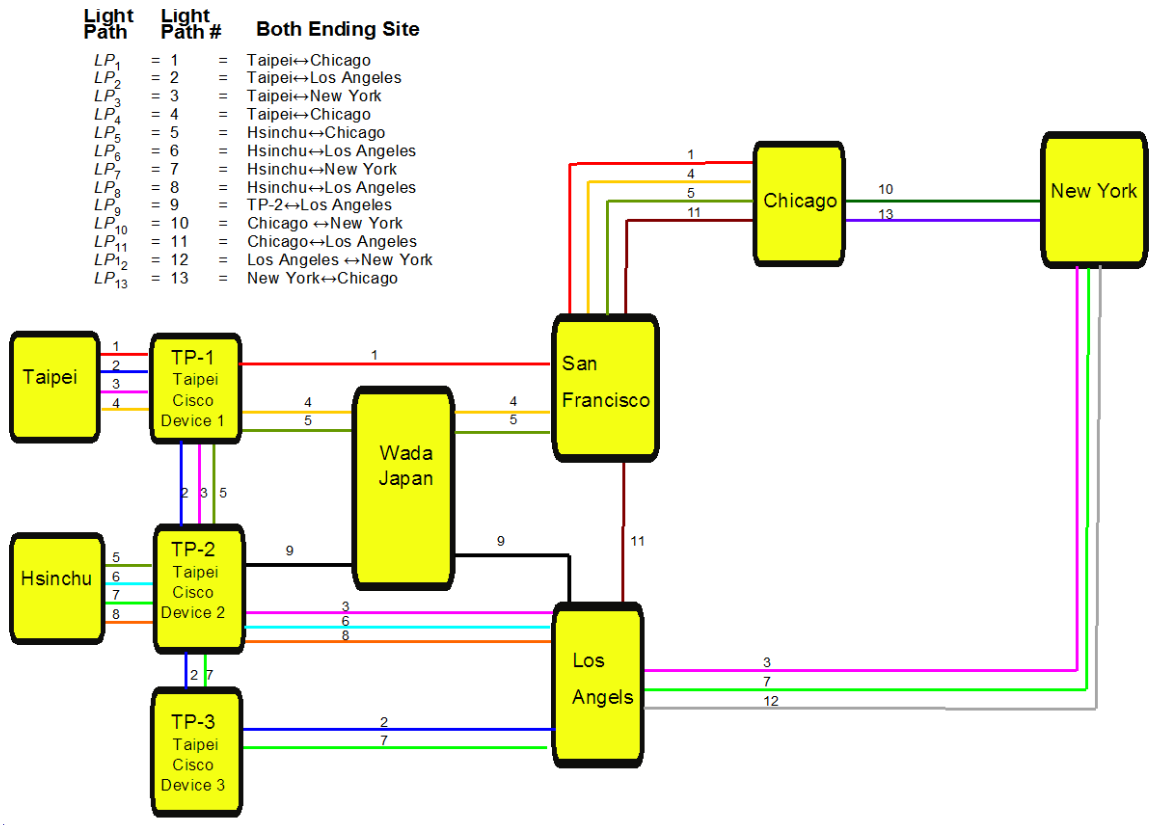

FIGURE 1. TWAREN's light path between Taiwan and the U.S.

3.2. **Some definitions.** As Figure 2 shows, those cities or site devices defined as nodes are denoted by n_k, where $k = 1, 2, \ldots, p$ with p being the number of nodes. For example, Taipei City is n_1 and TP-1 is n_2. We denote each LPS as $l_{i,j}$. $l_{i,j} \in LP_i$ which means the jth segment in LP_i ($j = 1, 2, \ldots, r_i$ with r_i being the number of LPS in LP_i). For example, in Figure 2, LP_1 is a tunnel from Taipei (n_1) to Chicago (n_8), which is combined with three LPSs $l_{1,1}$, $l_{1,2}$, and $l_{1,3}$, and goes through two nodes n_2 (TP-1) and n_6 (San Francisco). Its connection sequence is: $n_1 \leftrightarrow l_{1,1} \leftrightarrow n_2 \leftrightarrow l_{1,2} \leftrightarrow n_6 \leftrightarrow l_{1,3} \leftrightarrow n_8$. The capacity of each LP is 622 Mb, and each LP is combined by four 155 Mb channels. As each channel is regarded as one unit, there are 4 units for each LP.

The physical line (PL) is the actual optical cable where the LP is located and used for data transmission. For example, LPSs $l_{1,3}$, $l_{4,4}$, $l_{11,1}$ is combined in one PL from San Francisco to Chicago, as shown as PL P_{10} in Figure 3. The capacity of each PL is 2.5 G and is divided into four 622 Mb LPs.

The capacity state of an LPS is the same as a PL either when connected or disconnected. We call this network a binary state and the two capacity states are 0 units (0 G) and 4 units (622 Mb with four 155 Mb LPs), respectively. That is, once the PL fails, all the LPSs that are located in this PL also fail. Those LPSs located in the same PL have the same disconnection probability (or conversely, the same connection probability). For example, LPSs $l_{1,3}$, $l_{4,4}$, $l_{11,1}$ located in one PL P_{10} have the same disconnection probability.

3.3. **Model formulation.** The original stochastic-flow network evaluation technology developed in [4] is a method that is not suitable to be applied for TWAREN in Figure 2. There are some differences in this TWAREN problem, since each LP_i is combined with LPS $l_{i,j}$, which cannot be divided through any nodes or arcs, this kind of system model is

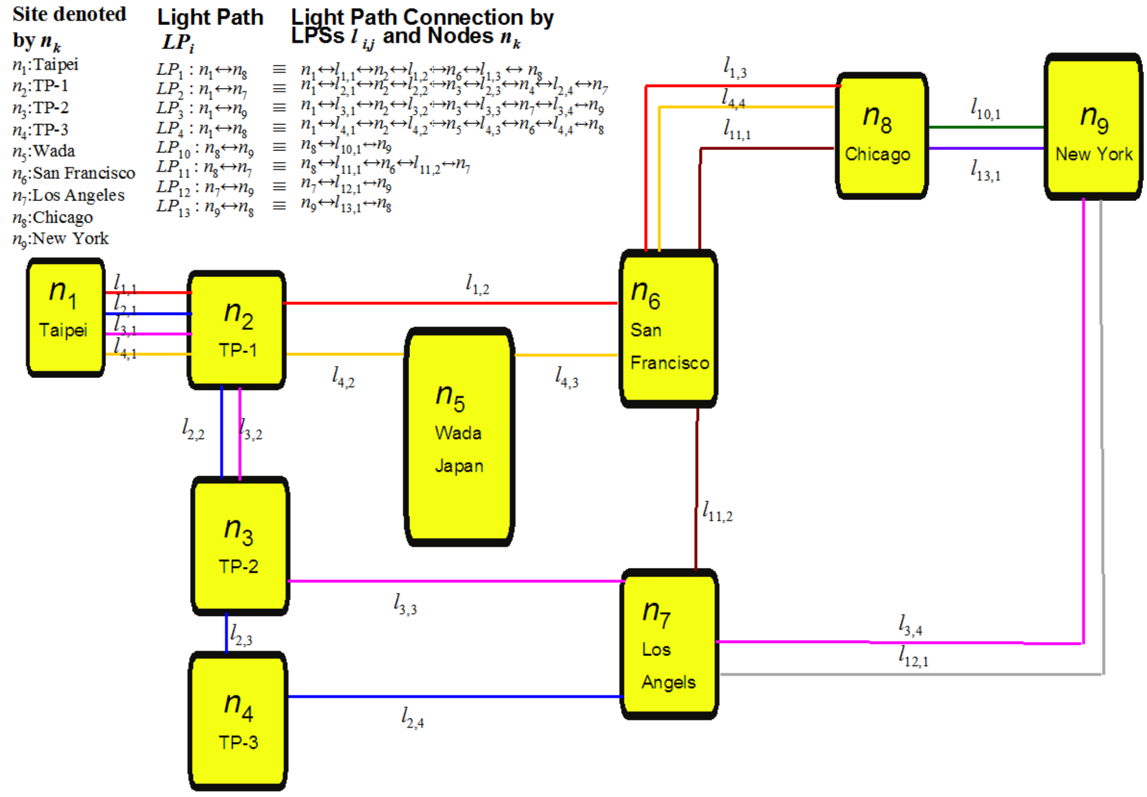

FIGURE 2. Revised network from Taipei to New York by using light path segments and nodes connection

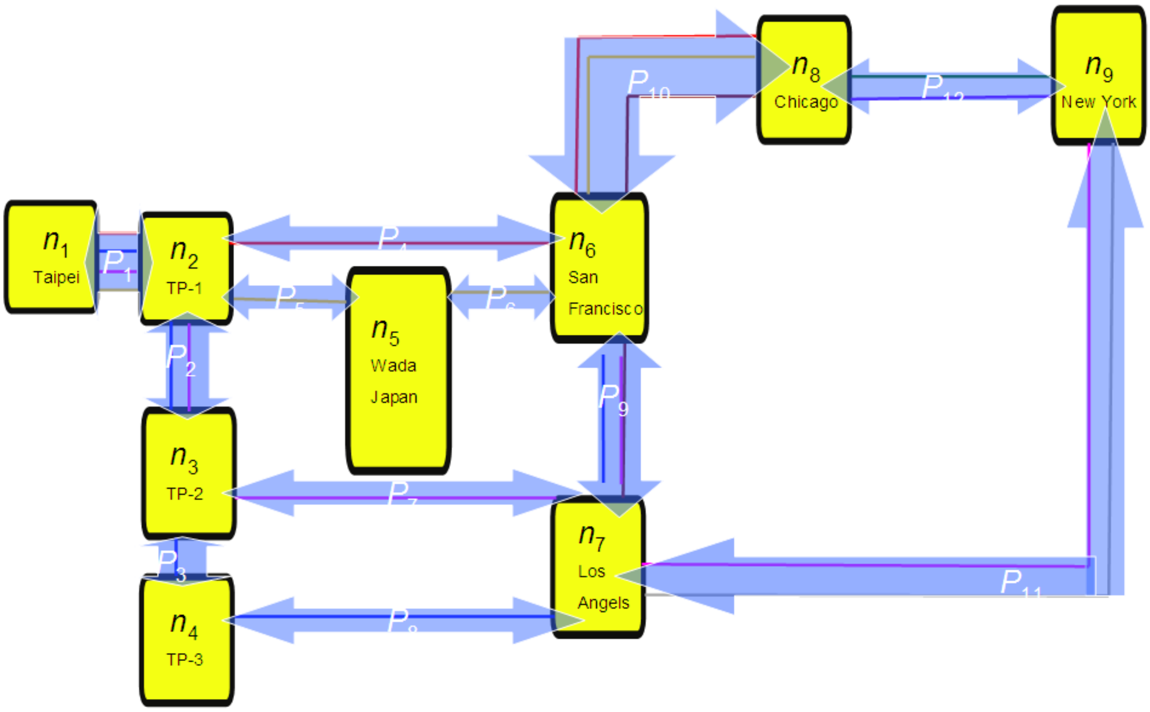

FIGURE 3. Physical line connection

different from the MP method that is described in [4]. Therefore, we revise the method and condition that have been proved in [4] and briefly introduce the following formulation.

To create an easier expression, we re-sort all LPSs as a_1, a_2, …, a_n, where n is the total number of LPSs, instead of $l_{i,j}$. Let $G = (A, N, M)$ be a stochastic flow network where $A = \{a_i | 1 \le i \le n\}$ is the set of LPSs, N is the set of nodes, and $M = (M^1, M^2, \ldots, M^n)$ with M^i (an integer) being the maximum capacity of each LPS a_i. Such a G is assumed to further satisfy the following assumptions:

1. Each node is perfectly reliable.
2. The capacity of each LPS is stochastic with a given probability distribution according to historical data.
3. The capacities of different LPSs are statistically independent.

A minimal light path (MLP) is a series of LPSs from a source node s to a sink node t, which contains no cycle. In particular, any segment that LP_i goes through cannot be divided during transmission. That is, each LPS belongs to only one LP. Suppose ml_1, ml_2, …, ml_m are all MLPs from s to t. Then, the stochastic flow network is described by the capacity vector $X = (x_1, x_2, \ldots, x_n)$ and the flow vector $F = (f_1, f_2, \ldots, f_m)$ where x_i denotes the current capacity of a_i, and f_j denotes the current flow on ml_j. The following constraint shows that the flow through a_i cannot exceed the maximum capacity of a_i,

$$\sum_{j=1}^{m} \{f_j | a_i \in ml_j\} \le M^i. \tag{1}$$

To fulfill the given demand d, the flow vector $F = (f_1, f_2, \ldots, f_m)$ has to satisfy

$$\sum_{j=1}^{m} f_j = d. \tag{2}$$

Let $V(X)$ denote the maximum flow that can be sent under state X. Any minimal vector in the set $\{X | V(X) \ge d\}$ is said to be a lower boundary point for d. That is, X is a lower boundary point for d, if and only if (i) $V(X) \ge d$ and (ii) $V(Y) < d$ for any capacity vector Y, such that $Y < X$ (where $Y \le X$ if and only if $y_i \le x_i$ for each $i = 1, 2, \ldots, n$ and $Y < X$, if and only if $Y \le X$ and $y_i < x_i$ for at least one i).

Let $\mathbf{F} = \{F | F$ satisfies constraints (1) and (2)$\}$. Given any $F \in \mathbf{F}$, we generate a capacity vector $X_F = (x_1, x_2, \ldots, x_n)$ in terms of the flow vector F, where the capacity of a_i is determined by

$$x_i = \sum_{j=1}^{m} \{f_j | a_i \in ml_j\}. \tag{3}$$

Let $\Omega = \{X_F | F \in \mathbf{F}\}$ and $\Omega_{\min} = \{X | X$ is $\le$ w.r.t. in $\Omega\}$. That is, $\Omega_{\min}$ is the set of lower boundary points for d. Suppose all MLPs have been pre-computed. Then, all lower boundary points for d can be derived by the following steps:

Step 1: Find all feasible solutions $F = (f_1, f_2, \ldots, f_m)$ of the constraints (1) and (2).
Step 2: Transform each F into $X_F = (x_1, x_2, \ldots, x_n)$ via (3), to get Ω.
Step 3: Remove the non-minimal ones in Ω to obtain $\Omega_{\min}$.

3.4. **Network reliability evaluation.** Network reliability R_d is the probability that the maximum flow is not less than d, i.e., $R_d \equiv \Pr\{X | V(X) \ge d\} \equiv \Pr\{X | X \ge X_i$ for a lower boundary point X_i for $d\}$, given, X_1, X_2, …, X_h, the set of minimal capacity vectors capable of satisfying demand d. Therefore, network reliability R_d is

$$R_d = \Pr\left\{\bigcup_{v=1}^{h} D_v\right\}, \tag{4}$$

where $D_v = \{X|X \geq X_v\}$, $v = 1, 2, \ldots, h$. Several methods such as the RSDP algorithm [10], the inclusion-exclusion method [11,15], the disjoint-event method [25], and state-space decomposition [12,13], may be applied to compute R_d. The RSDP algorithm has better computational efficiency to compute the network reliability here. It calculates the probability of a union with r vectors in terms of the probabilities unions with $(r-1)$ vectors or less by using a special maximum operator [10] "$\oplus$", which is defined as

$$X_{1,2} = X_1 \oplus X_2 \equiv (\max(x_{1i}, x_{2i})), \text{ for } i = 1, 2, \ldots, n. \tag{5}$$

For example, if $X_1 = (2, 2, 1, 1, 0)$ and $X_2 = (3, 0, 1, 0, 1)$, $X_{1,2} = X_1 \oplus X_2 = (\max(2, 3), \max(2, 0), \max(1, 1), \max(1, 0), \max(0, 1)) = (3, 2, 1, 1, 1)$. The RSDP algorithm is presented as follows.

RSDP algorithm //Calculate the network reliability R_d for $\Omega_{\min}$
function R_d = RSDP($X_1, X_2, \ldots, X_h$) //Input h vectors of $\Omega_{\min} \equiv (X_1, X_2, \ldots, X_h)$ and connection probability of each LPS

```
for   i = 1 : h
      if  i == 1
         R_d = Pr(X ≥ X_i);
      else
         Temp_RD_1 = Pr(X ≥ X_i);
         If  i == 2
            Temp_RD_2 = Pr(X ≥ max(X_1, X_i)); //max(X_1, X_i) = (X_1 ⊕ X_i)
         else
            for j = 1 : i − 1
               X_j = max(X_j, X_i); //max(X_j, X_i) = (X_j ⊕ X_i)
            end
            Temp_RD_2 = RSDP (X_1, X_2, ..., X_{i−1});
         end
      end
      R_d = R_d + (Temp_RD_1) − (Temp_RD_2);
```

4. Case Study: TWAREN between Taiwan and the U.S. Through the Light Path.

4.1. Level of demand and MLPs from Taipei to New York.

To calculate TWAREN's network reliability from Taipei to New York, there must be a reasonable demand level. For each arc's capacity, each LP occupies a bandwidth 622 Mb, and each 622 Mb bandwidth has four 155 Mb channels. We regard each 155 Mb as one unit. Therefore, there are four units in each 622 Mb LP channel. Thus, for each LP, we have two capacity states, zero units (failure) and four units (success). As the LPS in each physical line is either connected or disconnected, it is in a binary state.

Since there are four arcs besides New York, we try to compute the network reliability of demand level of $d = 4$ (resp. 3, 2) 622 Mb (i.e., $d = 16$ (resp. 12, 8) units) from Taipei to New York. Mainly, we want to calculate the network reliability from Taipei to New York of demand level $d = 16$ (resp. 12, 8) units of data. In this case, there are 10 MLPs from n_1 (Taipei) to n_9 (New York) as shown in Table 1.

4.2. Probability of all LPSs breaking.

To compute the connection probability of each PL, we use the disconnection data from 2008 through 2011. The longest duration of every break for each physical line during the 168 hours of every week is used to determine the disconnection probability of each line. For example, as the physical line P_{10} from San Francisco to Chicago broke for 403 minutes on 2010/5/25, its connection probability is

TABLE 1. All MLPs from Taipei (n_1) to New York (n_9)

MLP #	Light Paths Combination	Nodes & LPSs Combination Flow
ml_1	Taipei→LP_1 →Chicago→LP_{10} →New York	$n_1 \to l_{1,1} \to n_2 \to l_{1,2} \to n_6 \to l_{1,3} \to n_8 \to l_{10,1} \to n_9$
ml_2	Taipei→LP_1 →Chicago→LP_{13} →New York	$n_1 \to l_{1,1} \to n_2 \to l_{1,2} \to n_6 \to l_{1,3} \to n_8 \to l_{13,1} \to n_9$
ml_3	Taipei→LP_4 →Chicago→LP_{10} →New York	$n_1 \to l_{4,1} \to n_2 \to l_{4,2} \to n_5 \to l_{4,3} \to n_6 \to l_{4,4} \to n_8 \to l_{10,1} \to n_9$
ml_4	Taipei→LP_4 →Chicago→LP_{13} →New York	$n_1 \to l_{4,1} \to n_2 \to l_{4,2} \to n_5 \to l_{4,3} \to n_6 \to l_{4,4} \to n_8 \to l_{13,1} \to n_9$
ml_5	Taipei→LP_3 →New York	$n_1 \to l_{3,1} \to n_2 \to l_{3,2} \to n_3 \to l_{3,3} \to n_7 \to l_{3,4} \to n_9$
ml_6	Taipei→LP_2 →Los Angeles→LP_{12} → New York	$n_1 \to l_{2,1} \to n_2 \to l_{2,2} \to n_3 \to l_{2,3} \to n_4 \to l_{2,4} \to n_7 \to l_{12,1} \to n_9$
ml_7	Taipei→LP_2 →Los Angeles→LP_{11} → Chicago→LP$_{10}$ →New York	$n_1 \to l_{2,1} \to n_2 \to l_{2,2} \to n_3 \to l_{2,3} \to n_4 \to l_{2,4} \to n_7 \to l_{11,2} \to n_6 \to l_{11,1} \to n_8 \to l_{10,1} \to n_9$
ml_8	Taipei→LP_2 →Los Angeles→LP_{11} → Chicago→LP_{13} →New York	$n_1 \to l_{2,1} \to n_2 \to l_{2,2} \to n_3 \to l_{2,3} \to n_4 \to l_{2,4} \to n_7 \to l_{11,2} \to n_6 \to l_{11,1} \to n_8 \to l_{13,1} \to n_9$
ml_9	Taipei→LP_1 →Chicago→LP_{11} → Los Angeles→LP_{12} →New York	$n_1 \to l_{1,1} \to n_2 \to l_{1,2} \to n_6 \to l_{1,3} \to n_8 \to l_{11,1} \to n_6 \to l_{11,2} \to n_7 \to l_{12,1} \to n_9$
ml_{10}	Taipei→LP_4 →Chicago→LP_{11} → Los Angeles→LP_{12} →New York	$n_1 \to l_{4,1} \to n_2 \to l_{4,2} \to n_5 \to l_{4,3} \to n_6 \to l_{4,4} \to n_8 \to l_{11,1} \to n_6 \to l_{11,2} \to n_7 \to l_{12,1} \to n_9$

TABLE 2. All physical lines and LPSs' connection probability

PL#	LPS in this PL	Disconnection Starting Time	Disconnection Ending Time	Disconnection Duration	Connection Probability (t = a week = 4032 mins)	Root Caused
P_1	$l_{1,1}$; $l_{2,1}$; $l_{3,1}$; $l_{4,1}$	2011/4/21 10:17:00 AM	2011/4/21 11:56:00 AM	99 mins	$t-99/t = 0.98$	Circuit Broken
P_2	$l_{2,2}$; $l_{3,2}$	N/A	N/A	N/A	1	No
P_3	$l_{2,3}$	N/A	N/A	N/A	1	No
P_4	$l_{1,2}$	2010/9/28 10:08:00 AM	2010/9/28 02:07:00 PM	239 mins	$t-239/t = 0.94$	Card Broken
P_5	$l_{4,2}$	2011/4/21 22:01PM	2011/4/22 04:29:00 AM	388 mins	$t-388/t = 0.90$	Circuit Broken
P_6	$l_{4,3}$	2009/5/29 05:16AM	2009/5/29 08:27:00 AM	191 mins	$t-191/t = 0.95$	Circuit Broken
P_7	$l_{3,3}$	2009/9/16 04:40:00 PM	2009/9/16 05:01:00 PM	211 mins	$t-211/t = 0.99$	Circuit Broken
P_8	$l_{2,4}$	2011/3/11 01:53:00 PM	2011/3/12 01:37:00 AM	704 mins	$t-704/t = 0.83$	Japan Earth-quake
P_9	$l_{11,2}$	2011/2/17 01:19:00 AM	2011/2/17 03:33:00 AM	134 mins	$t-134/t = 0.97$	Card Disable
P_{10}	$l_{1,3}$; $l_{4,4}$; $l_{11,1}$	2010/5/25 04:28:00 AM	2010/5/25 11:11:00 AM	403 mins	$t-403/t = 0.90$	Circuit Broken
P_{11}	$l_{3,4}$; $l_{12,1}$	2009/3/21 08:58:00 PM	2009/3/22 03:23:00 AM	385 mins	$t-385/t = 0.90$	Card Disable
P_{12}	$l_{10,1}$; $l_{13,1}$	2011/2/8 01:17:00 AM	2011/2/8 11:07:00 AM	590 mins	$t-590/t = 0.85$	Card Disable

TABLE 3. LPS $l_{i,j}$ re-denoted by a_i, and its connection probability same with physical line P_i that it located

A	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}	a_{19}	a_{20}
LPS	$l_{1,1}$	$l_{1,2}$	$l_{1,3}$	$l_{2,1}$	$l_{2,2}$	$l_{2,3}$	$l_{2,4}$	$l_{3,1}$	$l_{3,2}$	$l_{3,3}$	$l_{3,4}$	$l_{4,1}$	$l_{4,2}$	$l_{4,3}$	$l_{4,4}$	$l_{10,1}$	$l_{11,1}$	$l_{11,2}$	$l_{12,1}$	$l_{13,1}$
Prob	0.98	0.94	0.9	0.98	1	1	0.83	0.98	1	0.99	0.9	0.98	0.9	0.95	0.9	0.85	0.9	0.97	0.9	0.85

$(168 \times 60 - 403)/(168 \times 60) = 0.90$. Therefore, its disconnection probability is $(1 - 0.9) = 0.1$. All the LPSs $l_{1,3}$, $l_{4,4}$ and $l_{11,1}$ located in this physical line P_{10} have the same disconnection probability of 0.1.

Table 2 shows all LPSs' connection probability after screening all physical lines' disconnection records and selecting the longest broken time for each. These breaks include disabled card devices, circuit failures, and breaks from the March 11, 2011 Japanese earthquake and tsunami that caused the physical submarine line P_8 to break. This line uses a submarine cable connection between TP-3 and Los Angeles. Artificial, devices, short circuits, and natural disasters simultaneously influence TWAREN's network reliability from Taipei to New York. Since each failure of a node device has been included and recorded in the physical line's disconnection record, each node is supposed to be perfect with a reliability of 1. For computational convenience, as described in Section 3.3, we converted LPS $l_{i,j}$ by using a_i and the probability of a_i, as shown in Table 3.

4.3. **Network reliability from Taipei to New York.** When line breaks occur, the suppliers of these pass-through physical lines provide all serviceable lines as backup lines, therefore increasing the network reliability. In this study, we do not discuss the backup lines, and concentrate only on the regular lines to determine those factors that affect their network reliability. First, we focus on the case demand level $d = 8$ units, given all MLPs in Table 1 and by using the algorithm in Section 3.3 as follows:

Step 1: Find all feasible MLP solutions F that satisfy constraints (6) and (7).

$$\begin{aligned} &f_1 + f_2 + f_9 \leq M^1 = 4, \\ &f_1 + f_2 + f_9 \leq M^2 = 4, \\ &\vdots \\ &f_6 + f_9 + f_{10} \leq M^{19} = 4, \\ &f_2 + f_4 + f_8 \leq M^{20} = 4, \end{aligned} \tag{6}$$

and

$$f_1 + f_2 + \cdots + f_{10} = d = 8. \tag{7}$$

In this step, each f_i has only two values, say 0 and 4, standing for the two capacity states of failure or success. From this, we obtain 23 flow vectors as shown in Table 4 (column 1).

Step 2: Transform each F into an LPS X, to get Ω by (8).

For $F_1 = (0, 0, 0, 0, 4, 0, 0, 0, 0, 4)$, the capacity vector X_1 is transformed by

$$\begin{aligned} &x_1 = f_1 + f_2 + f_9 = 0 + 0 + 0 = 0, \\ &x_2 = f_1 + f_2 + f_9 = 0 + 0 + 0 = 0, \\ &\vdots \\ &x_{19} = f_6 + f_9 + f_{10} = 0 + 0 + 4 = 4, \text{ and} \\ &x_{20} = f_2 + f_4 + f_8 = 0 + 0 + 0 = 0. \end{aligned} \tag{8}$$

Thus, $X_1 = (0, 0, 0, 0, 0, 0, 0, 4, 4, 4, 4, 4, 4, 4, 4, 0, 4, 4, 4, 0)$. Similarly, we obtain 23 capacity vectors as shown in Table 4 (column 2).

Step 3: Remove those non-minimal ones to obtain $\Omega_{\min}$. The lower boundary points for $d = 8$ are X_1, X_2, $\ldots$, X_{18}.

For computing its network reliability, we input the following parameters: demand d, connection probability and capacity of each LPS, and given all MLP by using above algorithm to get the minimal capacity vectors. In terms of RSDP [10], we output the network reliability $R_8 = 0.9710$ for $d = 8$. Similarly, we obtain $R_{12} = 0.7815$ and $R_{16} = 0.2887$ for the cases $d = 12$ and $d = 16$, respectively. The network reliability can be observed decrease as the total demand increases, as shown in Figure 4.

In regard to QoS, this is only a concern when there are insufficient networks resources. When there are enough resources and demand is low, for instance, as above with $d = 8$

Table 4. Results of example

F	X	$\Omega_{\min}$ or not?	Remark
$F_1 = (0,0,0,0,4,0,0,0,0,4)$	$X_1 = (0,0,0,0,0,0,0,4,4,4,4,4,4,4,4,0,4,4,4,0)$	Yes	–
$F_2 = (0,0,0,0,4,0,0,0,4,0)$	$X_2 = (4,4,4,0,0,0,0,4,4,4,4,0,0,0,0,0,4,4,4,0)$	Yes	–
$F_3 = (0,0,0,0,4,0,0,4,0,0)$	$X_3 = (0,0,0,4,4,4,4,4,4,4,4,0,0,0,0,0,4,4,0,4)$	Yes	–
$F_4 = (0,0,0,0,4,0,4,0,0,0)$	$X_4 = (0,0,0,4,4,4,4,4,4,4,4,0,0,0,0,4,4,4,0,0)$	Yes	–
$F_5 = (0,0,0,0,4,4,0,0,0,0)$	$X_5 = (0,0,0,4,4,4,4,4,4,4,4,0,0,0,0,0,0,0,4,0)$	Yes	–
$F_6 = (0,0,0,4,0,0,0,0,4,0)$	$X_6 = (0,0,0,4,4,4,4,0,0,0,0,4,4,4,4,0,0,0,4,4)$	Yes	–
$F_7 = (0,0,0,4,0,0,4,0,0,0)$	$X_7 = (0,0,0,0,0,0,0,4,4,4,4,4,4,4,4,0,0,0,0,4)$	Yes	–
$F_8 = (0,0,0,4,0,4,0,0,0,0)$	$X_8 = (0,0,0,4,4,4,4,0,0,0,0,4,4,4,4,4,4,4,0,4)$	Yes	–
$F_9 = (0,0,0,4,4,0,0,0,0,0)$	$X_9 = (0,0,0,4,4,4,4,0,0,0,0,4,4,4,4,4,0,0,4,0)$	Yes	–
$F_{10} = (0,0,4,0,0,0,0,0,4,0)$	$X_{10} = (0,0,0,0,0,0,0,4,4,4,4,4,4,4,4,4,0,0,0,0)$	Yes	–
$F_{11} = (0,0,4,0,0,0,0,4,0,0)$	$X_{11} = (4,4,4,0,0,0,0,0,0,0,0,4,4,4,4,0,4,4,4,4)$	Yes	–
$F_{12} = (0,0,4,0,0,4,0,0,0,0)$	$X_{12} = (4,4,4,4,4,4,4,0,0,0,0,0,0,0,0,0,0,0,4,4)$	Yes	–
$F_{13} = (0,0,4,0,4,0,0,0,0,0)$	$X_{13} = (4,4,4,0,0,0,0,4,4,4,4,0,0,0,0,0,0,0,0,4)$	Yes	–
$F_{14} = (0,4,0,0,0,0,0,0,0,4)$	$X_{14} = (4,4,4,0,0,0,0,0,0,0,0,4,4,4,4,4,4,4,4,0)$	Yes	–
$F_{15} = (0,4,0,0,0,0,4,0,0,0)$	$X_{15} = (4,4,4,4,4,4,4,0,0,0,0,0,0,0,0,4,4,4,0,4)$	Yes	–
$F_{16} = (0,4,0,0,0,4,0,0,0,0)$	$X_{16} = (4,4,4,4,4,4,4,0,0,0,0,0,0,0,0,4,0,0,4,0)$	Yes	–
$F_{17} = (0,4,0,0,4,0,0,0,0,0)$	$X_{17} = (4,4,4,0,0,0,0,4,4,4,4,0,0,0,0,4,0,0,0,0)$	Yes	–
$F_{18} = (0,4,4,0,0,0,0,0,0,0)$	$X_{18} = (4,4,4,0,0,0,0,0,0,0,0,4,4,4,4,4,0,0,0,4)$	Yes	–
$F_{19} = (4,0,0,0,0,0,0,0,0,4)$	$X_{19} = (4,4,4,0,0,0,0,0,0,0,0,4,4,4,4,0,4,4,4,4)$	No	$X_{19} = X_{11}$
$F_{20} = (4,0,0,0,0,0,0,4,0,0)$	$X_{20} = (0,0,0,4,4,4,4,0,0,0,0,4,4,4,4,4,4,4,0,4)$	No	$X_{20} = X_8$
$F_{21} = (4,0,0,0,0,4,0,0,0,0)$	$X_{21} = (4,4,4,0,0,0,0,0,0,0,0,4,4,4,4,4,4,4,4,0)$	No	$X_{21} = X_{14}$
$F_{22} = (4,0,0,0,4,0,0,0,0,0)$	$X_{22} = (4,4,4,4,4,4,4,0,0,0,0,0,0,0,0,4,4,4,0,4)$	No	$X_{22} = X_{15}$
$F_{23} = (4,0,0,4,0,0,0,0,0,0)$	$X_{23} = (4,4,4,0,0,0,0,0,0,0,0,4,4,4,4,4,0,0,0,4)$	No	$X_{23} = X_{18}$

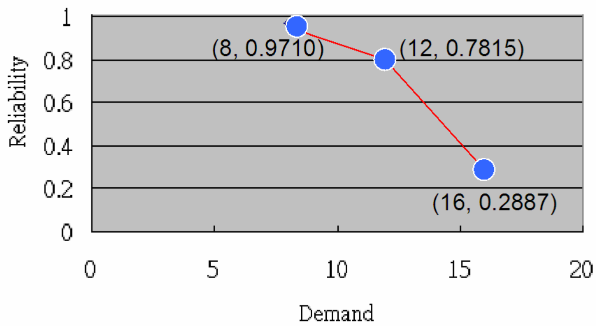

Figure 4. (Demand, reliability) for demand being 16, 12 and 8 units

units, there are still plenty of resources to handle other transmission requests, so the network reliability is quite high. On the other hand, if demand is high, say above $d = 16$ units, which is the maximum capacity, the network reliability will be low, since there are not enough resources to handle other data transmissions. To maintain the network reliability, it is important to avoid full transmission loads or increase line capacity. Depending on the results of our analysis, we may decide to allocate more economic resources to TWAREN to maximize future network utilities.

5. **Summary and Conclusion.** In this study we design an MLP-based network reliability evaluation technique for the international LP portion of TWAREN's academic and research network. This portion contains the domestic land surface line and the Asia Pacific submarine cables which connect to the global academic research network, including the Internet2 Network [17]. Since the LP cannot be divided through any of its nodes or LPSs during transmission, MLP is a new concept to evaluate the network reliability in an LP environment.

The main contribution of this work is to make real TWAREN data available for being analyzed in a stochastic-flow network model. Network reliability developed in this paper is a key performance index for NCHC that helps the supervisor of NCHC know how to improve the network performance. By using the MLP analysis technique, we can continuously adjust TWAREN's infrastructure to achieve higher network reliability and efficiency. In this study, we concentrate on the portion of the network that includes regular lines and does not include backup cables yet. This allows us to determine those factors that influence the dedicated regular lines' reliability. We also consider the effects of the earthquake that hit Japan on March 11, 2011. That is, we study all factors, including artificial, machine, and cable failures and natural disasters that simultaneously influence TWAREN's network reliability from Taipei to New York. In addition, the MLP reliability technique will enable us to increase the efficiency of TWAREN and help us to learn how to improve its network infrastructure and performance in the near future. Subsequently, we may study TWAREN's backup cable and dependent correlation factors of related regular lines that affect the network reliability.

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