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AN APPROACH TO REDUCE PATH-DEPENDENT-LOSS IN OPTICAL NETWORKS IMPLEMENTING PETRI NETS

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Abstract. The path-dependent loss and the switch crosstalks are two major challenges that arise in high-bandwidth and low-latency optical networks. In this paper we present an approach to cope with both challenges. The approach is based on determining minimum number of optical switches that is sufficient to perform desired communication patterns. We first represent an optical network with P/T-net and then use invariants method to check the reachability in P/T-nets. The approach is easy-to-use and can be expanded to various network topologies.

1 Introduction

The communication has become a critical issue the system designers must deal with to increase the performance of multiprocessors. The limits of current electronic communication technologies are already being pushed by multiprocessors. The research on optical communication however become more active and quite a number of choices for optical communication has been suggested. There is now a fairly clear understanding about the relative merits of electronics and optics in multiprocessor architecture that electronics is always best for data processing while optics is obviously preferable for data communication [12-14].

The two key choices for optical communication are all-optical and hybrid optical approaches. All-optical switching where both the controlling and the controlled signals are optical, is seemingly a long-term research item. In hybrid optical approach, which is based on use of dual technology (optical and electrical), the signals are optical but the control over the optical signals is carried out electronically. Despite the advantages such as the low-latency and high-bandwidth, the hybrid optical approach brings new problems into focus. For instance, optical signals usually become weak after passing through long connection path which may potentially cause signal distortion. This phenomenon is known as the *path-dependent loss* or *attenuation* [4,11,13]. In hybrid optical multistage interconnection network (OMIN), the path-dependent loss increases with increasing number of stages and consequently number of photonic switches (directional couplers) that the optical signal passes through [5]. One way to overcome this challenge is to design an OMIN with the minimum number of stages [3] that would be capable to establish desired communication patterns between network's inputs and outputs.

Each communication pattern in OMIN can be represented as a permutation π. An $N \times N$ OMIN performs a permutation $\pi : N \to N$ if there exists a setting of the switches in the OMIN such that the input terminal i is connected to the output terminal $\pi(i)$ for $0 \leq i < N$. The *permutation admissibility problem* is about determination whether an OMIN can perform a given permutation in a single pass [10]. A permutation is admissible to OMIN if conflict-free paths can be established for all input-output pairs simultaneously. More mathematically, an $N\times N$ permutation from the set of N inputs $\{0,\dots,N-1\}$ to the set of N outputs $\{0,\dots,N-1\}$ is *admissible*, if N conflict-free paths (one for each input-output pair) can be set up simultaneously in the OMIN. It has been reported [7-9] that the permutation admissibility problem for some OMIN topologies is somewhat equivalent to 2^k-colorability in graphs, which is NP-complete problem. The permutation admissibility problem has been investigated in [7-11].

In [3] an $O(Nn\log n)$ algorithm ($N=2^n$) is suggested to determine the minimum number of stages that is needed to perform arbitrary permutation in m-stage ($1\le m<n$) OMIN employing shuffle-exchange network topology.

In [1] we proposed an approach to analyze the permutation capacity problem in MINs that is based on modeling of multistage networks with colored Petri nets with further use of state spaces for reachability analysis in colored Petri nets. Another approach to analyze the permutation admissibility to OMINs was suggested in [2]. The idea was to represent OMIN as colored Petri net and use unfolding technique and invariants method to decide on permutation admissibility. In this work, we present another approach to determine minimum number of stages that is sufficient to perform a permutation in OMIN. Our approach is centered upon modeling OMINs with Petri nets and analyzing the reachability property in associated Petri nets. The main idea behind of present work is to reduce *the permutation admissibility problem in OMINs to the marking reachability problem in related Petri nets*. Further we use the invariants method to decide on reachability of desired markings. Our approach can be easily adapted to various OMIN topologies.

The paper is organized as follows. Section 2 gives background on path-dependent-loss and crosstalk in OMINs. Section 3 describes P/T-net model of (2×2)-switch and the way this model can be extended to create P/T-net model of OMIN made of (2×2) switches. Section 4 briefly explains the matrix invariants method for P/T-nets. Section 5 introduces the case study. Section 6 contains conclusions.

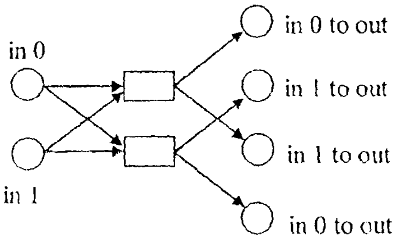

Figure 1: P/N-net model of (2×2)-switch.

2 Path-dependent-loss and switch crosstalk

Loss in optical fiber leads to a reduction of the signal power as the signal propagates over some distance. It has the following components: (1) propagation loss through the waveguide in a switch; (2) signal loss at waveguide bends; (3) signal loss at waveguide crossovers; (4) propagation loss in the medium; and (5) fiber-to-substrate and substrate-to-fiber coupling loss. Among those losses, the propagation loss through the switches is the major concern, and is proportional to the number of switches along an optical path.

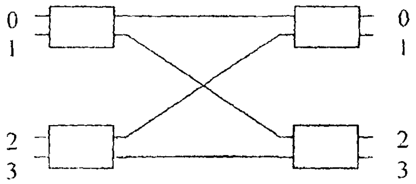

Figure 2: 4×4 2-stage OMIN.

Determining the minimum number of stages in an OMIN that is sufficient to generate a permutation also minimizes the number of switch crosstalks. Optical crosstalk is caused by the interaction between two signal channels. There are two kinds of optical crosstalk. One is switch crosstalk that is-caused when two paths sharing a switch experience some undesired coupling from one path to the other. The other one is waveguide crossover (or channel crossover) that occurs when the waveguides carrying the signals cross each other to embed a particular topology. It has been proved [15] that the number of crossovers in many switching networks could be greatly reduced through a topology transformation technique. And experimental results in [16] show that it is possible to make the crossover from passive intersections of optical waveguides negligible by keeping the intersection angles above a certain minimum amount.

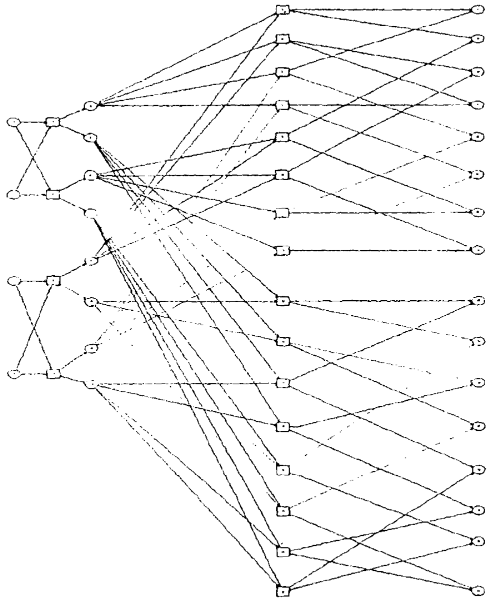

Figure 3: P/N-net of 4x4 2-stage network.

3 Creating the P/T-net model

Usually there are multiple choices at a model designer's disposal to follow up when creating a P/T-net model. The consistency of a P/T-net model being created is the issue of primary interest a model designer needs to pay attention at this stage needs.

Basic building block of any OMIN is a switch. P/T-net model of (2×2)-switch is illustrated in Figure 1. This model fully describes (2×2)-switch functionality. Both *straight* and *through* settings of (2×2)-switch can be obtained on this model.

The above described P/T-net can be easily extended to case of arbitrary OMIN. When designing a P/T-net of OMIN we need to arrange a place for each input to output mapping. As an example a P/T-net model of 4×4 2-stage OMIN (Figure 2) is shown in Figure 3.

4 Invariants method

For a P/T-net with n transitions and m places, the incidence matrix $A=(a_{ij})$ is an $n\times m$ matrix with integer entries defined as $a_{ij}=a_{ij}^{+}-a_{ij}^{-}$ where $a_{ij}^{+}=w(ij)$ is the weight of the arc from transition i to its output place j and $a_{ij}^{-}=w(ji)$ is the weight of the arc to transition i from its input place j. Each invariant in a P/T-net can be expressed as the system of linear algebraic equations called state equation

$$A^{T}\cdot x=M_d-M_0 \qquad (1)$$

where x is an $n\times 1$ column vector of nonnegative integers and is called the *firing count vector*, M_0 is the initial marking, and M_d is the destination marking. The ith entry of x denotes the number of times that transition i must fire to transform M_0 to M_d.

It has been reported [6] that the existence of a nonnegative integer solution x satisfying the state equation (1) is a necessary but, in general, not sufficient condition for M_d to be reachable from M_0. For acyclic P/T-nets the above condition is also sufficient.

Theorem 1. ([6]) In an acyclic P/T-net M_d is reachable from M_0, if and only if there exists a nonnegative firing count vector x satisfying the state equation (1).

In this work we use the state equation (1) to verify the reachability in acyclic P/T-nets. Given an acyclic P/T-net and two markings M_0 and M_d, we only need to write down related state equation and find nonnegative integer solution x of the state equation. If such x exists then M_d is reachable from M_0. Otherwise, it is not.

5 Case study

Consider a P/T-net (see Figure 3) of 4×4 2-stage network made of 2×2 stitches. The incidence matrix A is a matrix with 20 columns and 28 rows.

Assume that we want to check whether or not the permutations

$$\pi_1=\begin{pmatrix}0&1&2&3\\1&0&3&2\end{pmatrix}\text{and }\pi_2=\begin{pmatrix}0&1&2&3\\1&2&3&0\end{pmatrix}$$

are admissible to aforementioned OMIN. The initial marking and related destination markings are respectively described below:

$M_0=(1111000000000000000000000000)$,

$M_{\pi_1}=(0000000000000001001000011000)$,

$M_{\pi_2}=(0000000000000001010010001000)$.

$$A^T = \begin{bmatrix}
-1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 \\
0 & 0 & 1 & 0 & -1 & -1 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & -1 & -1 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & -1 & -1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & -1 & -1 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1
\end{bmatrix}$$

So, the two systems of algebraic equations are

$$A^T \cdot x = M_{\pi_1} - M_0, \quad (2)$$

$$A^T \cdot x = M_{\pi_2} - M_0. \quad (3)$$

Next we use integer programming software LINDO to solve aforementioned equations. The matrix equation (2) has no solution meaning that 4×4 2-stage network cannot generate the permutation π_1. However, the matrix equation (3) has a unique solution indicating that permutation π_2 can be generated by 4×4 2-stage network.

6 Conclusions

In present research, we propose a new approach to reduce the path-dependent-loss in hybrid optical networks. The approach is based on modeling of OMINs by P/T-nets with further reachability analysis by means of state equations. Using this approach we can determine minimum number of stages and switches in OMIN that is sufficient to perform communication patterns and therefore minimize the overall optical switch loss. By determining an optimal OMIN topology we also cope with number of switch crosstalks. The proposed approach is applicable to various OMIN topologies.

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