

OPTICAL WDM NETWORK DYNAMICS: AN ANALYTICAL APPROACH WITH APPLICATIONS TO ROBUST NETWORK DESIGN

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Abstract This paper presents an analytical approach for studying dynamics in optical networks. The approach is based on recasting the problem into the general modeling and simulation framework of control theory. General results on the transfer matrix representation for an optical network are developed and particularized to different optical network configurations. Explicit dependence of channel cross-coupling on different network parameters is shown. Applicability of these theoretical results to handling of sudden network failures, as well as to robust optical network design and management is presented.

Keywords: optical networks, dynamics, stability, robust design.

1 Introduction

Applications of methodologies from communication, information, control and optimization theory are becoming enablers of the future generation optical networks. These networks should be dynamic, robust and resilient, capable of handling various disturbances, such as planned on-line network reconfiguration or unplanned sudden failures. This evolution from *point-to-point, static* optical links to *mesh, reconfigurable* optical networks (Figure 1), leads to the need to study them in a dynamic context, with the physical-layer effects properly considered, [1], [2].

An important step forward towards developing future dynamic, robust optical networks is the understanding, analysis and control of dynamic phenomena in optical networks. These are challenging problems for these large-scale, complex systems, and most results are based solely on simulation or experimental studies. Recent studies, [7], [8], [9], have shown that, at network reconfiguration or at failures, sudden power changes on some channels, can cause abrupt power changes on other channels, followed by transient fluctuations. Moreover, these fluctuations have a bursty behavior that can lead in some case even to sustained power fluctuations in the network. This behavior was observed in simulations and experiments only, and based on this, heuristic rules developed for avoiding it. Unfortunately there are no systematic methodolo-

gies for dynamic network analysis and design. This observation highlights the need for theoretical understanding of optical network dynamics, together with modeling and simulation as a prerequisite for developing such methodologies.

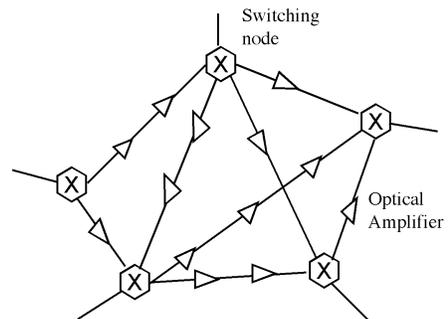


Figure 1: Optical communication network - mesh

In this paper we address this problem by means of modeling the optical network in a transfer matrix form, and then analytically investigating cross-coupling effects between groups of channels. We show an explicit dependence of the cross-coupling on different network parameters, such as the number of elements on the path, individual element transfer matrix (time-constant), as well as on the propagation path time-delay. We discuss the applicability of these theoretical results to handling of sudden network failures, as well as to robust optical network design and management.

This analytical approach to network dynamics fills in the gap between the physical-layer (optical transmission design), and the network layer (where typically an ideal physical-layer is assumed), and it is of interest for future reconfigurable networks, where closed-cycles affected by time-delay can be formed, [3].

2 Modeling of Optical Communication Network

Optical WDM networks are complex systems that encompass tens of optical devices and network ele-

ments, each with its own dynamic properties. Figure 2 shows a typical network configuration, representative of quasi-ring optical paths extracted from a mesh topology (Figure 1), with add/drop realized via optical add/drop multiplexers (OADM). Channels are grouped into two wavelength sets, λ_1 and λ_2 , each with m_1 and m_2 channels

$$\lambda_1 = \{\lambda_{1,1}, \dots, \lambda_{1,m_1}\}, \lambda_2 = \{\lambda_{2,1}, \dots, \lambda_{2,m_2}\} \quad (1)$$

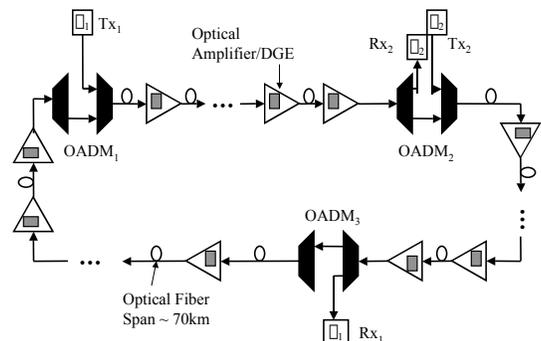


Figure 2: Optical communication network: quasi-ring

Channels λ_1 are added at the Tx_1 site (OADM₁) and dropped at the Rx_1 site (OADM₃). Channels λ_2 are added at the Tx_2 site (OADM₂) and dropped at the Rx_2 site (OADM₂). Let u and y denote the network input and output optical power vectors (Figure 2), with

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}, y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, u_{1,2}, y_{1,2} \in R^{m_{1,2}} \quad (2)$$

partitioned according to the two wavelength sets, λ_1 and λ_2 . For a linear system described by the transfer matrix $G(s)$, $y = G(s)u$, with u, y as in (2), we define a related system, \tilde{G} ,

$$\tilde{y} = \tilde{G}u, \quad \tilde{y} = \begin{bmatrix} y_2 \\ y_1 \end{bmatrix}, \quad \tilde{G} = \begin{bmatrix} 0 & I_{m_2} \\ I_{m_1} & 0 \end{bmatrix} G \quad (3)$$

such that \tilde{G} maps u to the reversed output vector \tilde{y} .

In the following we present theoretical results on optical network modeling, in two alternative formulations. Generic models are used that are technology-independent, while at the same time capturing the essential device characteristics.

An optically amplified span consists of optical fiber and either in-line optical amplifiers (OA) or optical dynamic amplifiers (ODA) (Figure 2). OAs are based on Erbium-doped fiber amplifier (EDFA), [4], and have active control for maintaining total output power or total gain constant. An OA is described by a transfer matrix, G_{OA} , modeled as a feedback interconnection, or linear fractional transformation (F_l), between the linearized model of an EDFA and a controller $K(s)$, $G_{OA}(s) = F_l(EDFA, K)$. The resulted G_{OA} is a multi-input multi-output (MIMO), square

transfer matrix, [4], [6] with diagonal terms having a high-pass behavior, and off-diagonal terms having a low-pass behavior, with typical time-constants are on the order of 1 - 10 ms.

Optical dynamic amplifiers (ODA) are realized by combining optical amplifiers (OA) with dynamic gain equalizer filters (DGE). DGEs are used for equalizing wavelength channel powers, [5], [6]. A linearized model of the ODA, G_{ODA} , is developed as a feedback interconnection of the OA, with a MIMO diagonal controller, $K_{DGE}(s)$ on the feedback path, [6],

$$G_{ODA}(s) = G_{OA}(s)(I_m + K_{DGE}(s)G_{OA}(s))^{-1} \quad (4)$$

$$K_{DGE}(s) = \begin{bmatrix} K_1(s) & \dots & 0 \\ & \ddots & \\ 0 & \dots & K_m(s) \end{bmatrix}$$

Across an optical span, the optical signals experience optical loss, typically the same for all channels, and incorporated into the ODA model, and propagation time-delay. All channels transmitted across an optical link experience the same propagation time-delay, $\tau_i = \tau$, for $i = 1, \dots, m$. Therefore the following relation holds in the frequency domain between the input and output of an optical fiber

$$y_s(s) = \mathcal{D}_\tau(s)u_s(s), \quad \mathcal{D}_\tau(s) = e^{-\tau s}I_m \quad (5)$$

Let the k^{th} optical span be described by an overall MIMO ($m \times m$) transfer matrix, $G_{(k)}(s)$, that combines transfer matrices of optical amplifiers (OA), optical dynamic amplifier (ODA) and optical fiber. The overall span transfer matrix, including the delay, (5), is given as

$$G_{\mathcal{D},(k)}(s) = G_{(k)}(s)\mathcal{D}_\tau(s) \quad (6)$$

The transfer matrix of an optical link with several cascaded optical spans is given next, [10].

Lemma 1 : *Let an optical communication link be realized by a series interconnection of N optical spans, each span having a transfer matrix, $G_{\mathcal{D},(k)}(s)$, (6), corresponding to a time-delay τ per span. The optical communication link has a transfer matrix $S_{\mathcal{D}}(s)$ given as*

$$S_{\mathcal{D}}(s) = \mathcal{D}_N(s)S(s) \\ S(s) = \prod_{k=1}^N G_{(k)}(s), \quad \mathcal{D}_N(s) = e^{-(N\tau)s}I_m$$

Note that Lemma 1 evidences an explicit dependence of the link transfer matrix on the number of elements on the path, N , individual element transfer matrix, $G_{(k)}(s)$, and hence time-constant, as well as on the propagation path time-delay, $N\tau$.

Next we find a general expression for the network transfer matrix. Let the network be characterized by a set of nodes, a set of links $\mathcal{L} = \{1, \dots, L\}$ connecting the nodes, and by $\mathcal{M} = \{1, \dots, m\}$ a set of sources

(channels). Each optical communication link l is realized by cascading N_l optical spans and is described by a $(m \times m)$ link transfer matrix $S_{\mathcal{D},l}(s)$ (see Lemma 1).

The input to each link is either from optical sources (Tx) or from other links via the OADM sites. As in a general network topology, [11], assume that there is a source-to-link connection/routing matrix F_l , of dimensions $(L \times m)$ that maps source channels to links, such that for any $i \in \mathcal{M}, l \in \mathcal{L}$

$$F_{l,i} = \begin{cases} 1, & \text{if channel source } i \text{ is connected to link } l \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

Similarly, define an $(m \times m)$ link-to-link interconnection matrix, $H_{l,j}$, that associates link j^{th} output to link l^{th} input. For all $l, j \in \mathcal{L}$, $H_{l,j}$ is a diagonal matrix with the diagonal element

$$h_{l,j}(i) = \begin{cases} 1, & \text{if channel } i, \text{ link } j \text{ is connected to link } l \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

The following result gives the transfer matrix for a generic configuration optical network.

Theorem 2 : *The transfer matrix, \mathcal{T} , of an optical network in Figure 1 (or Figure 2) is*

$$\mathcal{T}(s) = J_x (I_{mL} - S_{\mathcal{D},x}(s)H_x)^{-1} S_{\mathcal{D},x}(s) F_x u \quad (9)$$

where F_x , H_x , and J_x are source, link and output connection matrices, respectively, and $S_{\mathcal{D},x}(s)$ is the block diagonal matrix of link transfer matrices.

Proof: Recall that the network has m channels, with the network input vector denoted $u = [u_1, \dots, u_m]^T$. Denote by u_{L_l} , the l^{th} link input vector, and by y_{L_j} the j^{th} link output vector

$$u_{L_l} = [u_{L_{l,1}}, \dots, u_{L_{l,m}}]^T, y_{L_j} = [y_{L_{j,1}}, \dots, y_{L_{j,m}}]^T \quad (10)$$

Also define the augmented mL -dimensional input and output vectors, u_L and y_L ,

$$u_L = [u_{L_1}, \dots, u_{L_L}]^T, y_L = [y_{L_1}, \dots, y_{L_L}]^T \quad (11)$$

Then using the above notation and (7, 8) we can write for the l^{th} link input vector u_{L_l} connected to the network input u and the link outputs

$$u_{L_l} = F_l u + \sum_{j \in \mathcal{L}} H_{l,j} y_{L_j} \quad (12)$$

$$F_l = \begin{bmatrix} F_{l,1} & \cdots & 0 \\ & \ddots & \\ 0 & \cdots & F_{l,m} \end{bmatrix} H_{l,j} = \begin{bmatrix} h_{l,j}(1) & \cdots & 0 \\ & \ddots & \\ 0 & \cdots & h_{l,j}(m) \end{bmatrix}$$

Using (11, 12) we can write for the augmented link inputs in a matrix form

$$u_L = F_x u + H_x y_L \quad (13)$$

where F_x , H_x are full block matrices for source-to-link and for link-to-link interconnection, respectively. H_x is a $(mL \times mL)$ block-matrix with the (l, j) block equal to $H_{l,j}$, (8), and the diagonal blocks being identically null matrices, $H_{j,j} = 0$. F_x is a $(mL \times m)$ matrix with the l^{th} row block equal to F_l , (12), so that $F_x = [F_1^T \dots F_L^T]^T$.

From Lemma 1, for the output vector of link l we have $y_{L_l} = S_{\mathcal{D},l}(s)u_{L_l}$, where $S_{\mathcal{D},l}(s)$ is the $(m \times m)$ transfer matrix including the delay contribution.

Therefore $y_L(s) = S_{\mathcal{D},x}(s)u_L(s)$ with

$$S_{\mathcal{D},x}(s) = \begin{bmatrix} S_{\mathcal{D},1}(s) & \cdots & 0 \\ & \ddots & \\ 0 & \cdots & S_{\mathcal{D},L}(s) \end{bmatrix} \quad (14)$$

where y_L is defined in (11) and $S_{\mathcal{D},x}(s)$ is a $(mL \times mL)$ block diagonal matrix of link transfer matrices. Substituting (13) into (14) we obtain

$$y_L(s) = (I_{mL} - S_{\mathcal{D},x}(s)H_x)^{-1} S_{\mathcal{D},x}(s) F_x u$$

Define link-to-output connection matrix J_x , so that network output y is related to the augmented output y_L as

$$y = J_x y_L \quad (15)$$

From (2, 15) we see that $y = \mathcal{T} u$, with \mathcal{T} as in (9) and the result is proved. ■

Remark 1: This is a general representation with a very large dimensionality, i.e., $(mL \times mL)$. Depending on the specific configuration it can result in simplified reduced order models, as shown next for the configuration in Figure 2.

Let $P_{\mathcal{D}}$, $Q_{\mathcal{D}}$ and $X_{\mathcal{D}}$ be the optical link transfer matrices in Figure 2, given as in Lemma 1. Recall that u and y , (2), are the network input and output optical power vectors, partitioned for the two sets, λ_1 and λ_2 , (1). Then the equivalent diagram for Figure 2 is shown in Figure 3.

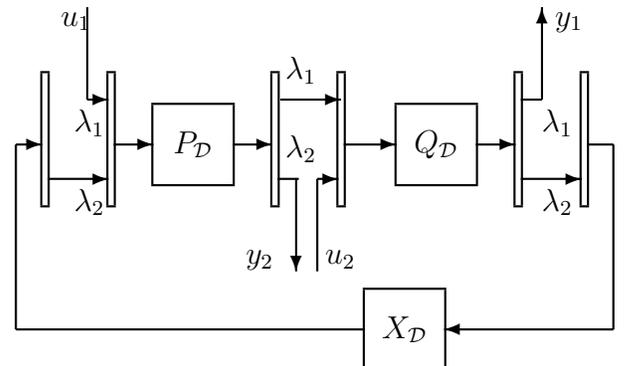


Figure 3: Network: Block-Diagram

Theorem 3 : Consider the optical network in Fig. 2 or Fig. 3. For the optical link transfer matrices $P_{\mathcal{D}}$, $Q_{\mathcal{D}}$, and $X_{\mathcal{D}}$, partitioned according to the two wavelength sets

$$P_{\mathcal{D}} = \begin{bmatrix} P_{\mathcal{D},11} & P_{\mathcal{D},12} \\ P_{\mathcal{D},21} & P_{\mathcal{D},22} \end{bmatrix}, \quad Q_{\mathcal{D}} = \begin{bmatrix} Q_{\mathcal{D},11} & Q_{\mathcal{D},12} \\ Q_{\mathcal{D},21} & Q_{\mathcal{D},22} \end{bmatrix}$$

the transfer matrix, \mathcal{T} , of the optical network in Fig. 2, $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathcal{T} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$, is given as $\mathcal{T} = \begin{bmatrix} \mathcal{T}_{11} & \mathcal{T}_{12} \\ \mathcal{T}_{21} & \mathcal{T}_{22} \end{bmatrix}$ with

$$\begin{aligned} \mathcal{T}_{11} &= Q_{\mathcal{D},11} \Psi_{\mathcal{D}} P_{\mathcal{D},11} \\ \mathcal{T}_{12} &= Q_{\mathcal{D},12} + Q_{\mathcal{D},11} P_{\mathcal{D},12} \tilde{\Psi}_{\mathcal{D}} X_{\mathcal{D}} Q_{\mathcal{D},22} \\ \mathcal{T}_{22} &= P_{\mathcal{D},22} \tilde{\Psi}_{\mathcal{D}} X_{\mathcal{D}} Q_{\mathcal{D},22} \\ \mathcal{T}_{21} &= P_{\mathcal{D},21} + P_{\mathcal{D},22} X_{\mathcal{D}} Q_{\mathcal{D},21} \Psi_{\mathcal{D}} P_{\mathcal{D},11} \end{aligned} \quad (16)$$

and

$$\begin{aligned} \Psi_{\mathcal{D}} &= (I - P_{\mathcal{D},12} X_{\mathcal{D}} Q_{\mathcal{D},21})^{-1} \\ \tilde{\Psi}_{\mathcal{D}} &= (I - X_{\mathcal{D}} Q_{\mathcal{D},21} P_{\mathcal{D},12})^{-1} \end{aligned} \quad (17)$$

Proof:

The proof can follow by applying Theorem 2 and finding the specific matrices H_x , J_x , F_x for Figure 3.

Also, note that Figure 3 is equivalent to the interconnected system in Figure 4. This is seen by switching the two vector outputs of $P_{\mathcal{D}}$, and using the reversed output system, $\tilde{P}_{\mathcal{D}}$, as in (3), i.e.,

$$\begin{bmatrix} y_2 \\ \xi_1 \end{bmatrix} = \tilde{P}_{\mathcal{D}} \begin{bmatrix} u_1 \\ v_2 \end{bmatrix} \quad (18)$$

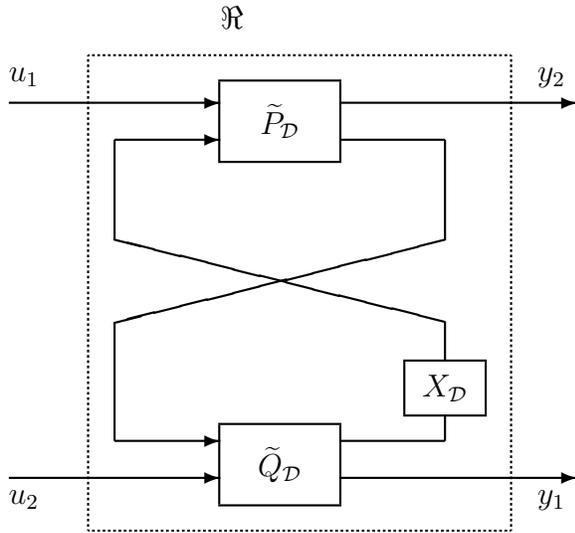


Figure 4: Network Representation in Star-Product Configuration

The closed-loop system in Figure 4 is described by a standard transformation used in control theory, [12], called the Redheffer star-product, \mathfrak{R} ,

$$\begin{bmatrix} y_2 \\ y_1 \end{bmatrix} = \mathfrak{R} \left(\begin{bmatrix} \tilde{P}_{\mathcal{D}} & \tilde{R}_{\mathcal{D}} \end{bmatrix} \right) \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

where $\tilde{R}_{\mathcal{D}}$ is defined as

$$\tilde{R}_{\mathcal{D}} = \begin{bmatrix} X_{\mathcal{D}} & 0 \\ 0 & I_{m_1} \end{bmatrix} \tilde{Q}_{\mathcal{D}} \quad (19)$$

and $\tilde{P}_{\mathcal{D}}$ and $\tilde{Q}_{\mathcal{D}}$ are link reversed output systems. ■

Remark 2: The result in Theorem 3 shows the explicit dependence of the optical communication network dynamics on the coupling between the two groups of wavelengths, and on the total time-delay across the network. This cross-coupling between group 1 and 2 of channels is described by \mathcal{T}_{12} , directly dependent on the link transfer matrices, $P_{\mathcal{D}}$, $Q_{\mathcal{D}}$. Time-delay feedback effects appear due to the feedback term $X_{\mathcal{D}}$. Explicit dependence of network stability on the feedback terms, $\Psi_{\mathcal{D}}$, $\tilde{\Psi}_{\mathcal{D}}$ is also shown. The distributed time-delay in (16) can be lumped along a path using the results in Lemma 1, so that

$$\mathcal{T}_{12} = \mathcal{D}^{N_2} (Q_{12} + \mathcal{D}^{N_t} Q_{11} P_{12} \tilde{\Psi}_{\mathcal{D}} X Q_{22})$$

where $\mathcal{D}^{N_t} = e^{-N_t \tau}$, with $N_t = N_1 + N_2 + N_3$ being the total number of optical spans, and $\tau_t = N_t \tau$, the total propagation delay across the network.

3 Network Dynamics for Special Cases and for Sudden Failures

The theoretical results will be specialized to particular optical network configurations and applied to transient optical network dynamics.

- **Two OADM nodes configuration:** This is a special case of Figure 2 (Figure 3), with add/drop being done at the same site (OADM1 and OADM3 collapsed), that can be obtained by setting $X_{\mathcal{D}} = I_{m_2}$ in Figure 3 and Theorem 3.
- **Four OADM nodes configuration:** This is case where each of the two groups is added and dropped at a different node, respectively, that can also be reduced to Figure 2 (Figure 3). In fact, this case corresponds to group λ_1 propagating through a separate optical path, $X_{\mathcal{D},1}$, similar to the separate path, $X_{\mathcal{D}}$, that group λ_2 is propagating through (Figure 3). Then the network transfer matrix is given as in Theorem 3 where $P_{\mathcal{D}}$ is replaced by

$$\hat{P}_{\mathcal{D}} = \begin{bmatrix} X_{\mathcal{D},1} & 0 \\ 0 & I_{m_2} \end{bmatrix} P_{\mathcal{D}}$$

- **Closed optical ring configuration:** This case can also be reduced to Figure 2 (Figure 3), by setting $u_2 = y_2$ so that

$$y_1 = F_i(P_{\mathcal{D}} Q_{\mathcal{D}}, X_{\mathcal{D}}) u_1$$

In this case the diagonal terms are involved, as opposed to the off-diagonal ones (cross-terms) involved in the quasi-ring configuration. This case corresponds to cycles realized by accumulation of noise in amplified links, [3].

- **Chain configuration:** This case is obtained by setting $X_{\mathcal{D}} = 0$ in Theorem 3.

Remark 3: A useful property of the results in the previous section is the fact that they provide insight into the network dynamics, as specialized to different particular cases.

- **$Q_{\mathcal{D},12} = 0$, and $P_{\mathcal{D},21} = 0$, i.e., identically null cross-transfer matrices:** In this case there is no wavelength coupling, equivalent to the network transfer matrix having a block diagonal form. This means that there will be no delay induced effects that will be propagated from one group to another. This corresponds to the case of perfect decoupling between the wavelength channels, or to a static case. Note that this is the case of typical electrical switched networks, which do not have link dynamics, but only static gain coefficients. For optical communication networks, the optical communication link dynamics due to the presence of optical amplifiers, is essentially affecting the overall network dynamics.
- **$X_{\mathcal{D}} = 0$, as in chain (point-to-point links).** In this case note from (16) that $\mathcal{T}_{12} = Q_{\mathcal{D},12}$. Therefore, channel coupling exists due to link dynamics (e.g., optical amplifiers), but there is no time-delay feedback coupling, so no bursts are expected.

Remark 4: The results can be used to study network transient response. Dynamic network reconfiguration (add/drop) or sudden failures correspond to step change in power on some channels. This step response can be studied via the use of frequency domain performance with respect to the H_{∞} norm. Consider the case of such power changes on channels in λ_2 set. The effect of such changes on the λ_1 set can be found via the transfer matrix from u_2 to y_1 , \mathcal{T}_{12} , and its H_{∞} norm, [12], since

$$\|y_1\|_2 = \|\mathcal{T}_{12}\|_{\infty} \|u_2\|_2 \quad (20)$$

This problem of ensuring limited cross-coupling effects can be analytically formulated as

$$\|\mathcal{T}_{12}\|_{\infty} \leq \gamma \quad (21)$$

with γ a very small value (e.g. 0.1). These theoretical results provide the basis for developing procedures for robust optical network design and management as indicating next.

- **Sudden network failure:** This case corresponds to designing robust, resilient networks. Specific network parameters (e.g. optical path length/propagation time-delay, time-constants) can be selected such that (21) holds. Analytically this can be formulated as a design problem (with fixed structure), such that the constraint (21) is imposed.
- **Network reconfiguration (dynamic reconfigurable networks):** This problem can be re-framed as an analysis problem. Routing algorithms could base the decision for selecting an optical path or not, on the computed path transfer matrix. For example, by computing \mathcal{T}_{12} , the condition that $\|\mathcal{T}_{12}\|_{\infty}$ satisfies (21) would be sufficient for selecting an optical path, from a dynamic point of view.

4 Simulation results

We show how these results can be used for sudden network failures and ability of the network to robustly sustain them. Sudden failures on some channels correspond to a step response for the network transfer matrix. We consider a good network response if such a failure is sustained with a performance of value of 0.1 cross-coupling disturbance rejection, as measured by $\|\mathcal{T}_{12}\|_{\infty}$.

Consider a network (Figure 2) with forty-eight optical dynamic amplifier spans, each span of approximately 70 km, corresponding each to $\tau \approx 0.33$ ms propagation delay. There are 80 wavelengths grouped in 10 sub-bands propagating across the total loop, with a total propagation delay of $\tau_t \approx 15$ ms. We assume that the two groups λ_1 and λ_2 are equal. This case corresponds to non-zero Q_{12} , P_{21} and $X_{\mathcal{D}}$ terms, hence cross-coupling via optical amplifier/DGE and propagation delay feedback. A Matlab calculated value of 2 is obtained for $\|\mathcal{T}_{12}\|_{\infty}$, so we expect a non-robust response. We simulate a sudden failure by a sudden increase in power on the λ_2 group at $t = 50\mu\text{s}$. As seen in Figure 5 (a), both groups of channels experience power fluctuations that become sustained oscillations, indicating a non-robust network. Next, we consider the maximum total optical path (propagation delay) reduced by four times, for which the calculated value of $\|\mathcal{T}_{12}\|_{\infty}$ is 0.1, and the results are shown in Figure 5 (b). As seen in Figure 5 (b), the power fluctuations become settled, indicating a robust network.

5 Conclusions

This paper presented an analytical study of optical network dynamics, at sudden failures or reconfiguration. We showed how this dynamic problem can be reformulated in the modeling framework of control theory, and can be addressed by using existent mathematical methodologies. By means of modeling

the optical network in a transfer matrix form, we analytically evidenced cross-couplings between groups of channels, and explicit dependence on network parameters. These theoretical results can provide the basis for robust network design, extending the rule-of-thumb methods currently used to address such dynamic phenomena.

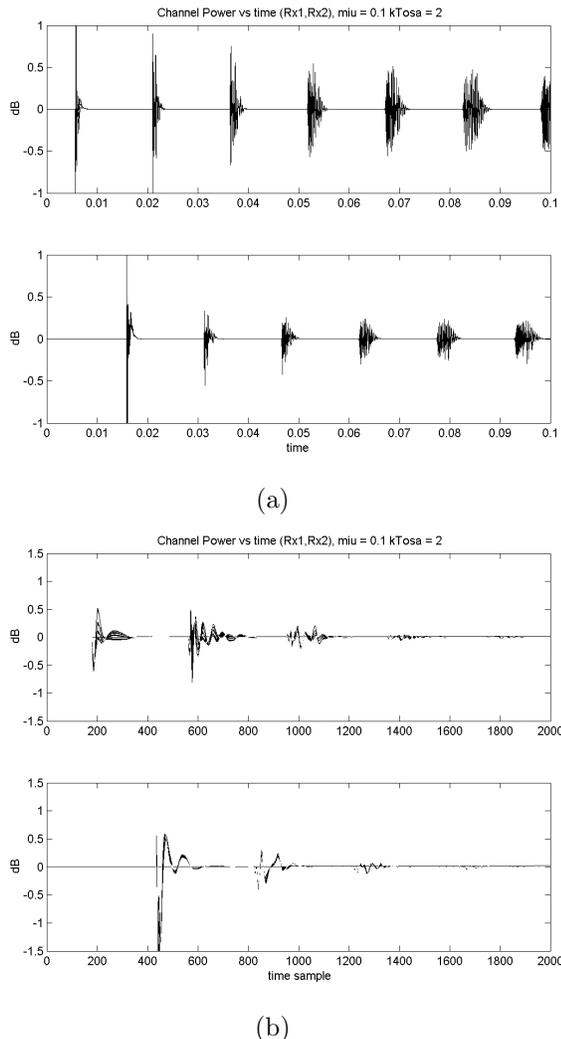


Figure 5: Simulation results: (a) 48 span optical path
(b) 12 span optical path

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