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GORA: an algorithm for designing optical cross-connect nodes with improved dependability

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Abstract

This paper considers the problem of enhancing the dependability (availability and its influencing factors) of optical cross connect nodes. These nodes are expected to be a crucial part of future optical communication networks. The genetic optimum redundancy allocation (GORA) algorithm proposed here is based on a hybrid genetic algorithm and solves the dependability enhancement problem by optimizing the allocation of redundant modules in the nodes. Three redundancy schemes are considered: (1) global duplicate (2) local standby and (3) k-out-of-n:G redundancy. After applying the GORA algorithm to four example nodes, the optimized third redundancy scheme provided the overall best dependability performance. This suggests that redundancy is more effective when provided at the OXN subsystem level. Further capabilities of the GORA algorithm as a network planning tool also presented and some improvements are proposed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Optical networks; Genetic algorithms; Dependability; Optical cross-connects

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1. Introduction

Current communication networks are essentially a heterogeneous combination of legacy networks with distinct signal formats, such as, asynchronous transfer mode (ATM) cells, synchronous digital hierarchy (SDH) STM-1 frames or Internet protocol (IP) packets. The signal format is usually modified—for compatibility reasons—as it is transported or routed from one network type to another [1]. This results in a reduced information carrying efficiency due excessive overhead (e.g. IP over ATM over SDH transport will include overhead from all 3 layers) and the unnecessary duplication of network management functions in different network layers (e.g. multiple recovery operations might be initiated for the same network fault). Future optical transport networks should alleviate these problems by providing a format-independent grooming, routing and management of signals by applying distinctions on their wavelengths (center frequencies) and using wavelength division multiplexing (WDM) [2]. Therefore, the WDM network is viewed as a core that is accessible to the legacy networks located at the edge via an open optical interface as shown in Fig. 1. Among the benefits expected from such multiwavelength optical networks is the increased capacity utilization of the underlying fiber infrastructure and the improved flexibility of multiservice provisioning by network operators.

The key to this idea of optical networking and its eventual success is the deployment of wavelength-selective optical cross connect nodes (OXNs) in the current incongruous networks [2] ([3] Chapt. 2). The primary task of an OXN is setup and tear-down wavelength-routed optical paths in a WDM meshed topology similar to the one depicted in Fig. 1. As a result, the OXNs introduce wavelength reconfigurability to the network thus creating the possibility of delivering bandwidth-on-demand, bandwidth trading, alleviation of network congestion and the non-disruptive scaling of the network. Moreover, wavelength-level management is also possible for monitoring the quality-of-service (QoS) integrity of existing connections and the rapid service restoration in the event of a fault in the network.

Future OXNs will be able to handle over 80 wavelength channels with each channel currently supporting 2.5 or 10 Gbit/s (40 Gbit/s systems expected in the near future [2]), guaranteeing OXN throughput in the Tbit/s regime. Therefore, the loss of even a single channel due to the failure of any OXN component is very significant, as it would deprive the operator considerable revenues generated for each channel they provide. Failure prevention measures can be implemented at the OXN components design stage by engineering robust designs or at the deployment stage by introducing redundancy in the discrete OXNs. The former

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Nomenclature

$\mathbb{Z}^+$	the set of positive integers
$S : \{s_1, s_2, \ldots, s_M\}$	the M subsystems that make up a single system
$W_s : \{w_{1,s}, w_{2,s}, \ldots, w_{N,s}\}$	modules of a subsystem s with N modules
$\Re_s : \{r_{i,s}\}_{i \in \mathbb{Z}^+}$	redundant modules of a subsystem s
F_s	set of modules of subsystem s that are in the failed state (faulty modules)
$[\lambda_s, \mu_s]$	[failure rate, repair rate] of any module in subsystem s
$c_{i,s}$	cost of the ith module in subsystem s
φ	factor accounting for miscellaneous operating costs (e.g. labor, taxation, transportation, space rental, powering etc.)
$\chi_{g,s}$	total wavelength channels handled by the g modules of subsystem s
δ_t	discount factor for calculating present values of costs occurring in period t
q	mean fraction of time a component unit is out for preventive maintenance
$A_{g,s}$	availability of at least g working modules in subsystem s
Γ	economic valuation of a leased channel (monetary unit per channel per hour per Gbit/s)
$\Psi(S)$	total annual revenues generated by OXN G

solution might lead to higher component fabrication costs while the latter redundancy solution is limited by the fact that optical components are relatively expensive compared to the mass-produced electronic components utilized in legacy networks. Nowadays, it is possible for network operators to rent dark (idle) fiber cables at a low cost from public utility (e.g. electricity, pipeline, railway, highway, etc.) companies that place cables on their infrastructure or trade dark fibers with other operators so as to improve their network coverage [4]. This implies that, the majority of the network investment costs is attributed to the deployment and upgrade of OXNs. Therefore, it is necessary to deploy *dependable* OXNs in order to strike a compromise between the network availability requirements and affordable

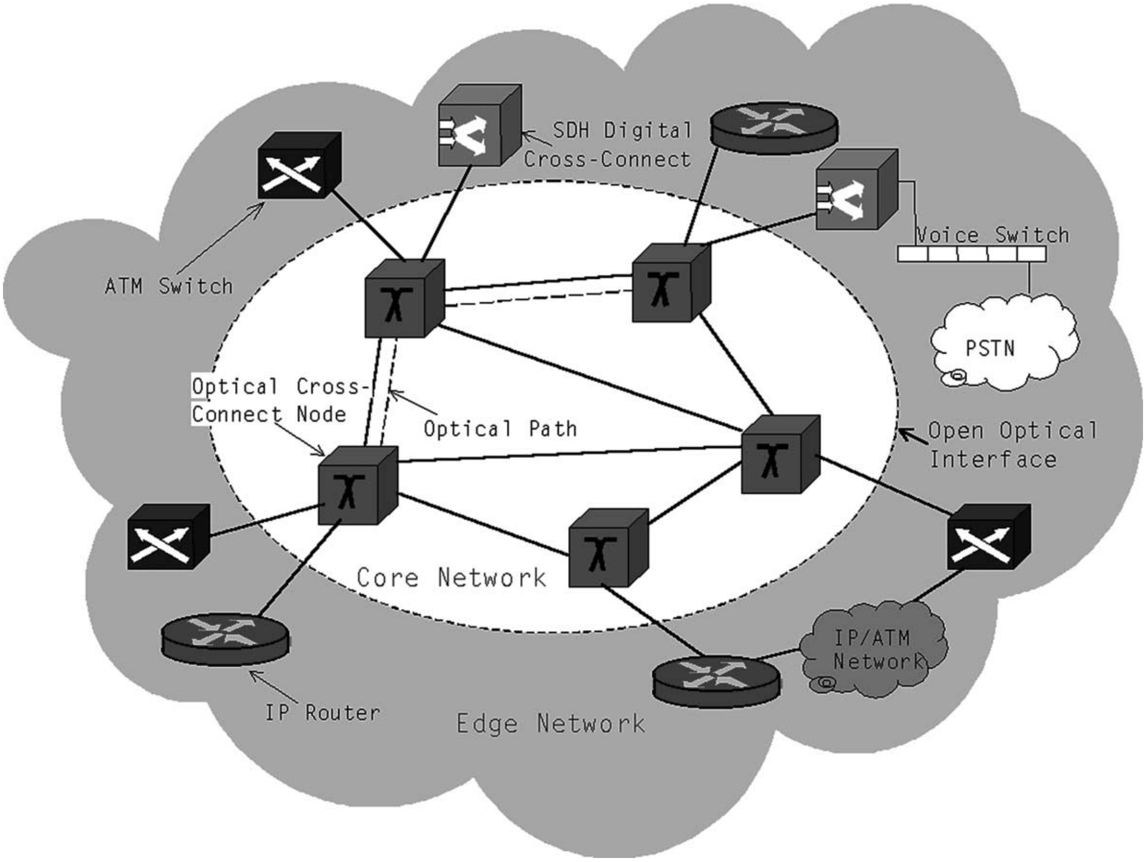

Fig. 1. Conceptual architecture of future communication transport networks.

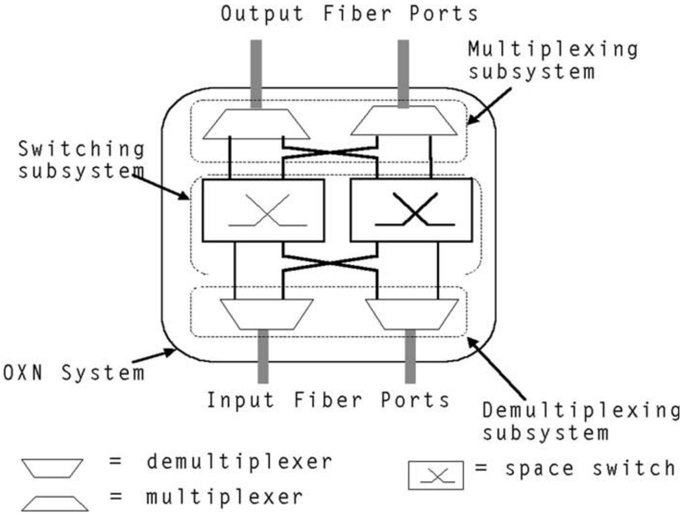

Fig. 2. A 2 × 2 OXN capable of handling up to two distinct wavelength channels from each incoming fiber.

investment costs. Dependability in this context refers to the availability performance and its influencing factors, such as reliability, maintainability, and maintenance support. This particular concept of dependability is further expounded in the International Telecommunications Union (ITU-T) Recommendation E.800 [5].

We propose a genetic algorithm-based scheme for enhancing OXN dependability by optimizing the allocation of redundancy in the OXN. Indeed, the genetic algorithms are gaining increased prominence in the field of optical networking, in both the network planning and operational stages (see for instance, Refs. [6–8]). In the rest of the paper, the problem of optimum redundancy allocation is outlined and formulated in Section 2. A selection of OXNs used to demonstrate the algorithm are described briefly in Section 3. In Section 4 the dependability of the example OXN designs is evaluated and compared for different redundancy allocation schemes.

2. Formulation and algorithm design

An OXN performs several operations on each component of a WDM signal that arrives at its input port. This includes, among others, amplifying, demultiplexing, regenerating, switching, multiplexing, routing, transmitting or receiving the signal [9]. Each one of those operations is executed by an OXN subsystem and each subsystem constitutes one or more similar modules depending on the OXN's architectural configuration and size.

Example 1. The switching subsystem of the 2 × 2 (i.e. with two input/out fiber ports) OXN of Fig. 2 is made of 2 switching modules.

A single module might be implemented by more than one different type of optical or electronic components. However, such details are beyond the scope of this paper. Therefore, the basic unit of the OXN considered in this analysis is the module. We consider three classes of redundancy schemes, namely: global duplicate redundancy (GD), local standby (LS) redundancy and k-out-of-n:G parallel redundancy.

Definition 2. A system is said to have global duplicate redundancy when $w_{i,s} \equiv r_{i,s}\ \forall i \in \mathbb{Z}^+\ \forall s \in S$ and all operations are moved to redundant modules when $\exists F_s \neq \emptyset\ \forall s \in S$.

Definition 3. Local standby redundancy is when $\Re_s\ \forall s \in S$ remain in a standby mode and only modules $\Re_s \equiv W_s \supset F_s\ \forall s \in S$ take over operations when $\exists F_s \neq \emptyset\ \forall s \in S$.

Definition 4. k-out-of-n:G parallel redundancy is a redundancy scheme whereby a subsystem s that requires at least k working modules is allocated a total of n modules where $n = |\Re_s| + k$.

To further illustrate the redundancy schemes, the OXN Fig. 2 is considered to be single system. The GD redundancy is shown in Fig. 3a whereby a protection switch is used to change over from the faulty system to the redundant system when a failure occurs in the working system. In the case of LS redundancy, a protection switch is used to change over from the faulty to redundant modules as shown in Fig. 3b. For a k-out-of-n:G redundant OXN, redundancy is provided at the subsystem level, so a protection is used to replace a faulty module in a subsystem with a redundant module (see Fig. 3c). The total number of subsystems $M = |S|$ and modules $N = \sum_s |W_s|$ needed by a $N_f \times N_f$ OXN with N_λ wavelength channels per fiber, depends on the architectural configuration of the OXN.

Example 5. For the OXN of Fig. 2 whereby $N_\lambda = 2$, the

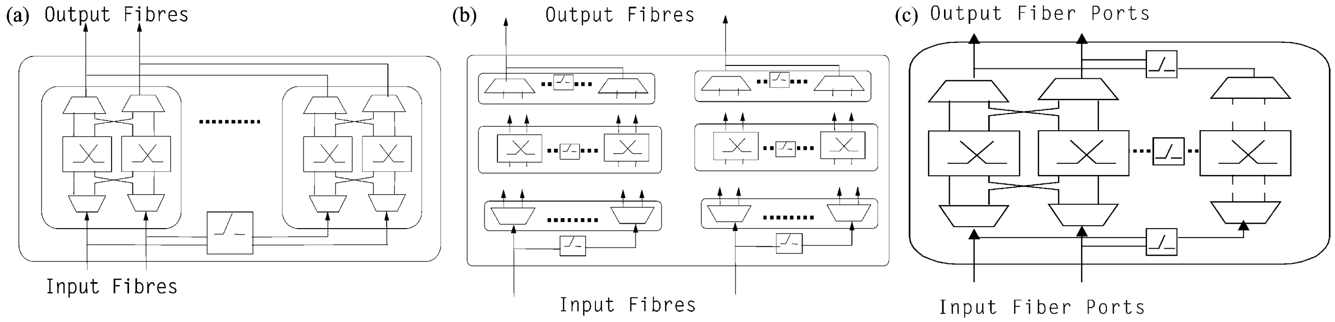

Fig. 3. Schematic of the 2 × 2 OXN with: (a) global duplicate, (b) local standby and (c) *k*-out-of-*n*:G redundancy.

number of subsystems and modules in the OXN are $M = 3$ and $N = 6$, respectively.

2.1. Problem formulation

Some necessary assumptions are made for the problem formulation, these include:

- All modules have a constant failure rate
- All modules fail independently
- Similar modules have equivalent failure and repair rates
- The protection switching from a faulty to a redundant is fully reliable and instantaneous
- All faulty modules are replaced with new but similar modules
- The cost of similar modules is equal $[c_{i,s} = c_{j,s}\ \forall (i,j) \in \mathbf{Z}^+]$
- Redundant modules never fail while in standby mode.

The level of dependability of an OXN can be represented by applying a quantitative model that expresses fault consequences in terms of some monetary unit [10]. This fault-related cost parameter has a direct bearing on the net present value (NPV) of the OXN over a given time.

Definition 6. The net present value of an investment is the difference between the present value of revenues and the present value of costs when all revenues and costs are discounted back to present time in reference to the investment cost [11].

Unlike the GD redundancy scheme, LS and *k*-out-of-*n*:G redundancy allocation can be optimized to improve the OXN's NPV. This is of great significance, since each OXN contributes to the overall outward and inward cashflow from/to the network. The cost (in cost units or CU) of the subsystem s of an OXN is given by

$$C_I(s) = (|W_s| + |\Re_s|)\varphi c_{i,s}. \tag{1}$$

Maintenance expenses are fault-related costs incurred due to corrective maintenance when a module(s) breaks down or routine preventive maintenance costs scheduled periodically in a time T_{mp}. Assuming that T_{mp} is fixed regardless of any corrective maintenance carried out (a memoryless maintenance policy), the maintenance expense of $w_{i,s}$ is [12]

$$C_M(i,s) = C_{CM}(i,s)\frac{1 - R(i,T_{mp})}{\int_0^{T_{mp}} R(i,T_{mp})\mathrm{d}t} + C_{PM}(i,s)\frac{R(i,T_{mp})}{\int_0^{T_{mp}} R(i,T_{mp})\mathrm{d}t}, \tag{2}$$

where

$$R(i,t) = \exp\left[-\int_0^t \lambda_s(t)\mathrm{d}t\right], \tag{3}$$

λ_s is the failure rate in FITs (failures per 10^9 h) and cost parameters $C_{CM}(\cdot)$ and $C_{PM}(\cdot)$ represent the cost of the corrective and preventive maintenance actions, respectively.

Outage cost is another fault-related cost signifying the expected loss in revenues due to module failure or outage. To estimate the cost related to a module outage, we make use of a fixed economic valuation quantity for the service offered (in this case leased wavelength channels) and an evaluated mean accumulated downtime of the module within a designated mission time (OXN operation time). Therefore, the module outage cost takes the form

$$C_O(s) = \Gamma B \sum_{g=0}^{|W_s|} \tau_{g,s}\chi_{|W_s|-g,s}, \tag{4}$$

where

$$\tau_{g,s} = \frac{1 - A_{g,s}}{A_{g,s}}\frac{1}{\lambda_s} \tag{5}$$

is the average time in which g modules of s are simultaneously unavailable [13]. The availability of standby redundancy systems was previously derived by Aven using Markov theory [14]. Assuming constant repair times, of g

working modules in a subsystems is

$$A_{g,s} = \sum_{j=0}^{|\Re_s|} \left[\frac{b_j q}{\left(1 + \sum_{l=2}^{n} b_l\right)} + \frac{c_j(1-q)}{\left(1 + \sum_{l=1}^{n} c_l\right)} \right], \tag{6}$$

where

$$b_j = \begin{cases} \dfrac{(n-1)!}{(n-j)!}\left(\dfrac{\lambda_s}{\mu_s}\right)^{j-1} & \text{if } j \in x \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

$$c_j = \begin{cases} \dfrac{(n-1)(n-1)!}{(n-j)!j!}\left(\dfrac{\lambda_s}{\mu_s}\right)^{j} & \text{if } j \in x \\ 1 & \text{otherwise} \end{cases} \tag{8}$$

with $n = |W_s| + |\Re_s|$ and $\{x \in \mathbb{Z}^+ : 1 \le x \le n\}$. The availability of a k-out-of-n:G redundancy subsystem comprising statistically independent modules with equivalent availabilities, is given by [15]

$$A_{g,s} = \frac{\sum_{j=0}^{n-g} \dfrac{n!}{(n-j)!}\left(\dfrac{\lambda_s}{\mu_s}\right)^j}{\sum_{j=0}^{n} \dfrac{n!}{(n-j)!}\left(\dfrac{\lambda_s}{\mu_s}\right)^j}, \tag{9}$$

where as in Eqs. (6)–(8) $n = |W_s| + |\Re_s|$. The total cost attributed to an OXN system S is an aggregate of Eqs. (1), (2) and (4) given by

$$C_{Tot}(S) = \sum_s \left[C_O(s) + C_I(s) + \sum_i C_M(i,s) \right].$$

It is further assumed that the network operator derives revenue from the OXN by charging for wavelength regeneration, cross-connection and termination operations carried out by the OXN on the leased wavelength channels. The upper bound on this revenues (inward cashflows) attributed to a single OXN is

$$\Psi(S) = T\Gamma B N_f N_\lambda,$$

where T is mission time throughout which the OXN operates and B is the wavelength granularity or bit rate of *a* single channel.

The primary objective of this optimum redundancy allocation algorithm is to search for an OXN with a redundancy that maximizes the NPV of the cashflow generated by the OXN. If the evaluation function $F(\cdot)$ of the redundancy algorithm represents the NPV of attributed to a particular OXN architecture S with a total of N_f input/output fibers and carrying N_λ wavelength channels per fiber. Therefore, the problem can be defined as [11]

`maximize`

$$F(S) = \left. \frac{\Psi(S) - C_{Tot}(S)}{(1+\delta_t)^t} \right|_{t=T} \tag{10}$$

`subject to`

$$\Re_{sL} \le |\Re_s| \le \Re_{sU} \qquad \forall s \in S \tag{11}$$

where $\Re_{sL}$ and $\Re_{sU}$ are the lower and upper bounds on $|\Re_s|$, respectively.

2.2. The genetic OXN redundancy allocation algorithm

As described in the previous Section2.1, the enhancement of an OXN's dependability (by maximizing Eq. (10)) is by achieving a suitable redundancy allocation. However, the optimum redundancy allocation problem is known to be NP-hard [16], thus making it difficult to obtain exact solutions to the problem. A wide range of alternative optimization techniques has been proposed for the redundancy allocation problem and they are collectively reviewed in Ref. [17]. We utilize a genetic algorithm (GA) as a foundation of the *genetic OXN redundancy allocation* (GORA) algorithm in order to increase the computation efficiency and improve the quality of the search for optimum solutions.

The GA [18] is versatile numerical optimization algorithm that manipulates a finite population of encoded solutions (or chromosomes) over a number of iterations, eventually producing an optimum or near-optimum solution. These manipulations are the frequent crossover, less frequent mutation and selection of the members of the population. The fitness (or figure of merit) of a particular solution is quantified by evaluating the coded solution using an objective function. In the case of GORA the objective function is (10) and the fitness is the NPV of an OXN. Since GAs demonstrate better efficiency for global search than local search of a problem space [18], then a more suitable local search routine is applied on the best solution obtained by the GA. The simplex local search method [19] is used to search the space within the close proximity of GA's best solution to obtain the eventual best solution of GORA.

2.2.1. Encoding

Every single chromosome in the population of *Pop* chromosomes is encoded to represent a particular number of redundant modules $\{|\Re_1|, |\Re_2|, \ldots, |\Re_M|\}$ allocated to the M subsystems of OXN. Binary strings can be used to encode each $|\Re_s|$. A robust GA generally requires encoding that closely resembles the problem space [18]. However, binary encoding does not fulfill this condition. To further illustrate this point, consider a small change in $|\Re_s|$ (e.g. from 7 to 8) and the corresponding change in its binary code from 0111 to 1000. It is noted that the new string is different from its predecessor in every bit position, this might slow down the convergence of the GA. Binary Gray encoding is known to produce only single bit changes for transitions between consecutive numbers [20]. Therefore, Gray encoded strings change is from 0100 to 1100. An example of a fully binary Gray encoded redundancy allocation is shown below.

Example 7. If $|\Re_1| = 3$, $|\Re_2| = 7$, $|\Re_3| = 10$ and $M = 3$, then the chromosome for $\{|\Re_1|, |\Re_2|, |\Re_3|\}$ is

$$\{|\Re_1|, |\Re_2|, |\Re_3|\} = \underbrace{0010}_{s=1}\ \underbrace{0010}_{s=2}\ \underbrace{0010}_{s=3}\ .$$

2.2.2. Selection strategy

Analogous to natural evolution, the selection of the fittest redundancy allocations to be retained is carried out prior to each successive iteration while all infeasible allocations are eliminated. The GORA algorithm uses the normalized geometric ranking Ref. [21] as the basis of its selection strategy. All chromosomes in the population are ranked in order of ascending fitness and each is assigned a probability of selection based on the normalized geometric distribution. If p is the probability of selecting the best chromosome then [HOUCK96]

$$P[\text{Selecting the } i\text{th ranked chromosome}] = \frac{p(1-p)^{i-1}}{1-(1-p)^{Pop}}. \tag{12}$$

2.2.3. Genetic OXN redundancy allocation Operators

The GORA algorithm utilizes the single point crossover and uniform binary mutation operators. In the crossover operation, two chromosomes swap strings that appear on one side of a randomly selected crossover point. As long as the two chromosomes are not identical, this operation produces two new offsprings that are different from the parent chromosomes.

Example 8. The crossover between chromosomes $C1$ and $C2$ with crossover point ρ produces offsprings $O1$ and $O2$.

$$C1 = \{|\Re_{1x}|, |\Re_{2x}|, |\Re_{3x}| \underset{\overset{\uparrow}{\rho}}{|} |\Re_{4x}|, |\Re_{5x}|\}$$

$$\Downarrow$$

$$\underline{O1 = \{|\Re_{1x}|, |\Re_{2x}|, |\Re_{3x}|, |\Re_{4y}|, |\Re_{5y}|\}}$$

$$C2 = \{|\Re_{1y}|, |\Re_{2y}|, |\Re_{3y}| \underset{\overset{\uparrow}{\rho}}{|} |\Re_{4y}|, |\Re_{5y}|\}$$

$$\Downarrow$$

$$O1 = \{|\Re_{1y}|, |\Re_{2y}|, |\Re_{3y}|, |\Re_{4x}|, |\Re_{5x}|\}$$

Uniform binary mutation occurs after the crossover operations whereby a chromosome C_i is randomly selected and then a bit in C_i is flipped from 1 to 0 or vice versa.

Example 9. A possible mutation operation (mutated bit is fifth from right);

$$011001111011 \xrightarrow{mutation} 011001101011$$

Considering all the operators, selection and encoding schemes, an outline of the structure of GORA is as follows:

```
GORA Algorithm()
{
  initialize encoded population of
  redundancy allocations;
  evaluate NPV of each member of
  population;
  while(termination criterion not met)
    {
      select solutions for next
      population;
      perform crossover and mutation
      operations;
      evaluate NPV each member of
      population;
    }
  apply local search
}
```

The termination criterion is when convergence is achieved as signified by the increased uniformity in the chromosomes.

Criterion 10. The GORA algorithm is said to have converged when 95% of the chromosomes share the same fitness value.

3. Example OXN designs

A wide range of OXNs has been reported over the last decade. These proposals were reviewed in Ref. [9] and more recently in Ref. [22]. The various OXN architectures can be classified according their blocking characteristics (strictly non-blocking, rearrangably non-blocking or blocking), routing strategies (wavelength or virtual wavelength path routing), inherent modularity (link and/or wavelength modular) or their underlying technologies (integrated-optics, micro-optics, all-fiber or hybrid). Four diverse OXNs are selected for demonstration of the GORA algorithm (see Fig. 4), they are

1. *OXN1*: With an architectural configuration similar to the OXN of Fig. 2 and utilizes electro-optic switches made of titanium waveguides diffused on a lithium niobate substrate (Ti:LiNbO$_3$) [9]. Optical amplifiers, typically erbium doped fiber amplifiers (EDFAs), are used at the input and output of the OXN to compensate for fiber loss and OXN insertion losses, respectively.
2. *OXN2*: An OXN which uses a combination of tunable filters and wavelength converters (based on semiconductor optical amplifiers) to perform optical switching [9]. This proposal was motivated by the lack of mature optical switching technologies suitable for field

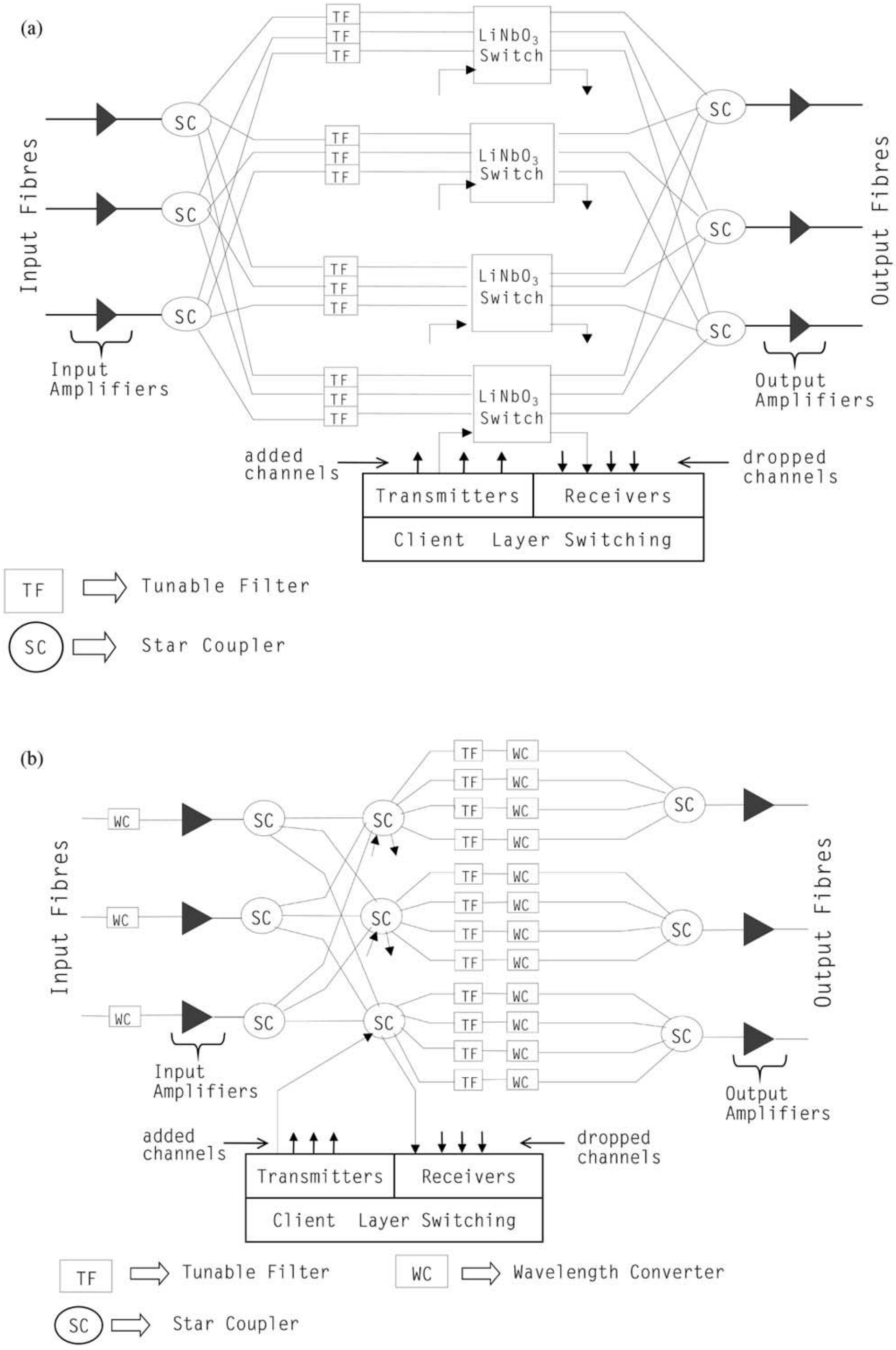

Fig. 4. Architectures of 3 × 3 OXN (4 channels) based on: (a) *OXC*1, (b) *OXC*2, (c) *OXC*3 and (d) *OXC*4 design.

implementation. The combination of the comb wavelength converters before the input EDFAs and wavelength converters after the tunable filters enables the OXN to adapt a virtual wavelength path routing strategy for reduced channel blocking ([3] Chapt. 6) STERN99.

3. *OXN3*: This OXN also avoids the use of conventional optical switches, relying instead on the reflectivity and tunability of fiber Bragg gratings (FBGs) for signal switching and routing [23]. The passive all-fiber design guarantees easily fabricable subsystems with low losses, polarization independence and high crosstalk isolation, thus reducing the OXN-induced signal degradations.
4. *OXN4*: Uses mostly on all-fiber devices, in the same way as *OXN3*, but with an alternative configuration that is based on the 3-stage Close network arrangement [24]. This configuration ensures that the OXN scales more

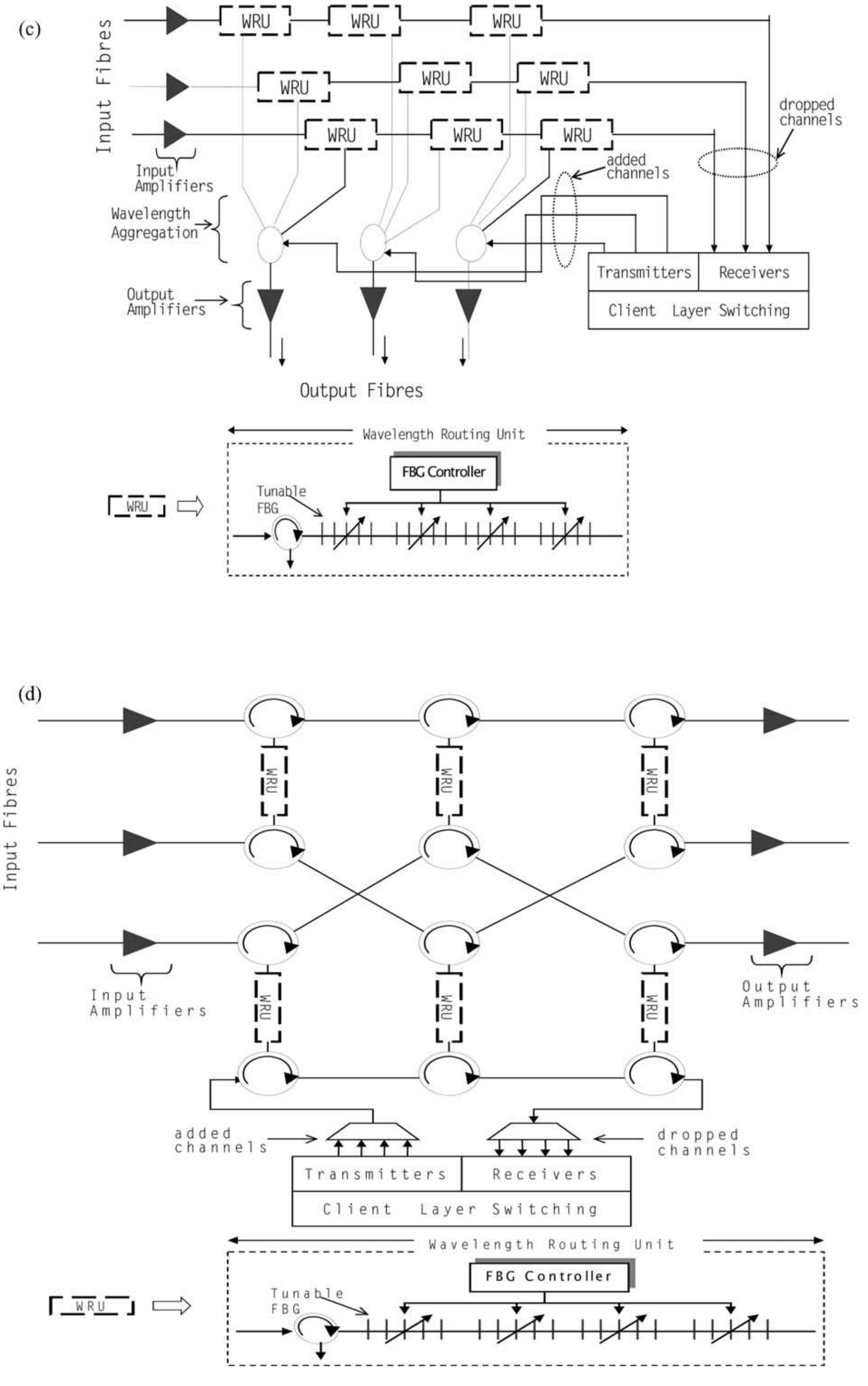

Fig. 4. (*continued*)

gracefully when the OXN dimensions are increased or an extra number of distinct wavelength channels are activated.

All the OXNs mentioned above are wavelength modular, that is, the number of wavelength channels can be increased on the incoming fibers without having to substitute any of the existing OXN subsystems. A subsystem would consist of modules performing the same function (e.g. the switching subsystem of *OXN1* has 4 individual switches etc.). New channels are accommodated by simply inserting the additional required number of modules in the various OXN subsystems. In the OXNs, large splitters and combiners are constructed from basic 1 × 2 or 2 × 1 units. Transmitters based on externally modulated laser diodes and PIN photodiode receivers are assumed throughout.

Table 1
Parameters used in GORA simulation runs

Category	Object/parameter	Value
General	Mean time to repair ($1/\mu$)	6 h
	Mission time (T)	1year (8760 h)
	Preventive maintenance period (T_{mp})	6 months
	Economic valuation of a leased channel (Γ)	6.7 CU/channel/h/(Gbit/s)
	Bit rate per channel (B)	2.5 Gbit/s
	Miscellaneous costs factor (φ)	1.15
	GORA population (Pop)	50
Modules	Ti:LiNbO$_3$ 4×4 electro-optic switch	$\lambda = 3630$ FITs, c $= 5600$ CU
	Input or output EDFA	$\lambda = 6340$ FITs, c $= 19200$ CU
	1×2 Splitter or 2×1 combiner	$\lambda = 300$ FITs, $c = 200$ CU
	Transmitter	$\lambda = 2500$ FITs, $c = 1500$ CU
	Receiver	$\lambda = 1800$ FITs, $c = 1000$ CU
	Tunable optical filter	$\lambda = 400$ FITs, $c = 1500$ CU
	Optical circulators	$\lambda = 300$ FITs, $c = 2320$ CU
	Fiber Bragg grating	$\lambda = 200$ FITs, $c = 240$ CU
	Wavelength converters	$\lambda = 5700$ FITs, $c = 18700$ CU
	Wavelength (de)multiplexer	$\lambda = 450$ FITs, $c = 5600$ CU

4. Simulation results

The evaluation parameters for various modules, were obtained from different equipment manufacturer/supplier specification data, technical publications ([25–27]) and private discussions. These parameters for the modules of the example OXNs are listed in Table 1. For the all the example OXNs, we consider redundancy allocation cases

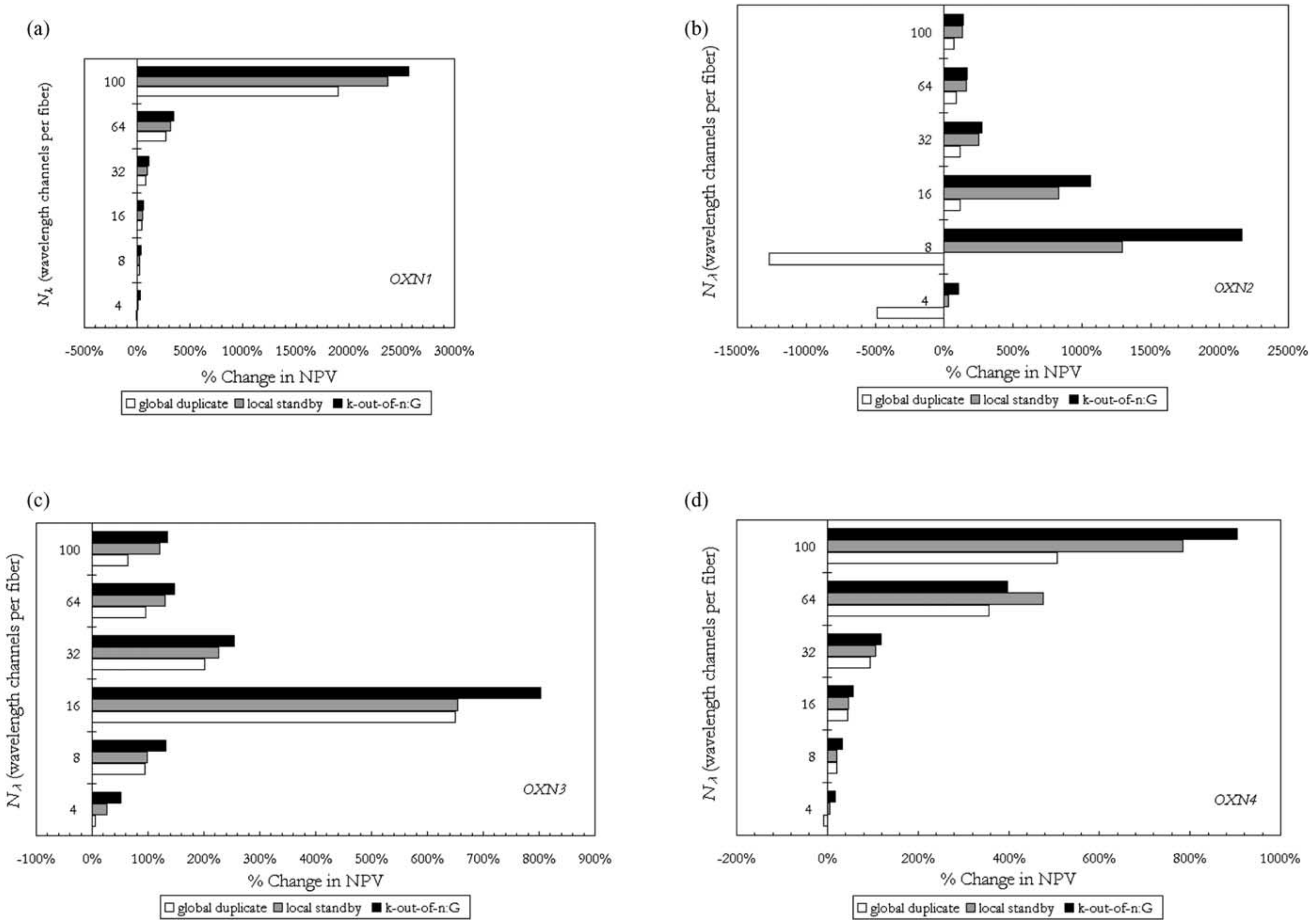

Fig. 5. Percentage change in NPV from corresponding OXNs with no redundancy for: (a) *OXC*1, (b) *OXC*2, (c) *OXC*3, (d) *OXC*4 architectures.

where $N_\lambda \in [4, 8, 16, 32, 64, 100]$ channels per fiber. The number of in/outgoing fiber links fixed at $N_f = 3$ and full wavelength channel utilization (always on) is assumed throughout the period of evaluation. A different combination of three values were tested for each GA parameter (crossover and mutation rates), creating a total of nine different GORA algorithm trial runs per OXN and each trial run was repeated five times resulting in 45 recorded observations per OXN. The run that recorded the best fitness result is retained for further analysis and comparisons. A total of $6 \times 4 \times 45 = 1080$ runs were performed to obtain the optimum architectures for the four example OXNs and the six different levels of N_λ.

By using the corresponding OXNs with no redundancy ($\sum_s |\Re_s| = 0$) as the benchmark, the percentage change in NPV after introducing redundancy is evaluated for each OXN. It is observed from the results of Fig. 5 that, in the majority of cases considered, k-out-of-n:G offers the best improvements in NPV. For *OXN1* and *OXN4*, the benefits of redundancy become more significant with an increase in N_λ. Unfortunately, this does not seem to be the case with *OXN2* and *OXN3* because the NPV increment ceases after N_λ exceeds a certain value. Therefore, the benefits of not using optical switches in *OXN2* are made insignificant in comparison their reduced dependability enhancement when compared with *OXN1* for $N_\lambda \geq 64$.

The architectural configuration of also OXNs seems to have a significant effect on the OXN dependability. For instance, *OXN3* and *OXN4* utilize similar types of modules and therefore, their main difference lies in their configurations. However, since *OXN4* has a configuration with suitable wavelength scaling characteristics, an increase in N_λ is consistently accompanied by an increase in NPV. Therefore, a business argument exists for a network operator to consider increasing the number of leased channels.

5. Discussions

The possibility of enhancing an OXN's dependability by using a GORA algorithm has been presented and results confirm the effectiveness of the algorithm. Take for instance, dramatic gains in NPV attained for *OXN1* when the number of distinct channels is 100. With the expected introduction of novel fiber designs and wideband optical amplifiers the number of channels should soon reach the 1000 mark [2]. Therefore, the benefits of using GORA to design OXNs for such WDM systems with high channel counts should be even more pronounced. For the majority of the cases considered, GORA based on the k-out-of-n:G redundancy scheme created the most dependable OXNs. This suggests that redundancy is most efficient when allocated to an OXN subsystem rather than individual modules or at the system-level. However, GD redundancy could still prove useful for compact integrated OXNs with irremovable modules, located on a common chip or substrate Ref. [28]. The cost benefits derived from using integrated OXNs are due to the reduced space requirements and ease of volume production. On the downside, these OXNs cannot be scaled once in operation therefore some form of overdimensioning is necessary at the deployment stage.

Techniques proposed for reducing OXN complexity (total module number), also have the potential to further improve OXN dependability. For instance, the number of modules in intermediate OXNs could be reduced by separating a WDM signal into its individual tributaries only at the destination OXN [29]. Alternatively, the module number could be reduced by relaxing the strict non-blocking requirement of OXNs to make allowances some form of rearrangably non-blocking characteristics [30]. At the module level, a large inventory of redundant transmitters could be replaced by fewer transmitters with tunable laser diodes capable of simultaneously transmitting several wavelength channels.

When the analysis is carried out over a longer time scale ($T > 1$ year), additional techno-economic estimation methodologies become necessary to obtain realistic NPV estimates, since $\Psi(\cdot)$ and $C_{Tot}(\cdot)$ are actually time dependent. This includes techniques, such as, forecasting of elasticity of demand for wavelength channels and expected revenues or learning curves for predicting the falling module costs. The GORA algorithm is equally applicable to other types of OXNs that have not been considered here. By taking advantage of its inherent evolutionary capability, it is also possible to further extend its use to incorporate time, scalability and transmission speed factors in order to analyze the techno-economical merits of various OXN in a continuously evolving telecommunications environment. Furthermore, other soft computing methodologies, namely: neural networks and fuzzy logic, could also be integrated in the GORA algorithm to create a synergy that offers superior performance and increased functionality.

Using the methods described in this paper, it is should be possible to incorporate GORA in a network planning tool thus providing an effective way to further improve the interaction among crucial network management processes such as planning, maintenance and impact analysis of new optical technologies. This should simplify the management of increasingly complex optical networks, the determination of appropriate management strategies as well as expediting project and business cases.

References

[1] K. Makki, J. Broussard, N. Pissinou, On optical communications networks and wideband network architecture, Computer Communications 23 (10) (2000) 901–911.

[2] H. Yoshimura, K.I. Sato, N. Takachio, Future photonic transport networks based on WDM technologies, Computer Communications 37 (2) (1999) 74–81.

[3] T.E. Stern, K. Bala, Multiwavelength Optical Networks: A Layered Approach, Addisson-Wesley, Reading, 1999.

[4] D. Tanis, Carriers can maximize their dark-fiber returns, Fibre Systems Europe 5 (1) (2001) 41–44.

[5] ITU-T Recommendation E.800: Terms and definitions related to quality of service and network performance including dependability (August 1994).

[6] K. Poon, A. Conway, G. Wardrop, J. Mellis, Successful application of genetic algorithms to network design and planning, BT Technology Journal 18 (4) (2000) 32–41.

[7] D. Saha, M. Purkatastha, A. Murkhejee, An approach to wide area WDM optical network design using genetic algorithm, Computer Communications 22 (2) (1999) 156–172.

[8] M. Sinclair, Minimum cost wavelength-path routing and wavelength allocation using a genetic-algorithm/heuristic hybrid approach, IEE Proceedings-Communications 146 (1) (1999) 1–7.

[9] E. Iannone, R. Sabella, Optical path technologies: a comparison among different cross-connecting architectures, Journal of Lightwave Technology 14 (10) (1996) 2184–2196.

[10] ITU-T Recommendation E.862: Dependability planning of telecommunication networks (June 1992).

[11] E.P. DeGarmo, J.R. Canada, W.G. Sullivan, Engineering Economy, Macmillan, New York, 1984.

[12] J.E. Arsenault, J.E. Roberts, Reliability and Maintainability of Electronic Systems, Pitman, London, 1980.

[13] J. Bentley, Introduction to Reliability and Quality Engineering, Addison-Wesley, Harlow, 1999.

[14] T. Aven, Availability formulae for standby systems of similar units that are preventively maintained, IEEE Transaction on Reliability 39 (5) (1990) 603–606.

[15] A.H. Hevesh, Comments on: steady-state availability of k-out-of-n:G system with single repair, IEEE Transaction on Reliability 39 (5) (1990) 603–606.

[16] M.S. Chern, On the computational complexity of reliability redundancy allocation in series systems, Operations Research Letters 11 (5) (1992) 309–315.

[17] W. Kuo, V.R. Prasad, An annonated overview of system-reliability optimization, IEEE Transaction on Reliability 49 (2) (2000) 176–187.

[18] D. Coley, An Introduction to Genetic Algorithms for Scientist and Engineers, World Scientific, Singapore, 1999.

[19] M.A. Branch, A. Grace, MATLAB Optimization Toolbox, The MathWorks Inc, Massachusets, 1996.

[20] R.W. Hamming, Coding and Information Theory, Prentice-Hall, New Jersey, 1986.

[21] C.R. Houck, J.A. Joines, M.G. Kay, A genetic algorithm for function optimization: a Matlab implementation, Technical Report, North Carolina State University, 1995.

[22] N.A. Jackman, S.H. Patel, B.P. Mikkelsen, S.K. Korotky, Optical cross connects for optical networking, Bell Labs Technical Journal 4 (1) (1999) 246–261.

[23] D. Hjelme, H. Storoy, Reconfigurable all-fiber all-optical cross-connect node using synthesized fiber Bragg gratings for both demultiplexing and switching, Technical digest of the Optical Fiber Communications Conference'98, vol. 1, San Jose, USA, 1998, pp. 65–66.

[24] Y.K. Chen, C.C. Lee, Fiber Bragg grating-based large nonblocking multiwavelength cross-connects, Journal of Lightwave Technology 16 (10) (1998) 1746–1756.

[25] L. Wosinska, L. Thylens, Reliability performance of optical cross-connect switches requirements and practice, Technical digest of the Optical Fiber Communications Conference'98, vol. 2, San Jose, USA, 1998, pp. 28–29.

[26] P. Batchelor, B. Van Caenegem, B. Daino, P. Heinzmann, D.R. Hjelme, R. Inkret, H.A. Jäger, M. Joindot, A. Kuchar, E. Le Coquil, P. Leuthold, G. De Marchis, F. Matera, B. Mikac, H.-P. Nolting, J. Späth, F. Tillerot, N. Wauters, C. Weinert, Ultra high capacity transmission networks. Final Report of Action COST 239, Technical Report, University of Zagreb, Zagreb, 1999.

[27] T. Volotinen, W. Griffioen, M. Gadonna, H. Limberger, Reliability of Optical Fibres and Components: Final Report of COST 246, Prentice-Hall/Springer, London, 1999.

[28] C.G.P. Herben, X.J.M. Leijtens, D.H.P. Maat, H. Blok, M.K. Smit, Crosstalk performance of integrated optical cross-connects, Journal of Lightwave Technology 17 (7) (1999) 1126–1134.

[29] E. Ciaramella, Introducing wavelength granularity to reduce the complexity of optical cross connects, IEEE Photonics Technology Letters 12 (6) (2000) 699–701.

[30] G. Wilfong, B. Mikkelsen, C. Doerr, M. Zirngibl, WDM cross-connect architectures with reduced complexity, Journal of Lightwave Technology 17 (10) (1999) 1732–1741.