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Abstract

This paper surveys important parameters for the design of large scale networks topology such as the YottaWeb topology [1, 2, 3]. First, a wide range of performance measures to evaluate the behavior of envisaged topologies are presented, discussed and classified according to their meaning and their effectiveness on large scale networks. Secondly, different types of topologies, from simple to more complex, are identified and the features of the called $k-$ary $n-$cube topologies [4] such as ring, torus and hypercube topologies are surveyed and discussed. Full details and advantages of the recently introduced YottaWeb topology are pointed out, in the light of the predefined concepts. Finally, the application of the performance measure to the design of the topologies is surveyed.

Keywords: Topological Design, Performance Measures, Large Scale Network, Optical Networks, YottaWeb, PetaWeb, Next Generation Internet

Résumé

Ce papier présente une revue de littérature de paramètres importants dans la conception topologique de réseaux optiques de grande capacité tels que le YottaWeb [1, 2, 3]. Premièrement, différentes métriques de performance, pour évaluer les topologies envisagées, ont été présentées, discutées et classifiées suivant leur signification et leur pertinence pour des réseaux de grande taille. Deuxièment, différents types de topologies, des plus simples aux plus complexes, ont été identifiées et les caracatéristiques de ces topologies comme l'anneau, le tore et l'hypercube ont été discutées. Finalement, des détails et avantages de la récente topologie en treillis du YottaWeb ont été montrés, à la lumière des concepts de performance prédéfinis.

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1 Introduction

Following the progression of the Internet, the communication networks are growing and developing very fast. New services are being required and developed. The evolution involves the improvement of the performance of the existing network technologies. Then, the need to find efficient scalable networking methods at different levels: topological layout, access rules to the communication medium, traffic routing, transport procedures, applications handling, etc. An important point for achieving good results is to suitably choose the network topology at the beginning. The topological layout defines the schematic description of the arrangement of a network, including its nodes and connecting lines. For indepth introduction to holding and outcomes of topological network design problems, the reader is referred to the book of Sharma [5].

The topological layout is an important factor for reducing many bottlenecks that happen when dealing with large scale networks. Those bottlenecks could be congestion at nodes or on links, when a network evolves to large size. Thus, the topological design of the envisaged versatile, evolutive and high capacity networks requires the use of meaningful and reliable performance measures that help the designer in predicting and tuning the behavior of the networks. The performance measures become important decision tools to decide the best topology, and must therefore be carefully chosen.

This paper aims to survey and discuss both performance measures and topological proposals for expanding high capacity networks. In addition, optimization tools for designing topologies, that meet the requirements of the chosen performance measures, are discussed.

The content of this article could be summarized in four parts. The first part is devoted to the definition of concepts and notations of topological design. The second part concerns the definition and the classification of fundamental performance measures. The most important metrics are surveyed and grouped in two sets. They are structural and functional metrics that will be defined below. The third part is about the choice of topologies in both physical and higher levels. Existing topologies could be classified in two large groups: *arbitrary* and *regular* topologies. Moreover, in the light of the above cited topological studies, we evaluate the new proposed regular YottaWeb lattice based topology [1, 2, 3]. The lattice topology is constructed by aggregation of connection arcs between edge nodes into “tunnels” between those edges nodes. The concept of the YottaWeb is enabled by recent advances in agile optical core technology and it is well suited to large scale optical networks. In the fourth part, the optimization tools used in topological design are surveyed. We describe in this part, the application of the measures to the choice of the topologies. The practical use of the performance measures in designing the topologies is presented.

This article is organized as follows. In Section 2, concepts and illustrations of topological design are given. Section 3 deals with the survey of fundamental performance measures. Section 4 is devoted to the classification of some usual topologies compared to the new proposed lattice topology. In Section 5, the optimization strategies are showed up. Results are discussed in Section 6. General conclusions are presented in Section 7.

2 Topological Design: Concepts and Notations

Before surveying the fundamental performance measures, let us define some basic concepts, notations and assumptions.

2.1 Physical and Logical Topology

In telecommunication networks design, the topological design intervenes at two levels: at the *physical* level and at the *logical* level. The physical topology can be defined as the set of physical nodes and the set of physical links that connect the nodes. Links could be counted, for instance, as distinct optical fibers or distinct physical channels that connect two adjacent nodes.

The logical topology [6, 7], also referred as *virtual topology* [8, 9], *lightpath topology* [10], *lightpath network* [8], *IP topology* and *optical topology* [11] is a higher level. As an illustration, in WDM networks, signals are routed and switched based on wavelengths composing the fibers. The current technologies allow more than 150 distinct wavelength channels within the same fiber. The logical topology consists of the set of logical switching nodes and the set of lightpaths, where a *lightpath* refers to an optical path between two adjacent nodes, formed by a sequence of physical fibers and associated wavelength(s). Each link in the logical topology is a directed lightpath. Illustration of physical and its embedded logical topologies is shown in Elmirghani and Mouftah [12], to which the reader is referred for a complete description of WDM networks technologies and architectures for scalable networks. In Figure 1, that we retrieved from [12], an example of 5−nodes networks is given, with 3 wavelengths per bi-directional links (solid lines) between the nodes. Figure 1(a) shows that there is no direct physical link between nodes C and E. However based on the wavelength assignment to the lightpaths (dotted lines), a direct logical path between nodes C and E is established in the resulting logical topology of Figure 1(b).

Most of the time in the literature addressing the particular case of optical transport topological design, the physical topology already exists or is chosen, and the challenge consists of designing the logical topology to be embedded onto the physical one. The independence of the logical topology from the physical topology has been underlined in Mukherjee *et al.* [10], Banerjee *et al.* [6], and most recently in Mellia *et al.* [7].

2.2 Topology Representation

The topology is generally represented by a graph. Figure 2 gives an example of the configurations of physical and logical topologies of a typical transport network. Using the notation introduced by Plante and Sansò [13], the network layer l is represented by the graph $G^l(V^l, E^l)$ where V^l is the set of nodes and E^l is the set of links between nodes. The pair of nodes (x, y) in G^{l+1} is connected by a set of routes R in G^l consisting of a sequence of adjacent links e in E_l, with $R = \{e_1, \ldots, e_i\}$.

For the remainder of this paper, we consider the two network sets using the preceding notation as:

G^0: the physical layer;
G^1: the logical layer.

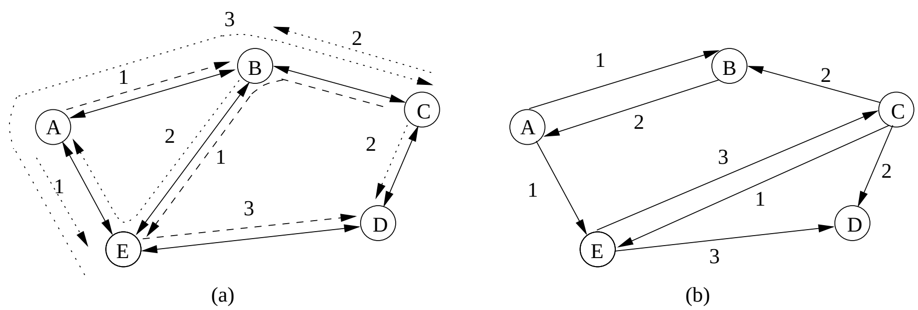


Figure 1: Wavelength routing networks: (a) physical topology and wavelength assignment; (b) virtual topology. (Retrieved from [12])

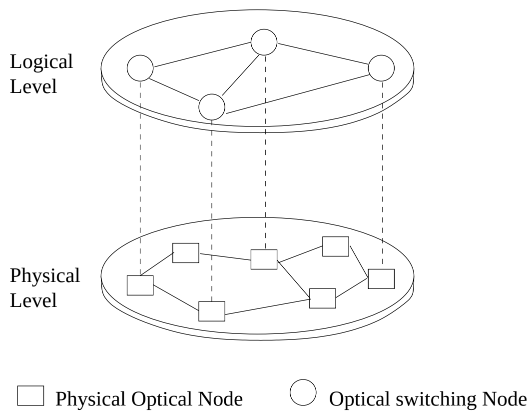


Figure 2: The Configurations of Physical Topology and Logical Topology of an Optical Network.

We also use the notation of graph $G(V,E)$ (without any subscript), to refer to any of the predefined physical or logical layer. Let $|V| = n$ be the number of nodes and $|E| = m$ the number of links within the network. Unless otherwise stated, physical edge nodes here could independently represent all-optical network access nodes, optical core routers or switches. The difference between physical and logical nodes generally arises from the way logical connections are chosen.

For example, when in the physical network, the switch at a node is already tuned in order to enable one hop communication between two adjacent nodes to the given switch, the node related to the switch could be ignored in the logical topology. An illustration is given in Figure 2 with the number of nodes n reduced from 7 to 4, from the physical to the logical network.

On the other hand, we consider in this paper that arcs between two edge nodes are bi-directional at both physical and logical levels. This assumption is well admitted in the literature, specially for physical optical topology, for which the assumption matches the reality of optical fibers that are generally deployed per pair, for communication in the two directions.

In what follows, most of the performance measures defined are related to the logical topology. Indeed, most of the time, any logical layout could be put on top of a physical layer, the performance of the whole network depends most intimately on the logical layout. However particular attention must be paid to the physical constraints.

3 Performance Measures

The goals of the performance metrics are to provide tools for the classification, the comparison and the gauge of the features of the studied topologies. Numerous metrics exist in literature, but only those that are fundamental for the high capacity optical topologies in this study, will be presented and discussed.

Based on the design concepts pointed out in Section 2.1, the performance measures involved in a topological design problem could be classified into two categories: *structural metrics* and *functional metrics*. Structural metrics are designed to characterize the topology without any knowledge of traffic engineering (flows on the links, routing schemes, ...). For example, the considered number of nodes within a topology is a structural metric. On the other hand, functional metrics take into account the traffic engineering within the network, and the expression of a functional metric is a function of parameters such as flows on the links, routing schemes, node functionalities, etc. Thus, the total amount of traffic within a network is considered as a functional metric.

Since many of these measures are interrelated, we will group them around the most fundamental and explain the relationship between them.

In what follows, we present for each metric or group of metrics, a formal definition, its utilization and impact in gauging and comparing topologies.

3.1 The Structural Metrics

Some fundamental structural metrics encountered in literature are the following.

3.1.1 The Number of Nodes n It is also known as the *order* of the network. This is a basic metric, which is required to be flexible, specially in a large sized network, in order to facilitate network expansion. A "good" topology must easily enable the simple operations of addition or withdrawal of a single node. Some authors [6] refer to the required flexibility for the *order*, as the *extensibility* which allows a topology to easily expand, while preserving its desired features.

In terms of large size networks, we consider in this work that $n \geq 1000$.

3.1.2 The Diameter $\mathcal{D}$ and the Degree Δ The diameter and the degree are respectively the longest distance (generally expressed in number of hops [15] or in fiber length [16]) between a pair of nodes and the maximum number of links attached to a node within the topology. When the diameter is expressed in fiber length [16], it can be seen as an indicator of the network *cost*, and then, must be as low as possible. On the other hand, the *degree* is directly linked to the number of ports at a node, and then represents not only an indicator of the amount of *functionalities* of the node, but also an indicator of the *cost* of the node. The *degree* is related to the *capacity* of nodes and is an index of the node complexity.

Thus for an appropriate design, a trade-off is necessary between the needed increasing *capacity* and the *cost* or the *degree* of a topology. Also, lowering the *diameter* and the *degree* at the same time is contradictory, since the two measures evolve in opposite directions. Thus there is a need for a metric that combines the previous parameters. For instance, there is the *cost effectiveness* defined in [17] as $\mathcal{C} = \Delta \times \mathcal{D}$. Other authors [18] define the *node degree distribution* which is the average node degree computed as $\frac{2m}{n}$.
The relationship between the *order*, the *degree* and the *diameter* could vary widely. However, there is the well-known *Moore's bound* [11] $n_{\text{Moore}}(\Delta, \mathcal{D})$, which represents an upper bound for the *order* of a topology with given degree and diameter. In fact, the fundamental goal of the design is to find the densest possible topology (graph) for which, given the degree and the diameter, the order is equal or close to :

$$n_{\text{Moore}}(\Delta, \mathcal{D}) = 1 + \Delta \sum_{i=0}^{\mathcal{D}-1} (\Delta - 1)^i \tag{1}$$

Important progress has been made in constructing such topologies, specially in the field of multicomputers [19], but results are still far away from Moore bound. For now, most of the proposed constructed topologies that are close to Moore Bound, for $n \geq 1000$, are impracticable, because of their complexities [19].

3.1.3 The Average Inter-Nodal Distance $\bar{\mathcal{D}}$ Rather than the *diameter*, the *average inter-nodal distance* $\bar{\mathcal{D}}$ is often considered [15]. It is calculated as

$$\bar{\mathcal{D}} = \sum_{x,y \in V} \frac{\delta(x,y)}{n^2}, \tag{2}$$

where $\delta(x,y)$ is the distance (in hop or fiber length) between the pair of nodes (x,y). Such a metric has been used by Sen *et al.* [20], Banerjee *et al.* [14, 6] and Li and Ganz [21]. This structural metric leads to a functional metric when the traffic within the network is taken into account. The derived extended metric will be presented in Section 3.2 devoted to functional metrics.

3.1.4 The Number of Links m It corresponds to the number of arcs in the graph and is equal to $\frac{1}{2}\sum_{i=1}^{n} \Delta_i$, where Δ_i is the degree of node i. The number of links is a cost factor and must be reasonably low. It equals to $\frac{n\Delta}{2}$ for regular topologies. The number of links is also an indicator of the required number of wavelengths, and then, the number of required optical fibers in the case of optical networks.

3.1.5 The Fault Tolerance The fault tolerance is counted as the number of alternate paths (with disjoint nodes and disjoint arcs) existing between each pair of source and sink nodes. A high fault tolerance is desirable for high capacity topologies. This number can be expressed as in [6], as the maximum number of nodes and/or links that can be removed (or broken) from the network without disconnection. In brief, a good design aims at a logical connected topology where the traffic could be easily re-routed in case of faults in the network. More precisely, Oh and Chen [22] have defined the metric of *strong fault tolerance* to characterize the property of parallel routing. A network G with degree Δ is said to be *strong fault tolerant* when with at most $\Delta - 2$ faulty nodes within the network, each remaining pair of nodes is still connected by $\min\{\Delta_f(x), \Delta_f(y)\}$ disjoint paths where $\Delta_f(x)$ and $\Delta_f(y)$ are, the numbers of neighbors, of the nodes x and y respectively, that are not faulty. Due to the importance of satisfying this metric, many ways have been studied to guarantee a high fault tolerance.

3.1.6 The *Regularity* of the Topology The regularity is also an attractive feature which is defined as a *symmetry* in the distribution of the nodes one compared to others. Many regular topologies such as hypercubes, torus, etc..., have been proposed. In Section 4.2, we present their advantages and their drawbacks while surveying some particular regular topologies.

3.2 Functional Metrics

We list in this section the functional metrics used to characterize the topologies.

3.2.1 The Traffic Weighted Metrics Instead of using the notion of distance presented above, [21] proposes a metric of *probable average distance* or *weighted average distance* calculated as:

$$\mathcal{D}_{prob} = \sum_{\delta=1}^{\mathcal{D}} \delta\Phi(\delta), \tag{3}$$

where $\Phi(\delta)$ holds for the probability that an arbitrary message (packet) transmitted from a source node to a sink node is delivered in a distance of δ hops. Li and Ganz [21] remind that the probability $\Phi(\delta)$ takes into account not only the topology of the network, but also the routing schemes to be used. The probability could also be replaced, in a more precise manner, by the fraction of the real traffic, when this fraction is known. The authors deduce from their analysis that a small *average inter-nodal distance* $\bar{\mathcal{D}}$ is not a guarantee of a small communication delay. Indeed, packet delivery delays could be long, despite a small $\bar{\mathcal{D}}$, according to the loading and the processing of traffic at the nodes. Then, more sophisticated measures are needed to catch the network complexity.

3.2.2 The Total External Traffic The configuration of the topology determines the total external traffic T_t that could be accommodated by the network. This measure can be in the order of several peta (10^{15}), and even yotta (10^{24}) bits per second [1] in high capacity networks. The total external traffic is sometimes defined by incorporating in it a certain quality of service within the network. Then, for the study of the PetaWeb that gives rise to the YottaWeb, Blouin *et al.* [16] define T_t as the highest traffic load that a network could support, while providing a specific level of service such as no more than 5% of blocked channels requests for any pair of origin-destination, and no more than 1% of blocking throughout the whole network.

3.2.3 Node Processing Related Metrics In [21], other functional measures, mostly related to hardware performance, have been defined. One could name the *average processed traffic per node* γ, the *density of traffic per node* μ and the *processing efficiency* ρ of a node. These measures impact the performance of the whole network, and play an important role in the network optimization. They are also dependent on the previously cited node capacities.

3.2.4 Flow Number With the effort to construct measures that guide more accurately the behavior of optical networks, Sen *et al.* [20] proposed the *Flow Number*, *fn*, which is a measure required to be small for a desirable network, as it is an indicator of the total number of wavelengths needed to reach full connectivity. Formally, let us define *fn* for a graph $G(V, E)$, where $R_1, ..., R_k$ are the set of all possible paths destined to route traffic from any source to any destination. The traffic flow is set as $d_{x,y} = 1\,\forall x, y,\ x \neq y$. Let T be the matrix of dimension $m \times k$ where each entry $T[i, j]$ indicates the number of flows traversing link e_i under the routing procedure R_j. Then the *Flow Number* of the graph $G = (V, E)$ is computed as:

$$fn(G) = \min_{1\leq j\leq k}[\max_{1\leq i\leq m} T[i, j]]. \quad (4)$$

The authors specify that the flow number defined above is close to the *load* metric defined in [23], but with the difference that the *load* metric is a function of three parameters: the optical path requests (represented by pairs of origin-destinations), the routing procedure used to establish the optical paths and the topology of the network. Indeed, the flow number would depend only on the topology of the network.
To conclude this list of some significant performance measures used in topological design, let us say that multiple combined forms of measures are also presented in literature. Those combined forms are used to arise certain aspects of the networks, that only one metric could not seize in a precise way [24].

4 Usual and YottaWeb Topologies

The optical network topology proposals encountered in literature could be considered from different points of view. As a first consideration, flat versus hierarchical topologies are designed. The important obstacles in designing such topology structure, specially for large size networks, is the very high numbers of variables involved. The modeling of networks such as the Internet could lead to a problem size of at least thousands of nodes, requests and paths. Most of the procedures to optimize the design are confronted to bottlenecks arisen by size. Hierarchization has been opposed to the flatness of the graph, in the goal to divide and conquer the size difficulties. It is a question of classifying nodes following different functionalities.

Indeed, in the flat topology, depicted in Figure 3, each node could communicate in peer-to-peer fashion, where the nodes are equipped with the same functionalities. The main advantages of the flat topology is to enable more obvious addressing and routing procedures, even when the size of the network increases.

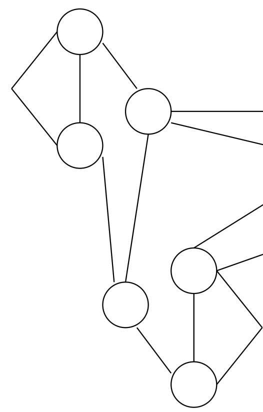


Figure 3: Sketch of a flat topology.

On the other hand, the hierarchical topology comprises at least two levels, as it is depicted in Figure 4. Indeed, at the lowest level, there are peer-to-peer exchanges between nodes, but some of the nodes hold for gateways for a network of higher level. In this case, the functionalities at the nodes are different. The problem with the hierarchical topology is that the limitation of the hierarchical structure is quickly reached at the level of the intermediate nodes, when the size of the network increases.

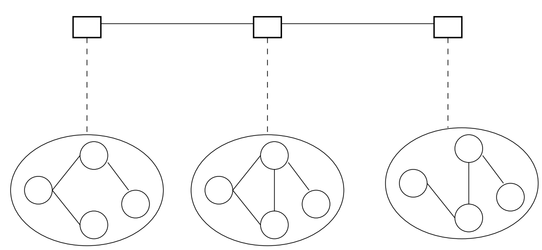
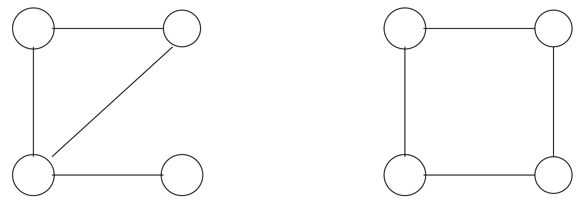


Figure 4: Sketch of a Hierarchical Topology.

On the other hand, the usual topology proposals, flat or hierarchical, could be classified into two different types: arbitrary topologies and regular topologies. The arbitrary topologies are represented by graphs without a known structure, while the regular topologies are well structured and present a certain symmetry between its components. Figures 5(a) and 5(b) provide examples of a four nodes arbitrary and regular topologies. The regular topologies are popular in literature, since they possess interesting well predictable properties such as easy addressing and routing. However, they present some limitations, especially in the case of large scale networks where some performance measures are very sensitive, or can be affected by the size of the networks.



(a) Arbitrary Topology (b) Regular Topology

Figure 5: Arbitrary and Regular Topologies.

Using the notation above defined for n and m, the total amount of possible non-oriented graphs is

$$T_{rand} = \binom{\frac{n^2}{2}}{m}$$

which corresponds to the m non-null entries in the triangular connection matrix of size $n \times n$. In these possible topologies, there is an important number that does not have any known, or apparent obvious recognizable structure: these are the so called arbitrary topologies. In the next sections we present the outcomes of each topology group.

4.1 Arbitrary Topologies

Some authors have studied the possibility of producing random arbitrary topologies [25] in designing optical networks. As it is noticed in Rose [26], the use of full random graphs with a given number of links randomly distributed, presents in practice some difficulties. For example, the connectivity, that is an important characteristic, cannot be insured by a random graph. Thus, many authors assume additional constraints that lead to a "semi-random" or "semi-arbitrary" graph.

Although they often present a very good performance in term of the mean hop value, arbitrary topologies require more complex routing procedures. Moreover, some authors consider that the total external capacity of arbitrary topologies is low [26]. Furthermore, sufficient fault tolerance is not guaranteed. Rose [26], under certain conditions, has recommended the use of "semi"-random topologies, for their low mean hop value. Otherwise, network designers prefer well structured regular topologies which are defined and discussed in the next paragraph.

4.2 Regular Topologies

Among the well structured, regular topologies, one can distinguish two classes: simple and composed structures. The first class consists of simple topologies such as the ring, the bus and the stars. The composed ones are more elaborated structures, which are the repetition of simple structures in a regular fashion. In the following paragraphs, we first define the different topologies followed by the description of their structural behavior for large scale networks.

For this survey, we have chosen a progressive approach to introduce the topologies. The topologies are presented for simple ones to more complex ones, the complex topologies derived from the composition of the simple ones. This approach reveals the way to progressively improve the topologies by adding nodes or links.

4.2.1 The Simple Topologies

The Bus Its configuration is given in Figure 6(b) where the five nodes are connected one after beside one, with bi-directional link.

Structural behavior: As the previous one, the bus optical topology has also the great advantage of being simple. Moreover, it requires a few number of links ($n - 1$) to be operational and to be extended, with low cost. However, the optical signal attenuation problem due to the length of the fibers could quickly become significant. In addition, a network based on a bus topology could quickly be the victim of congestion, since all the traffic passes through the same link. Moreover, the problem at one node is easily transmitted to the others, or could isolate a whole part of the network.

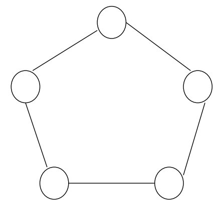
Thus, the bus topology is not appropriate for network expansion. The degree is 2 while the diameter is equal to the number $n-1$ of links. As a comparison to the ring, the mean hop distance in a bi-directional bus topology is of $n/3$ nodes compared to $n/4$ nodes for the ring [6].

The ring Depicted in Figure 6(a), the nodes are connected in a loop configuration.

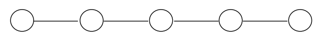
Structural behavior: because of its regularity and its simplicity, the ring allows all nodes equal access to the network, even when the number of nodes increases. However, the lack of reliability is an important drawback, as, ring topologies don't provide enough alternative paths between their nodes. Also, the simple operation of adding and removing a node from such a topology involves the interruption of the communication within the network. Therefore, ring topology is not extensible, and is not appropriate for large sized networks. However, its simple interface, and its unidirectional version is minimal, in the sense that it requires minimum number of links to reach full inter-connectivity. Degree in the simple ring is constant and equal to 2 while its diameter is about $n/2$ (for large n). As an illustration, the mean hop distance in a bi-directional ring topology is $n/4$ nodes.

The star In this simple topology illustrated in Figure 6(c), the nodes are connected through the same central node.

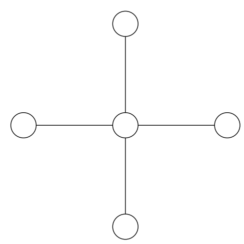
Structural behavior: When compared to the ring topologies, the standard star based topology presents the drawback that it requires more links, thus more optical fibers. Also, a faulty central node implies the rupture of communication within the network. The degree



(a) Ring



(b) Bus



(c) Star

Figure 6: The simple topologies.

of the central node is $n - 1$, while it is 1 for the other nodes. However, the star has the advantage of being simple and it is easy to add new components, or to modify existing devices. The monitoring and management of the star could be centralized. In addition, the rupture of a link does not affect the whole network. Moreover, the central node could be a switch controlled from the edge node as it is in the "composite-stars" of the PetaWeb [16] presented in Paragraph 4.2.2.

In the subsequent sections, we give descriptions of some interesting composed regular topologies, and we point out their performance according to several metrics.

4.2.2 The Composed Topologies The composed structure is called regular since for each node, it presents the same view of the topology. The reasons to recommend the choice of a regular topology are multiple [21, 8]. Before presenting some examples of such composed regular topologies, let us enumerate their important common desirable characteristics:

- They enable simple routing procedures, so that in most cases, there is no need to have a routing table at the nodes. Node addresses are sufficient for each traffic to self-route to the destination. The network engineering is then simplified.
- They provide a small diameter and a rather low mean hop value.

- Their fault tolerance is good, given that many alternative paths between nodes are provided.
- They facilitate network reconfiguration of the network, when the traffic varies.

On the other hand, the drawbacks of the composed regular topologies could be listed as follow:

- The resource consumption is sometimes too gluttonous [21], resulting from the use of several wavelengths to build the regular structure.

- The composed regular structure is in practice more appropriate to uniform traffic [8]. Then, its performance decreases when the traffic pattern is not uniform.
- The order of the network n is rigid, since it varies proportionally with other resources, then preventing a soft expansion of the network.

Despite all these disadvantages, the properties of regular composed topologies remain very attractive for optical networks. A wide range of proposals exist in literature; for instance, the hypercube [27, 28], the metacube [29], the generalized mesh [20], the d-neighbors regular topology [15], the multi-dimensional torus [14] and the Shufflenet [6, 30, 31, 32]. Also, in order to circumvent the weak points of these topologies, "semi"-regular topologies have been derived from the previous ones.

In what follows, we present some of the most used regular topologies: the mesh, the multi-dimensional torus, and the hypercube. Those topologies finally lead to the definition of the novel designed regular YottaWeb topology.

The mesh A $\mathcal{D}-$*dimensional regular mesh* topology (with k row) is defined as the interconnection of $k_1 \times k_2 \times k_3 \times \cdots \times k_{\mathcal{D}}$ nodes, where k_i is the number of nodes in the i^{th} dimension of the radix $\mathcal{D}$. Each node is identifiable by its position in each dimension and is represented by the vector $(x_1, x_2, x_3, \cdots, x_{\mathcal{D}})$, with $0 \leq x_i < k_i$. An illustration of the mesh topology is given in Figure 7, where an example of $2 \times 2 \times 3$ mesh is sketched. As can be appreciated in the figure, two nodes $(x_1, x_2, x_3, \cdots, x_{\mathcal{D}})$ and $(y_1, y_2, y_3, \cdots, y_{\mathcal{D}})$, in general notation, are neighbors if and only if it exists a digit i such that $x_i = y_i \pm 1$, and $x_j = y_j$ for all $i \neq j$.

Structural behavior: Routing in the regular mesh is self performed knowing origin and destination addresses. The expansion of such a topology is performed by increasing the number of nodes for a specific dimension, while nodes in other dimensions remain at their original position.

Various type of meshes were also proposed in the literature to improve the structure. There are, for example, the tori (see the paragraph below) which are derived from meshes, by adding toroidal bonds for general three dimensional torus. [20] has introduced the *generalized multimesh* (GM) for lightwave networks. The GM is a semi-regular structure comparable to the torus, but with less diameter.

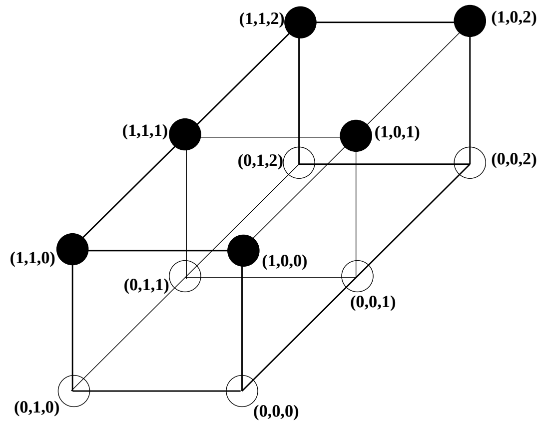


Figure 7: $2 \times 2 \times 3$ Mesh in dimension 3.

The multi-dimensional Torus A multi-dimensional torus topology structure, also called $\mathcal{D}$-cube and k-row, is defined as the interconnection of k nodes in each of the $\mathcal{D}$ dimension. Nodes are addressed in the same fashion as in meshes, and two nodes $(x_1, x_2, x_3, \cdots, x_{\mathcal{D}})$ and $(y_1, y_2, y_3, \cdots, y_{\mathcal{D}})$ are neighbors (interconnected), if an only if it exists a digit i such that $x_i = (y_i \pm 1) \bmod k$, and $x_j = y_j$ for all $i \neq j$. Thus, there are looping bonds in the $\mathcal{D}$-cube with k-row, which is not the case of the meshes. Figure 8 gives an illustration of those looping bonds.

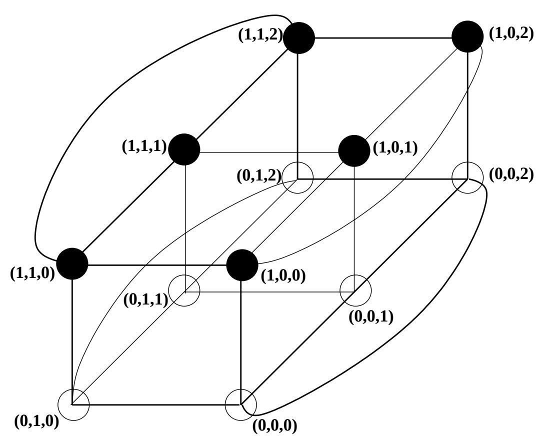


Figure 8: $2 \times 2 \times 3$ Torus in dimension 3.

Structural behavior: When $k = 2$, each node has $\mathcal{D}$ neighbors, and with $k \geq 2$, the number of neighbors for each node scales to $2\mathcal{D}$. The number of neighbors corresponds to the degree of each node, and contrarily to the meshes where the node degree vary with its position, every node have exactly the same degree in the torus. Such toroidal topology is regular and symmetric. For $\mathcal{D} = 2$, directed bi-dimensional tori are named *MSNs* (for Manhattan Street Networks) throughout the literature.

To generalize, a $\mathcal{D}$-dimensional torus is a $\mathcal{D}$-cube and looping bonds, where each node is addressed as a $\mathcal{D}$-tuple $(x_1, x_2, x_3, \cdots, x_{\mathcal{D}})$, with $0 \leq x_i < k_i$ and k_i the number of nodes in the i^{th} dimension. The number of nodes in each dimension could vary as long as the product of the number of nodes per dimension is equal to the total amount of nodes in the network. The routing is facilitated within such topology, since it just needs the destination node address in order to have the routing path. The expansion principle remains the same as in the case of meshes, except that re-connections are needed for the looping bonds.

The hypercube One of the most popular topologies found throughout the literature on multi-processor interconnection is the hypercube. Proposed by Bhuyan *et al.* [28], its extended general properties has been derived in Saad *et al.* [34]. The generalized structure of the hypercube presented in [28], consists of a r-dimension structure with k_i nodes in the i^{th} dimension, where a node in a particular axis is connected to every other node in the same axis. A number n of nodes (with n not prime) in a simple mixed radix representation system, leads to a variety of hypercube structures, where the integers $k_1, k_2, \cdots, k_r$, that are the number of nodes per dimension, are chosen such that:

$$\prod_{i=1}^{\mathcal{D}} k_i = n. \quad (5)$$

An example of a generalized hypercube is depicted in Figure 9, where only viewed components are drawn and each node is addressed in a radix system by a r-tuple $(x_1, x_2, \cdots, x_{r-1}, x_r)$ with $0 \leq x_i \leq (k_i - 1)$ for $i = 1, 2, \cdots, r$. The popular particular case of a binary hypercube corresponds to $k_1 = k_2 = \cdots = k_r = 2$ and is intensively studied in the literature.

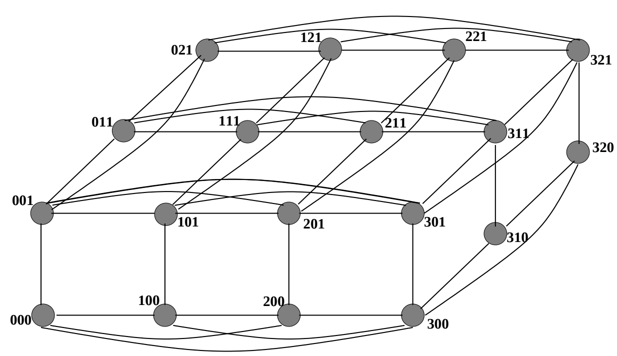


Figure 9: A generalized $4 \times 3 \times 2$ Hypercube.

Structural behavior: The properties of the hypercube structure [34] could be resumed as follow:

- The degree of each node is $\Delta = \sum_{i=1}^{r}(k_i - 1)$; this number increases with the size of the network. This is a main weakness of the hypercube topology.
- The distance $\delta(x, y)$ between two nodes x and y, in term of number of hops, is equal to the Hamming distance. Indeed, the Hamming distance between any two nodes is the sum of the number of coordinates in which the addresses of the two nodes are different. This distance is upper bounded by $\mathcal{D}$. Thus the diameter of the hypercube is $\mathcal{D} = r$.
- The total amount of links needed for a generalized hypercube is $\sum_{i=1}^{\mathcal{D}}(k_i - 1)$.
- The total amount of nodes at a distance of d hops from a given node is calculated as: $N_d = \sum(k_i - 1)(k_j - 1)(k_k - 1)\cdots$ where $i, j, k \in \{1, 2, \cdots, \mathcal{D}\}$ and $i \neq j \neq k$ and the sum includes $\binom{\mathcal{D}}{d}$ terms. As a particular case, let $k_i = k$ for $i = 1, 2, \cdots, \mathcal{D}$; we have $N_d = \binom{\mathcal{D}}{d}(k-1)^d$ and the average inter-nodal mean distance within the network becomes:
$$\bar{\mathcal{D}} = \mathcal{D}.(k-1).k^{\mathcal{D}-1}/(n-1), \tag{6}$$
with $k = \sqrt[\mathcal{D}]{n}$.
Saad *et al.* [34] has shown that the hypercube structure of diameter r is optimized, when the total amount of needed link is minimized. Formally, this happens with $k_1 = \cdots = k_r = k = \sqrt[r]{n}$.
- There are d node disjoint shortest paths and $d!$ alternate paths between every pair of nodes separated by the d Hamming distance. Several schemes of fault tolerance have been presented in the literature [22].
- The hypercube structure allows simple routing procedures, based on a binary representation addressing system that is equivalent to the basic radix system. In fact, the i^{th} digit in radix system address is at most $(k_i - 1)$, and could be expressed as $\lceil \log_2 k_i \rceil$ binary bits, with $\lceil k \rceil$ representing the least digit greater or equal to k. Then, every node in the network could be addressed with $\sum_{i=1}^{\mathcal{D}} \lceil \log_2 k_i \rceil$ bits. A part of the message unit header contains the destination address. Then, for the routing, each node compares its own address with the destination address in a bit-per-bit fashion, and route the message to direction of the first different bit.

Important works have been devoted to the studies of the hypercube and its derived topologies. [21] and [38] have studied the generalization of the hypercube structure. On the other hand, [27], [35] and [36] have introduced and studied the notions of incomplete and more incremental hypercube structure

From usual topologies to the lattice topology

Up to now, we presented some regular topologies suited to optical topology design. The list is not exhaustive since there are also regular topologies like de Bruijn and Kautz graphs [6, 11]. However, only directed versions of de Bruijn and Kautz graphs are regular and do not comply with the hypothesis of bi-directionality we have admitted in this paper. On the other hand, the unidirectional Shufflenet [6] has been mostly proposed as an interconnection topology for communication networks composed of $n = kp^k$ nodes. A Shufflenet is associated to a couple (k, p), and its nodes are arranged into k columns of p^k nodes each. For the unidirectional version, each node p incoming and k outgoing links, as it is shown in Figure 10. Gerla *et al.* [30] have studied the behaviors of the bi-directional version of the shufflenet.

In addition, de Bruijn and Kautz graphs are not well suited for expansion. However, composed topologies based on de Bruijn and Kautz graphs, like the Gem Net [6] that is a composition of the Shufflenet with de Bruijn graph, have been proposed to support large optical networks.

Our previous survey has shown that both, arbitrary and regular topologies have been proposed for next generation optical networks. The properties of regular topologies seem to be suited for a high performance large size topology design. However, even with a flat or hierarchical structure, some drawbacks still persist. Naturally, resource aggregation could enhance the design task by reducing the size of the variables. A fundamental question is how to proceed with the aggregation. The YottaWeb topology that we discuss in the next section is an answer to that question. In the YottaWeb, a multi-dimensional lattice is defined, where nodes in each dimension belong to the same sub-network and could communicate through a "tunnel". The final structure that resembles the hypercube, presents additional advantages that will be later explained.

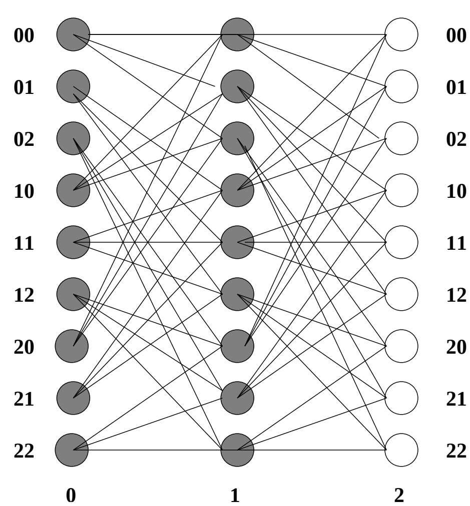


Figure 10: A Shufflenet with $k = 2$ and $p = 3$. The first and third columns represent the same nodes.

The Regular YottaWeb Topology The YottaWeb topology derived from the PetaWeb architecture proposed in [1] and [16] for a high capacity, distributed, edge controlled, optical core network. The PetaWeb topology is a "composite" star shown in Figure 11(A). Therefore, the configuration of the Agile Core allows to consider one PetaWeb as a subnet of a greater network. We will use the term "Agile Core" (AC) to signify the set of high capacity optical core nodes of a PetaWeb. This set of optical core nodes forming a PetaWeb is grouped within the dotted circle of Figure 11 and is symbolized by the big star at the right which represents an Agile Core. This constitutes the physical level G^0 of the YottaWeb composed of a plurality of Edge Nodes and Agile Cores as it is represented by the left side graph of Figure 12.

The YottaWeb lattice structure defines a way of efficiently connecting the Edge Nodes to the Agile Cores (ACs). A path between each origin-destination is constituted only by links from the Edge Nodes to the ACs, as no direct link exist between nodes or between ACs. The YottaWeb regular lattice structure is pointed up by the notion of dimension D of the network, which is defined as the number of ACs at which an Edge Node is connected to at the same time. The lattice structure represents the logical level. Figure 12(a) illustrates a unit-dimension YottaWeb, where each of the four Edge Nodes is connected to only one AC, represented by a single line in the lattice structure. The difference between the representation by the lattice topology and the traditional one is the use of a "tunnel" (line) to link all the edges within a subnet, instead of arcs linking them. Assuming that

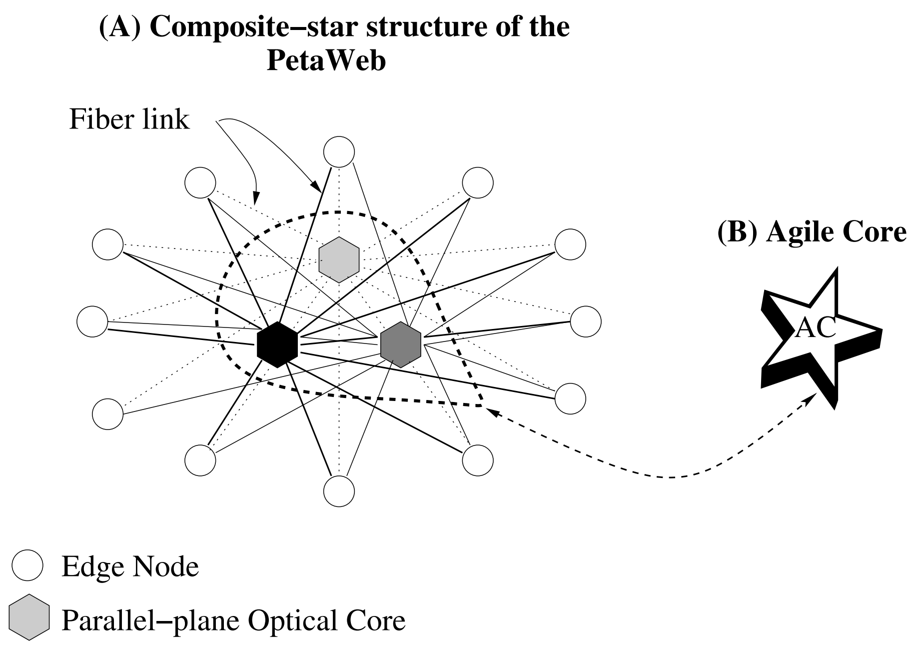


Figure 11: Structure of PetaWeb

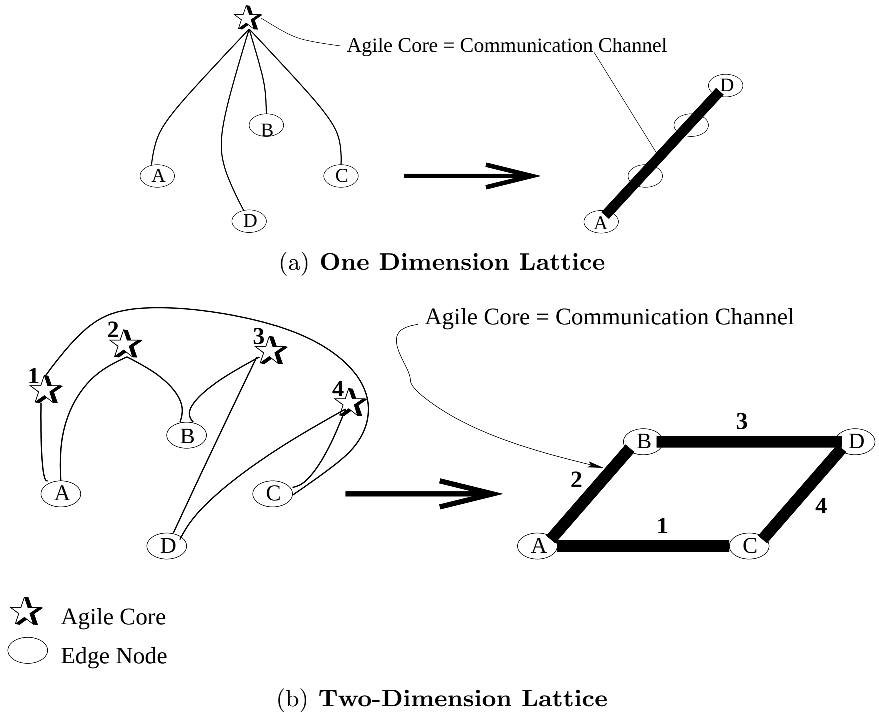


Figure 12: YottaWeb Arrangement into Lattice Structure.

two lines (ACs) can only intersect at one point and defining them to be perpendicular to a regular lattice structure (each AC is connected to exactly $\mathcal{K}$ Edge Nodes, $\mathcal{K}$ being the ACs capacity), one could easily increase the dimension of the YottaWeb to 2 as in Figure 12(b) and to more than 2 as needed.

A more complex example is portrayed in Figure 13 where there are two types of lines connecting the Edge Nodes: the light ones and the shadowed ones. Each line represents a different Agile Core to which the Edge Nodes in the line are connected. It is called "Yotta"Web topology since in terms of global capacity, the range of the yotta bits/s can be reached by the following simple calculation. Let us consider that the nodes are grouped into a lattice structure and that the access capacity per node could be equal to one terabit per second (10^{12} bit/sec). Let us suppose 1000 Edge Nodes per subnet. In a two dimension YottaWeb, the total external capacity within the network is computed as $1000 \times 1000 \times 10^{12}$ bits/sec $= 10^{18} = 1$ exa bits/sec. This total external capacity reaches $= 10^{21} = 1$ zetta bits/sec in dimension three and $= 10^{24} = 1$ yotta bits/sec in dimension four. From this definition of the regular lattice topology, every Agile Core connects the same number $\mathcal{K}$ of nodes.

Structural behavior: In Dégila and Sansò [2, 3], some properties of the lattice structure have been derived. The structure of the lattice topology is comparable to the topology of

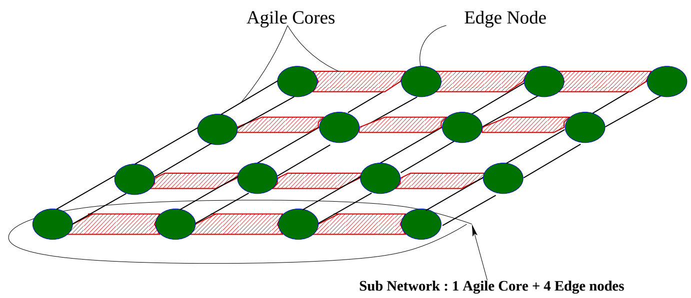


Figure 13: 16-Nodes YottaWeb Arrangement into two dimensions Lattice.

the generalized hypercube [28] defined for a multi-processors interconnection architecture. From that point of view, the lattice structure holds many interesting properties from the hypercube, while keeping the advantage of being simple. Indeed, the "tunnel" line linking the nodes simplifies the representation, and the manipulation of subnets defined by ACs.

Fundamental properties of the lattice topology are enumerated as follow.

- **On the degree:** From the lattice point of view, the notion of node degree is slightly different. Here, the degree represents the number of Agile Cores at which a node is connected to. Then the "degree" of each node is $\Delta = D$ the dimension of the YottaWeb. It is an important fact that the considered "degree" at each node does not depend on the size of the network, but is only related to its dimension. Once the degree is chosen, it remains fixed.
- **On the inter-nodal distance:** The distance $\delta(x, y)$ between two nodes x and y, in term of number of hops, is equal to the Hamming distance as in the case of the hypercube, and thus, the distance is upper bounded by D and the diameter of the lattice is equal to the dimension. The total amount of nodes at a distance of d hops from a given node is calculated as: $n_d = \binom{D}{d}(\mathcal{K} - 1)^d$ and the average inter-nodal mean distance within the network is:

$$\bar{\mathcal{D}} = D.(\mathcal{K} - 1).\mathcal{K}^{D-1}/(n - 1), \tag{7}$$

where $\mathcal{K} = n^{\frac{1}{D}}$. Then, substituting the value of $\mathcal{K}$ in equation 7, we have after simplifications:

$$\bar{\mathcal{D}} = D.(n - n^{1-\frac{1}{D}})/(n - 1). \tag{8}$$

- **On the number of links:** To compare with the total amount of links needed for a generalized hypercube, which is $\sum_{i=1}^{r}(k_i - 1)$, there is the total number of needed ACs that is computed as $m = D \times \mathcal{K}^{D-1} = D \times n^{1-\frac{1}{D}}$.
- **On the fault tolerance:** There are d node disjoint shortest paths and $d!$ alternate paths between every pair of nodes separated by a d Hamming distance. Then the

lattice structure is highly fault tolerant, as the hypercube [22] and the number of alternate paths remains constant.

- **On the addressing and routing:** The addressing is the same as in the hypercube and is simply based in a mixed radix system where the i^{th} digit in radix system address is at most $(\mathcal{K}-1)$, and could be expressed with $\lceil \log_2 \mathcal{K} \rceil$ binary bits, with $\lceil \mathcal{K} \rceil$ representing the least digit greater or equal to $\mathcal{K}$. Then, every node in the lattice network could be addressed with $\sum_{i=1}^{D} \lceil \log_2 \mathcal{K} \rceil = D \times \lceil \log_2 \mathcal{K} \rceil$ bits. Also, the routing procedure is lightened, since there is no need to conserve (memory consumption) and to frequently update (CPU and time consumption) a routing table at each node.

5 Design of Topologies with the Performance Measures

In this section, we explain how the performance measures are used in practice for the design of topologies for large scale optical networks. It is well known [8] that the problem of optical topology design that is a sub-case of the general network design problem, leads to difficult optimization problems. Hence, to simplify the problem, two approaches are generally used in a complementary way as successive sub-problems: a logical topology structure is first chosen according to its structural properties [6], then the nodes are arranged into the chosen structure by solving an optimization problem of the kind proposed in [7, 10], where the traffic flows within the topology is given by the traffic matrix.

This section has two parts. In the first part, we survey the different ways by which, the designer analyzes the structural properties of the topologies with the different structural metrics. The second part is devoted to the topological design by the means of mathematical programming.

5.1 Topological Design by Structural Analyses

Here, the topological design considers the structural behavior of the graph representing the networks. One compares qualitative and quantitative aspects of the considered graphs. In the general case, the surveyed structural metrics in Section 3.1 are used and their values for each topologies are computed. Then, depending on the obtained values that are compared to required values, a topology is chosen by the designer.

Overview of the literature trend on optical topologies design by the means of structural metrics is given in the next section. Thereafter, an explicit illustration of the application of the structural measures to the surveyed topologies is given. A sensitivity scale is given for each measure, in order to allow another level of comparison between topologies.

5.1.1 Key Literature Review In the papers written on the subjects, new network topologies are generally introduced and compared to some previous ones, or additional properties of existing topologies are exhibited. Based only on structural properties, the numerical comparison results for optical networks dealt with the size of the order of thousand nodes [6]. Then, their results for large scale networks.

Early in the 90's, Li and Ganz [21] studied regular virtual topologies for optical networks. The following regular topologies are investigated: Shufflenet, Binary Hypercube, Generalized Hypercube and 2-Dimensional Torus. Uniform traffic are considered within the network, i.e., there is the same amount of traffic between the pair of nodes. Their results showed various hardware/performance compromises for high speed networks.

Later, in order to allow a variable number of nodes in the optical networks, Tan and Du [36], introduced the embedding of Incomplete Hypercubes [27, 35]. The performance of the proposed scheme of design is comparable to those of both unidirectional and bi-directional hypercube.

In 94, Banerjee *et al.* [14] extended the studied torus for multihop lightwave network from dimension two to higher dimension. In fact, until there, only two dimension torus had been applied to the design of optical networks. Here, the authors analyze the properties, especially the average hop distance, of three dimension torus and hypothesized approximate results for higher dimensions.

Recently, Banerjee *et al.* [6] provided a comparative intrinsic presentation of some regular topologies widely proposed for optical networks, considering different performance metrics, such as the structural properties, broadcasting issues and the scalability of these topologies. The following topologies have been considered: bus, ring, star, multi-connected ring, shufflenet, de Bruijn graph, hypercube, HCRNet, Cayley graph connected cycles and TreeNet. Further reference and properties of those topologies are provided.

Nowadays, new topologies and metrics are being proposed, using other known topologies, and avoiding some of their shortcomes.

5.1.2 Comparison of Topologies and Sensitivity Scale We give in Table 1 an illustration of the performance of the topologies presented in this paper, compared to the new YottaWeb topologies, according to the following fundamental structural performance measures: number of nodes, number of links, diameter, degree and average internodal degree. To facilitate the comparison, we consider that all the topologies have the same number $n = k^2$ of nodes.

In addition to the value $\mathcal{M}$ of each performance measure, we propose in this paper, to discuss also the evolution of the measures. For the purpose, we define its *sensitivity scale* $\mathcal{SS}_{\mathcal{M}}$ as the minimum variation of its value in the course of the time. For example, the number of nodes for ring, star and bus topologies have one as sensibility scale, while it is $2K + 1$ for the other regular topologies. This information is important for the designer, when facing to the upgrade of its network. Also, the networks are generally in place, and their evolution toward large scale is the main concern. From that point of view, two types of structural measures should be distinguished. The first type groups the measures of the number of nodes and the number of links that we call "incremental structural measures". The sensitivity scale of these incremental measures should ideally be equal to one. The second groups are the "consequential structural measures" since their evolution is inducted by the evolution of the first group measures. The consequential measures are then, the diameter, the degree and the average Inter-Nodal Distance. The sensitivity scale of the inducted measures should ideally be equal to zero, since they are generally wished to be constant.

Table 1 shows in the second column, the notation of each structural measure $\mathcal{M}$ followed by its *sensitivity scale* $\mathcal{SS}_{\mathcal{M}}(I)$ with I the ideal value of the sensitivity scale. The values of the measures are computed for both the simple topologies and the two dimension case regular topologies. Based upon the sensitivity scale, one could notice that only the simple topologies met the "incremental structural measures" requirements. This is a confirmation of one of the drawback of the regular structure. On the other hand, considering the consequential sensibility scale, only the YottaWeb topology met all the required properties for large values of the number k. Indeed, for the measures of the YottaWeb, only one sensitivity scale, $\frac{2}{(k+1)(k+2)}$, is not equal to zero. However, it that sensitivity scale tends to null for large n.

Table 1: Measurements of the Structural Behavior of the k^2-nodes Topologies.

		Simple topologies for small networks			2 − D Regular topologies			
		Ring	Star	Bus	Mesh	Torus	Generalized Hypercube	YottaWeb Topology
Structural Measures	**Not.**							
Number of Nodes	n	k^2	k^2	k^2	k^2	k^2	k^2	k^2
	$\mathcal{SS}_n(1)$	1	1	1	$2k+1$	$2k+1$	$2k+1$	$2k+1$
Number of Links	m	k^2	k^2-1	k^2-1	$2k(k-1)$	$2k^2$	$2k^2(k-1)$	$2k^2$
	$\mathcal{SS}_m(1)$	1	1	1	$4k$	$4k+2$	$6k^2+2k$	$4k+2$
Diameter	$\mathcal{D}$	$k^2/2$	2	k^2-1	$2(k-1)$	k	2	2
	$\mathcal{SS}_{\mathcal{D}}(0)$	1/2	0	1	2	1	0	0
Degree	Δ	2	k^2-1	2	4	4	$2(k-1)$	2
	$\mathcal{SS}_{\Delta}(0)$	0	1	0	0	0	2	0
Average Inter-Nodal Distance (approx.)	$\bar{\mathcal{D}}$	$k^2/4$	2	$k^2/3$	$k-1$	$k/2$	$\frac{2k}{k+1}$	$\frac{2k}{k+1}$
	$\mathcal{SS}_{\bar{\mathcal{D}}}(0)$	1/4	0	1/3	1	1/2	$\frac{2}{(k+1)(k+2)}$	$\frac{2}{(k+1)(k+2)}$

To conclude this illustration, the sensitivity scale gives a fast mean to classify and to compare topologies according to their structural properties, when dealing with the enlargement of those networks. On the other hand, under the same basis, we have shown the structural performance of the YottaWeb over the other topologies for large scale networks.

5.2 Topological Design by Functional Analyses

Mathematical programming tools have been intensively used for designing networks, using the functional measures. One generally formulates the design problem as a mathematical programming problem. Then solving tools are generally applied to find the topology that optimize the functional measures. The goals of this section are to illustrate the way, the optical network design problems have been tackled. In the next section, we cited in detail, three papers that surveyed and widely addressed the subjects. Then, in the following section, we illustrate the formulation.

5.2.1 Key Relevant Literature Mukherjee *et al.* [10] were one of the first to explore widely the principles for designing large scale optical network topologies. The authors formulated the logical topology design as an optimization problem with the objectives to minimize the network average packet delay (a packet switching network is considered) or to maximize the scale factor by which the traffic matrix can be scaled up (to provide the maximum capacity upgrade for future traffic demands). The considered objectives related to the delay are non-linear function, leading then to non-linear difficult optimization problems. Survey of previous heuristics methods followed by Simulated Annealing combined with flow deviation based methods were presented. Numerical results are finally discussed and open problems have been arisen.

Later in 2000, Leonardi *et al.* [7] addressed the linear programming formulation of the problem, by considering the maximum congestion level in the network. In this paper, the authors classified the heuristics approaches for the sub optimal solution for the logical topology design problem in four classes: heuristics solutions of the MILP problem, maximizations of the single-hop traffics flows, heuristics maximizations of the single-hop and multi-hop traffic flows and finally, algorithms based on the adoption of a pre-established regular logical topology and on the optimization of the nodes placement according to the traffic pattern. Numerical results are also discussed for networks with at most 120 lightpaths. The results showed that heuristics that both consider single-hop and multi-hop traffic, starting from a fully-connected logical topology and removing lightpaths. Another important result is that optimal routing algorithms should be coupled with the logical design algorithms in order to have good solutions.

In the same year, Dutta and Rouskas [9] gave a wide survey of the topics related to the virtual topologies design for wavelength routed optical networks. Those topics are related to the context and scope of the components of the wavelength routed optical architecture. Additional covered topics are the survey of network performance optimization tools followed by the reconfigurability considerations. The last point refers to the problem of reconfiguring a network from one virtual topology. This problem is interesting not only to save the cost of having to reconfigure the whole network, but also, it helps to achieve a global strategy to optimize the initial problem of designing a logical topology.

5.2.2 Using the Functional Measures We give firstly in this section, the general framework for the formulation of the design of virtual optical networks as a mathematical programming problem. Table 2 present the different part of the framework with key references for further readings. Our classification is based on the survey of Dutta and Rouskas [9]. When, additional elements are added, their references are provided.

Table 2: General Functional Measures Optimization Framework for the Topological Design for Optical Networks.

Given	1- Physical Topologies/ Hardwares 2- Traffic Matrix 3- (Routing Scheme)	
Objectives	4- Maximization	a- Total External Traffic [10] b- One Hop Traffic [7]
	5- Minimization	c- Maximal Congestion [7] d- Average Weighted Internodal Distance [7] e- Mean Delay [10]
Variables	6- Flow	f- Portions of traffic over links [7][10]
	7- Link	g- Lightpath-Fiber indicators [7][10] h- Lightpath-Fiber-Wavelength indicators [10]
Constraints	8- Virtual Structure	i- Virtual Node Degree j- Lightpath hop or length limitation
	9- Flow	k- Flow conservation l- Flow Delay
	10- Coupling Constraints	m- Flow-Lightpath n- Lightpath - Wavelength o- Wavelength - Fiber
	11- Wavelength Constraints	
	12- Variables range	m- Binary variables p- Positive real variables
Find	13- Virtual Topologies 14- (Routing Scheme)	

This table shows the position of the functional measures, that we have surveyed in this paper, in the general logical optical topologies design. The functional measures are used as targets of the objectives 4-5, when finding the points 13-14, given 1-3. In fact, the routing scheme could be neglected [10], thus considered as an input of the problem of finding virtual topologies. Otherwise, Routing is given by the lightpath-Fiber-Wavelength indicators variables (h).

On the other hand, our functional measures are subdivided in two groups. The first group is associated to the maximization problem (4), and the second group is associated to the minimization problem (5). Different formulations of those measures could be found in Literature. The formulations including the delay lead generally to non-linear functions, thus non-linear problems [10]. Otherwise, linear formulations of the problem are often proposed when the delay functions are neglected, or simply linearized.

Solving the resulted problems is not easy. Numerical examples in the literature are obtained for networks with size less than hundred nodes. The exact methods for solving mathematical optimization problems are generally inefficient. Most of the times, the global problem is subdivided in different successive sub-problems. Successive approximative solutions are found by heuristics [9] and could lead to a worst final solution.

However, the methods that consists to first choose a virtual regular topologies, such as the YottaWeb, and then tackling the problem of nodal arrangement into the chosen structure, is still oftenly privileged. These methods lead to combinatorial optimization problems, for which heuristic methods could gave good solutions [3].

6 Discussions

In this section, we summarize the results of this paper and finally extrapolate on their usage in real-world networks.

In Table 3 and 4 the performance measures surveyed in this article are grouped around their fundamental metrics. In the first column of each table, fundamental structural or functional performance metrics are given, followed in the second column, by related measures found in the literature.

At a glance on these tables, it can be seen that the proposed classification around the fundamentals metrics, facilitates the comparison between the numerous performance measures proposed in the literature. Further application of these measures to the studied

Table 3: Classification of some Fundamental Structural Performance Measures.

Performance Measures $\mathcal{M}$	**Related Performance Measures**
Number of nodes n	- extensibility [6]
Number of Links m	- Fibers length [16][37]
Diameter $\mathcal{D}$	- Hop-Depth Distribution [15][18] - Length-Depth Distribution [16][18] - Maximal distance [15]
Degree Δ	- Node Degree Distribution [19]
Average Inter-Nodal Distance $\bar{\mathcal{D}}$	- Normalized average inter-nodal distance [19]
Symmetry $\mathcal{S}$	- node-symmetry [19] - edge-symmetry [19] - homogeneity [19] - combinatorial properties [38]
Fault Tolerance $\mathcal{R}$	- Reliability [6] - Strong fault tolerance [22] - Connectivity [20] - Number of biconnected components [33]

Table 4: Classification of some Fundamentals Functional Performance Measures.

Performance Measures	**Related Performance Measures**
Total External Traffic	- Throughput T_t [26][16]
Node Processing	- Average processing traffic per node γ [21] - Density of traffic per node μ [21] - Node processing efficiency ρ [21]
Traffic Weighted Inter-nodal Metrics	- Probable average Inter-Nodal Distance [21] - Mean hop traffic weighted by the traffic [2][3] - Maximal congestion [7][9][10] - Mean delay (Latency) [7][8][10] - One hop traffic [7][9][10] - Multiple hops traffic [7][9][10]
Flow Number fn	- Load [20]

topologies has shown the highest performance of the YottaWeb, for large scale networks, assuming that we are dealing with regular networks, with its known drawbacks.

Concerning the topologies, our presentation follows a progressive construction toward large scale networks. In fact, one could transform an optical bus topology to an optical ring topology simply by adding an additional link between the first and the last node. Then benefits are gained with the diminution of the diameter and the unweighted mean average hops. The fault tolerance is also improved. These simple topologies are not suited for large scale networks. However, most of existing deployed optical networks are long-haul and don't have many nodes. So they are based on such simple topologies.

Furthermore several optical buses or rings lead to mesh or torus respectively. A mesh also could be transformed easily in Torus, just by adding looping bonds. Continuing, a torus gives rise to the Hypercube by linking directly the nodes of the same line. Thus the evolution of the network could be seen following such perspective of converting one topology to another, simply by adding additional links. On the other hand YottaWeb proposal drastically changes the topology construction philosophy. Using the optical technologies, composed-stars networks have been aggregated in a conceptual mesh-like networks with highest structural performances. These networks are costly to be settled down. Since it requires additional optical devices (fibers, optical parallel planes, etc...) [16]. However they allow to reach enormous overall network capacities, with less drawbacks.

The other challenge of the design of optical topologies is about the functional analyses, that we have shown to occupy an important place. Our survey shows that, despite all of the mathematical formulation of the problems, only heuristics methods gave acceptable results. We have shown the general framework of such analyses. In the reviewed literature, only simplified versions of the problem have been investigated. On the other hand, results depend intimately on the considered traffic pattern. However, the traffic of a next generation network is difficult to predict. It is then encouraging that different types of heuristics are designed for different types of traffic. Further research should investigate the integration of multiple heuristics in order to efficiently handle different variation of the traffic pattern in the course of the time.

7 Conclusions

Parameters of optical topologies design have been surveyed. Performance measures as well as topologies have been classified, compared and referenced. Admitting that any simple topologies like the bus, the ring and the star cannot support large scale networks, the favored array based regular topologies have been gradually described and discussed, from the basic mesh to the more popular hypercube. The characteristics and the limitations of each type of topologies have been explained, in particular, when its size increases, and the results have been analyzed. The performances of the hypercube topologies over the previous one have been gradually showed up. The lattice structure topology proposal has been described from the physical to the logical representation. The lattice structure appeared as a solution for many shortcomings of the hypercube. Further works on the optimization and updating of such a lattice structure could be found in Dégila and Sansò [24]. A sensitivity scale measure has been introduced, in order to group the structural measures under the same analysis basis. The functional optimization of large scale optical topologies have been also surveyed. The main challenges in this case come from the variable traffic patterns. The reader is referred to Dégila and Sansò [3] for an example of designing an efficient heuristic for logical optical topology design that work for different types of traffic.

Up to recently [6], the regular topologies were just used in testbed optical networks such as Teranet at Columbia University. However there is a need to ensure that the next generation networks will not be a patchwork [16] of current networks. One the other hand, it is more difficult to study the evolution of current topologies to arbitrary large scale topologies. Thus our feeling is that the regular networks will play important role in the future networks. The easy accessibility of optical devices will accelerate the process.

References

[1] M. Beshai and A. Yu, “YottaWeb topology,” *Disruptive Network Solutions - Nortel Networks - Ottawa*, vol. Personal Communication, August 2000.

[2] J. Dégila and B. Sansò, “Design Optimization of a Next Generation Yottabit-per-second Network,” *Communications, 2004 IEEE International Conference on, Volume: 2, 20-24 June 2004 Pages: 1227 - 1231.*

[3] ——, “Topological Design Optimization of a Yottabit-per-second Lattice Network,” *To appear in the special series of the “Optical Communications and Networking (OCN)” of the IEEE Journal on Selected Areas in Communications (J-SAC), November 2004.*

[4] W. Mao and D. Nicol, "On k-ary n-Cubes: Theory and Applications," ICASE Report 94-88, Tech. Rep., 1994.

[5] R.L. Sharma, *Network Design Using EcoNets*. Van Nostrand Reinhold (June 1997).

[6] S. Banerjee, V. Jain, and A. Shah, "Regular Multihop Logical Topologies for Lightwave Networks," IEEE Communications Surveys, http://www.comsoc.org/pubs/surveys, Tech. Rep., First Quarter 1999.

[7] M. M. E.Leonardi and M. Marsan, "Algorithms for the Logical Topology Design in WDM All-Optical Networks," *Optical Networks Magazine "Premiere Issue"*, pp. 35–46, January 2000.

[8] C. Murthy and M. Gurusamy, *WDM Optical Networks: Concepts, Design and Algorithms*. Prentice Hall PTR, 2002.

[9] R. Dutta and G. Rouskas, "A Survey of Virtual Topology Design Algorithms for Wavelength Routed Optical Networks," *Optical Networks Magazine "Premiere Issue"*, January 2000.

[10] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, "Some Principles for Designing a Wide-Area Optical Network," in *Proc. IEEE INFOCOM '94*, Toronto, June 1994, pp. 117–129.

[11] T. Stern and K. Bala, *Multiwavelength Optical Networks: A Layered Approach*. Addison-Wesley, 1999.

[12] J. Elmirghani and H. T. Mouftah, "Technologies and Architectures for Scalable Dynamic Dense WDM Networks," *IEEE Communications Magazine*, vol. 38, no. 2, pp. 58–66, February 2000.

[13] M. Plante and B. Sansò, "A Typology for Multi-Technology, Multi-Service Network Synthesis Methods," *Telecommunication Systems*, vol. 19, no. 1, pp. 39–73, 2002.

[14] D. Banerjee, B. Mukherjee, and S. Ramamurthy, "The Multidimensional Torus: Analysis of Average Hop Distance and Application as a Multihop Lightwave Network," in *IEEE International Conference on Serving Humanity through Communications*, S. . ICC'94, Ed., vol. 3, 1994, pp. 1675–1680.

[15] R. Trobec and U. Jovanovič, "Regular d-Neighbors Topologies," in *Nineth Euromicro Workshop on Parallel and Distributed Processing*. IEEE, 2001, pp. 34–38.

[16] F. Blouin, A.W. Lee, A.W. Lee, and M. Beshai, "Comparison of two Optical-Core Networks," *Journal of Optical Networking, Optical Society of America*, vol. 1, no. 1, January 2002.

[17] G. Chen, "Shuffle-X Graphs and their Cayley Variants," Ph.D. dissertation, University of Hong Kong, 1997.

[18] E. W. Zegura, K. L. Calvert, and S. Bhattacharjee, "How to Model an Internetwork," in *Fifteenth Annual Joint Conference of the IEEE Computer Societies.*, I. Proceedings, Ed., vol. 2, 1996, pp. 594–602.

[19] G. Kotsis, "Interconnection Topologies and Routing for Parallel Processing Systems," Austrian Center for Parallel Computation, Tech. Rep. ACPC/TR 92-19, 1992.

[20] A. Sen, S. Bandyopadhyay, and B. P. Sinha, "A New Architecture and a New Metric for Lightwave Networks," *Journal of Lightwave Technology*, vol. 19, no. 7, pp. 913–925, May 2001.

[21] B. Li and A. Ganz, "Virtual Topologies for WDM Star LANs - the Regular Structures Approach," in *INFOCOM'92. Eleventh Annual Joint Conference of the IEEE Computer and Communications Societies*, 1992.

[22] E. Oh and J. Chen, "Parallel Routing Networks with Faulty Nodes," in *Eighth International Conference on Parallel and Distributed Systems*, IEEE, Ed., 2001, pp. 338–345, iCPADS 2001.

[23] R. Ramaswami and K. N. Sivarajan, "Optical Networks: A Practical Perspective," *Morgan Kaufmann Publishers, Inc.*, p. 632 pages, 1998.

[24] J. Dégila and B. Sansò, "Optimization, Updating and Expansion of a High Capacity Optical Network Lattice Architecture" , [In Preparation].

[25] J.-F. Labourdette and A. Acampora, "Wavelength Agility in Multihop Lightwave Networks," in *IEEE Infocom'90, San Francisco, California*, June 1990.

[26] C. Rose, "Mean Internodal Distances in Multihop Store and Forward Networks," *IEEE Transactions on Communications*, vol. 40, no. 8, pp. 1310–1318, 1992.

[27] A. J. Boals, A. K. Gupta, and N. A. Sherwani, "Incomplete Hypercubes: Algorithms and Embeddings," *The Journal of Supercomputing*, vol. 8, pp. 263–294, May 1994.

[28] L. Bhuyan and D. Agrawal, "Generalized Hypercube and Hyperbus Structures for a Computer Network," *IEEE Transactions on Computers*, vol. c-33, no. 4, pp. 323–333, April 1984.

[29] J. Chen, G. Wang, and S. Chen, "Locally Subcube-Connected Hypercube Networks: Theoretical Analysis and Experimental Results," *IEEE Transactions on Computers*, vol. 51, no. 5, pp. 530–540, May 2002.

[30] M. Gerla, E. Leonardi, F. Neri, and P. Palnati, "Routing in the Bidirectional Shufflenet," *IEEE/ACM Transactions on Networking*, vol. 9, no. 1, pp. 91–103, February 2001.

[31] P. To and T. Lee, "The Multi-Dimensional Shuffle-Exchange Network: a novel topology for regular network architectures," in *INFOCOM '98. Seventeenth Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1. INFOCOM '98, 1998, pp. 110–117.

[32] K. Yeung and T.-S. Yum, "Node Placement Optimization in Shufflenets," *IEEE/ACM Transactions on Networking*, vol. 6, no. 3, pp. 319–324, June 1998.

[33] B. Yener, "Virtual embeddings on regular topology networks," in *Eighth IEEE Symposium on Parallel and Distributed Processing*, IEEE, Ed., 1996, pp. 562–565.

[34] Y. Saad and M. Schultz, "Topological Properties of Hypercubes," *IEEE Transactions on Computers*, vol. 37, no. 7, pp. 867–872, July 1988.

[35] M. Horng and D. Chen, "Parallel Routing Algorithms for Incomplete Hypercube Interconnection Networks," in *CompEuro '92*, Computer Systems and Software Engineering. IEEE, 1992.

[36] S. T. Tan and D. H. C. Du, "Embedded Unidirectional Incomplete hypercubes for Optical Networks," *IEEE Transactions on Communications*, vol. 41, no. 9, pp. 1284–1289, September 1993.

[37] M. Tornatore, G. Maier, and A. Pattavina, "WDM Network Optimization by ILP Based on Source Formulation," in *INFOCOM*, 2002.

[38] S. Young and S. Yalamanchili, "Adaptative Routing in Generalized Hypercube Architecture," in *Proceedings of the Third IEEE Symposium on Parallel and Distributed Processing*, 1991, pp. 564–571.