Design of Hierarchical WDM Networks

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Abstract: Hierarchical (multi-core) Wavelength Division Multiplexing (WDM) networks present a challenging design problem to the network designer who wishes to establish all-optical circuits end-to-end and across multiple network cores. Due to the nature of the hierarchical structure and its traffic distribution, it is likely that the inner core requires more capacity when compared to the capacity required by the metro cores, which are individually connected to the inner core. This capacity mismatch cannot be addressed by assigning distinct transmission rates to each core, as this solution would result in using electronic time division add-drop multiplexer to interconnect the traffic across cores with distinct rates.

An alternative solution to addressing the capacity mismatch between WDM metro and inner core is explored in this paper, which is based on a limited number of wavelengths (a subset of the full set) being used in the metro core, when compared to the full set of wavelengths being used in the inner core. Two available architectures are presented in the paper, discussing their respective advantages and disadvantages.

1. Introduction

For both modularity and scalability, networks are typically designed in a hierarchical manner, e. g., multiple metro cores are directly connected to one central (inner) core. Due to this hierarchical structure, different cores might have different total bandwidth requirements, e.g., the inner core is likely to require more capacity, compared to metro cores. This capacity mismatch is often handled by using *transmission rate diversity*. For example, both SONET and SDH offer multiple transmission rates in multiple values of 4: e.g., the metro cores may use the 2.5 Gbps rate, while the inner core may use the 10 Gbps rate. Four 2.5 Gbps traffic streams (from four metro cores) can be multiplexed together to form the 10 Gbps traffic stream in the inner core via time division add-drop multiplexer at the edge node connecting the metro core to the inner core.

With the continuously increasing traffic levels and demands for higher bandwidth in both metro cores and inner core, Wavelength Division Multiplexing (WDM) networks are increasingly used in both cores. WDM networks are thus expanding their reach, to span over and across both metro and inner core. To cope with the capacity mismatch between WDM metro and inner core, transmission rate diversity is a possible option too. However, due to the lack of commercially available time division optical add-drop multiplexer, electronic time division multiplexing/demultiplexing is required at the edge node connecting the metro core to the inner core, i.e., optical/electrical/optical (OEO) conversion. Hence, the optical signal must be converted back and forth to the electronic domain (OEO conversion) — which is a relatively expensive operation in high speed optical networks.

In this paper the authors investigate an alternative solution to dealing with the capacity mismatch between WDM metro and inner core, termed *wavelength count diversity*. The wavelength count diversity solution does not require OEO conversion when traffic demands are routed across cores, in exchange for wavelength converters (WC's) that

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may be required when the wavelength continuity constraint cannot be satisfied Transmission rate is chosen to be the same across all cores, thus avoiding the need for electronic time division add-drop multiplexers. The capacity mismatch between metro and inner core is dealt with by making use of only a subset of wavelengths in the metro core, when compared to the full set of wavelengths available in the inner core. The simplest case is when N wavelengths are used in the inner core, and only $N/2$ of these wavelengths are used in the metro core. However, other options are possible too, e.g., $N/4$, $N/8$, etc.

Under the assumption that $N/2$ wavelengths are used in the metro core, two architectures are investigated in the paper. In the *SubSet architecture*, all metro cores make use of the same subset of wavelengths (say the wavelength with even identifier from the full set of N wavelengths used in the inner core. In the *OddEven architecture*, some metro cores make use of the even set of wavelengths and the remaining metro cores make use of the odd set of wavelengths. As described in the result section, these two architectures are compared against one another in terms of the number of WC's that are required to provision a given and common set of lambda services that span across the inner core, originating in one metro core and terminating in another metro core. As simulation results show for a number of network topologies, each of the two architectures has its own advantages and disadvantages with respect to the other.

2. System Description

Fig. 1 depicts a hierarchical network, comprising of one central inner core, and a number of metro cores individually connected to the inner core. Assume that both inner and metro are WDM networks. Assume that a set of bidirectional lambda services is to be established, each lambda service originating in one metro core and terminating in another metro core, i.e., no lambda services originate or terminate in the inner core. Every lambda service is routed via the inner core. Lambda services must be established by reserving one wavelength on every fiber pair (for bidirectionality) along the route computed for the lambda service. Signal OEO conversion is not allowed along the route. Wavelength conversion may be required along the route when the wavelength continuity constraint cannot be met [1]. Assume that a full set of N wavelengths is required in the inner core to support the set of given lambda services. Assume that $N/2$ wavelengths are sufficient in every metro core to support the set of given lambda services. Assume that the $N/2$ wavelengths are chosen to be a subset of the N wavelengths available in the inner core. A possible choice for the subset of $N/2$ wavelengths is the set of wavelengths with even (odd) identifier in the full set, as shown in Fig. 2.

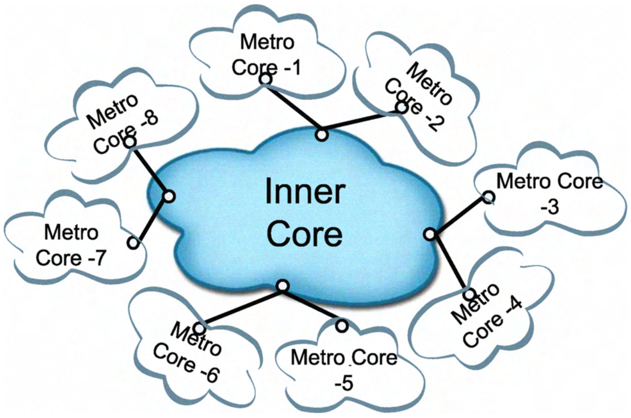

Fig. 1. Network topology.

This choice has the advantage of doubling the channel spacing of the wavelength comb in the metro core, when compared to the channel spacing of the wavelength comb in the inner core. WDM multiplexers and demultiplexers in the metro core have then a less stringent design constraint compared to the multiplexers and demultiplexers used in the inner core[1].

Zooming into one of the inner core nodes that serve as edge to interconnect metro cores to the inner core, an *optical crossconnect* is required as schematically illustrated in Fig. 3. The fiber connecting the edge node to an inner node must carry N wavelengths. The fiber connecting the edge node to a node that belongs to a metro core must carry a subset of $N/2$ wavelengths, either the even subset or the odd subset. An example of possible optical crossconnet using

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[1] Note that the spectral requirements of the optical transceiver must be consistent with the channel spacing used in the inner core for the lambda services that are routed through the inner core.

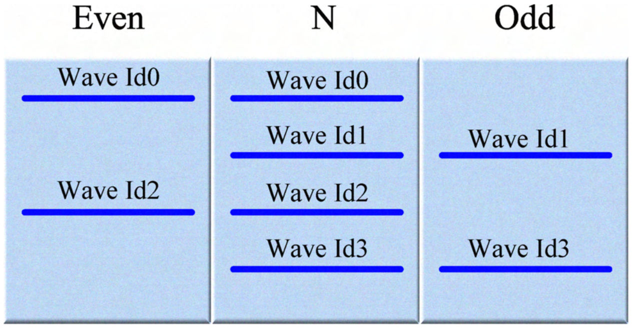

Fig. 2. Wavelength grid.

ROADM [2] is shown in Fig. 4. A lambda service being routed from a metro fiber carrying the even (odd) subset of wavelengths to the inner core fiber (full set) can be switched using WSS_2 and WSS_4 respectively, the former being a wavelength selective switch (WSS) with 2 wavelengths and the later a WSS with 4 wavelengths.

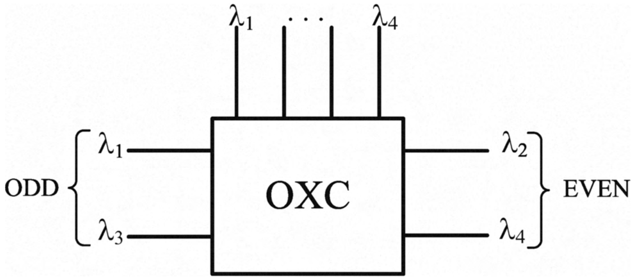

Fig. 3. Optical crossconnect at edge nodes.

A lambda service being routed from the metro fiber carrying the odd subset of wavelengths to the metro fiber carrying the even subset of wavelengths must use a wavelength converter, as illustrated in the figure. This latter case is also illustrated in Fig. 5.

As already mentioned in the Introduction, two architectures are investigated in this paper. In the SubSet architecture, all metro cores make use of the even subset of wavelengths, while the inner core makes use of the full set. In the OddEven architecture, half of the metro cores make use of the even subset, the other half of the metro cores make use of the odd subset, and the inner core makes use of the full set. The next section deals with the problem of computing the routing and wavelength assignment for every lambda service across the cores in order to minimize the total number of wavelength converters that are required in the hierarchical network. In addition, it presents an algorithm to choose which metro cores are assigned the even subset of wavelengths and which metro cores are assigned the odd subset of wavelengths, keeping into account the distribution of the given set of lambda services and the objective of minimizing the number of wavelength converters.

3. Network Planning Algorithms

This section describes the problem to be solved and the details of the algorithms used to obtain the results presented. The problem considered in this paper can be stated as follows. The following parameters are given:

- the network topology;
- the nodes and links that belong to the inner core;
- the nodes and links that belong to the metro core(s);
- the number of wavelengths (N) per fiber in the inner core and the number of wavelengths per fiber ($N/2$) in the metro core(s);
- the traffic matrix, i. e., the set of bidirectional lambda services between metro cores.

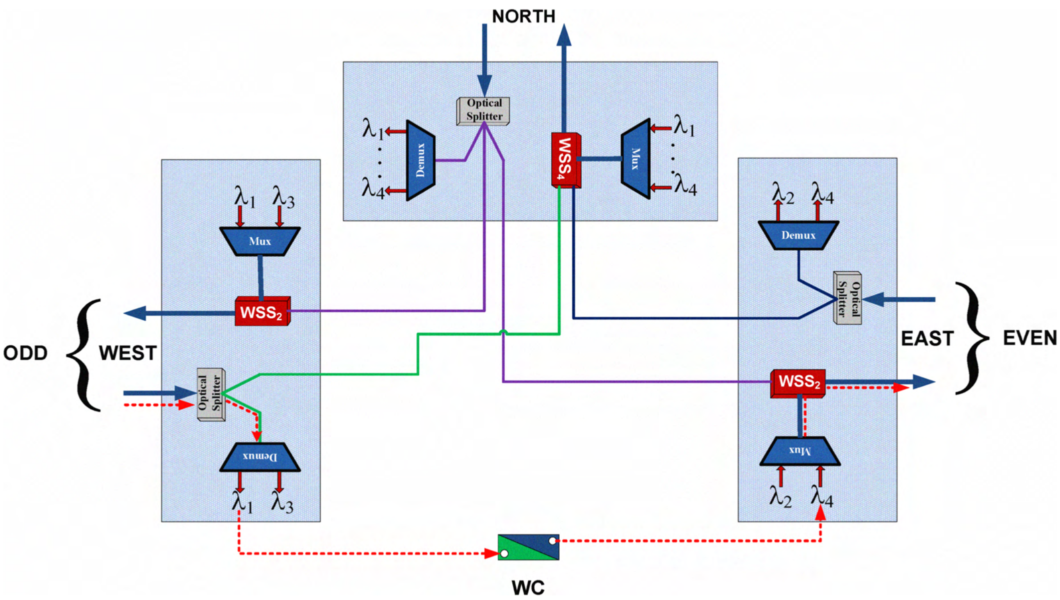

Fig. 4. Lambda service routed through crossconnect.

The objective is to determine the routing and wavelength assignment for each lambda service, such that the number of wavelength converters required is minimized. The problem must be solved keeping into accounts the constraints set by each of the two considered architectures, i.e., (*SubSet*, and *OddEven*).

3.1 *SubSet Solution*

In this solution, without loss of generality, it is assumed that each metro core uses the Even subset of wavelengths. The RWA algorithm in [3] — which jointly optimizes (i) the route of, (ii) the node location for the wavelength converters (if any) required by, and (iii) the wavelength(s) assigned to each lambda service — is modified to solve the problem. The algorithm in [3] is based on creating an auxiliary graph. Figure 6 shows an example with $N = 4$.

The auxiliary graph is created as follows. For each fiber, one link representing one wavelength is created and for each link two vertices are added to the auxiliary graph. Each vertex corresponds to the end node of the fiber. This link is assigned a cost equal to one. Vertices that originate from different wavelengths and that correspond to the same physical node are then interconnected by a link. This link is assigned a cost equal to the number of nodes in the network topology V. This link corresponds to using one of the wavelength converters inside the node. A shortest path algorithm is then run on the auxiliary graph. This choice guarantees to avoid wavelength converters as much as possible. The algorithm is run for each lambda service, one service at a time, in random order. The algorithm in [3] is modified as follows. On fibers that belong to the inner core, N wavelengths are available, i.e., N links are added to the auxiliary graph, while on fibers belonging to the metro core, only the $N/2$ Even wavelengths are available, i.e., only $N/2$ links are added to the auxiliary graph. An example is shown in Figure 7.

3.2 *OddEven Solution*

This solution is obtained in two steps:

- assign each metro core the appropriate $N/2$ subset, i. e., Odd or Even;
- perform routing, wavelength assignment, and wavelength converter placement for each lambda service.

Recall that services from one metro core to another are routed through the inner core, Wavelength conversion is required for every lambda service connecting two metro cores with different $N/2$ subsets, i.e., Odd to Even or Even to Odd. Traffic intensity is used to choose the subset of wavelengths to be assigned to each metro cores, e.g., metro core pairs with high traffic exchange must be assigned to the same subset of wavelengths. Subsets of wavelengths are assigned to metro cores using the partition algorithm in [4]. An auxiliary graph is obtained in the following way:

- all cores, both inner and metro are collapsed to a vertex;

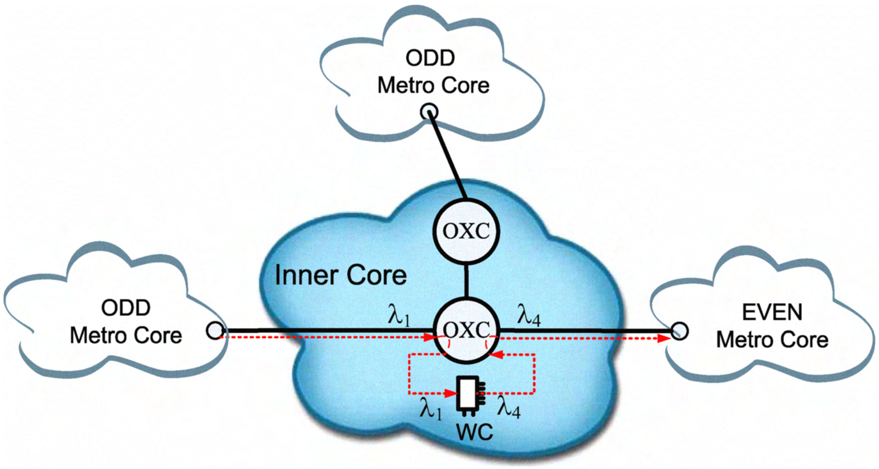

Fig. 5. Lambda service crossing from ODD metro to EVEN metro core.

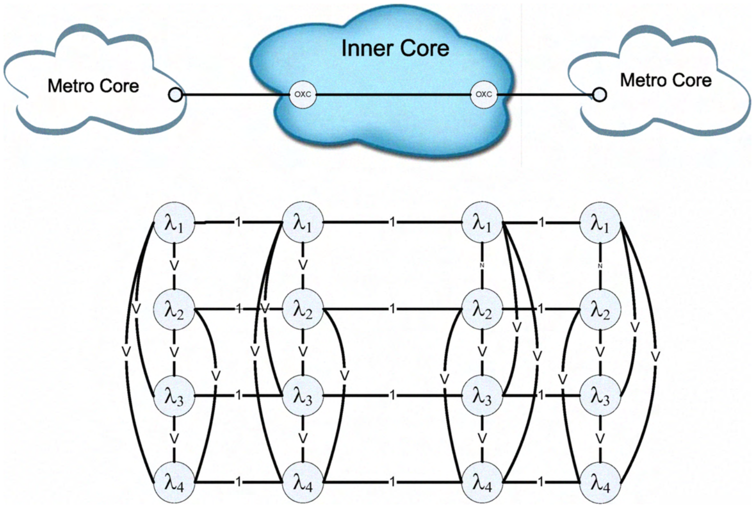

Fig. 6. Auxiliary graph used by the algorithm in [3].

- the inner core is not a vertex in the auxiliary graph;
- each of the metro cores is represented by one vertex in the auxiliary graph;
- two vertices are connected by an edge if there is traffic i.e., at least one lambda service, connecting the two metro cores;
- the edge weight is set to be equal to traffic intensity, i.e., the number of lambda services, connecting the two metro cores.

The algorithm is run requiring to partition the graph into two equally sized subgraphs, while minimizing the cut (defined as the weight sum of the edges across the subgraphs). The vertices (metro cores) in the same subgraph are assigned the same $N/2$ subset, i.e., either Odd or Even subset.

Once each metro core is assigned to either the Odd or Even subset, routing is performed using the modified version of the algorithm in [3]. The algorithm is modified in a way similar to the one described in Section *3.1*, the difference being that on fibers belonging to the Even metro cores, only the $N/2$ Even wavelengths are available, while on fibers belonging to the Odd metro cores, only the $N/2$ Odd wavelengths are available.

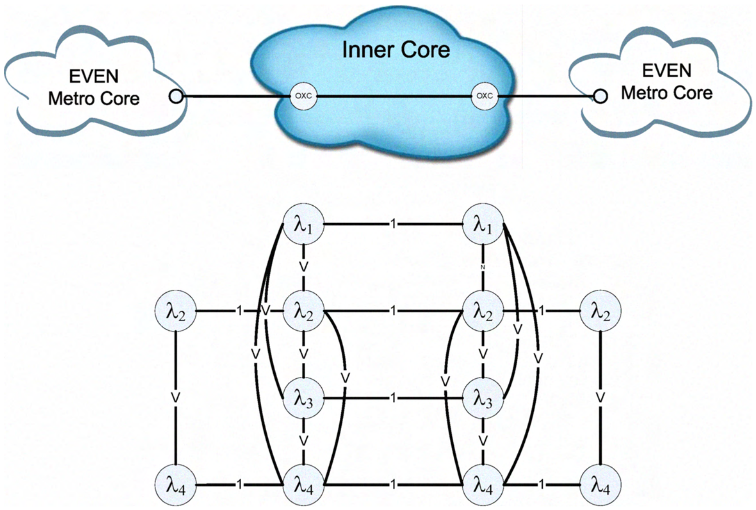

Fig. 7. Modified auxiliary graph to account for the SubSet architecture.

4. Simulation Results

This section presents simulation results that are used to assess the performance of the SubSet and OddEven architectures. Results are obtained on a number of scenarios where the number of wavelengths in the inner core is set to $N = 32$. In order to perform a fair comparison, i.e., a comparison that is independent of the physical topology of the metro cores, the following technique is used. Each metro core consists of one node only and a fiber with $N/2$ wavelengths connects the metro core node to an inner core node[2]. Traffic, i.e., bidirectional and symmetric lambda service requests, is then generated in the following way:

1. randomly select a source metro core;
2. if the number of lambda services that start or terminates at the selected metro core is $> N/2$ repeat step 1;
3. randomly select a destination metro core;
4. if the number of services that start or terminates at the selected metro core is $> N/2$ repeat step 3;
5. Repeat steps 1. to 4. until the desired number of lambda services is reached.

The above technique, ensures that the traffic generated will fit on the fibers between metro cores and inner core, while no wavelength converters are used inside metro cores. As a consequence, presented results consider wavelength converters placement in the inner core only.

Network topologies with different number of metro cores are studied. The traffic load is increased until saturation is reached, i.e., no more lambda services can be routed on the given network topology. For each network topology and traffic, numerical results are computed by averaging over 20 experiments.

A first set of experiments is run using the network topology shown in Figure 8(a). Figure 8(b) shows the number of wavelength converters required with SubSet and OddEven solution versus the number of lambda services. The difference in the number of wavelength converters between the two solutions is as large as 49%.

Then, the topology shown in Figure 9 is used. Fig. 9(b) shows the number of wavelength converters required with SubSet and OddEven solution versus the number of lambda services. In this case, the difference between the two solutions grows up to 45%. When traffic intensity is low, the SubSet solution requires a lower number of wavelength converters as the inner core can sustain the lambda services using less than half of its wavelengths (the Even subset). When this happens, lambda services between metro cores may not require wavelength converters with the SubSet solution. With the OddEven, a lambda service from an Odd metro core to an Even metro core will always require at least one wavelength converter no matter what is the load in the inner core. However, when traffic intensity is low, the inner core capacity is underutilized. As traffic increases, the OddEven solution is more effective in exploiting the

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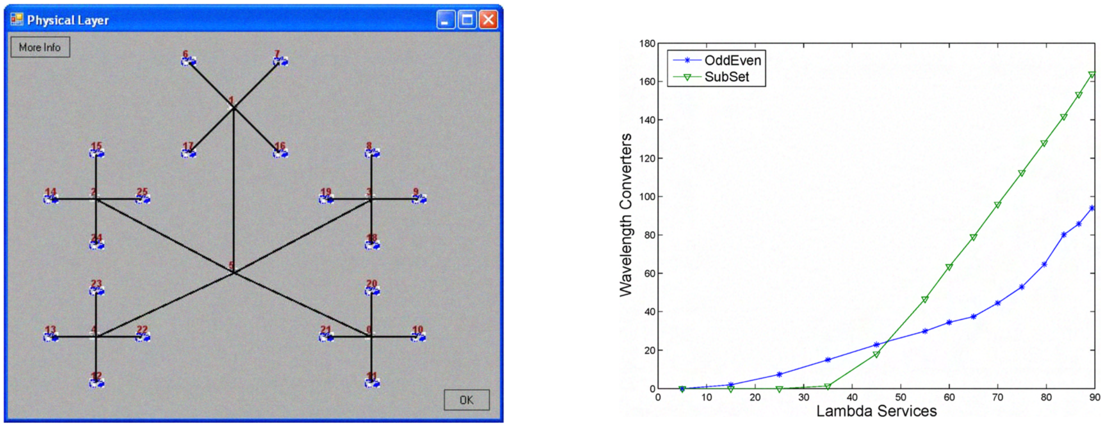
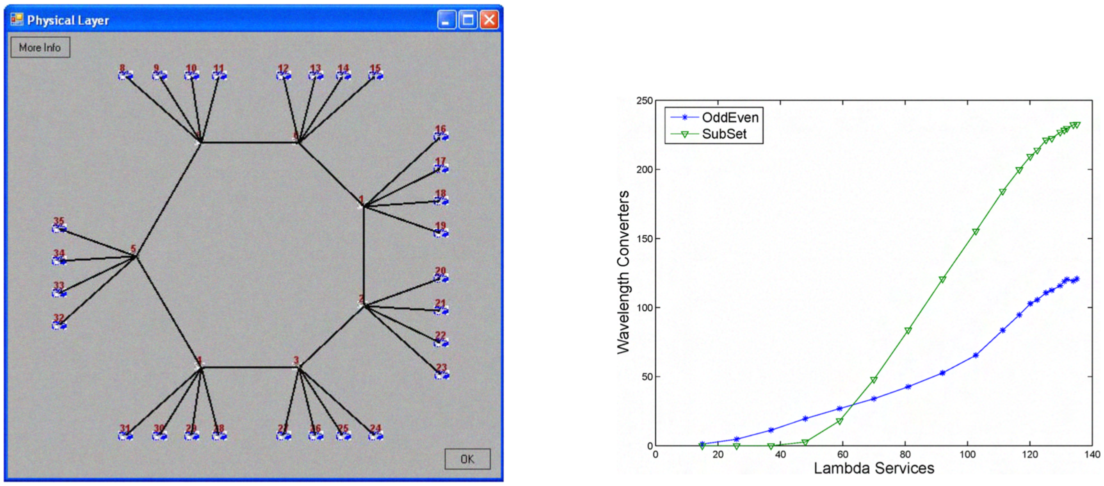
[2] Notice that while this technique is used to obtain the presented results, the algorithms presented in section **3.** do not require this technique.



(a) (b)

Fig. 8. Network topology with 5 groups and the required number of WC's.



(a) (b)

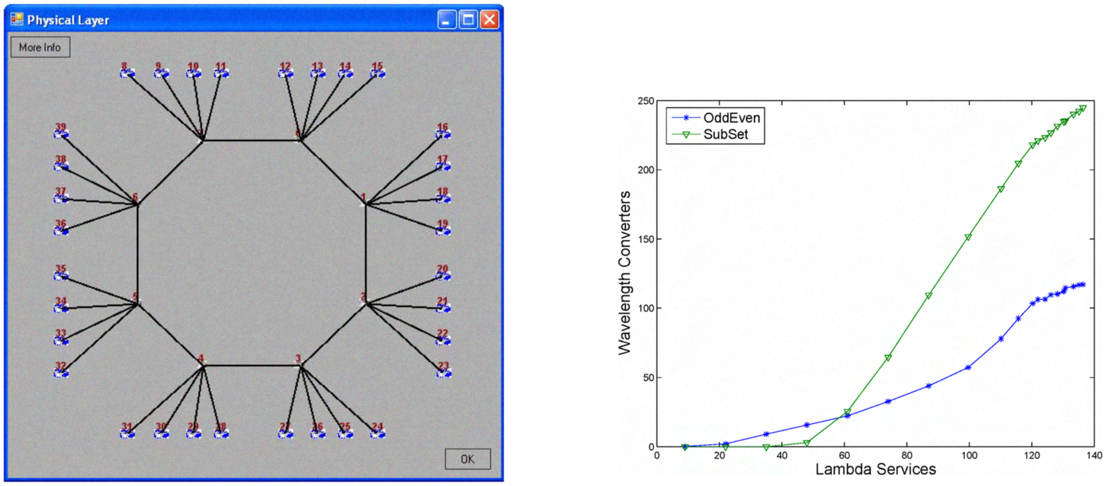
Fig. 9. Network topology with 7 groups and the required WCs.

$N = 32$ wavelengths present in the inner core, without requiring an excessive number of converters. When traffic intensity is high, the SubSet solution requires two converters for each additional lambda service in order to gain access to the Odd wavelengths in the inner core: one between the source metro core and the inner core, the other between the inner core and the destination metro core.

5. Conclusion

In this paper, the authors explored a *wavelength count diversity* solution to addressing the capacity mismatch between metro and inner core of a hierarchical WDM network. The solution is based on a limited number of wavelengths (a subset of the full set) being used in the metro core, when compared to the full set of wavelengths being used in the inner core. Two architectures are investigated: the SubSet architecture, in which all the metro cores use the same subset of wavelengths, and the OddEven architecture, in which half of the metro cores uses the even subset, and the other half uses the odd subset.

Simulation results obtained with a number of inner core topologies consistently indicate that the SubSet architecture is preferred at low traffic loads, as it requires fewer wavelength converters, when compared to the OddEven architecture. This conclusion is corroborated by intuition, as at low load, most part of the traffic in the SubSet architecture is routed using only the subset of wavelengths that is common to all the metro cores, thus requiring very few wavelength converters when entering and exiting the inner core. At medium and high traffic loads, however, the OddEven architecture requires fewer wavelength converters, when compared to the SubSet architecture. This conclusion is



(a) (b)

Fig. 10. Network topology with 8 groups and the required WCs.

also confirmed by intuition, as at high load the SubSet architecture is forced to use two pairs of wavelength converters (one pair at the source metro core edge and one pair at the destination metro core edge of the lambda service) every time a wavelength that is not in the subset of the metro cores must be reserved in the inner core to route the service.

While the simulation results are presented for the case of $N/2$ wavelengths in the metro core, similar results are found when using $N/4$ wavelengths in the metro cores, where N is the number of wavelengths in the full set used the inner core.

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