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Lambda-group Model and Optical Switching Fabric with Traffic Grooming*

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Abstract For multi-granularity application, both a lambda-group model used in traffic grooming and a new intelligent switching fabric based on the new model were presented. The optical switching fabric presented a distinctive approach of dividing granularities into specific tunnels for effective optical treatment. In addition, two key dynamic algorithm modules of configuration for granularity separation in the control layer were discussed. Simulation results show that the method of particular channel partition can greatly improve the average channel quality and the blocking performance along every optical path for dynamic connection requests.

Keywords Multi-granularity switching; GMPLS; Traffic grooming; Lambda-group; Execute area

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0 Introduction

To achieve G-LSP in GMPLS[1,2] which subdivide the switching types and traffic granularities, such items as L-LSP and WB-LSP have been added on new multi-granularity switching node discussed by many recent studies. Reference [3] studies the WRWA problem in hierarchical mesh networks with OXC that can route multiple granularities. Reference[4] presents four optical grooming switching architectures which imply that the connection bandwidth-granularity distribution has deep impact on network throughput and network resource utilization. Ref. [5～7] proposed more complicated structures that can expand the total switching capacity under dynamic environment. However, for complicated mesh topology, large-capacity working fibers and increasing number of available channels in fibers, these models could not provide enough support on multi-node configuration under dynamic environment of traffic with complex contribution. To meet future networking needs, a thorough research need to conducted, and observe the new characteristics of multi-granularity switching: 1) support the variable-length waveband and mitigate the restriction of fixed-length waveband. It also need a kind of logical granularity to handle the remaining channels in addition to the obvious local wavebands, and regard appropriate and non-uniform channels with the same routing direction as a logical group; 2) support the granularity operation among multiple fibers and permit the combination and disassembly of homogeneous granularities, i. e., the virtual granularity. Previous studies of the waveband switching structure prefer to recognize continuous co-directional channels as a waveband, without consideration of the coalition among multiple fibers. Such designs do not ease the burden of WXC. But virtual granularities will reduce the times of multiplexing and demultiplexing greatly in switching nodes, and improve the average SNR of channels; 3) remove some inefficient modules and layer in multi-granularity model. In this paper, it proposed a new node architecture with granularity grooming based on the new lambda-group theory. Results of channel and network performance would be presented.

1 Lambda-Group Model

1.1 Basic conception

1) Lambda-group or virtual lambda-group: a designated bundle of wavelength channels with the non-uniform interval but for the same factor, distributed in a fiber or several specific fibers. No overlap of wavelength channels in frequency domain is permitted among different fibers in the case of several fibers. The load of every channel in the λ-group (λG) is non-zero.

$$\begin{cases} \lambda G = \mathop{Y}\limits_{k=1}^{G} a_k' \cdot \lambda_k' = \mathop{Y}\limits_{i=1}^{M} a_i \cdot \lambda_i + \sum\limits_{j=1}^{N} B_j & (1) \\ G = M + \sum\limits_{j=1}^{N} |B_j| & (2) \end{cases}$$

Constraints: ① $\forall\, k \in (1, G-1)$ if $a_k', a_{k+1}' \neq 0$, $\exists \Delta_{\lambda'}(k) = |\lambda_{k+1}' - \lambda_k'| \neq$ constant

Or $\forall\, r \in (1, M + \sum\limits_{j=1}^{N} |B_j| - 1), \lambda_r \in \{a_i \cdot \lambda_i\} \cdot Y\{B_j\}, \exists \Delta_\lambda(r) = |\lambda_{r+1} - \lambda_r| \neq$ constant ② $\{a_i \cdot \lambda_i\}$

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$I\{B_j\}=\phi$

G is the dimension of a lambda-group from the first wavelength to the last, including all possible channels; M is the dimension of all isolated wavelength region when $M=0$ means that no isolated wavelength for the designated destination; N is the number of all wavebands, distributed in one fiber or several specific fibers. $N=0$ means that no waveband for the designated destination. Formula (1) means that a λ-group represents the group of non-uniform wavelength channels or the combination of isolated channels and waveband channels, that is, there are several shapes: ① a group of isolated wavelength channels with non-uniform interval; ②a group of isolated wavebands with the distance unequal to the inner interval ΔB_j of any neighbor waveband; ③a group of combining isolated wavelength channels with isolated wavebands.

2) Waveband or virtual waveband: a designated bundle of wavelength channels with the uniform interval for the same factor, distributed in one fiber or several specific fibers. No overlap of wavelength channels in frequency domain is permitted among different fibers in the latter case. A waveband λ_B has b effective wavelengths ($b \geqslant 3$). Constraints of waveband are omitted here.

3) Possible factors include the next hop, the source fiber, the priority of service, the degree of stability, the manageable degree and default settings. In practice, the recognition of λ-group or waveband may refer to several factors simultaneously to perform a reasonable adjustment of routing algorithms for various applications.

1.2 Concept of Lambda-group switching

Numerous adjacent nodes, high capacity fibers and complex traffic in mesh topology, are basic characteristics of multi-granularity switching node. The static setup of a switching node must show good ability to judge complicated traffic. The front module of the node should be capable to confirm the scale of wavebands existing in input fibers, and evaluate the possibility of forming advanced granularities (such as waveband) among different fibers. We think that if a fiber has already reached a certain scale of homogeneous wavelength channels (for example 1/3 of fiber capacity) and has the enough potential to form larger waveband with the help of other fibers, the routing direction (the label of node) is called an Execute Direction (ED) of this fiber. This fiber is also the Execute Fiber (EF) of the ED. Besides the waveband with continuous channels, the above definition also allows special waveband in which some channels are loaded with nothing ; If a waveband in a fiber

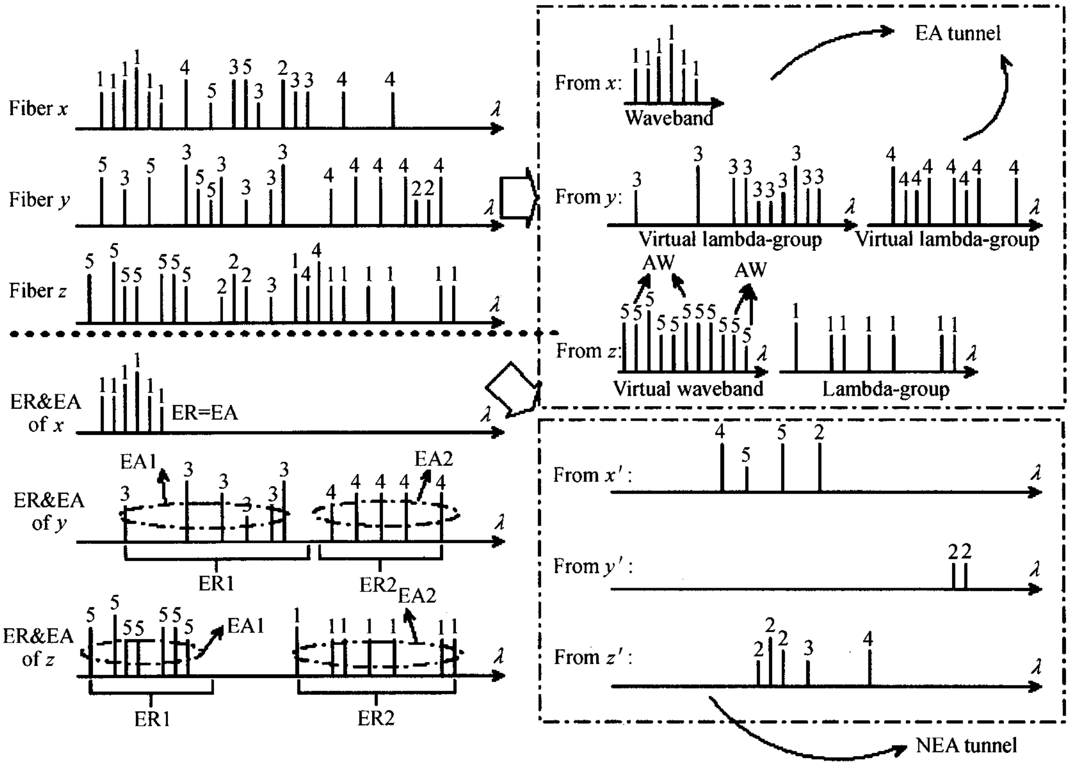

Fig. 1 Example of Lambda-Group switching

has a few channels without traffic load, we define the 'waveband' as a new logical granularity, namely Lambda-Group; If the virtual waveband (from multiple fibers) has a few channels without traffic load, define the 'waveband' as another logical granularity, namely Virtual Lambda-Group. Also, the definition of ED and EF involve four kinds of 'waveband': normal waveband, virtual waveband, lambda-group and virtual lambda-group. Note that, when recognizing a virtual waveband or virtual lambda-group among fibers, have to abandon what may impair the channel performance when the realization of advanced granularity causes excessive optical treatment. There may be several EDs in a fiber. One fiber is called a Non-Execute Fiber (Non-EF) if no execute direction exists in this fiber. After the static algorithm of configuration confirms all EDs of fibers, we can estimate the size and number of all advanced virtual granularities among fibers. Here, the frequency range of a logical granularity or an advanced virtual granularity possible in a fiber is defined as Execute Range (ER), including existing wavelength channels with ED and channels to be filtered for the granularity. The former channels are specified as an Execute Area (EA) which must be within the corresponding ER; all other channels except EA channels in the fiber are channels of Non-Execute Area (NEA). Few wavelength channels to be filtered to expand other fiber′ s waveband or lambda-group are called Assistant Wavelength channels (AW). Fig. 1 provides a vivid explanation of all symbols. The numbers from 1 to 5 denote the routing direction or the label of a neighboring node. According to our definition, '1' is the ED of fiber x, '3' '4' are ED of fiber y, and '1' '5' are ED of fiber z. In other words, EF of '1' is fiber x and fiber z, EF of both '3' and '4' is fiber y, EF of '5' is fiber z, and '2' has no EF. ER and EA of every fiber are also showed in the figure. There is no Nom-EF here.

1.3 Basic signs about multi-granular traffic

NH, d: Next Hop, the next hop or routing direction of a wavelength channel.

NH(): NH(λ, t), the function of NH. We can get the routing direction of channel λ at the moment t.

ER: Execute Range, the recognized range of wavelength channel to be disposed by pre-layer or pre-module for a NH in a fiber. The execute range is affirmed and recognized by the dynamic algorithm.

EA: Execute Area, all wavelength channels for the NH of ER inside ER in a fiber before pre-layer or pre-module. There may be wavelength channels for other NH inside ER but outside EA. There may be co-directional channels outside ER as channels inside EA.

NEA: Non-EA, all wavelength channels outside any EA in a fiber.

EF: Execute Fiber, the fiber containing at least one ER for the given NH. There may be several ERs for different NH.

EF(): EF(NH, t), the function of EF. We can get all fibers for the given NH at the moment t.

NEF: Non-EF, the fiber without any ER.

AW: Aiding Wavelength, few wavelength channels which can be filtered to expand EA of other fiber.

1.4 Brief parameters for traffic analysis

ComV is the Combination Value and the total sum of effective sizes of possible wavebands combined with traffic from all fibers theoretically, considering all routing directions. ComV = 120% means that the ideal sum of effective sizes of possible wavebands combined reaches to 120% of the capacity of a fiber. BC is the Block Coefficients of traffic and the mean value of the sum of effective sizes of all existing wavelength blocks from all fibers every routing direction to the total number of fibers. For example, BC = 50% means that the mean size of all existing wavelength blocks reaches to 50% of the capacity of a fiber.

2 Working scheme of switching fabric

In Fig. 2, present a smart structure based on the IETF models[1]. All input traffic is firstly recognized and divided by the partition module into possible six logical granularities to EA tunnel and NEA tunnel. Six granularities are Execute Area in Execute Fiber (EA@EF), Assistant wavelength channel in Execute Fiber (AW @ EF), Non-Execute Area within Execute Range in Execute Fiber (NEA:ER@EF), Non-Execute Area out of Execute Range in Execute Fiber (NEA:$\overline{ER}$@EF), Assistant wavelength channel in Non-Execute Fiber (AW@NEF) and Non-Execute Area in Non-Execute Fiber (NEA@NEF). Three clusters of granularities are large wavebands and lambda-groups along EA tunnel, complex λ-groups along NEA tunnel and separate wavelengths along NEA tunnel. Three different parts in the core switching layer will be responsible to switch these granularities respectively . Since EA tunnel can

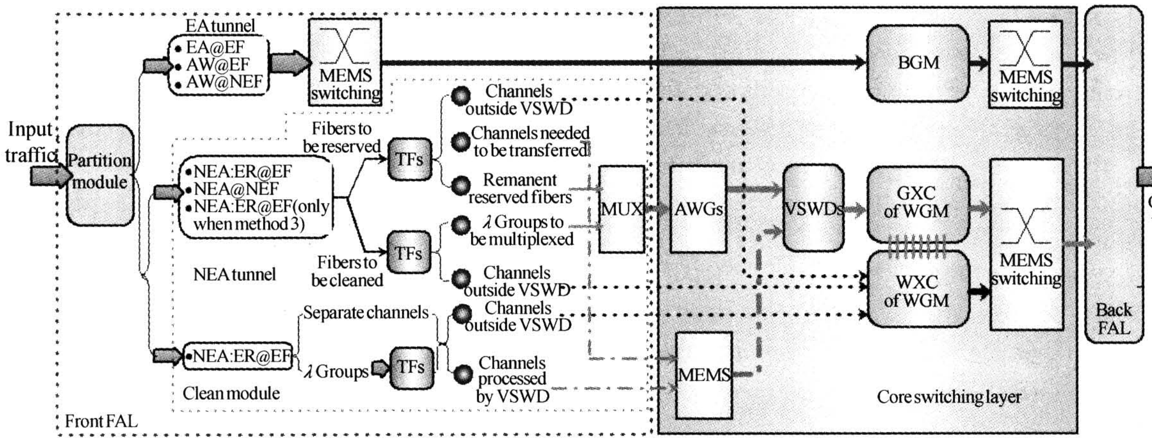

Fig. 2 Flowchart of the new switching fabric

provide higher average SNR of channel than SNR NEA tunnel can give, the overall performance of channel will be improved when main traffic is processed by BGM with good policies and algorithms about traffic grooming and rearrangement of granularities. Control Layer includes four modules of Resource Utility Module (RUM), Module for Efficiency Estimation (MEE), Algorithm Module for Static Traffic (AMST) and Algorithm Module for Dynamic Traffic (AMDT).

Objective Functions: the first minimize the total cost of LGS-OXC ports. The second minimizes the average attenuation of channel at the given offered load or the near maximum offered load in every node.

3 Dynamic algorithm of configuration

Due to limited space, we will only discuss two key algorithm modules for granularity separation used in Front FAL New modules in FAL takes pressure off core switching layer by trying its best to integrate granularities with the same next-hop into a waveband block or a combined λ-group without wavelength conversion. We distinguish the variation of routing direction into two cases: single request and multiple requests, that is, two critical modules, DMSR and DMMR.

- DMSR (Dynamic Module for Single Request)

After the previous configuration of the node by static algorithm BWGA, when single request is coming, the node will firstly affirm both routing directions at the moment t_0 (before the request) and t (after the request). Then the configuration of input traffic is adjusted by six function modules according to different transformation from NH(λ, t_0) to NH(λ,t). λ+@EF, λ-@EF, λ+@NEF, λ-@NEF, NA@EF and NA@NEF are six sub-modules to execute relevant manipulations of routing assignment. There are relevance and transformation among six function modules as the most important part in DMSR.

```
Run static module BWGA (Balanced Wavegroup Gromming and Assignment with Execute Area)
Analyze the single request
Affirm NH($\lambda$,$t_0$),NH($\lambda$,$t$)
Compare NH($\lambda$,$t_0$):(NA,EA,NEA) with NH($\lambda$,$t$):(NA,EA,NEA)Confirm Type?
    Switch(type)
    {case EA→EA:$\lambda$-@EF;$\lambda$+@EF;
    case EA→NEA:$\lambda$-@EF;$\lambda$+@NEF;
    case EA→EA:$\lambda$-@EF;
    case EA→NEA:$\lambda$-@NEF;
    case EA→EA:NA@EF;
    case NEA→EA:NA@NEF;
    case NEA→EA:$\lambda$-@NEF;$\lambda$+@EF;
    case NEA→NEA:$\lambda$-@NEF;$\lambda$+@NEF;}
```

- DMMR (Dynamic Module for Multiple Request)

Until dynamic requests are coming, traffic from all nodes has been adjusted or disposed based on the static algorithm BWGA. When more than one request is coming, the node will run the dynamic module for multiple requests, i.e., DMMR. DMMR will assume the F-EA table TA_2 figured from the dynamic F-λ table, and compare it with the F-EA table TA_1 figured by BWGA at t_0. If the difference between TA_1 and TA_2 is large, TA_1 and TA_2 will be converted to the Dig-Fill form respectively in which each element denote the next signal carrying on other channel of fiber. For example, λ_{31} in the Dig-Fill TA_1 denote that the signal carried on the first channel of the third fiber is carrying on the first channel of the second fiber at t_0. λ_{34} in the Dig-Fill TA_2 denote that the signal carrying on the fourth channel of the third fiber is requesting to carry on the first channel of the first fiber. Then two matrices in Dig-Fill form are combined to get a ready scheme according to the process in figure 8 and relevant resource policy. Only if the ready scheme does not utilize too much resource, the node will put it into operation. Otherwise the node may look for another TA_2 in view of different EA (Execute Area) until a preferable TA_2 is confirmed. On the other hand, if the difference between TA_1 and TA_2 is small, the node will perform the scheme of running DMSR several times in order.

```
Run static module BWGA at $t_0$;
Get the F-EA table $TA_1$ in the FAL at $t_0$;
Analyze all requests;
FEA: assume all F-EA table $TA_2$ in the FAL at $t$
for ($i=1; i<=Max; i++$)
{Estimate from $TA_1$ to $TA_2$(i)
If variation=great
{Compare $TA_1$ with $TA_2$(i);
Convert $TA_1$ to the form of Dig-Fill table;
Convert $TA_2(i)$ to the form of Dig-Fill table;
Compare every element of two Dig-Fill tables:
DFCom($TA_1$, $TA_2(i)$);
  Get retum value of DFCom, DFC (1-lack of resource, 0-else)
  If DFC=1
    {If($i$=Max)
      {Weighting all requests;
      refuse a request;
      Goto FEA;}
    else{Ready next $TA_2$;
      $i$++; break;}}
  else{Enforcement: Adjust TF/Free TF/Add TF;
      Confirm F-EA table $TA_2=TA_2(i)$ at $t$;
      break;}}
  else{Sort all request expressions;
      for ($n=1; n<=Max; n++$)
      {Call DMSR;}
    Confirm F-EA table $TA_2=TA_2$(iat $t$;}
  DFCom (A, B) //with the help of Resource Policy, RUM and MEE
  {for ($j=1; j<$row number; $j++$)
    {Switch(Compare $A[j,k]$ with $B(i)[j,k]$)
      case same: Combine;
      case similar: Combine and request more resource;
      case different: Request more resource;}}}
```

4 Performance evaluation

Simulation satisfies the following assumptions: Every network node is equipped with the same type of grooming OXCs . There are two pairs of unidirectional fibers between any two nodes. The network has no wavelength-converter and each fiber link can support 32 wavelength channels. The capacity of each wavelength is OC-48 (2. 4Gbps). Since recent a great amount of measurements[9] confirm very high speed traffic of self-similar, it is assumed the connection- arrival process is self-similar and the connection-holding time follows a negative exponential distribution. A connection request can have any bandwidth granularity of OC-1, OC-3, OC-12 and OC-48. The connection-arrival process is self-similar and the connection-holding time follows a negative exponential distribution. Network offered load (in Erlang) is defined as the connection-arrival rate times the average holding time times a connection's average bandwidth and it is normalized to the unit of OC-48.

At first, study the average attenuations of all possible granularities at peak access ratio with optimized algorithms as Fig. 3 and 4. Attenuations of granularities through the entire node reduce rapidly with increasing ComV when BC or ComV is not small. In addition, when it is a small ComV among input fibers, attenuations of granularities reduce slowly with increasing BC. When the ComV is not small , attenuations of granularities

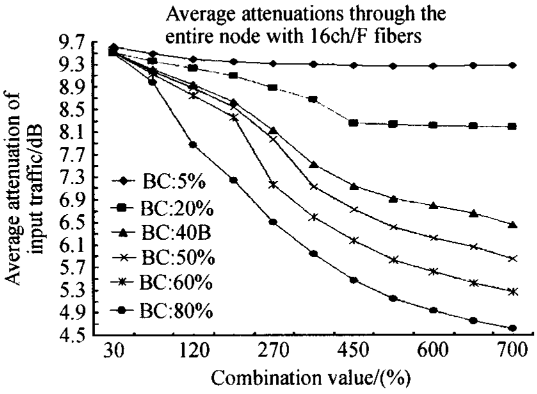

Fig. 3 Variation of traffic attenuation with changing ComV

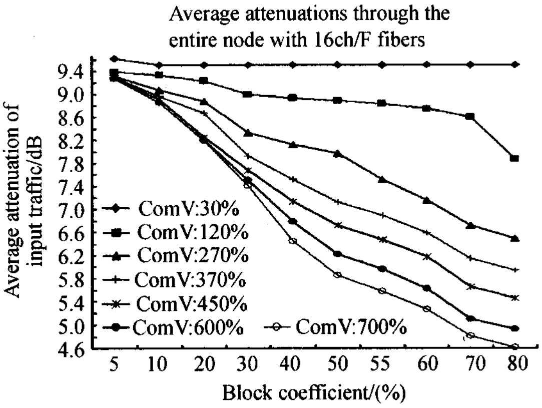

Fig. 4 Variation of traffic attenuation with changing BC

also reduce rapidly throughout with increasing BC.

Then, compare results of representative fabrics from researches[4,5,7] with results of our new design under the same dynamic environment as Fig. 5. When the traffic load is low, the network performance with new design is not good.

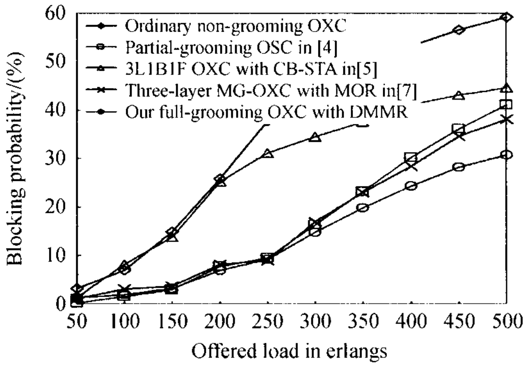

Fig. 5 Blocking probabilities of networks with different structures

However, with increasing offered load in the network, the advantage of new fabric is apparent more and more. Depending on specific structure of node and improved dynamic algorithms, succeed to decrease the blocking probability below about 35% under very high traffic load. Results from simulation confirm the lambda-group switching fabric of high performance and cost-effective.

In addition, select some representative nodes and record a series of results of node performance with changing combination value. Results provide significant reference for optimizing dynamic algorithm and promoting better routing assignments in mesh network. Fig 6 shows a given node connected by 5 neighboring nodes and the tendency of blocking performance with changing ComV at specific traffic loads. Results confirm the necessity of enlarging the combination degree of channels among input and output fibers for effective utilization of limited resources.

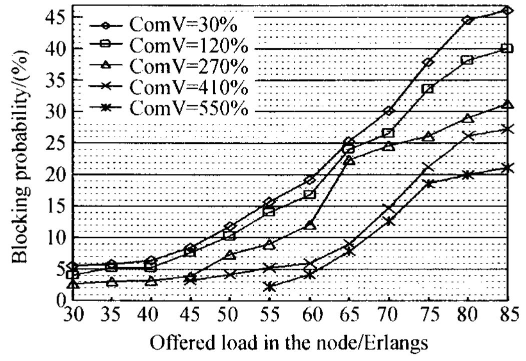

Fig. 6 Blocking performance with increasing load at different ComVs

5 Conclusion

For high efficiency of traffic grooming under dynamic environment, introduce a prominent switching architecture based on updated lambda-group theory. Three layers and six modules in the fabric present a distinctive approach of dividing granularities into specific tunnels for effective treatment. In addition, dynamic algorithms and various results of evaluation are discussed here. It is apparent from experiment results that the new design of optical switching has potential enough to cut cost and improve the flexibility for dynamic application.

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波群模型和支持流量疏导的光交换结构

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摘 要 针对多粒度应用,开发了一种用于流量疏导的波群模型,并引入一种基于此模型的新型智能交换结构.该光交换结构提供了独特的区分粒度到相应隧道进行有效处理的方法.此外,还讨论了控制层粒度分离时采用的两个关键的动态算法模块.仿真结果显示这种特殊的通道分离方法有效提高了处理动态连接请求时每个光路径的平均信号通道质量和阻塞性能.

关键词 多粒度交换;通用多协议标记交换;流量疏导;波群;执行域

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