3D Elastic Optical Networks in Temporal, Spectral, and Spatial Domains with Fragmentation-Aware RSSMA Algorithms

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Abstract *We propose two fragmentation-aware routing, spectral, spatial mode, and modulation format assignment algorithms for 3D elastic optical networks in temporal, spectral and spatial domains. Performance evaluation results validate that the proposed schemes can greatly reduce blocking probability in 3D EONs.*

Introduction

Recently, elastic optical networks (EONs) investigated routing, spectral, and modulation format assignment (RSMA) along with defragmentation in the spectral domain. However, defragmentation is complicated from the network operational point of view. Therefore, it is always beneficial to perform fragmentation-aware and alignment-aware RSMA[1, 2] during provisioning to minimize the need for future defragmentation.

More recently, the paradigm of a 3D EON in temporal, spectral and spatial domains is being explored to achieve 10x~100x network capacity enhancements[3] by exploiting space-division-multiplexing (SDM) and flexible wavelength grids. However, resource allocation algorithms with full elasticity in spatial domains have not been explored.

In this paper, we propose 3D EONs by exploiting elasticity in the spatial mode by using Orbital Angular Momentum[4] (OAM states) and investigate routing, spectral, spatial mode, and modulation format assignment (RSSMA) with fragmentation-awareness and alignment-awareness. To the best of our knowledge, this is the first time that fragmentation-aware RSSMA is investigated for 3D EONs.

EON in Spatial-Temporal-Spectral Domains

Dynamic optical arbitrary waveform generation (OAWG) and dynamic optical arbitrary waveform measurement (OAWM) based transport has been demonstrated for EONs to exploit elasticity in temporal and spectral domains[5]. In addition, the elasticity in the spatial domain can be exploited by OAM, which supports well-defined orthogonality and cylindrical symmetry[4]. Fig.1 illustrates OAM multiplexing and demultiplexing[6] based on photonic integrated circuits (PICs). The superposition principle of waves applied to Fig.1 indicates that multiplexing of multiple OAM states is possible, and propagating the waves in reverse will achieve demultiplexing of multiple OAM states. The OAM Mux/Demuxes designed for *N* OAM states can also support OAM channel spacing of *N*/2, *N*/4,… or *N*/*N,* to enable elasticity in the spatial domain analogous to the elasticity in the spectral (or temporal) domain with spectral slots (or with modulation formats).

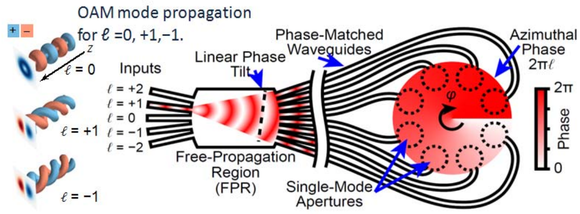

Fig.1: Planar waveguide configuration of OAM multiplexer/demultiplexer which includes the Rowland circle free propagation region and the phase matched waveguides interfacing antenna apertures placed on a perimeter of the circle. Thus the OAM multiplexer converts the linear phase front tilt to the azimuthal varying phase. Input OAM states at ℓ = +2,+1,0,−1,−2 will project to an array of phase-matched waveguides to excite apertures with azimuthally varying phase dependant on the state number ℓ. This way, multiple OAM states can be multiplexed spatially (SDM).

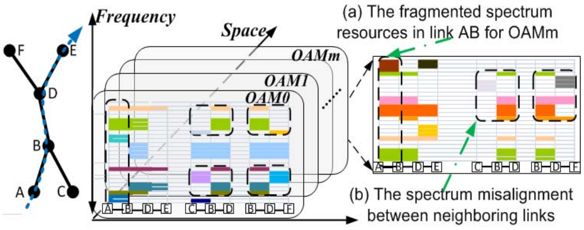

Fig. 2: (a) Spectral fragmentation and (b) spectrum misalignment on 3D EON.

Fragmentation-aware RSMMA for 3D EON

Fig.2 shows the spatial fragmentation when multiple OAM states are introduced in an example network. Fig.2(a) illustrates the fragmented spectrum resources in link *AB*, which is the fragmentation in the spectral dimension. Since the spectral misalignment between neighboring links tends to increase the end-to-end blocking probability, as shown in Fig.2(b), the RSSMA algorithm should assign a new connection in such a way that it avoids or minimizes the fragmentation of the continuous spectral blocks on candidate links, preferably by filling up as many misaligned spectral slots as possible for each OAM state.

Fig.3 shows an example of the effect on the spectral fragments before and after a lightpath provisioning process for a given OAM state (e.g., OAM0 in Fig.3(a)). The parameter "*cut*"[1, 2] is a nonnegative integer (e.g. 0, 1, 2…) that accounts for the number of consecutive spectrum that a new connection will fragment, and this number will quantitatively assess the spectral fragmentation. As the example in Fig.3(a) illustrates, a new request from *A* to *E* with a bandwidth requirement of 1 slot can be routed using the paths shown in Fig.3(b). The arrows in Fig.3(b) indicate different possible spectral slots for provisioning this request together with the corresponding "cut" values. For instance, the provisioning of the request on path *ABCE* with slot 10 will break two contiguous spectrum blocks on link *BC and CE*, so the "cut" value for this assignment is 2. Clearly, a connection with a larger "cut" value creates more fragments, so the "cut" can be regarded as the cost in a fragmentation-aware RSSMA algorithm.

On the other hand, the provisioning of a connection can also increase or decrease the misalignment of the available spectral blocks between the candidate links and their neighboring links[2]. A good alignment of the available spectrum slots between neighboring links is beneficial for future requests to satisfy the spectrum-continuity constraint. The example in Fig.3(c) shows the misalignment change if a connection is provisioned on path *ADE* with slot 8 or slot 2 (the slash blocks). The misalignment will increase by one if the assignment reduces the commonly available spectrum for neighboring links by one slot, and vice versa. Likewise, this misalignment change in a network can also be regarded a cost for future lightpath provisioning and spectrum fragmentation.

Therefore, by taking the fragmentation-awareness, alignment-awareness and different OAM states into account, we propose two algorithms which are referred to as fragmentation-aware RSSMA (FA-RSSMA) and FA-RSSMA with congestion avoidance (FA-RSSMA-CA) respectively. For a given OAM state, the FA-RSSMA algorithm tries to minimize the number of "cut" on the candidate routes and spectrum slots. If there are more than one solutions that achieve the identical minimum number of “cut”, then the algorithm starts to calculate the misalignment change between the candidate links and their neighboring links. The shortest-path first-fit rule kicks in if more than one RSSMA solutions are found. If no RSSMA solution can be found for an OAM state, the algorithm repeats the above procedure and checks the feasible solutions for the next OAM state until a RSSMA solution is found.

Moreover, it should be noted that when the network is heavily loaded, congestion on some links, rather than the spectrum fragmentation, becomes the major reason for blocking. In this sense, for the FA-RSSMA-CA algorithm, a polynomial F_{cmt} is introduced which considers not only cuts and misalignments, but also traffic, as detailed in[2]. When the traffic load is low, the "cut" is the dominated factor for F_{cmt}, and when the traffic load is high, the link congestion status is the dominated factor for F_{cmt}. For a given OAM state, the FA-RSSMA-CA algorithm tries to find a solution with the minimum F_{cmt} to minimize the spectrum fragmentation or link congestion according to traffic load. If no solution can be found for an OAM state, the algorithm checks the feasible solutions for the next OAM state until a RSSMA solution is found. The algorithm description is shown as below.

Algorithm 1: FA-RSSMA

1. Calculate *k* shortest routes from Source (*S*) to Destination (*D*) and add them to the set *P*;
2. For each OAM state ℓ (*loop #1*);
3. For each candidate route *r* in *P* (*loop #2*);
4. For each candidate assignment in *r* (*loop #3*);
5. Count the number of “*cuts*” as F_c on the links;
6. *End of loop #3*
7. *End of loop #2*
8. Choose the route and spectrum assignment(s) with minimum F_c;
9. If there is only one RSSMA solution with the

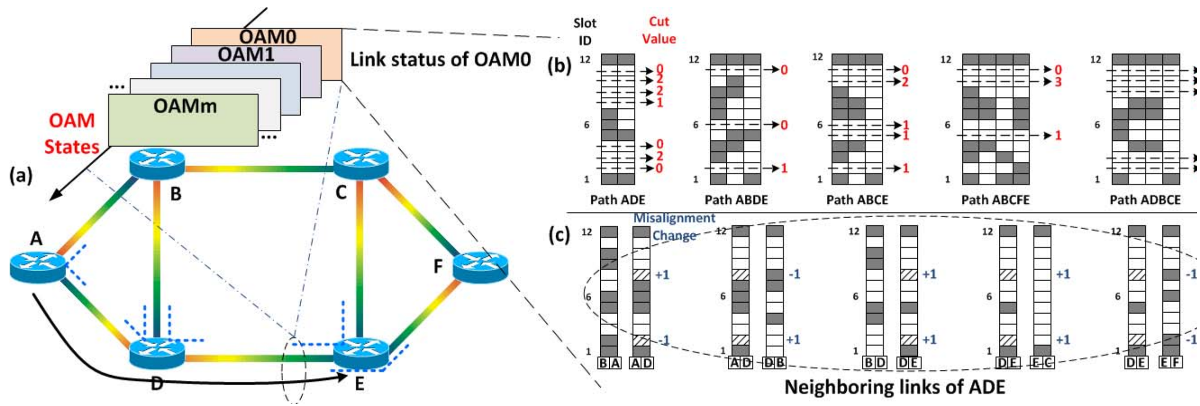

Fig. 3: (a) example network and the spectral assignment status on the links. For simplicity, in this example we assume only 12 spectrum slots on each fiber link for each OAM state; (b) The “cut” values to all the candidate solutions to connection request *A-E*, and (c) Misalignment change if choosing path *ADE* with slot 8 or slot 2

minimum F_c, return the solution and program ends; otherwise, go to the next step;

10. For every solution with the minimum F_c (*loop #4*)
11. Generate link pairs between the candidate links and their neighboring links;
12. For every generated link pair (*loop #5*)
13. Calculate the misalignment change;
14. *End of loop #5*
15. Sum up the misalignment change for all link pairs as F_m
16. *End of loop #4*
17. *Choose the RSMMA solution with the min F_m;*
18. If there is only one RSMMA solution with the minimum F_m, return the solution and program ends; otherwise, choose the RSMMA solution with shortest route and first-fit spectrum assignment; Once a RSMMA solution is find, return the solution and program ends.
19. *End of loop #1*

Algorithm 2: FA-RSSMA-CA

1. Calculate k shortest routes from Source (*S*) to Destination (*D*) and add them to the set *P*;
2. For each OAM state *ℓ* (*loop #1*);
3. For every candidate route *r* in *P* (*loop #2*);
4. For every candidate assignment in *r* (*loop #3*);
5. Count the number of "*cuts*" as F_c on the links;
6. Generate link pairs between the candidate links and their neighboring links;
7. For every generated link pair (*loop #4*);
8. Calculate the alignment change;
9. *End of loop #4*
10. Sum up the alignment change for all link pairs as F_m
11. *End of loop #3*
12. Calculate the parameter F_{cmt}
13. *End of loop #2*
14. Choose the RSMMA solution with the min F_{cmt};
15. If there is only one solution with the minimum F_{cmt}, return the solution and program ends; otherwise, choose the RSMMA solution with shortest route and first-fit spectrum assignment
16. *End of loop #1*

Performance evaluation and discussion

We have conducted simulations to evaluate the proposed algorithms and compare them with the commonly used benchmark algorithm, namely the shortest path routing and first-fit QAM state and spectrum assignment (SP-FF) algorithm. Dynamic connection arrival and departure events are simulated on a 14-node NSFNET network and on a 24-node US backbone network respectively, as the detailed topologies shown in[1]. Each spectral slot is set to be 12.5 GHz and each fiber link has 400 slots. In the simulation, each source-destination pair is generating connection requests randomly according to a Poisson process. The holding time of each connection follows a negative exponential distribution averaging 5 time units. The connection bandwidth is randomly distributed in the range of [1-slot, 10-slots]. The number of OAM states is set to 8. Fig.4 and Fig.5 compare the blocking probability of the different provisioning algorithms. The results show that both the FA-RSSMA and FA-RSSMA-CA algorithms can greatly reduce the blocking probability, compared to the non-fragmentation-aware SP-FF algorithm. The FA-RSSMA-CA outperforms FA-RSSMA, but the difference is relatively small.

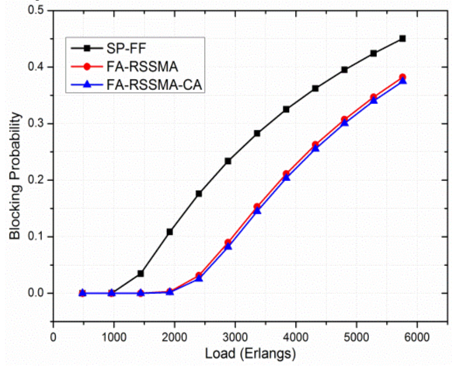

Fig. 4: Blocking probability comparison of different algorithms in the 14-node NSFNET network

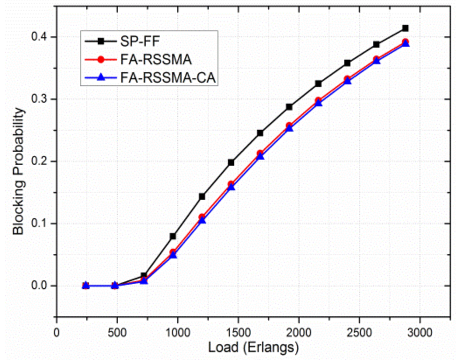

Fig. 5: Blocking probability comparison of different algorithms in the 24-node US backbone network

Conclusions

In this paper, we propose two fragmentation-aware RSSMA algorithms for 3D EONs in temporal, spectral and spatial domains. The simulation results validate their efficiency in reducing the network blocking probability.

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