Sub-band Virtual Concatenation Lightpath Blocking Performance Evaluation for CO-OFDM Optical Networks

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Abstract: Existing studies on the CO-OFDM optical networks are mostly based on the assumption that all the sub-bands of a lightpath are continuous in spectrum and transmitted on the same route. For better network capacity utilization, we apply Virtual Concatenation (VCAT) technique to the frequency domain by transmitting the sub-bands of a CO-OFDM optical channel via different routes. Simulation results show that the VCAT technique can significantly improve lightpath blocking performance and the improvement is more significant under a smaller VCAT sub-band granularity.

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1. Introduction

As the Internet traffic demand increases so fast, how to improve the capacity and throughput of the optical transport network is an important research problem to sustain the growth of traffic demand. Nowadays, Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) received many research interests due to its advantage of better spectrum efficiency over the traditional Wavelength Division Multiplexing (WDM) [1]. Extensive investigations have been performed for the CO-OFDM optical transport networks. Most of them are however based on an important assumption that all the CO-OFDM sub-bands that make up the spectrum of a lightpath are continuous and carried on the same route [2]. There is an important technique, Virtual Concatenation (VCAT) [3] in the traditional optical transport networks (OTN) that gives us an alternative method to further improve CO-OFDM-based lightpath provisioning performance. Virtual Concatenation in the time domain breaks a set of contiguous bandwidth into multiple Virtual Containers (VCs), transports the VCs on different routes, and recombines them at the receiver. A CO-OFDM optical channel is made up of multiple CO-OFDM sub-bands, each containing multiple sub-carriers. We can apply VCAT to a CO-OFDM optical channel in the frequency domain by sending multiple sub-bands via different routes and then recombining them at the receiver. Such an application is referred to as CO-OFDM sub-band Virtual Concatenation.

In this paper, we evaluate the benefit of the sub-band Virtual Concatenation for the CO-OFDM optical networks. We consider two network scenarios, namely Without Spectrum Conversion (WithoutSC) and With Spectrum Conversion (WithSC). The term “spectrum conversion” is similar to “wavelength conversion” in a wavelength routed WDM network. A node with spectrum conversion capability can convert any incoming spectrum to any output spectrum for a lightpath. Such capability is expected to improve spectrum efficiency and lightpath blocking performance.

2. VCAT in the frequency domain

In the frequency domain, we consider CO-OFDM sub-bands as VCs of a lightpath. We split the successive spectrum of a lightpath into multiple sub-bands, transport the sub-bands via different routes, and finally recombine them back into continuous spectrum at the receiver. Fig. 1 shows an example for the concept of CO-OFDM sub-band VCAT. Assume that lightpath demand between nodes A and B requires \( S \) spectrum slots and there are \( n \) different routes between the node pair. We split the \( S \) spectrum slots into a set of smaller sub-bands, i.e., \( \{ S_1, S_2, S_3, ..., S_n \} \). Each route carries a certain number of sub-bands and these sub-bands are recombined at the receiver, i.e., node B. In general, because it is easier to provide a smaller number of consecutive spectrum slots along a route, the VCAT
technique is expected to have better chances to succeed in establishing a lightpath and therefore achieve better lightpath blocking performance.

3. Service provisioning algorithm under VCAT
To enable VCAT, we first need to find different routes for each pair of nodes. We adopt a modified Dijkstra’s algorithm for this purpose. The modified algorithm is essentially a K-disjoint-shortest-route searching process. The use of multiple disjoint shortest routes between each node pair helps avoid highly used links and balance the load of the network. The detailed steps of the algorithm are as follows:

Step 1. Assume there are \( n \) pairs of nodes, and let \( i \) be node pair index and set \( i = 1 \).
Step 2. Search the shortest route for node pair \( i \) on the network topology. If there is a route found, add the route to the route list of node pair \( i \); otherwise, move to Step 3. To find other routes, remove all the links traversed by a recently found route between the node pair from the network topology, and then re-apply Step 2.
Step 3. Set \( i = i+1 \) (i.e., to consider the next node pair), and recover the topology to be the initial full topology, and then return to Step 2 until all the node pairs have found all their eligible routes.

For the VCAT technique, this study considers multiple scenarios including VCAT(1), VCAT(2), VCAT(4) and VCAT(8), where VCAT(\( x \)) means that each sub-band contains \( x \) continuous spectrum slots. For a lightpath that requires a certain number of continuous spectrum slot \( y \), if VCAT(\( x \)) is employed to establish the lightpath, then \([y/x] \) VCAT(\( x \)) sub-bands are required, where operator \( [x] \) finds a minimum integer that is no smaller than \( x \). Note that under such a sub-band allocation, there could be some spectrum waste as the total number of spectrum slots of \([y/x] \) VCAT(\( x \)) could be larger than \( y \) (with \([y/x] \times x - y \) spectrum slots unused). For example, we consider VCAT(2) and we need to establish a lightpath requiring 5 spectrum slots, then \( [5/2] = 3 \) sub-bands are needed with one spectrum slot unused when 3 sub-bands are used to establish the 5-spectrum-slot lightpath. Thus, though technically it is easier to transmit sub-bands that have larger granularities, the VCAT technique may suffer from more spectrum slot waste.

Once we find the number of sub-bands under a certain VCAT(\( x \)), the next step is to allocate these sub-bands onto different routes between a pair of nodes. The detailed allocation algorithm is as follows:

Step 1. Assume there is a lightpath demand with \( n \) sub-bands, and there are \( m \) disjoint shortest routes between a pair of nodes.
Step 2. Set \( r = 1 \), \( i = n \), where \( r \) is the route index and \( i \) is the number of sub-bands to be allocated.
Step 3. Find the largest number \( s \) (\( 1 \leq s \leq i \)) of free continuous sub-bands on route \( r \) and record these sub-bands, and meanwhile update \( i = i - s \). If \( i = 0 \), then move to Step 5.
Step 4. Set \( r = r + 1 \), if \( r \leq m \) (i.e., not all the routes are visited), move to Step 3.
Step 5. If \( i = 0 \), then assign all the recorded sub-bands to the lightpath demand. Otherwise, clear the recorded sub-bands, and block the lightpath request.

In the above algorithm, we consider two types of sub-band VCAT, including VCAT on the same route and VCAT on different routes. In the former case, there can be multiple non-continuous spectrum segments on the same route that provide sufficient spectra to accommodate multiple complete sub-band(s). In the latter case, spectrum segments on different routes are used to provide VCAT sub-bands.

In addition, besides the assumption that each sub-band has the same number of spectrum slots, it is also possible for a lightpath to be made up of multiple sub-bands with each of them being in different granularities. For example, a 5-spectrum-slot lightpath can be made up of a 3-spectrum-slot sub-band and a 2-spectrum-slot sub-band. This type of VCAT is referred to as cross-VCAT [4]. However, in this study we assume that all the sub-bands that make up the whole lightpath have the same granularity. The benefit of the cross-VCAT that considers mixed sub-bands in different granularities will be evaluated in our future study.

Finally, for performance comparison, we also consider the case of Non-VCAT. Specifically, when there is a lightpath demand with a certain number of spectrum slots, we try each of the routes between a pair of nodes one by one from the shortest to the longest until the first route is found to accommodate the lightpath demand. If all the routes are tried and no route has sufficient spectrum slots to accommodate the lightpath, then the demand is blocked.

4. Simulations
To evaluate the benefit of VCAT, we employ the 14-node 21-link NSFNET network as our test network. We assume dynamic lightpath traffic demand under the conditions that the arrival of the lightpath service follows a Poisson distribution and the holding time of each established lightpath takes a negative exponential distribution. Without losing generality, we assume that the average departure rate of each established lightpath is \( \mu = 1.0 \). Also, we assume that there are a total of 400 spectrum slots on each fiber link. The number of spectrum slots of each lightpath demand follows a random distribution with a mean of 12. The first-fit strategy is applied for spectrum slot assignment. We set Erlang traffic load on each node pair to be the same, ranging from 1.5 to 2.0 Erlang for the
WithoutSC case, and from 1.7 to 2.2 Erlang for the WithSC case. Each test point is simulated for $10^6$ lightpath requests. We evaluate the network performance in terms of lightpath blocking probability and spectrum blocking ratio. The former is defined as a ratio of the total number of blocked lightpath requests to the total number of lightpath requests, and the latter is defined as a ratio of the total number of blocked spectrum slots to the total number of total requested spectrum slots.

Figs. 2 and 3 show the results for the case of without spectrum conversion. We can see that VCAT(1) performs best, VCAT(2) follows, and VCAT(8) performs worst. This is because with the increase of sub-band granularity, a larger number of spectrum slots are wasted. For example, if a lightpath demand needs only one spectrum slot and a VCAT(8) sub-band is used to accommodate it, we would waste seven spectrum slots since the sub-band is dedicated to one-slot lightpath. For the performance in terms of spectrum blocking ratio, we have similar observations as shown in Fig. 3. In addition, comparing the results of VCAT($x$) and Non-VCAT, we see that due to the flexibility of transmitting sub-bands of a lightpath via different routes, the VCAT($x$) cases can perform much better than the Non-VCAT case. Even though the granularity of VCAT(8) is very coarse, which may lead to much spectrum waste as explained, VCAT(8) still performs closely to Non-VCAT. For the case of with spectrum conversion, we have similar results as shown in Figs. 4 and 5. Again, VCAT(1) performs best, VCAT(2) follows, and VCAT(8) performs worst. Non-VCAT achieves almost the same performance as that of VCAT(4) for the case of spectrum conversion versus VCAT(8) for the case of without spectrum conversion. This is because the capability of spectrum conversion helps improve the lightpath blocking performance and hence leaves less space for the VCAT technique to improve compared to the case of without spectrum conversion.

4. Conclusions
We evaluated the benefit of using the VCAT technique in the CO-OFDM optical networks. We developed a lightpath service provisioning algorithm that employs the VCAT technique for the cases of without and with spectrum conversion. Simulation results indicate that the VCAT technique can significantly improve lightpath blocking performance compared to the case of Non-VCAT, and the performance improvement becomes more significant with the decrease of VCAT sub-band granularity.

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