A Cost-Effective Node Placement Method in EONs Using Superposition Coding

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***Abstract*—Elastic optical networks (EONs) have shown promise as a new technology to cope with increasing communication traffic demands in the field of optical core networks. Previous studies have proposed path establishment methods that apply superposition coding, a technique that was originally developed in the field of wireless communications. These studies demonstrated the effectiveness of superposition coding in increasing the number of accommodated optical paths. However, they assumed it could be applied across the entire network, which leads to the problem of expensive upgrades to existing equipment. In this study, we aim to improve the network performance efficiency while minimizing upgrade costs by applying superposition coding to only a limited part of the network. To this end, we propose an appropriate placement method of nodes for supporting superposition coding. Our simulation results demonstrate that prioritizing superposition coding support for large-population nodes can efficiently improve the performance, as these nodes are more likely to serve as sources or destinations. The proposed population-based placement method reduced the call-blocking probability by approximately 48.5% with superposition nodes placed in just seven out of 25 total nodes.**

***Index Terms*—Elastic Optical Networks, Superposition Coding, Successive Interference Cancellation, Node Placement, Reallocation**

I. Introduction

Communication traffic has continuously grown due to the expansion of content capacity and the proliferation of cloud-based applications. According to Japan's Ministry of Internal Affairs and Communications, the download traffic in Japan has been increasing at an average annual rate of 25%, and this trend is expected to continue in the future [1]. To address this rapid increase, elastic optical networks (EONs) have gained attention in the field of optical core networks [2], [3]. Conventional wavelength division multiplexing networks allocate a fixed bandwidth to all communication requests with different bandwidths, which causes problems with unused bandwidth when the utilized bandwidth is smaller than the allocated one. In contrast, EONs subdivide the frequency spectrum using the optical-orthogonal frequency division multiplexing technique and allocate only the necessary amount of bandwidth for each request. This enables flexible bandwidth utilization. In EONs, the establishment of optical paths is determined by RMSA, which consists of routing, modulation level, and spectrum allocation. Making these decisions appropriately is crucial for improving network performance [4], [5]. Additionally, EONs face the challenge of frequency fragmentation because they allocate different bandwidths for each request. Suppressing this fragmentation has a significant impact on the frequency utilization efficiency [6], [7].

In the wireless communication field, the superposition coding technique has been proposed to help save frequency resources [8]–[10]. Superposition coding allows two signals to be transmitted on the same frequency by superimposing and separating the signals. This enables the conservation of frequency resources. Prior studies have proposed an optical path establishment method that applies the superposition coding technique to EONs when accommodating new path requests [11], [12]. These studies demonstrated the effectiveness of applying superposition coding to EONs in terms of increasing the number of accommodated optical paths in the network and reducing call-blocking probability. Another study proposed a method that applies superposition coding between existing paths through path reallocation, in addition to when accommodating new paths [13]. This study demonstrated further improvements in frequency utilization efficiency, such as a reduction in call-blocking probability and the suppression of fragmentation. However, these works have assumed an environment where superposition coding is available throughout the entire network, which leads to increased costs associated with equipment upgrades or adding new functions.

In light of this background, we define the functions for superposition transmission and propose an effective placement method to achieve a cost-performance-optimized network by limiting the introduction of superposition coding to critical points within the network. Additionally, we evaluate the impact of the selection of locations where superposition coding is introduced on performance.

II. Related Work

A. Superposition Coding Technique

Superposition coding is a technique primarily designed for wireless communications that enables the transmission of two signals on the same frequency. Figure 1 shows an example of transmission using superposition coding in EONs. First, a power difference is applied to two signals with different destinations, and a superposed signal is generated at the source node by superimposing them. In this process, the signal intended for the near-side destination is assigned a lower

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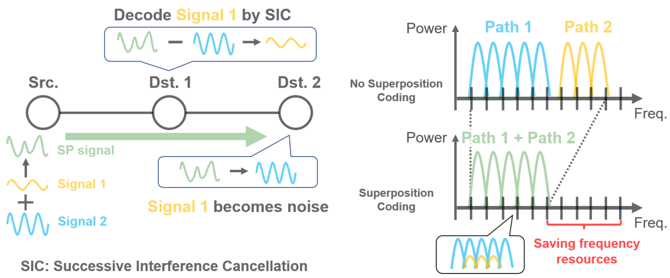

Fig. 1. Example of superposition coding.

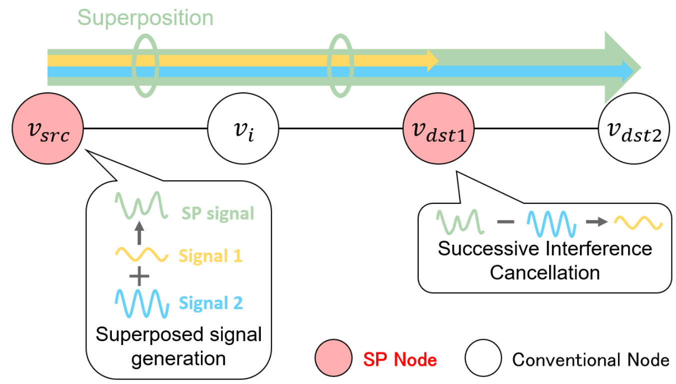

Fig. 2. Function of SP node.

power, while the signal for the far-side destination is assigned a higher power. Second, the superposed signal is transmitted to the near-side destination (Dst. 1) via several relay nodes. Dst. 1 then demodulates its own signal from the superposed signal using successive interference cancellation (SIC). During SIC, a replica of the high-power far-side signal is generated and subtracted from the superposed signal. This allows the extraction of the low-power near-side signal [14], [15]. Finally, the far-side destination (Dst. 2) demodulates its own signal by treating the weakened near-side signal between Dst. 1 and Dst. 2 as noise.

On the basis of the above, the conditions for applying superposition coding in EONs are as follows: 1) the source node is the same, 2) the destination nodes are different, 3) one route fully encompasses the other, and 4) the difference in hop count to the destination is equal to or greater than the required hop-count difference D. Superposition coding can be applied when all of these conditions are satisfied.

B. Application of Superposition Coding to EONs

An earlier study proposed a path establishment method that applies superposition coding to EONs [11], [12]. In this method, new path requests arriving statically or dynamically are accommodated by applying superposition coding whenever possible. If there is an existing path that satisfies all four conditions mentioned above along with the new path request, the new path is superimposed on that existing path and accommodated in the network. This approach resulted in a reduction in the call-blocking probability and an increase in the number of accommodated optical paths.

Another method applies superposition coding not only for accommodating new paths but also for reallocating existing paths to apply superposition coding between them [13]. When one of the two superimposed paths is terminated, the remaining optical path is maintained as a regular path until a new path request that can be superimposed arrives. Specifically, when an existing path that can be superimposed with the remaining path exists in the network, one of them is reallocated to increase the opportunities for applying superposition coding, thus enabling more efficient resource utilization. During superposition through reallocation, the path with fewer hops that will be encompassed after reallocation is reallocated using the make-before-break method. This makes additional resource search unnecessary and achieves seamless reallocation without disruption.

III. Cost-Effective Node Placement Method

A. Definition of a Node Supporting Superposition Coding

Figure 2 shows an example of signal transmission using superposition coding. In this process, the source node v_{src} combines two signals to generate a superposed signal. At the near-side destination node v_{dst1}, the node extracts its own signal from the received superposed signal using SIC. At the far-side destination node v_{dst2}, the signal is demodulated by treating the signal intended for v_{dst1} as noise, since it is attenuated due to the propagation loss difference between v_{dst1} and v_{dst2}. This allows the node to extract its own signal. Therefore, no additional function is required for signal demodulation at v_{dst2}. Based on these considerations, the network equipment used for the superposed signal transmission must have the functions to generate superposed signals and perform successive interference cancellation.

In this paper, we refer to a node with these functions as a superposition node (SP node) and consider its appropriate placement. Signal relay at the intermediate node v_i and demodulation at the far-side destination node v_{dst2} do not require these functions and can be performed by conventional nodes with standard functions. Therefore, in addition to the four conditions mentioned in Sec. II-A, superposition coding can only be applied when both the source node v_{src} and near-side destination v_{dst1} are SP nodes.

B. Selection of SP Node Placement

In previous studies, the network environment was assumed to have all nodes as SP nodes, which made the costs associated with equipment upgrades and installation work a significant challenge. To address these challenges, we place SP nodes in only a subset of nodes within the network. For effective and cost-efficient application of superposition coding, it is essential to strategically place SP nodes while considering factors such as network topology and communication traffic characteristics. We implement three selection methods to place N SP nodes: (1) Select nodes randomly, (2) Select nodes with high betweenness centrality, and (3) Select nodes in areas with

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Bandwidth per slot	12.5 GHz
Number of slots per link	320 slots
Number of calls per load	3 million
Selection of node (src/dst)	Population distribution
Arrival rate of requests	Poisson distribution with an average arrival rate λ
Duration of paths	Exponential distribution with an average of 30 s
Number of candidate routes	$K = 3$
Required hop count difference	$D = 2$
Time required for reallocation	$t_{sw} = 1.0$ s
Number of SP nodes	$N = 12$

TABLE II
NUMBER OF REQUIRED FREQUENCY SLOTS

Distance [km]	Modulation method	Required slots
–1200	8-QAM	1
1201–2400	4-QAM	3
2401–	BPSK	5

large population. In method (1), SP nodes are placed based on a uniform distribution across all nodes in the network. This serves as a baseline method for comparison with the other two selection methods, which do not take into account network or traffic characteristics. In method (2), SP nodes are placed starting with nodes that have the highest betweenness centrality. Betweenness centrality is a metric that indicates the importance of a node in graph theory, representing how frequently it appears on the shortest paths between two points. In particular, nodes with a high degree or those located near the center of the topology tend to have higher values, and nodes with high betweenness centrality are more likely to be utilized as transit nodes. Therefore, we can expect that an SP node would be placed at the location corresponding to v_{dst1} in Fig. 2. In method (3), SP nodes are introduced starting from nodes with the largest population. In this approach, nodes with larger populations and greater communication demand are more likely to be selected. By choosing nodes that serve as sources (v_{src}) or destinations (v_{dst1}) requiring signal processing for superposition transmission as SP nodes, the opportunities for applying superposition coding are expected to increase.

IV. PERFORMANCE EVALUATION

A. Simulation Environment

We evaluated the performance of our method through computer simulations with JPN25 topology, which consists of 25 nodes and 43 links [16]. Table I lists the parameters used in this simulation. The source and destination nodes were selected based on the population distribution in [16]. The number of required slots for each established optical path was assigned as a fixed value based on the distance, as shown in Table II. In this evaluation, we introduce 12 SP nodes ($N = 12$) out of the total 25 nodes in the network, based on the three method mentioned in Sec. III-B. The placement of SP nodes is shown in Fig. 3. The order of node numbers selected based on betweenness centrality and population is shown in Table III. The optical path establishment method follows the approach described in [13]. The random placement method (method 1) was simulated 500 times, and the average result was used. For comparison, we evaluated two cases: one where no SP nodes were introduced ($N = 0$) and another where all nodes were introduced as SP nodes ($N = 25$).

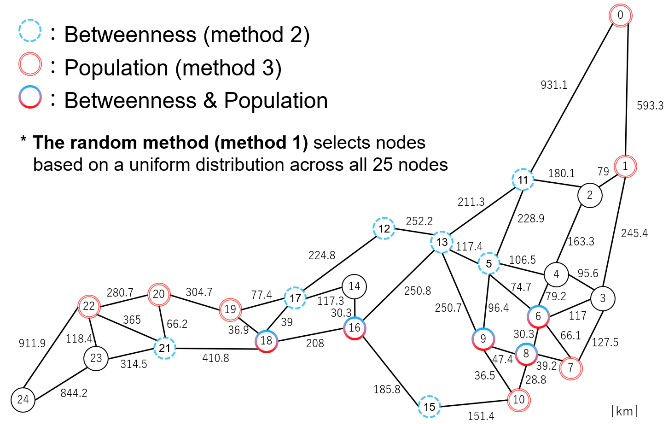

Fig. 3. JPN25 topology (25 nodes, 43 links)

TABLE III
ORDER OF SP NODE PLACEMENT (DESCENDING)

Order	Betweenness centrality	Population
1	Node 13	Node 18
2	Node 16	Node 16
3	Node 18	Node 10
4	Node 21	Node 22
5	Node 5	Node 20
6	Node 11	Node 9
7	Node 17	Node 1
8	Node 6	Node 6
9	Node 12	Node 8
10	Node 9	Node 7
11	Node 8	Node 19
12	Node 15	Node 0

B. Comparison of Placement Methods for SP Node

Figure 4 shows the call-blocking probability using the three evaluated placement methods. Among these methods, the population-based approach (method 3) resulted in the greatest reduction in call-blocking probability. At $\lambda = 10.0$, the call-blocking probability was reduced by 90.0% when all nodes were SP nodes compared to the case with no SP nodes, while method 3 resulted in a reduction of 61.3%. Since signal processing in superposition transmission is performed at the source node and the near-side destination node, it was effective to replace nodes with large population, which are more likely to serve as source or destination nodes. On the other hand, the placement method based on betweenness centrality (method 2) did not show a significant difference compared to the random selection method. Betweenness centrality is a metric where nodes that are frequently part of the shortest paths between

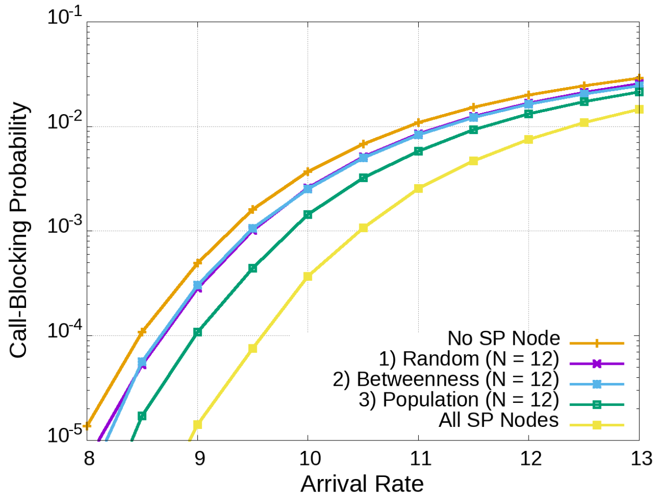

Fig. 4. Call-blocking probability.

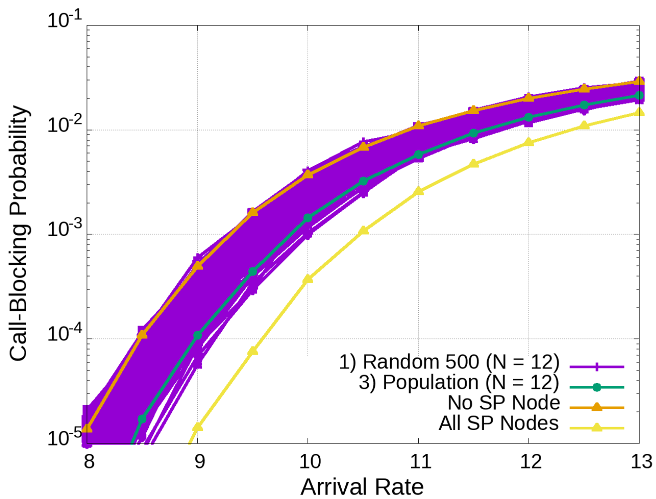

Fig. 5. Range of request-blocking probability for random placement.

two points have higher values. Therefore, we had expected that v_{dst1} performing SIC would be more likely to be selected, but the results showed no significant improvement, as relay nodes like v_i were also frequently selected. These results indicate that, unless the network experiences significant fluctuations in communication demand for each node over time, selecting nodes with high communication demand is effective.

Additionally, in the JPN25 topology used in this simulation, five nodes (numbers 6, 8, 9, 16, and 18) met both the betweenness centrality and population requirements when $N = 12$. When conducting simulations in environments with different topology shapes or population ratios, the placement locations may vary significantly, potentially affecting the results as well.

Figure 5 shows the call-blocking probability before averaging, for the random selection case that was averaged over 500 iterations in Fig. 4. Although the number of SP nodes was fixed at $N = 12$, the performance varied significantly

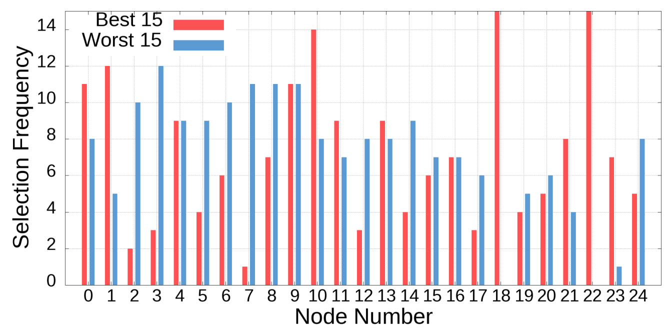

Fig. 6. Ratio of placed SP nodes.

depending on the placement: for example, at $\lambda = 10.0$, there was a maximum difference of 75.3%. These results indicate that the appropriate placement of SP nodes is crucial for improving performance. Furthermore, the population-based placement method (method 3) showed relatively good results, even within the range of outcomes observed with the random placement method.

Figure 6 shows the distribution of nodes selected in the best 15 and worst 15 trials out of 500 random trials. Node numbers 18 and 22 were selected in all of the best 15 trials, while they were not selected in any of the worst 15 trials. These nodes are ranked first and fourth in terms of population, highlighting the importance of selecting and placing SP nodes in large-population nodes. Additionally, we observed that node numbers 11, 13, and 21 are ranked lower in terms of population. However, they were still selected relatively often in the best 15 trials. These nodes have high betweenness centrality within the network and are often located on paths between nodes with larger populations. This suggests that they were likely utilized as the near-side destination node v_{dst1}. These findings demonstrate that while SP nodes should primarily be placed in large-population nodes, some should be placed in high-betweenness centrality nodes located between large-population nodes. This approach could further improve the performance.

C. Impact of the Number of Introduced SP Nodes

Figure 7 shows the results at $\lambda = 10.0$ when varying the number of introduced SP nodes in the population-based placement method (method 3), which achieved the best performance. This graph shows the ratio of call-blocking probability relative to the case where no SP nodes are placed. We can see here that the call-blocking probability significantly decreased when the number of SP nodes ranged from two to seven. Compared to the case where no SP nodes were introduced ($N = 0$), the call-blocking probability decreased by 48.6% with the introduction of only seven nodes. Additionally, as the number of SP nodes increased, the effect per node became smaller. This is likely because the expanded range of superposition coding created more network capacity, which reduced the impact of performance improvements gained by further expanding the capacity. These results suggest that introducing

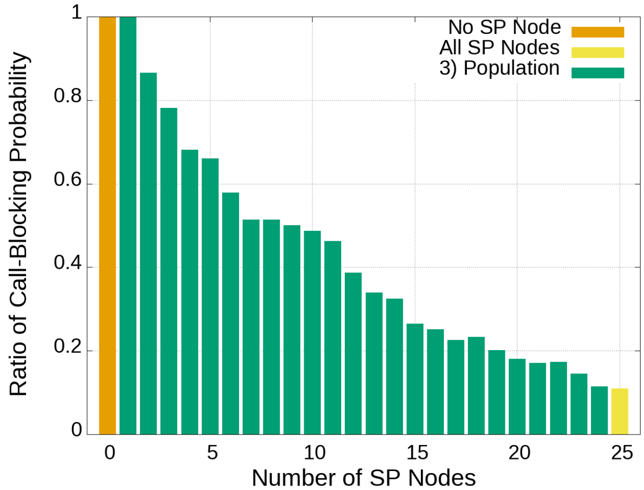

Fig. 7. Impact of the number of placed SP nodes.

SP nodes locally to high-demand nodes can improve the performance more efficiently. This approach also minimizes the cost of equipment upgrades compared to distributing SP nodes evenly across the entire network. In cases of particularly high load or when the network is nearing its capacity limit, a small number of SP nodes can sufficiently reduce the call-blocking probability.

V. Conclusion

To improve the performance efficiency and cost-effectiveness in EONs, we proposed a method for selectively implementing superposition coding in certain nodes and determining their optimal placement. The simulation results demonstrated that enabling superposition coding in areas with larger populations increases the opportunities for its application and leads to efficient performance improvements. Additionally, when the network was nearing its capacity limit, even the placement of a small number of SP nodes was more effective in improving performance compared to a conventional method. As future work, we aim to further improve the performance by enhancing the routing control algorithms under the conditions of the node placement proposed in this study.

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