Employ Unidirectional Design to Alleviate Impact of Traffic Asymmetry for Elastic Optical Networks

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***Abstract*—Internet traffic demand keeps on increasing and tends to show strong bidirectional asymmetry. To tackle this asymmetry issue, we propose here a novel unidirectional design approach to alleviate the impact of asymmetry for elastic optical networks (EONs). We decouple a bidirectional transponder into an isolated unidirectional transmitter (Tx) and an isolated unidirectional receiver (Rx). Based on this, we further study how different multi-flow transmitters will affect the design performance, i.e., whether the transmitter is using an array of laser diodes or a broadband laser source with a filter to generate multiple sub-carriers. We evaluate the proposed approach by considering the routing and spectrum allocation (RSA) optimization problem, for which Integer Linear Programming (ILP) models and a SWP-based heuristic algorithm are developed. Simulation studies show that the proposed approaches are efficient to significantly improve the network capacity utilization and minimize the network cost compared to a network design limited to considering only bidirectional symmetric traffic flows.**

Keywords—asymmetric traffic; transmitter (Tx); receiver (Rx); RSA; ILP model; SWP

I. Introduction

With the popularity of new technologies such as cloud computing, content distribution networks (CDNs), distributed storage, and video on demand [1], the global Internet traffic has increased rapidly. A lot of this traffic tends to be bi-directionally asymmetric where a significant difference in the bandwidth has been observed between the upstream and downstream directions of a flow [2]. However, almost all of today's networks have been designed to carry symmetric traffic demand, i.e., on both upstream and downstream directions, the same amount network capacity is provisioned either on each link or between each node pair. Using a network designed in a symmetric manner to carry network traffic that demonstrates high asymmetry is clearly not efficient. This can lead to much wastage of network resources in aspects like link capacity usage and transponder deployments since all of these are dimensioned based on the maximum traffic flow in both directions. The increasing popularity of video-related network applications would further enhance this asymmetry. An urgent look at the issue of network design to consider this asymmetry is therefore required.

Some studies on asymmetric networks have been carried out for dense wavelength division multiplexing (DWDM) networks. Woodward *et al.* [3] quantified the asymmetry of traffic on a current large IP backbone and showed the equipment savings by the use of unidirectional circuits. Bathula *et al.* [4] explored the potential savings possible by treating each direction independently using measured traffic from over 100 metro networks. Morea *et al.* [5] proposed asymmetric bidirectional routing based on IP-over-WDM architectures, leveraging elastic optoelectronic devices.

In addition to the DWDM network, some researchers also considered the asymmetric issue in the context of EONs. Ju *et al.* [6] investigated power-efficient directed preconfigured cycles (*p*-Cycles) for asymmetric traffic protection in EONs against the single-link failure. Walkowiak *et al.* [7] studied the impact of anycast and unicast traffic on transponder usage in both symmetric and asymmetric lightpath provisioning scenarios in EONs. They also examined the impact of traffic asymmetry on the usage of multi-flow transponders (MFTs) in EONs with dedicated path protection [8]. Finally, they showed how both symmetric and asymmetric lightpath provisioning scenarios influenced spectrum usage and network CAPEX cost [9].

These preliminary studies on how the traffic asymmetry can affect the performance of an EON have assumed conventional bidirectional transponders and are based on simple fixed shortest path routing heuristics. More advanced studies such as optimization models dedicated for this kind of asymmetric situation in the context of the RSA problem are still not available. For the DWDM network, a preliminary study was performed based on the assumption that a transponder can be split into an isolated transmitter and an isolated receiver. However, there is no similar study carried out to tackle the traffic asymmetry issue for EONs. Because a multi-flow transponder in an EON is much more expensive and complicated than a transponder in the DWDM network, a study assuming split transmitters and receivers would be more challenging in an EON than in the case of a DWDM network. Moreover, because different architectures [10] can be used to realize the multi-flow transponder, comparing the network design performance for these architectures in the context of traffic asymmetry would be desirable but is still not available.

This study focuses on evaluating the impact of bidirectional traffic asymmetry on the design performance of an EON. Specifically, to save network hardware costs, we propose to decouple a conventional bidirectional transponder into an isolated transmitter (Tx) and an isolated receiver (Rx).

Based on this, we further study the impact from the limitation of a transmitter, i.e., whether the transmitter is using an array of independent laser diodes or a broadband laser source with a filter to generate multiple sub-carriers. We evaluate the proposed unidirectional design approach in the context of the RSA optimization problem, for which ILP models and an efficient heuristic algorithm are developed. To the best of our knowledge, this is the first work dedicated to tackling the traffic asymmetry issue by using split optical transmitters and receivers for an EON.

The rest of the paper is organized as follows. In Section II, we introduce the related concepts and network scenarios of this study. We present the ILP models for the RSA problem in Section III. Section IV presents an efficient heuristic algorithm for the solution in cases of a large network. Section V presents the simulation results and analyzes system performance based on these results. Finally, we conclude the paper in Section VI.

II. Related Concepts

A. Asymmetry Ratio

Suppose the traffic demands between each node pair are bidirectional, i.e., for each node pair (*s*, *d*) there are an upstream demand and a downstream demand at the same time. To measure the traffic asymmetry between the upstream and downstream directions, we define a parameter called asymmetry ratio (AR), given as

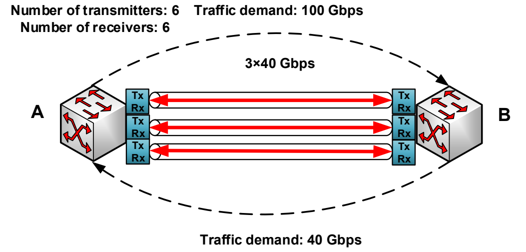
$$\mathrm{AR} = D^{Down}/D^{Up} \qquad (1)$$

where D^{Down} denotes the downstream traffic demand and D^{Up} denotes the upstream traffic demand. For convenience, we assume that the upstream traffic demand is always lower than the downstream traffic demand. As examples, AR=1 means the network traffic is fully symmetric, i.e., the upstream and downstream demands are equal, while AR=2 means that the downstream demand is twice the upstream demand.

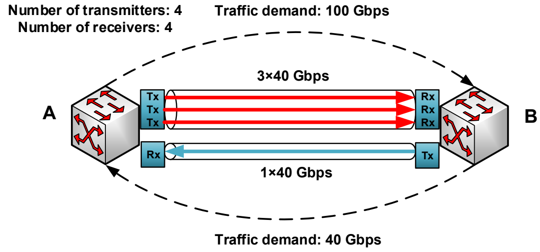
B. Decoupling Multi-flow Transponder into Transmitter and Receiver

The traditional transponder would generally have a transmitter and receiver pair and is mainly configured for communications with bi-directionally symmetric traffic demands. However, the increasing trend of asymmetry in today's bi-directional traffic demands would lead to inefficiency of the transmitter and receiver pair in handling the direction with the lower traffic demand. To tackle this issue, we therefore propose to decouple a bidirectional multi-flow transponder into an isolated transmitter and an isolated receiver. Such a separation enables more efficient assignment of transmitters and receivers in both directions to minimize the number of components and achieve a lower cost.

Fig. 1 shows an example for configuring these decoupled transmitters and receivers between a pair of nodes given a certain asymmetric traffic demand distribution in the two directions. Because the direction from A to B has a higher amount of traffic demand, a larger number (i.e., 3) of transmitters are deployed at node A and the same number of receivers are deployed at node B. In the opposite direction, there is a smaller number (i.e., 1) of transmitters and receivers respectively at nodes B and A. Compared to the symmetric configuration, splitting transmitters and receivers will greatly reduce the overall number of transmitters and receivers required.



(a) Example of non-split transponders



(b) Example of split transmitters and receivers

Fig. 1. Decoupling a transponder into a transmitter and a receiver.

C. SW and MW transmitters and their constraints

The multi-flow transmitter in an EON can be implemented using two different architectures. The first employs an array of *N* tunable lasers as shown in Fig. 2. Each of the lasers is independent and can be freely tunable to any spectrum. Thus, the sub-carriers need not be spectrally contiguous even though they are from the same transmitter. This implementation is referred to as the *single-wavelength (SW) source*. The second architecture employs a broadband *multi-wavelength (MW) source* to create multiple sub-carriers from a single laser as shown in Fig. 2. An MW source is composed of an integrated tunable laser, a dual-drive Mach-Zehnder modulator (DD-MZM), and a filter [11][12], which can produce *N* sub-carriers from a single laser source. These generated sub-carriers are spectrally locked together, which means they are spectrally neighboring. Tuning the MW source's central frequency will shift all the sub-carriers together.

For the RSA problem in the EON, the SW source is not subject to any constraint on the spectrum as it can provide full and independent tunability for each sub-carrier. Conversely, the spectra of a lightpath from a MW source must be contiguous, which is less flexible compared to the SW source. However, the MW source uses a single laser to generate multiple sub-carriers and therefore is much cheaper than the SW source where multiple laser sources are required.

D. Network Example with Split Transmitters and Receivers to Carry Asymmetric Traffic Demands

Fig. 2 shows an EON example where split transmitters and receivers are used to establish unidirectional lightpaths between node pairs for asymmetric traffic flows. Between node pair (0, 4), 2 and 1 sub-carriers are allocated respectively in the opposite

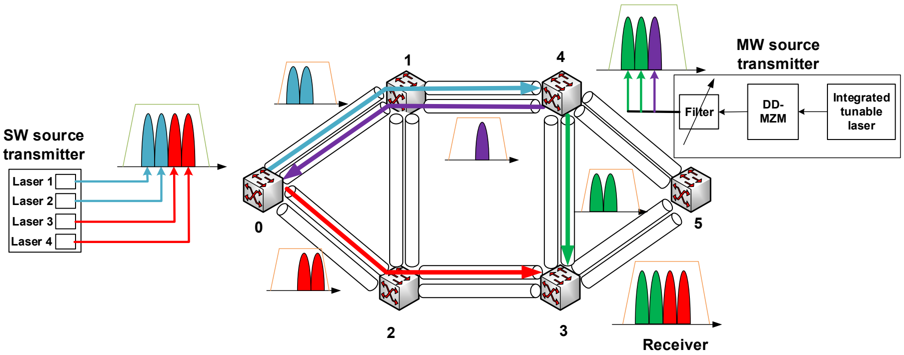


Fig. 2. An EON with isolated multi-flow transmitters and receivers.

directions. The sub-carriers at node 0 are generated by a SW source and the sub-carrier at node 4 is generated by a MW source. Meanwhile, node 0 is also sending 2 sub-carriers generated from the same SW source to node 3. Thus, the transmitter at node 0 is essentially serving the two lightpaths simultaneously to different destination nodes. Similarly, in addition to node 0, node 4 is also sending 2 sub-carriers to node 3 using the same MW source. At node 3, a common receiver is used to receive all the sub-carriers from the two different source nodes.

III. ILP Models for RSA Problem under Traffic Asymmetry

A. *Problem Statement*

We first define the RSA problem under the asymmetric traffic demand scenario. We represent a general EON as *G* (***V***, ***E***), where ***V*** is the set of nodes and ***E*** is the set of (bi-directional) fiber links in the network. A request is represented by *CR* (*S, D, R*), where *S* and *D* are the source and destination nodes respectively, and *R* is the bandwidth of the request. Considering the asymmetric traffic feature, to optimally solve the RSA problem, we release the co-routing constraint for the upstream and downstream lightpaths between each node pair; instead, these can be routed differently for greater flexibility in resource allocation.

Also, in order to best utilize the network's spectrum resources, we consider an adaptive modulation format scenario using the most efficient modulation format for each lightpath according to their individual physical transmission conditions. Based on the required bandwidth and the selected modulation format, we calculate the number of sub-carriers or frequency slots (FSs) for each lightpath. The details of this can be found in [13].

B. *Basic ILP Model for Asymmetric Traffic*

In this part, we present the basic ILP model for the RSA problem under asymmetric traffic. This model is extended from the conventional RSA model used for symmetric traffic demands [14]. For each request, we consider all the link-disjoint routes between the node pair. In the basic model, we assume that the transmitter is a type of SW source with no constraint on the usable spectrum when assigning transmitters. We define the sets, parameters, and variables for the model as follows.

Sets:

$\boldsymbol{N}$ Set of network nodes.

$\boldsymbol{NP}$ Set of node pairs in the network. Here each node pair is directional, which means that we should differ node pair (A, B) from node pair (B, A).

$\boldsymbol{L}$ Set of network links, each of which is unidirectional. This means that we should differ link A-B from link B-A.

$\boldsymbol{P_r}$ Set of candidate paths between node pair r ($r \in \boldsymbol{NP}$).

$\boldsymbol{\lambda_p^r}$ Set of links traversed by path p ($p \in \boldsymbol{P_r}$) between node pair r ($r \in \boldsymbol{NP}$).

Parameters:

DT_r Unidirectional traffic demand in units of Gb/s between node pair r ($r \in \boldsymbol{NP}$). Since each node pair is unidirectional, its traffic demand is also unidirectional.

ρ_p^r The spectrum efficiency of path p ($p \in \boldsymbol{P_r}$) between node pair r ($r \in \boldsymbol{NP}$) when the most efficient modulation format is applied on the route. Given the route information, we can pre-determine and choose the most efficient modulation format. $\rho_p^r = 1, 2, 3$, when BPSK, QPSK, and 8-QAM are used.

M A large value.

α A small value.

μ The maximum number of FSs that each transmitter or receiver can accommodate. In this study, we set this value as 8.

ε The bandwidth of each FS in units of GHz. Here we assume that it is 12.5 GHz.

βtx The cost of each transmitter.

βrx The cost of each receiver.

Variables:

f_p^r An integer variable denoting the starting FS index of path p ($p \in \boldsymbol{P_r}$) between node pair r ($r \in \boldsymbol{NP}$).

$\mathcal{L}_{t,q}^{r,p}$ A binary variable taking the value of 0 if the starting frequency index of path p ($p \in \boldsymbol{P_r}$) between node pair r ($r \in \boldsymbol{NP}$) is smaller than that of path q ($q \in \boldsymbol{P_r}$) between node pair t ($t \in \boldsymbol{NP}$);

1, otherwise.

X_p^r A binary variable that equals 1 if path p ($p \in \boldsymbol{P_r}$) between node pair r ($r \in \boldsymbol{NP}$) is used for establishing a lightpath; 0, otherwise.

F_p^r An integer variable that denotes the amount of traffic demand in units of FSs carried by path p ($p \in \boldsymbol{P_r}$) between node pair r ($r \in \boldsymbol{NP}$).

γt_i An integer variable that denotes the total number of transmitters at node i ($i \in \boldsymbol{N}$).

γr_i An integer variable that denotes the total number of receivers at node i ($i \in \boldsymbol{N}$).

φt An integer variable that denotes the total number of transmitters in the whole network.

φr An integer variable that denotes the total number of receivers in the whole network.

τ_i An integer variable denoting the total number of FSs used on all the links incident to node i ($i \in \boldsymbol{N}$). This term sums the total number of FSs of the lightpaths whose destination nodes are node i.

ω_i An integer variable denoting the total number of FSs assigned on all the links sourcing at node i ($i \in \boldsymbol{N}$). This term sums the total number of FSs of the lightpaths whose source nodes are node i.

c The maximum FS index used in the network.

Ce The total cost of transmitters and receivers in the whole network.

Objective:

$$\text{Minimize} \quad Ce+\alpha \cdot c \tag{2}$$

Subject to:

$$\mathcal{L}_{t,q}^{r,p} + \mathcal{L}_{r,p}^{t,q} = 1 \quad \forall r,t \in \boldsymbol{NP}, \forall p \in \boldsymbol{P_r}, \forall q \in \boldsymbol{P_t}, r \neq t, \boldsymbol{\lambda_p^r} \cap \boldsymbol{\lambda_q^t} \neq \emptyset \tag{3}$$

$$f_p^r + F_p^r - f_q^t \leq M \cdot \mathcal{L}_{t,q}^{r,p} \quad \forall r,t \in \boldsymbol{NP}, \forall p \in \boldsymbol{P_r}, \forall q \in \boldsymbol{P_t}, r \neq t, \boldsymbol{\lambda_p^r} \cap \boldsymbol{\lambda_q^t} \neq \emptyset \tag{4}$$

$$\sum_{p \in \boldsymbol{P_r}} X_p^r = 1 \quad \forall r \in \boldsymbol{NP} \tag{5}$$

$$\rho_p^r \cdot F_p^r \cdot \varepsilon \geq X_p^r \cdot DT_r \quad \forall r \in \boldsymbol{NP}, \forall p \in \boldsymbol{P_r} \tag{6}$$

$$C \geq f_p^r + F_p^r - 1 \quad \forall r \in \boldsymbol{NP}, \forall p \in \boldsymbol{P_r} \tag{7}$$

$$\tau_i \geq \sum_{ji \in \boldsymbol{NP}} \sum_{p \in \boldsymbol{P_r}} F_p^{ji} \quad \forall i \epsilon \boldsymbol{N} \tag{8}$$

$$\omega_i \geq \sum_{ij \in \boldsymbol{NP}} \sum_{p \in \boldsymbol{P_r}} F_p^{ij} \quad \forall i \epsilon \boldsymbol{N} \tag{9}$$

$$\mu \cdot \gamma t_i \geq \omega_i \quad \forall i \epsilon \boldsymbol{N} \tag{10}$$

$$\mu \cdot \gamma r_i \geq \tau_i \quad \forall i \epsilon \boldsymbol{N} \tag{11}$$

$$\varphi t \geq \sum_{i \in \boldsymbol{N}} \gamma t_i \tag{12}$$

$$\varphi r \geq \sum_{i \in \boldsymbol{N}} \gamma r_i \tag{13}$$

$$Ce \geq \beta tx \cdot \varphi t + \beta rx \cdot \varphi r \tag{14}$$

Objective (2) is to minimize the total cost and the maximum number of FSs used. Here α is a weight factor, which is small so that the first objective has a higher priority. Constraints (3) and (4) ensure that the spectra of two paths that share common link(s) do not overlap. Constraint (5) ensures that only one path should be chosen for lightpath establishment between a node pair. Constraint (6) ensures that once a path is chosen between a node pair, all the traffic demand between this node pair is allocated onto it. Constraint (7) ensures that the maximum index of the used FSs is no smaller than the ending index of the path between any node pair. Constraint (8) calculates the total number of FSs assigned for the lightpaths incident to node i. Constraint (9) calculates the total number of FSs assigned for the lightpaths outbound from node i. Constraint (10) ensures that there are sufficient transmitters at node i that can generate FSs required by the lightpaths outbound from node i. Constraint (11) ensures that there are sufficient receivers at node i that can receive FSs more than those required by the lightpaths incident to node i. Constraints (12) and (13) calculate the total number of transmitters and receivers in the whole network, respectively. Constraint (14) calculates the total cost of the whole network.

C. ILP Model with MW Source Spectrum Contiguous Constraint

In the previous section, we have assumed that the transmitter uses the SW source where each contained laser diode can be tuned to any frequency in the C-band. However, if the transmitter uses the MW source, then the constraint that all the FSs generated by a common MW source should be spectrally contiguous must be considered. The ILP model considering this constraint can be extended from the previous basic model by adding an extra dimension k to represent the status of each sub-carrier in a transponder at node i ($i \epsilon \boldsymbol{N}$). We have also developed this ILP model, but considering the page limit, the details for this have not been presented here.

IV. HEURISTIC ALGORITHM

The ILP model can find the optimal solution to the RSA problem under asymmetric traffic demands. However, because this problem is NP-complete, for large networks, the ILP model cannot be solved to obtain an optimal solution within a reasonable time. To tackle this, we also develop efficient heuristic algorithms for the RSA problem.

For this, we extend the standard SWP-based heuristic algorithm [15] that has been used for the RSA problem under a symmetric traffic demand. However, unlike that existing algorithm, the new heuristic algorithm proposed here must specifically consider two unique aspects. First, all the traffic demands between node pairs are unidirectional and need not necessarily be co-routed. This means that the lightpaths in opposite directions may traverse different routes and can be assigned with different FSs. Second, in addition to assigning the spectra on each fiber link for lightpaths, the algorithm also needs to take into account the availability of eligible transmitters and receivers at the source and destinations nodes. The optimization should be carried out jointly to minimize both the number of transmitters and receivers used as well as the spectrum resources consumed on the fiber links. Thus, compared to the conventional standard SWP-based heuristic algorithm, the current algorithm is more complicated and challenging in order to attempt for the optimality with multiple objectives. To provide a complete algorithm that can handle all the network scenarios, we specifically assume a transmitter using a MW source such that its limitation of spectrum assignment would be considered. The main steps of the algorithm are as follows.

Algorithm: SWP-based heuristic algorithm for the RSA problem and cost calculation

Step 1 Get the first service request DT_r from the demand list. Choose the most advanced modulation format M according to the shortest distance between the source and destination nodes of DT_r. Based on M, find the number of FSs required and then generate corresponding SWPs. Find the shortest route (if there is one) on each of the SWPs. Each of the routes has a starting frequency index f_s and number of FSs, F, corresponding to its SWP.

Step 2 For each route R found on the SWPs (which has its associated f_s and F), scan all the deployed transmitters at the source node to decide the minimum number of newly added transmitters T_R required in order to establish the lightpath along route R.

Step 3 Scan all the SWPs to choose the route $R^* = \underset{R}{\operatorname{argmin}}\{T_R\}$; add T_{R^*} new transmitters and assign corresponding FSs for lightpath establishment.

Step 4 Remove the served request from the demand list; if the demand list is empty, terminate the RSA process; otherwise, repeat from *Step 1*.

Step 5 At each destination node, calculate the number of receivers using (13).

Step 6 Calculate the total numbers of transmitters and receivers used at each node, and then calculate the total cost of the network.

Step 1 finds the lightpath route and corresponding assigned FS index on each SWP. Step 2 finds the minimum number of new transmitters required to be added to establish the lightpath along the route found in each SWP. Considering all the routes and their numbers of transmitters required to be added, step 3 chooses the one requiring the minimum number of newly added transmitters. We repeat the same process from step 1 to 4 until all the service requests are served. In this algorithm, we scan the spectrum usage status of the existing transmitters and assign spectrum to the lightpath that is currently usable on the existing transmitters as much as possible. Doing this can minimize the need to bring in a new transmitter, thereby minimizing the hardware cost.

V. Test Conditions and Performance Analyses

To evaluate the performance of the RSA problem under the asymmetric traffic demand, we consider two test networks, i.e., a 6-node, 9-link N6S9 network and a 14-node, 21-link NSFNET network (see Fig. 3 in [13]). The link distance (in units of km) is shown next to each link. Three modulation formats (i.e., 8-QAM, QPSK, and BPSK) are assumed to be used for establishing lightpaths. We assume that the downstream demand between each node pair is uniformly distributed over [100, 700] Gb/s, and the upstream demand is calculated based on the downstream demand divided by the asymmetry ratio.

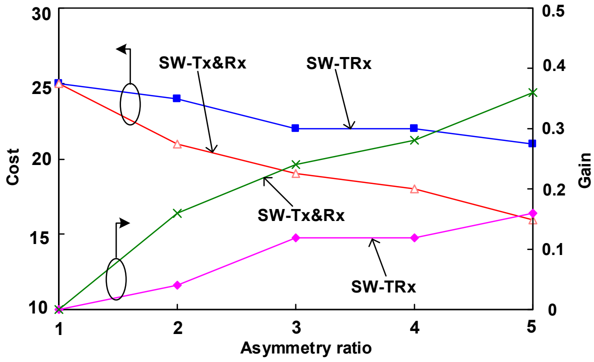
For the case of a SW source transmitter, we evaluated the performance of both N6S9 and NSFNET networks based on the ILP model. For the case of a MW source transmitter, due to the high computational complexity of the corresponding ILP model, we have only solved the model for the small N6S9 network, while for the larger NSFNET network, we only employed the heuristic algorithm for the solution.

We assume that the maximum number of FSs that can be carried by each transponder or split transmitter/receiver is 8. We set the cost of each bidirectional transponder (that is used for the conventional symmetric design) as 1.0. For the situation of split transmitters and receivers, we set the cost of each receiver as 0.4, and the costs of the transmitters that use different sources to be different. Specifically, because a SW source transmitter contains an array of tunable lasers, while a MW source transmitter needs only one laser, we set the costs of a SW source transmitter and a MW source transmitter as 0.6 and 0.5, respectively. Note that these costs can be modified according to the actual hardware costs. We employed the commercial AMPL/Gurobi software package (version 5.6.2) to solve the ILP models on a 64-bit machine with 2.4-GHz CPU and 24-GB memory. The MIPGAP for the ILP solutions was set to be 0.1%. We have used JAVA to implement the heuristic algorithm.

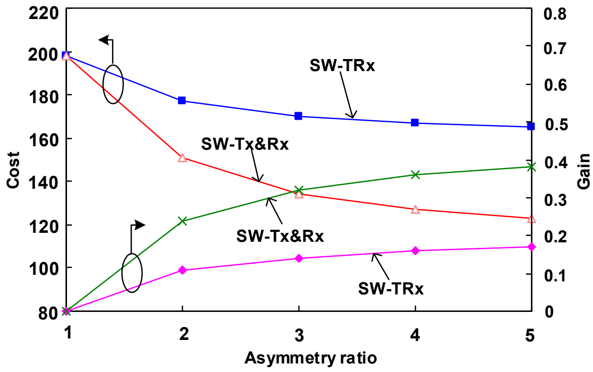
A. Results for SW Source Transmitters

In this part, we evaluate the cost and the total FSs used based on the basic ILP model, in which the SW source transmitter is assumed. Fig. 3 shows the total cost change with an increasing asymmetry ratio (AR). The total cost is calculated as the sum cost of all the transmitters and receivers or the sum cost of all the transponders in the network. The case of AR=1.0 essentially corresponds to the case of symmetric traffic demand. The legends for each curve has the following meaning. The legend “SW” means that the SW source transmitter is used. The legend “TRx” means the case of conventional transponders for symmetric traffic demand and the legend “Tx&Rx” means the case of split transmitters and receivers.

It is easy to see that with an increasing AR, all the study cases show decreased hardware costs. We define the cost reduction compared to the case of symmetric traffic demand as the gain of using split transmitters and receivers, which is shown on the right *y*-axis. Correspondingly, an increasing AR leads to a higher gain by the asymmetric design approach. For example, when AR=5.0, there is a gain of more than 35% compared to the symmetric case for both the N6S9 and NSFNET networks. In addition, comparing the results of “TRx” and “Tx/Rx,” we see that split transmitters and receivers do help to reduce the hardware cost for the asymmetric traffic demand, and moreover, with an increasing AR, such a reduction becomes even more significant, i.e., up to 20% compared to the case with conventional symmetric transponder for the N6S9 network. The maximum cost reduction is up to 25% for the NSFNET network. These results can be expected because with the increase of AR, upstream traffic demand will decline gradually and there would be a higher transmission capacity wastage in that direction if using symmetric transponders. The Tx/Rx approach decouples the transmitters and receivers, which ensures the most efficient allocation of a sufficient number of these components, thereby avoiding the wastage. The above results verify the benefit of applying the asymmetric design approach.



(a) N6S9



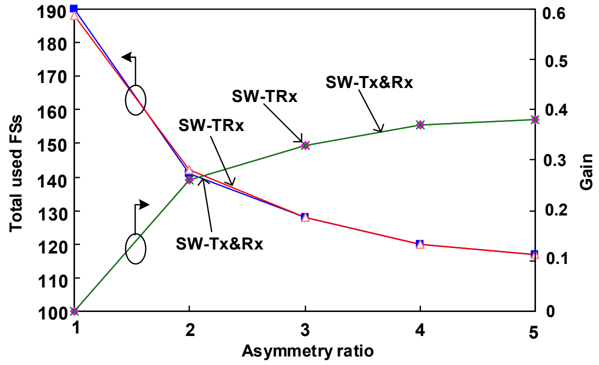
(b) NSFNET

Fig. 3. Total hardware cost (ILP model).

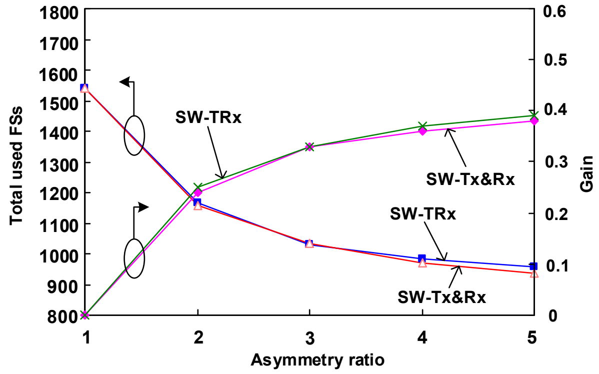
In addition to the hardware cost, we also evaluate the spectrum efficiency in terms of total FSs used in the whole network. This is shown in Fig. 4. Here total FSs used is defined as the sum of all the FSs used in all the links in the network. As was observed for the hardware costs, we see that with an increasing AR, the asymmetric design approach requires a smaller number of FSs to accommodate all the traffic demand. Compared to the symmetric case, the reductions of FSs used are close to 40% for both the two test networks. This verifies the effectiveness of the proposed asymmetric design approach for improving spectrum utilization of EON. In addition, comparing the results of the "TRx" and "Tx/Rx" cases, we see that there is no clear difference between these two cases. This implies that splitting transmitters and receivers would not bring much benefit for spectrum utilization though it can help to reduce the hardware cost.

B. Impact of Spectrum Contiguity of MW Source Transmitter

In addition to the SW source transmitter, we also consider the case of the MW source transmitter. Based on the N6S9 network, Fig. 5 shows the results of how the MW source transmitter can limit the hardware cost of the asymmetric network design. The MW source transmitter uses only a single laser, which is much lower than the number required by the SW source. Thus, the former has a lower hardware cost than the latter. We have set their relative costs as 0.5 and 0.6, respectively. In the results, the legend "MW" means the MW source case and the legend "heu" means the result obtained by the SWP-based heuristic algorithm.



(a) N6S9



(b) NSFNET

Fig. 4. Total FSs used (ILP model).

First, similar to the previous results, we see that with an increasing AR, the MW source-based scenarios also show reduced hardware costs. Second, comparing the results of the SW-ILP and MW-ILP models, we can see that the design based on the SW source has a much lower cost though the cost of a single SW source transmitter is higher than that of a single MW source transmitter. This is because the SW source transmitter is more flexible in its spectrum assignment than the MW source transmitter, which helps to reduce the number of transmitters required. Third, comparing the results of the ILP model and heuristic algorithm for the MW source case, we see that for the conventional transponder, the two approaches have very close costs. This confirms the efficiency of the proposed algorithm. Moreover, we notice that, for the case of split transmitters and receivers, the result of the heuristic algorithm is even better than that of the ILP model. This is because the ILP model considers a fixed set of link-disjoint routes for lightpath establishment between each node pair. In contrast, the heuristic algorithm is a type of adaptive routing algorithm to find a route for lightpath establishment, which tends to use the FSs with low indexes. With these FS indexes taken together, a smaller number of MW source transmitters is required.

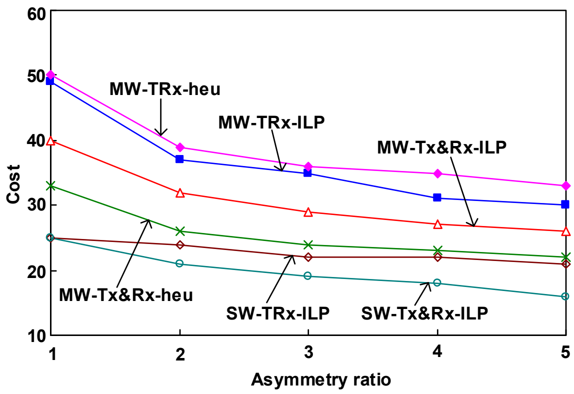


Fig. 5. Comparison of the total hardware cost between the SW and MW source transmitters (N6S9).

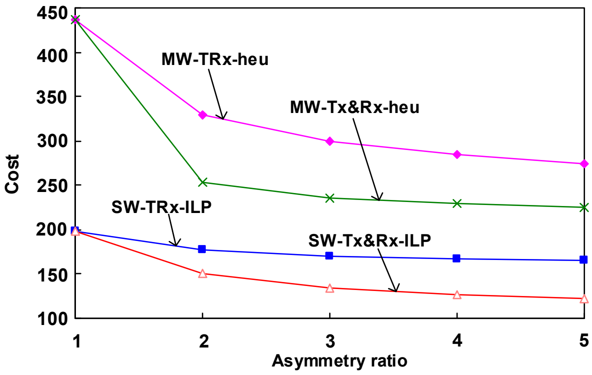


Fig. 6. Comparison of the total hardware cost between the SW and MW source transmitters (NSFNET).

We also compare the cost of the different design schemes for the NSFNET network as shown in Fig. 6. Due to the large size of the NSFNET network, for the case of a MW source, we only provide the results based on the heuristic algorithm. As was observed in the N6S9 network, we see that an increasing AR will lead to a decreased hardware cost. Meanwhile, the cost of the case with the SW source transmitter is much lower than that of the case with the MW source transmitter. Again, this is attributed to the higher flexibility of the SW source transmitter in providing different FSs.

Finally, we have also calculated the total numbers of FSs used by all the schemes for the two test networks. It is found that all the schemes use close numbers of FSs like the results in Fig. 4. Here due to the page limit, we do not provide these result curves.

VI. Conclusions

To tackle the issue of an increasing asymmetry between the upstream and downstream traffic demands in today's networks, we proposed a new asymmetric design approach for the EON. We proposed to split a conventional bidirectional transponder into an isolated transmitter and an isolated receiver. Furthermore, two types of architectures (i.e., SW source and MW source transmitters) were used to implement the transmitter. The performance of the proposed asymmetric network design approach was evaluated based on the RSA problem of the EON by developing the corresponding ILP models and a SWP-based heuristic algorithm. The simulation results show that the proposed asymmetric design approach is effective in significantly reducing the hardware cost and spectrum resources required compared to the design based on the symmetric traffic demand. In addition, the strategy of split transmitters and receivers also helps to significantly save hardware costs compared to the case without such splitting. Finally, using a SW source transmitter can reduce the network hardware cost compared to the case of the MW source transmitter because of the higher flexibility in spectrum allocation of the former.

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