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On Energy Efficient Survivable Multipath Based Approaches in Space Division Multiplexing Elastic Optical Network: Crosstalk-Aware and Fragmentation-Aware

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ABSTRACT In this paper, we have proposed two energy-efficient heuristics: (i) CMDE-RSCA (crosstalk-aware), and (ii) FMDE-RSCA (fragmentation-aware) to address the issues of inter-core crosstalk, and fragmentation within the core respectively- to ensure quality transmission of the optical signal for dynamic traffic in space division multiplexing elastic optical network (SDM-EON), while maintaining survivability of the network against single link failure. These heuristics based on multipath based survivability are compared with three existing survivable approaches based on p-cycles and shared path in terms of bandwidth blocking, energy consumption, crosstalk, and fragmentation. Both these algorithms outperform all three existing heuristics in terms of all parameters. In between CMDE-RSCA and FMDE-RSCA, CMDE-RSCA leads to consume lesser energy, whereas FMDE-RSCA produces lesser bandwidth blocking.

INDEX TERMS Cross-talk, energy consumption, multipath based survivability, SDM-EON, spectral fragmentation.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) based elastic optical network (EON) has evolved as an excellent solution nowadays to combat the challenging issue of efficient allocation of spectrum under the circumstances of massive exponential growth of network traffic. In OFDM, the spectrum resources are divided into beautiful granular spectrum bands known as subcarriers, and a requisite number of contiguous subcarriers are allocated to satisfy each demand based on its traffic volume (known as spectrum contiguity constraint) [1]. Each adjacent pair of requests is separated in each link by a fixed number of subcarriers (guard band) to avoid coherence (called non-overlapping constraint) [1]. The fixed amount of contiguous subcarriers should be allocated on each link of the selected path (known as spectrum continuity constraint) [1]. Allocating spectrum efficiently via a suitable route for a traffic request meeting all three constraints is known as routing and spectrum allocation (RSA) in EON. Minimizing spectrum requirements will lead to an increased scalability i.e., more number of connections can be accommodated with the available spectrum. The use of distance adaptivity in RSA plays a crucial role in minimizing the subcarrier requirement for the routes connecting the source-destination (s-d) node pairs by applying appropriate modulation format (MF) while maintaining the quality of the optical signal [2]. MF again depends upon the length of the path and the nearest available optical/ transparent reach, which is greater than or equal to the length of the path.

Single-core optical networks have almost reached the limit to its achievable capacity [3]. The adoption of space division multiplexing in EON (SDM-EON) using multiple (say, n) cores in parallel has led to the evolution of multi-core fiber (MCF) technology to provide n fold increase in capacity. Due to the additional spatial domain, there develops another constraint: core assignment in SDM-EONs [4]. The interference in between adjacent cores due to propagation of signals with the same frequency in MCF based EONs is called inter-core crosstalk [5]. Reducing crosstalk among adjacent cores is a primary concern nowadays.

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Allocating spectrum efficiently via a suitable route for a traffic request meeting all four constraints is known as routing, spectrum, and core assignment (RSCA) in SDM-EON [6]. The routing approaches can be roughly classified into two types- offline (static) and online (dynamic) [1]. Offline traffic is known beforehand, whereas in online traffic connections arrive randomly following Poisson distribution. In this dynamic environment, traffic is allocated on demand and also de-allocated on the expiry of holding time, which is exponential in nature. Fragmentation of cores due to random arrival/ departure of dynamic connections is another major issue to be taken care of. Dynamic arrival and departure of connections create many small-sized gaps throughout the links which cannot be utilized by the next incoming requests with larger spectrum requirement. This increased spectral fragmentation, in turn, increases the bandwidth blocking ratio. Thus, proper fragmentation-aware techniques need to be implemented for handling growing traffic demands [7].

Due to rapid growth in data traffic, power consumption in SDM-EON increases quite fast because of the usage of more network elements, which becomes one of the major areas of concern nowadays. Three main components: bandwidth variable transponders (BVTs), bandwidth variable optical cross-connect (BV-OXC), and erbium-doped fiber amplifier (EDFA) are responsible for power consumption in SDM-EON amongst which bandwidth variable transponders take a major and significant role [8].

Disruption of services due to any link failure or disaster in SDM-EON transporting voluminous data results in a huge loss of data, which again makes survivability a great issue. Many survivable schemes [9], [10] [11] such as dedicated path protection, shared path protection, multipath based protection, p-cycle based protections already exist. Both shared and dedicated path protection schemes use a link-disjoint backup path along with the working path for each request so that the backup path can be used for data transmission in the presence of any failure in the working path. In shared path protection, the backup path is designed for each request in a manner such that more than one backup path of different requests can share resources if their working paths are link disjoint. P-cycles are pre-configured cycles which can pre-configured backup resources by providing protection to on-cycle spans [5]. Multipath based survivability allows traffic routed through a link-disjoint set of paths connecting source-destination (s-d) node pair to ensure the propagation of a significant amount of traffic data through other paths despite the presence of a single link failure in any of these selected paths. If B is the bandwidth requirement for a request and q ($0 < q < 1$) is the protection level requirement then at least $q \cdot B$ amount of traffic load must propagate for the connection request to ensure survivability in presence of single link failure in any of the selected paths. Multipath based survivability scheme significantly reduces bandwidth blocking ratio (BBR) by reducing fragmentation of paths to a great extent [12].

In this paper, two new energy-efficient multipath based survivable RSCA schemes have been proposed. The objective of the first heuristic is to reduce inter-core crosstalk in the network as much as possible. The second one primarily tries to reduce spectral fragmentation as much as possible, while maintaining inter-core crosstalk below some threshold level. Both of them are compared with the algorithms proposed in [5] with respect to BBR, network energy consumption, fragmentation ratio, and crosstalk per slot ratio.

Section II presents the literature review. In section III, the problem has been defined, followed by assumptions and a lemma. Section IV discusses about energy consumption model. In section V two heuristics: crosstalk aware and fragmentation aware (CMDE-RSCA and FMDE-RSCA) are described. Section VI presents the simulation results and comparative study among different approaches. The paper is concluded in section VII.

II. LITERATURE SURVEY

Tode and Hirota [13] first proposed the core classification approach for RSCA in SDM-EON without considering inter-core crosstalk as an issue. Muhammad *et al.* [14] designed an equation to measure the mean crosstalk for any core due to other neighboring cores in a fiber. Tode and Hirota [15] proposed a prioritized area based RSCA algorithm for crosstalk measurement. Lei *et al.* [4] tried to minimize crosstalk by presenting a new RSCA heuristic for online traffic in SDM-EON. Zhu *et al.* [16] proposed a service-classified based routing, spectrum, and core assignment for multicore fiber-based SDM-EON. Yang *et al.* [17] proposed a dynamic fuzzy clustering-based resource assignment scheme in SDM-EON, which effectively reduces blocking probability and resource utilization.

Zhu *et al.* [18] designed a metric called the multi-dimensional resource compactness to measure fragmentation both in space and time domain. They also proposed a suitable RSCA scheme using this metric. Later in [19], they proposed a multipath based fragmentation-aware routing, modulation, and spectrum assignment (RMSA) scheme for both advanced and immediate reservation requests. Arpanaei *et al.* [20] worked with few-mode multicore fibers and presented a three-dimensional resource allocation scheme in SDM-EON. Zhao *et al.* [3] redesigned the metric spectrum compactness to introduce a new crosstalk aware spectrum defragmentation algorithm for online traffic in multicore based SDM-EON. Yousefi and Rahbar [21] first proposed a fragmentation aware multipath based RSA scheme for SDM-EON using core classification method [13].

Luo *et al.* [22] presented a scheme that significantly reduces the probability of virtual optical network failure, which further reduces spectrum utilization. Yang *et al.* [23] proposed a multipath protection technique for data center services in Open-flow based software-defined EONs to increase network reliability. Yang *et al.* [24] proposed a multi stratum resource integration architecture for accommodating data center services by resource integration in software-defined data center networks.

Zhao *et al.* [25] used different switching techniques for providing an auxiliary graph-based traffic grooming approach, which dramatically reduces the number of transponders in the network. In 2016, Yang *et al.* [26] presented a new optimal shared protection mapping scheme in EON, where they put forward a metric known as ambiguity similitude to solve any optimization difficulty. Fujii *et al.* [27] first simplified the building modules of AoD node architectures to address the power consumption problem and also proposed an RSA algorithm for reducing blocking probability in online environment.

Tan *et al.* [28] proposed a crosstalk aware dedicated path protection scheme for elastic MCF based networks. H. M. N. S. Oliveira and N. L. S. da Fonseca first proposed a FIPP (failure independent path protection) p-cycle based protection algorithm, which induces less interference in the network [29]. They later proposed a shared path based survivability scheme in 2017 [6], which produces better results compared to their previous work [29]. Again in [30], they presented a new algorithm called PERFECTA for path protection in SDM-EON using modulation in RSA. They later proposed a shared path based survivability scheme in 2017 [6], which produces better results compared to their previous work [29]. In [5], H. M. N. S. Oliveira and N. L. S. da Fonseca proposed three different RSCA algorithms, namely SBPPMC (shared path based), FIPPMC (p-cycle based) and MIFMC (p-cycle based) for protecting routes in SDM-EON in case of single link failure. Inter-core cross talk is measured, and a connection is established based on the value of threshold crosstalk (-16dB). They have neither proposed any typical crosstalk-aware or fragmentation-aware scheme nor did their algorithm try to minimize total network energy consumption. Several related recent works considering online traffic in SDM-EON along with their functionalities are summarized in Table 1.

In this paper, two new energy-efficient multipath based survivable RSCA schemes, namely crosstalk-aware and fragmentation-aware, have been proposed and are compared with the algorithms proposed in [5] concerning different network parameters.

III. PROBLEM DEFINITION

The SDM-EON is represented as a graph $G = (V, E, C)$ where V, E, and C are the sets of nodes, links, and cores present in each link respectively. Each connection arrives randomly as $R < s, d, B, q >$ where s and d are the source and the destination nodes respectively, B is the bandwidth demand and q is the protection ratio, $0 < q < 1$. The graph is modeled in the form of a multi-graph [5] i.e. the graph may be divided into n subgraphs where $n = |C|$. Multipath based survivability ensures the communication of minimum $B \cdot q$ amount of traffic in between s-d pair of a connection request even if a single link fails in any of the selected multipath for the request.

TABLE 1. Comparative study among related works.

Method	RSCA	Protection	Network Power	Joint
H. Tode et al. (2014) [13]	Yes	No	No	No
A. Muhammad et al. (2015) [14]	Yes	No	No	No
H. Tode et al. (2017) [15]	Yes	No	No	No
Y. Lei et al. (2018) [4]	Yes	No	No	No
Q. Zhu et al. (2018) [16]	Yes	No	No	No
R. Zhu et al. (2016) [18]	Yes	No	No	No
F. Arpanaei et al. (2018) [20]	Yes	No	No	No
Y. Zhao et al. (2018) [3]	Yes	No	No	No
F. Yousefi et al. (2018) [21]	Yes	No	No	No
Y. Tan et al. (2016) [28]	Yes	Yes	No	No
H. M. N. S. Oliveira et al. (2016) [29]	Yes	Yes	No	No
H. M. N. S. Oliveira et al. (2017) [6]	Yes	Yes	No	No
H. M. N. S. Oliveira et al. (2018) [30]	Yes	Yes	No	No
Y. Zhao et al. (2017) [25]	Yes	No	Yes	No
S. Fujii et al. (2017) [27]	Yes	No	Yes	No
H. M. N. S. Oliveira et al. (2019) [5]	Yes	Yes	Yes	Yes
CMDE-RSCA	Yes	Yes	Yes	Yes
FMDE-RSCA	Yes	Yes	Yes	Yes

The objective is to design two distance adaptive RSCA heuristics: crosstalk-aware and fragmentation aware for SDM-EON under dynamic environment having the characteristics as follows:

i) Survivability based on multipath to reduce spectral fragmentation and bandwidth blocking ratio to a large extent [12].

ii) Energy-efficiency obtained by selecting proper paths to reduce power-consuming network elements [2].

Assumptions:

i) At least two link-disjoint paths must exist between each node pair of the network to ensure multipath based survivability.

ii) Number of paths to be selected in multipath based survivability is considered to be either two or three.

iii) Cores are classified [13], [16] [27] into various regions which helps reduce spectral fragmentation to a great extent [21].

iv) Core switching has not been considered here.

v) Spectrums of different connections can be allocated in consecutive slots of fixed size regions without any interference [21].

Lemma 1: Total traffic data to be allocated for multipath based survivability scheme is always less than that for shared path-based and p-cycle based schemes.

Proof: Multipath based survivability scheme: In case of 2-paths solution, traffic demand propagated through the paths is always equal to B when $q \leq 0.5$ and $(2 \cdot B \cdot q)$ when $q > 0.5$. In case of 3-paths solution, traffic demand propagated through the paths is always equal to B when $q \leq 2/3$ and $((3/2) \cdot (B \cdot q))$ when $q > 2/3$. [Section V, Algorithm 1 and 2]

Shared path or p-cycle based survivability scheme: Shared path or p-cycle based survivability scheme requires 2B bandwidth of data to be transmitted through s-d pair where B travels through primary path and B through p-cycle/ backup path.

Again, 2B > 2Bq and 2B > 3.B.q/2

Hence the proof.

IV. ENERGY CONSUMPTION MODEL

Amongst three power consuming elements in SDM-EON named as bandwidth variable transponders (BVTs), optical amplifiers (AMPs) and optical cross-connect switches (OXCs), BVTs contribute major share [8]. Energy consumption by BVT directly depends on total number of utilized spectrum [2], [8]. Thus reducing number of subcarriers using suitable modulation format (using Table 2) helps decrease the power consumed by BVTs. Selection of paths in SDM-EON implies basically selection of the core and also the slot within the core. Paths consuming energy to the lowest possible extent are selected while maintaining the values of cross-talk below the threshold level in cross-talk aware heuristic. Fragmentation aware scheme similarly selects low- energy consuming paths by reducing fragmentation of the path to the value as low as possible and crosstalk below some threshold level. Variables and parameters used in energy consumption models of all these network elements have been detailed in the following subsection.

A. PARAMETERS

K = Set of paths chosen for multipath solution

M = Set of modulation formats

f^k = Number of subcarriers allocated in k^{th} path

w^l = Weight of link l

e^m = Energy consumed by a subcarrier with m^{th} modulation format

e^a = Energy consumed by a^{th} amplifier

t_m = Transparent reach of m^{th} modulation format

γ_k^m = Number of subcarriers allocated to k^{th} path with m^{th} modulation format

e^v = Energy consumed by node v due to OXCs

d^v = Degree of node v

D = Add/ drop degree for each node

N^v = Neighbours of node v

z = Number of subcarriers that can be allocated in each link of a path

B. VARIABLES

$b_k^l/(b_k^{u,v})$ = Binary variable, 1 *iff* path k goes through link $l/(u,v)$, 0 otherwise.

y_l^c = Binary variable, 1 *iff* core c is selected in link l, 0 otherwise.

C. OPTICAL AMPLIFIERS (AMPs)

The optical amplifiers are placed at 80 *km* apart from each other. Hence, the number of amplifiers to be placed in the network increases with the increase in link length (w^l) of the path to be selected. If the power consumed by each AMP (e^a) is assumed to be 100 *W* [2] per direction then the energy consumed by all AMPs along link l is shown in (1) [2], [9].

$$e^a = \left\lfloor \frac{w^l}{80} + 1 \right\rfloor * 100 \tag{1}$$

The power consumption of amplifiers during resource allocation depends not only on the length of the links present in the path established but also on the number of used subcarriers f^k and link capacity z. Equation (2) calculates energy consumed (E^A) by all AMPs [2], [9] in a single-core network once a connection is established.

$$E^A = \sum_{k=1}^{|K|} \sum_{l=1}^{|E|} \frac{b_k^l}{z} \cdot f^k \cdot e^a \tag{2}$$

In SDM-EON, each link is divided into several cores, and also in our core selection strategy, multiple cores can be selected based on the demand. Total power consumed by the amplifiers (E^{AM}) in SDM-EON during connection establishment is given in (3).

$$E^{AM} = \sum_{c=1}^{|C|} \sum_{l=1}^{|E|} y_l^c \cdot E^A \tag{3}$$

D. BANDWIDTH VARIABLE TRANSPONDERS (BVTs)

Energy consumed by the BVT (E^{BV}) depends on the optical reach (t_m) and the adopted modulation format and increases with an increase in the number of spectrums utilized. Longer path again requires a larger number of spectrums for allocation. Energy consumed by BVT (e^m) for a single frequency slot is calculated in (4) [2], [9].

$$e^m = 1.683 \cdot t_m + 91.333 \tag{4}$$

Although SDM-EON divides a single fiber into multiple cores yet in spite of the selection of more than one core for an incoming connection, the modulation format to be assigned in the established path does not get affected. This is because the selection of multiple cores in any particular fiber does not tamper the path length. As a result, BVT power consumption does not depend on core selection. The energy E^{BV} consumed by all BVTs is measured using (5) [2], [9].

$$E^{BV} = \sum_{k=1}^{|K|} \sum_{m=1}^{|M|} \gamma_k^m \cdot e^m \tag{5}$$

E. CROSS CONNECT SWITCHES (OXCs)

Power consumption of OXCs depends on the nodal degree (d^v), add/ drop degree (D) and other factors such as power supply etc. Power consumed by a single OXC (e^v) at node v is calculated using (6) [2], [8].

$$e^v = 85 \cdot d^v + 100 \cdot D + 150 \tag{6}$$

Energy E^O consumed by all OXCs is computed using and (7) [2], [8]. It also depends on number of used subcarriers (f^k) and link capacity (z).

$$E^O = \sum_{k=1}^{|K|}\sum_{v=1}^{|V|}\sum_{u\in N^v} \frac{b_k^{(u,v)}}{z} \cdot f^k \cdot e^v \tag{7}$$

If more than one core is selected in any particular fiber link, then the total power consumption of all OXCs is given in (8).

$$E^{OX} = \sum_{c=1}^{|C|}\sum_{l=1}^{|E|} y_l^c \cdot E^O \tag{8}$$

V. HEURISTICS CMDE-RSCA AND FMDE-RSCA

In this section, two energy-efficient and multipath based survivable heuristics, namely the inter-core crosstalk-aware (CMDE-RSCA) and fragmentation-aware (FMDE-RSCA) approaches have been discussed for SDM-EON. Pre-computation, path selection, and core selection processes are the same for both the heuristics.

A. PRE-COMPUTATION

Energy consumed by any path increases primarily with the length of the path [2]. So, we have pre-computed link-disjoint shortest paths to minimize energy consumption in between each s-d pair using Bhandari's k-shortest path algorithm [31] and those are stored in set P for a particular request. We have restricted the upper limit of the number of link-disjoint paths for a specific s-d pair to 3.

Pre-computation of the number of link-disjoint paths uses Bhandari's algorithm having worst-case complexity as $O(|E|)$ considering k as a constant.

B. PATH SELECTION

When a request $R(s, d, B, q)$ arrives, link-disjoint paths between s-d pair are extracted from the set P. If P contains only two paths, then the traffic demand B is divided into two parts, as mentioned in algorithm 2, and the total power consumed for each of the two paths is calculated (using algorithm 3). In case P contains three paths, four possible permutations of the paths $P1$, $P2$, $P3$, and $P4$ are obtained from the set P (in algorithm 1). Each of the first three sets $P1$, $P2$, and $P3$ contain two paths, and the last set $P4$ contains all the three paths.

Distance-adaptive modulation format is applied to calculate the required number of subcarriers for each path. Table 2 describes all the modulation formats along with subcarrier capacity, the power consumed by each subcarrier, and transparent reach. Depending on the path length, which is less than or equal to the nearest transparent reach, the respective modulation format, m is the appropriate one to be selected. The number of subcarriers is then calculated using (9) as follows.

$$sb = \lceil \frac{B}{s^m} \rceil \tag{9}$$

where B = Demand to be propagated through selected path

sb = Number of subcarriers to be assigned in the path

Algorithm 1 Algorithm for Path Selection

```
INPUT: R(s, d, B, q), P
OUTPUT: Success/ Rejection of request
1. if P contains only 2 paths then
    call Algorithm 2 //for division of demands between two
    paths and power computation
end
else
    //make 4 path sets by taking permutations of paths in P
    Create P1, P2, P3 and P4
    if P1/P2/P3 is chosen then
        call Algorithm 2 //for division of demands between
        two paths and power computation
    end
    else
        if q ≥ 2/3 then
            x = (B · q)/2 //demand to be propagated through
            each path
        end
        else
            x = (B · q)/2
            y = B − (B · q)
            if x > y then
                Propagate demand x through the first two
                shortest paths and y through the third path.
            end
            else
                Propagate demand y through the shortest path
                and x through other two paths.
            end
        end
        call Algorithm 3 for P4 //for power computation
    end
    Sort P1, P2, P3 and P4 in non-decreasing order of
    E^TOTAL
end
2. for each path set in the sorted list do
    call Algorithm 4 //for selection of core
    call Algorithm 5 //for crosstalk aware scheme
    or call Algorithm 6 //for fragmentation aware scheme
    if spectrum allocation is possible then
        Request is established.
        Break;
    end
end
3. if all path sets are scanned, and spectrum cannot be
allocated then
    Request is blocked.
end
```

s^m = Subcarrier capacity of m^{th} modulation format

Power consumption by BVT on the selected path equals to $p_m * sb$.

Once modulation format is decided using Table 2, the total power consumed by each set of paths is computed next in algorithm 3. The primary objective of the proposed method is

TABLE 2. Table for distance-adaptive modulation formats [2].

Modulation Formats	*Subcarrier Capacity,* s^m *(Gbps)*	*Power consumption per subcarrier,* p_m *(Watt)*	*Transparent reach (km)*
BPSK	12.5	112.374	9600
QPSK	25	133.416	4800
8QAM	37.5	154.457	2400
16QAM	50	175.498	1200

Algorithm 2 Algorithm for Subcarrier Division and Power Computation in Case of Two Path Solution

INPUT: $R(s, d, B, q)$, P
OUTPUT: Power consumed by two paths
1. **if** $q \geq 0.5$ **then**
    $x = B \cdot q$ //demand to be propagated through each path
    call Algorithm 3 //to calculate energy consumption
end
else
    $x = B \cdot q$ //demand to be propagated through first path
    $y = B - (B \cdot q)$ //demand to be propagated through second path
    call Algorithm 3 //to calculate energy consumption
end

to allocate connections in the best possible way using paths that consume energy as low as possible. Hence, four path sets $P1, P2, P3$, and $P4$ are sorted in non-decreasing order of power consumption, and each of them is then considered for spectrum allocation (Crosstalk-aware or Fragmentation-aware) one-by-one in the same order (non-decreasing order of power consumption). For each path set, cores are selected based on the traffic demand for the connection request, and spectrum is allocated in eligible slots. In case of the non-availability of suitable slots in a path set, the next path set is considered for core selection followed by spectrum allocation in eligible slots of the cores. Once the spectrum is allocated in eligible slots of any path set, the rest path sets are ignored. In case of non-availability of eligible slots for all path sets, the request is blocked.

The worst-case time complexity for sorting the paths is $O(|V| * |E|)$. Computation of the energies consumed by optical amplifiers and BVTs are of complexity $O(k * |E|)$ and by OXCs is of complexity $O(k * |V| * |E|)$. In all these cases, k is a constant with value 2 or 3.

Hence overall computational complexity for path selection is $O(|V| * |E|)$.

C. CORE SELECTION

The proposed core selection strategy (described in algorithm 4) uses core classification [13], [16] [27] method based on the traffic demand for the connection request. The central (first) core is the common core, which can accommodate demands of any size. Each of the peripheral cores is organized into consecutive regions of the same size as it reduces path fragmentation to a great extent, while the size (based on prime numbers) varies from one core to another one [21]. Assuming the existence of seven cores in each fiber link of the network

Algorithm 3 Algorithm for Network Energy Computation

INPUT: P
OUTPUT: E^{TOTAL}

1. **for** *each path* $i \in P$ **do**
    Find out the distance.
    Find out number of subcarriers to be allocated using (9) and Table 2.
    Calculate E^{BV}, E^{AM}, E^{OX} as mentioned in Section IV.
end
2. Find $E^{TOTAL} = E^{BV} + E^{AM} + E^{OX}$; //total consumable network energy
3. **return** E^{TOTAL}

Algorithm 4 Algorithm for Core Selection

INPUT: #subcarriers to be allocated (sub), $C[7]$ (set of seven cores)
OUTPUT: Selected cores

1. cr[6]={1, 2, 3, 5, 7, 11}; //set containing region size of the last six cores
2. **for** *each core c* = 6 *to 1* **do**
    if *sub >= cr[c]* **then**
        A core is chosen randomly between C[c] and C[c-1]
        if *Core[c] is selected* **then**
            $a = (sub/cr[c]) * cr[c]$ //number of subcarriers to be allocated
            call Algorithm 5 //for crosstalk aware scheme
            or call Algorithm 6 //for fragmentation aware scheme
        end
        else
            $a = (sub/cr[c-1]) * cr[c-1]$ //number of subcarriers to be allocated
            call Algorithm 5 //for crosstalk aware scheme
            or call Algorithm 6 //for fragmentation aware scheme
        end
        if *spectrum can be allocated in the selected core* **then**
            $sub = sub - a$
        end
        if *sub=0* **then**
            Break;
        end
    end
end
3. **if** *sub* $\neq$ *0* **then**
    C[0] is selected //common core is selected
    call Algorithm 5 //for crosstalk aware scheme
    or call Algorithm 6 //for fragmentation aware scheme
end

the peripheral six cores 2, 3, 4, 5, 6 and 7 considered in this work consist of regions of 1 frequency slot (FS), 2 FS, 3 FS, 5 FS, 7 FS, and 11 FS respectively [Fig. 1].

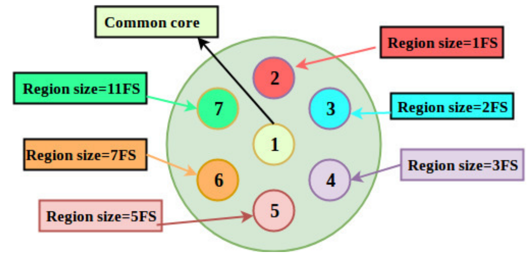


FIGURE 1. Core classification considered in the paper.

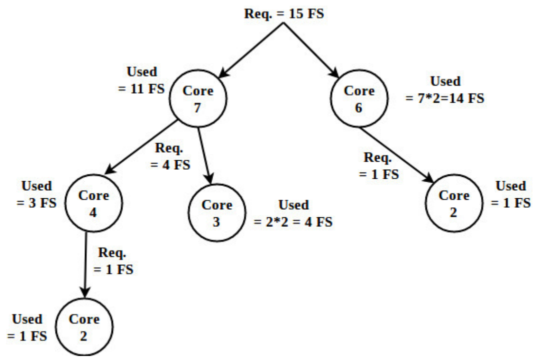


FIGURE 2. Selection process of cores (an example).

Example: In order to clarify core selection strategy, we assume arrival of a connection of 15 FS requirement after applying proper modulation format (using (9) and Table 2).

The heuristic finds out the cores having two consecutive highest frequency slots, which is less than or equal to its requirement. In this case, core 7 of region size FS 11 and core 6 of region size FS 7 are the two eligible cores. A choice between the two cores is randomized in order to avoid starvation or exhaustion in a particular core due to its repetitive selection.

Choice of Core 7: Selection of core 7 allocates 11 FS traffic in it. The remaining traffic to be allocated is 4 FS. Eligible cores are now core 4 of region size 3 FS and core 3 of region size 2 FS. Anyone of them is now selected randomly. If core 4 is chosen at random, then 3 FS will be allocated in it. Applying the same logic remaining 1 FS will be allocated in core 2. If core 3 instead of core 4 is selected at random while the requirement is 4 FS, 2*2 FS = 4 FS may be allocated in it.

Choice of Core 6: Selection of core 6 allocates 7*2 FS = 14 FS in it. Using the same logic remaining 1 FS traffic will then be allocated in core 2 of region size 1.

If any of the classified cores 2-7 cannot accommodate the incoming demand, the common core (Core 1) is checked. If no space is available in the common core, then the request is blocked. This is to mention that the guard band needs to be allocated between two connections allocated consecutively within the common core to avoid interference.

The pictorial representation of the example for selection of the core is shown in fig. 2. Spectrum can be allocated by selecting the cores following any path of the tree from the root node to the leaf node shown in the figure.

The worst-case computational complexity of this algorithm is proportional to |C| where |C| represents a constant value.

Algorithm 5 Algorithm for Selection of Eligible Regions and Subcarrier Allocation in CMDE-RSCA

INPUT: Selected core

OUTPUT: Allocation/deallocation of connection

1. flag=0; //variable that confirms whether subcarriers can be assigned in selected core
2. Find out the available gaps where spectrum can be allocated.

for *each available gap* **do**
  Calculate the inter-core crosstalk using (10) and (12)
  if *crosstalk calculated* $< XT_{th}$ **then**
    flag=1;
  end
end
3. **if** *flag = 1* **then**
  Assign spectrum to the gap, which creates least inter-core crosstalk.
end

D. SELECTION OF ELIGIBLE SLOT

In crosstalk-aware scheme, slots or regions with the least crosstalk value is chosen among all eligible slots with inter-core crosstalk values below the threshold level. Consideration of eligible slots in the fragmentation-aware scheme is based on finding the least fragmented core, while inter-core crosstalk value remains below the threshold level. Our next subsections thus discuss about two heuristics: Crosstalk-aware Multipath Distance-adaptive Energy-efficient RSCA (CMDE-RSCA) scheme (described in algorithm 5) and Fragmentation-aware Multipath Distance-adaptive Energy-efficient RSCA (FMDE-RSCA) scheme (described in algorithm 6).

1) CROSSTALK-AWARE MULTIPATH DISTANCE-ADAPTIVE ENERGY-EFFICIENT RSCA SCHEME (CMDE-RSCA)

If the same slot in adjacent cores is used, then inter-core crosstalk happens, which serves as one of the major issues in SDM-EON. Fig. 3 clearly illustrates the inter-core crosstalk problem. If signals propagate through the same slots of adjacent cores, then inter-core crosstalk occurs. In fig. 3, red-dotted lines signify crosstalk affected region (since cores 2 and 5 are adjacent to core 1), and green-dotted lines signify crosstalk unaffected region (since cores 2 and 5 are not adjacent cores). Thus before allocating spectrum to the region(s) of a particular core for an incoming connection, the level of crosstalk imposed by other existing connections to it as well as that imposed by the new connection (to be allocated) to other existing connections in the network needs to be measured and checked for maintaining the quality of transmission in the network. A matrix $H^{l}_{c,s}$ has been maintained that stores the current status of s^{th} frequency slot (whether the slot is available or not) in c^{th} core of link l. Crosstalk for each individual core is measured separately, and all of them are summed up to obtain total crosstalk value.

Algorithm 6 Algorithm for Selection of Eligible Regions and Subcarrier Allocation in FMDE-RSCA

INPUT: Selected core, #subcarriers to be allocated in the path of the selected core (sb)
OUTPUT: Allocation/deallocation of connection

1. Find out the eligible gaps where the spectrum can be allocated.
2. **if** *a single exact gap is found* **then**
  Allocate spectrum to it if calculated crosstalk $< XT_{th}$.
end
else
  if *more than one exact gap is found* **then**
    Calculate fragmentation ratio using (13).
    Calculate the inter-core crosstalk using (10) and (12).
    Select the gap that creates least fragmentation with crosstalk value $< XT_{th}$
    Assign spectrum to the selected gap.
  end
  else
    if *each gap size > sb* **then**
      Select the largest gap whose calculated crosstalk $< XT_{th}$
      Assign spectrum to the selected gap.
    end
  end
end

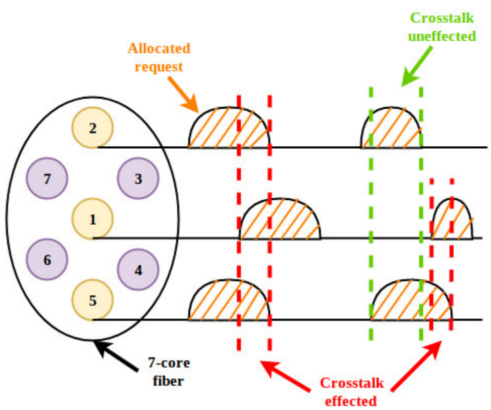


FIGURE 3. Crosstalk problem due to core assignment in SDM-EON.

Equation (10) and (11) measure the mean crosstalk (XT_l^c) value for any core in any link l [5], [14].

$$XT_l^c = \frac{h\{1 - exp(-(\alpha + 1) * 2 * \Delta * \beta)\}}{1 + \alpha\{exp(-(\alpha + 1) * 2 * \Delta * \beta)\}} \quad (10)$$

$$\Delta = \frac{2 * \eta^2 * \phi}{\rho * \omega} \quad (11)$$

where,
Δ = Increase in crosstalk per unit length
h = Number of active adjacent cores
α = Number of adjacent cores
β = Fiber length
η = Coupling coefficient
ϕ = Bending radius of fiber
ρ = Propagation constant
ω = Core pitch

The values of η, ϕ, ρ and ω are 2×10^{-5}, $50\,mm$, 4×10^6 and $45\mu m$ respectively [5], [14]. The value of h is obtained from the matrix $H_{c,s}^l$ which maintains the details about all adjacent active cores. Finally, total intercore crosstalk (XT) for any established connection is obtained from (12) as mentioned below.

$$XT = \sum_{c=1}^{|C|}\sum_{l=1}^{|E|} y_l^c \cdot XT_l^c \quad (12)$$

If the crosstalk measured for a region to be used for allocation of spectrum in a core remains below the threshold value (XT_{th}) (−16 dB) [3], [5] then spectrum is allocated in the selected region. Otherwise, the incoming connection is blocked since it hampers the existing quality of transmission.

In case of availability of more than one suitable region for allocation of spectrum, the region associated with the least crosstalk value is chosen. If the same crosstalk value is generated for more than one exclusive region after the allocation of spectrum, the first-fit approach is used i.e., the first available region/ gap is selected.

The complexity of the selection of slots in CMDE-RSCA depends on the selection of available regions where the spectrum can be allocated and also on the selection of the region with the least crosstalk value. The availability of regions takes $O(|V|+|E|)$ time, and the selection of a single eligible region depends on the number of total available regions. Number of regions depends on link capacity, which is again a constant value. Thus, the selection of slots in CMDE-RSCA has a worst-case complexity of $O(|V| + |E|)$.

• Worst case computational complexity of CMDE-RSCA considering the phases of path selection, core selection, and selection of eligible slots is computed as $O(|V| * |E|)$ which is polynomial in nature.

2) FRAGMENTATION-AWARE MULTIPATH DISTANCE-ADAPTIVE ENERGY-EFFICIENT RSCA SCHEME (FMDE-RSCA)

FMDE-RSCA allocates spectrum in the least fragmented gap of the path, which plays a vital role in reducing bandwidth blocking ratio. Multipath based routing scheme divides the bandwidth demand into smaller sizes to propagate via multiple paths connecting s-d node pair and uses suitable modulation format (Table 2) to reduce further into smaller sized subcarriers [2]) which severely helps reduce fragmentation of paths also.

FMDE-RSCA uses a formula in (13) to measure the fragmentation ratio (Frag) in the path. It then selects the gap, which, if utilized by the spectrum, least fragments the path and whose calculated crosstalk value (using (12)) is less than the threshold. The fragmentation ratio is checked only in the case of the common core and is irrelevant for other cores because the objective of core classification itself is to minimize fragmentation of cores [13], [21].

$$Frag = \frac{L}{F} * \frac{S}{G} * (|(X * \delta) - (Y * \theta)| + 1) \quad (13)$$

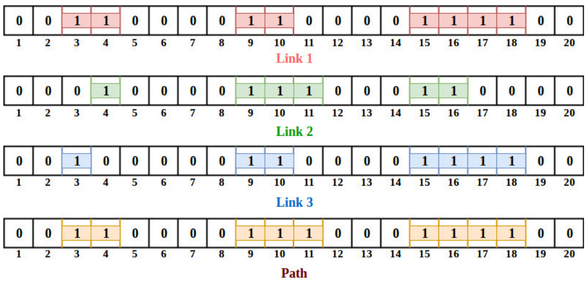


FIGURE 4. Spectrum status of a path with three links (an example).

where,

$L =$ Last occupied position in the path
$F =$ Last free position in the path
$S =$ Total number of gap segments
$G =$ Total number of gaps
$X =$ Frequency of the biggest gap in the path
$\delta =$ Size of biggest gap in the path
$Y =$ Frequency of the smallest gap in the path
$\theta =$ Size of smallest gap in the path

Due to allocation in any exact gap in the path $\frac{S}{G}$ value is minimum, and fragmentation value also reduces. The factor $\frac{L}{F}$ emphasizes on choosing the first available gap in the path so that the value of the factor does not increase anymore. Multiplication of both these factors helps select the first available exact gap for spectrum allocation. $(|(X*\delta)-(Y*\theta)|+1)$ tries to handle the effect of fragmentation caused by different gap sizes in the path. In the absence of any exact-fit gap, the biggest gap needs to be allocated to keep spectral fragmentation minimum [21]. The fragmentation ratio is directly proportional to all these three factors mentioned above. The objective of the work is to obtain a suitable solution by minimizing the factors as much as possible.

Example: Fig. 4 presents the status of the three links and also the path comprising of these three links at any point of time where 0/ (1) represents availability/ (non-availability) of the gap. The state of the path is obtained by taking the logical OR operation of the respective gap in three links.

During spectrum allocation, a situation may arise where spectrum requirement is 2FS. There exists more than one exact gap of size 2FS. Fragmentation ratio due to them is calculated and the one with least fragmented value is selected. For the gap indexed 1-2, $pLO = 18$, $pLF = 20$, $tGSeg = 3$ (indices 5-8, 12-14 and 19-20), $tG = 9$, $sBG = 4$ (indices 5-8), $BG = 1$ (only one large gap of size 4 is available), $sSG = 2$ (indices 19-20) and $SG = 1$ (only one small gap of size 2 is available). Hence, value of **Frag** for indices 1-2 = 0.9 (using formula in (13)).

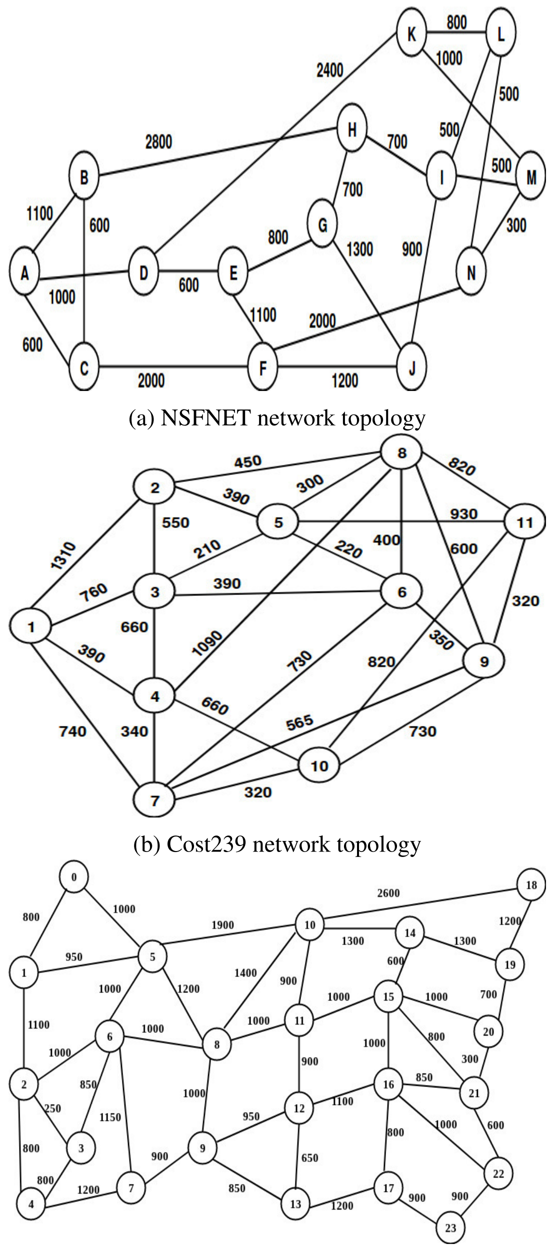
Similarly, fragmentation ratio caused due to second gap (calculated as **Frag** for indices 19-20) = 1.43. Since, 0.9 < 1.43, the first gap is chosen for allocating the spectrum, which also satisfies the first fit approach.

The complexity of the selection of slots in FMDE-RSCA is the same as that of CMDE-RSCA i.e., $O(|V| + |E|)$.

• Worst case complexity of FMDE-RSCA considering the phases of path selection, core selection, and selection of eligible slots is computed as $O(|V|*|E|)$ which is polynomial in nature.

TABLE 3. Simulation environment.

Parameters	*Values*
Request load (in erlangs)	25-500
Number of cores in each fiber	7
Subcarrier capacity of each link in each core (z)	320
Traffic demand, B (in Gbps)	50-500
Protection ratio (q)	0.5-1.0
Threshold Crosstalk (XT_{th})	-16dB
Guardband subcarrier	2 FS



(a) NSFNET network topology

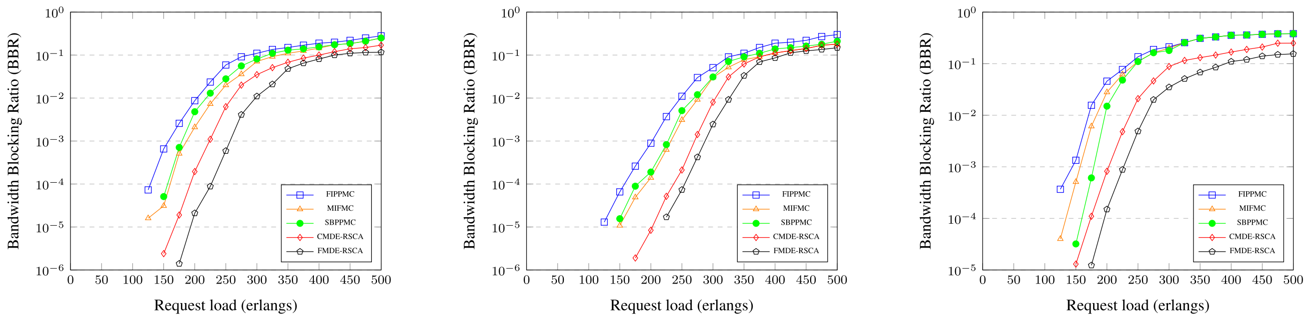
(b) Cost239 network topology

(c) USA network topology

FIGURE 5. Network topologies.

VI. SIMULATION RESULTS AND COMPARATIVE STUDY

This section presents the simulation experiments to assess the efficacy of the proposed algorithms. The connection requests arrive randomly following Poisson's distribution with an



(a) USA network (b) Cost239 Network (c) NSFNET

FIGURE 6. Variation of Bandwidth Blocking Ratio (BBR) with request load.

average arrival rate of λ, and the holding time is exponentially distributed with mean $1/\mu$ in the network. The execution of these algorithms is repeated 20 times, and a confidence level of 95% is adopted. The simulation setup is shown in Table 3.

In this paper, two new RSCA algorithms have been proposed based on distance-adaptive multipath survivable scheme with two different objectives. CMDE-RSCA aims at reducing the inter-core crosstalk among all established connections. On the other hand, the objective of FMDE-RSCA is to reduce fragmentation of paths as much as possible, which in turn helps reduce the blocking of requests. The crosstalk measured should be below an achievable threshold value XT_{th} [3], [5] for both CMDE-RSCA and FMDE-RSCA.

Three well-known network topologies such as USA topology [5] with 24 nodes and 43 links, Cost239 network topology [32] with 11 nodes and 26 links and NSFNET network topology [5] with 14 nodes and 22 links are used for simulation in this work where the distance between each node pair is measured in km (shown in Fig. 5).

Both CMDE-RSCA and FMDE-RSCA are compared with FIPPMC, SBPPMC, and MIFMC algorithms proposed by Oliveira *et al.* [5] in terms of Bandwidth Blocking Ratio (BBR), total energy consumption in the network, fragmentation ratio and crosstalk per slot ratio. BBR is defined as the ratio of total blocked traffic demand to total traffic demanded by all the incoming connections. Energy consumption in the network is calculated as the summation of the powers consumed by various network elements like transponders, amplifiers, and cross-connect switches. Crosstalk per slot is defined as the mean ratio of the slots being affected by crosstalk to the total number of slots used in the link [5]. Fragmentation ratio is defined as the ratio of the number of unused slots to total number of slots present in the links.

A. VARIATION OF BANDWIDTH BLOCKING RATIO (BBR) WITH REQUEST LOAD

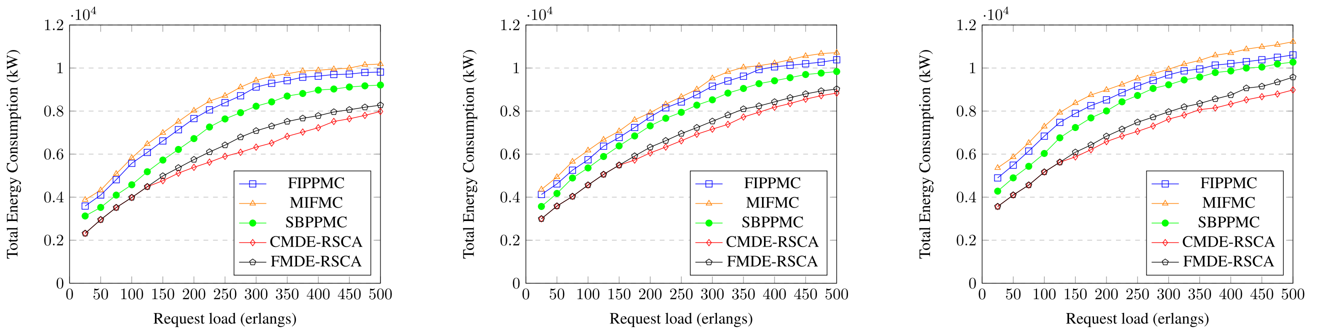
Fig. 6(a), Fig. 6(b) and Fig. 6(c) shows the variation of BBR against request size (in erlangs) for FMDE-RSCA, CMDE-RSCA, FIPPMC, MIFMC and SBPPMC [5] for USA net, COST 239 and NSF net respectively. As usual, BBR for each approach increases with request load. FMDE-RSCA and CMDE-RSCA show better results compared to the other three schemes, whereas BBR for a particular request load is minimum for FMDE-RSCA among all the schemes. Both FMDE-RSCA and CMDE-RSCA are multipath based RSCA schemes which use a suitable core classification technique that reduces fragmentation of paths to a great extent [21]. They not only divide traffic among multiple paths but also divide the traffic in each path among multiple cores. As a result, the blocked number of requests for FMDE-RSCA and CMDE-RSCA is much lesser in comparison with that obtained for the other three existing algorithms for any particular request load irrespective of graph connectivity. FMDE-RSCA allocates spectrum in the gap, which, if allocated, generates the least fragmentation in the selected core of the path whereas CMDE-RSCA allocates spectrum in the gap which, if allocated results to minimization of inter-core crosstalk. This leads FMDE-RSCA to provide better results in comparison with CMDE-RSCA for all three networks.

Among other existing survivable approaches, MIFMC and FIPPMC both are based on p-cycle survivability, and SBPPMC is based on shared path one. All of them show higher bandwidth blocking in comparison with our approaches FMDE-RSCA and CMDE-RSCA, which use multipath based survivability. All three schemes MIFMC, FIPPMC, and SBPPMC, follow the same pattern of variation as observed in [5] considering the node connectivity for all three networks.

This is also to mention that our algorithm FMDE-RSCA shows 18.3%/ (10.62%) improvement in BBR using USA net/ (Cost239) in comparison with MIFMC (the best performing one among three MIFMC, FIPPMC, and SBPPMC) at high request load 450 Erlang. In NSFNET, this improvement is 29.24% over SBPPMC (the best performing one among the three) at high request load 500 Erlang. At other request loads, the improvement in BBR is more than that mentioned above.

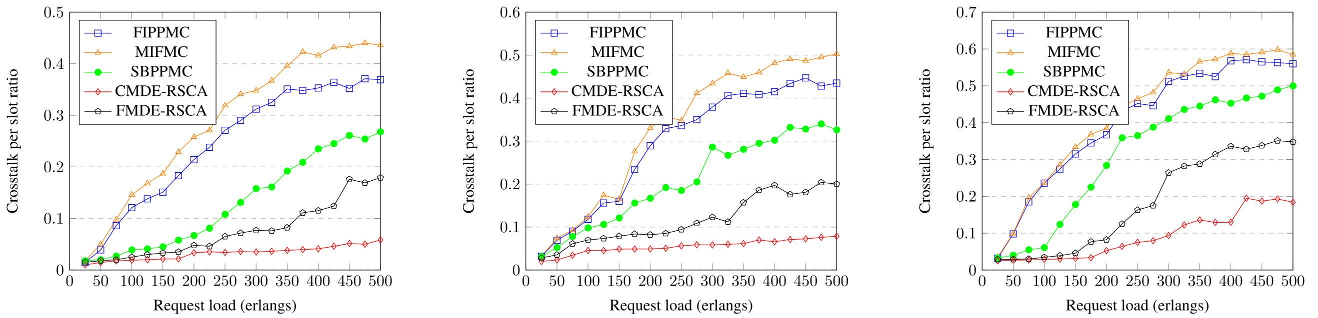
B. VARIATION OF TOTAL ENERGY CONSUMPTION WITH REQUEST LOAD

Fig. 7(a), Fig. 7(b) and Fig. 7(c) illustrate the variation of total energy consumption against request size (in erlangs) of FMDE-RSCA, CMDE-RSCA, FIPPMC, MIFMC and SBPPMC [5] for USA net, COST 239 and NSF net respectively. As usual, energy consumption for each approach increases with the request load. CMDE-RSCA and FMDE-RSCA both perform better than other existing three approaches due to the following two reasons. (i) Our proposed RSCA algorithms use energy consumption



(a) USA Network (b) Cost239 Network (c) NSFNET

FIGURE 7. Variation of Total Energy Consumption (kW) with request load.



(a) USA Network (b) Cost239 Network (c) NSFNET

FIGURE 8. Variation of Crosstalk per slot ratio with request load.

model to minimize energy consumption in the network. (ii) Multipath based survivability scheme leads to place lesser number of subcarriers in SDM-EON compared to p-cycle and shared path based protection schemes, which in turn reduce energy consumption again. In between the two, we already observed the presence of higher bandwidth blocking in the case of CMDE-RSCA compared to that in FMDE-RSCA in Fig. 5, which justifies the lesser energy consumption by CMDE-RSCA than that by FMDE-RSCA.

Moreover, FIPPMC, MIFMC, and SBPPMC [5] do not apply any energy consumption model to select paths consuming the least energy. Due to the formation of large cycles, resource requirement is more in the case of FIPPMC and MIFMC compared to SBPPMC in all three networks. The same type of variation of energy consumption with request load has been observed in this work for FIPPMC, MIFMC, and SBPPMC, as shown in [5].

This is also to note that our algorithm CMDE-RSCA uses 13.31%/ (12.58%)/ (10.18%) less energy using USA net/ (NSFNET)/ (Cost239) in comparison with SBPPMC (the best performing one among three MIFMC, FIPPMC and SBPPMC) at request load 500 Erlang. At any other request load, the energy consumption is found to be lesser than that mentioned above in each case. Also, as more the connections get blocked, lesser is the total energy consumption.

C. VARIATION OF CROSSTALK PER SLOT RATIO WITH REQUEST LOAD

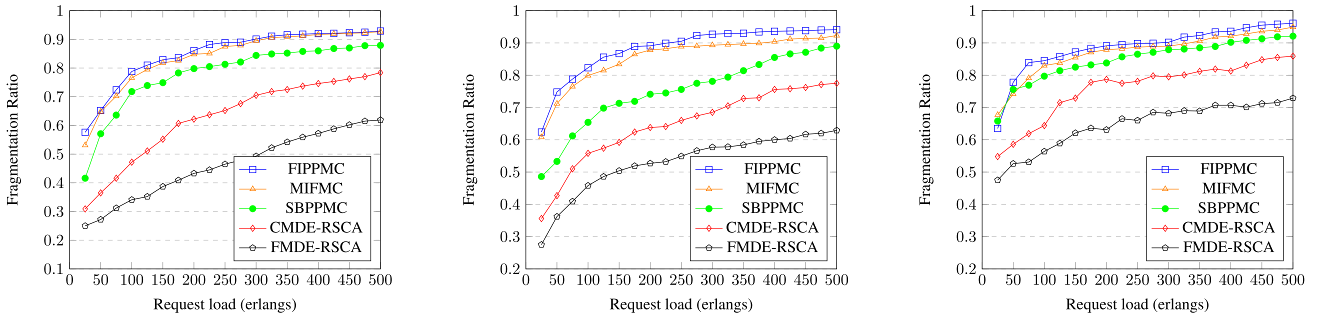
Fig. 8(a), Fig. 8(b) and Fig. 8(c) shows the variation of crosstalk per slot ratio with request load (in erlangs) for USA net, COST239, and NSF net, respectively. As obvious, crosstalk per slot for each approach increases with request load. In this case, also CMDE-RSCA and FMDE-RSCA are performing much better than others due to multipath based survivability approach. CMDE-RSCA provides better results compared to FMDE-RSCA because of its motivation towards maintaining the least crosstalk level below some threshold value.

FIPPMC, MIFMC and SBPPMC [5] shows the same pattern of variation in this work as observed in [5].

This is also to note that our algorithm CMDE-RSCA produces 27.5%/ (23.08%)/ (36.5%) less inter-core cross-talk using USA net / (NSFNET)/ (Cost239) in comparison with SBPPMC (the best performing one among three MIFMC, FIPPMC and SBPPMC) at request load 50/ (25)/ (25) Erlangs. At any other request load, crosstalk generated is observed to be lesser than that mentioned above.

D. VARIATION OF FRAGMENTATION RATIO WITH REQUEST LOAD

Fig. 9(a), Fig. 9(b) and Fig. 9(c) shows the variation of fragmentation ratio against request size (in erlangs) of FMDE-RSCA, CMDE-RSCA, FIPPMC, MIFMC and SBPPMC [5] for all three networks. As obvious, the fragmentation ratio for each approach increases with the request load. Application of multipath based survivability in FMDE-RSCA and CMDE-RSCA helps produce far better results in terms of fragmentation ratio than that obtained from FIPPMC, MIFMC, and SBPPMC schemes. FMDE-RSCA, being motivated to minimize fragmentation ratio, generates



(a) USA Network (b) Cost239 Network (c) NSFNET

FIGURE 9. Variation of Fragmentation Ratio with request load.

the best result, whereas CMDE-RSCA follows it. The same type of variation with request load is noted for FIPPMC, MIFMC, and SBPPMC algorithms in this work as in [5].

This is also to note that our algorithm FMDE-RSCA produces 29.58%/ (20.47%)/ (26.12%) less fragmentation using USA net/ (NSFNET)/ (Cost239) in comparison with SBPPMC (the best performing one among three MIFMC, FIPPMC and SBPPMC) at high request load 500/ (375)/ (300) Erlangs. At any other request load, fragmentation level is observed to be lesser than that mentioned above in each case.

VII. CONCLUSION

Rapid growth in data traffic worldwide in recent days is responsible for increasing energy consumption in Space Division based Multi-core Elastic Optical Network (SDM-EON), which is considered as the backbone technology in computer networks. Because of the huge data-carrying capacity of SDM-EON, the survivability of SDM-EON also becomes a crucial issue due to the massive loss of data even if a single link/node fails. In a dynamic scenario, multipath based survivable EON reduces blocking of connections compared to shared path [12] or p-cycle based survivable EONs. In the multipath protection scheme, traffic data is divided into small fragments that propagate though link-disjoint paths, thereby reducing spectral fragmentation [12] and bandwidth blocking ratio to a large extent.

Inter-core crosstalk and fragmentation within the core are two major issues associated with routing, spectrum, and core assignment (RSCA) for dynamic traffic in SDM-EON. Our work proposes two energy-efficient multipath based survivable RSCA heuristics in SDM-EON against single link failure to combat two issues- inter-core crosstalk and fragmentation. The heuristics show a significant reduction in power consumption when compared with other existing survivability schemes based on p-cycles and shared path ones.

We propose here two energy-efficient multipath based survivability schemes: CMDE-RSCA and FMDE-RSCA with the objectives to minimize crosstalk among multiple cores and fragmentation (considering inter-core crosstalk as well) within the core itself respectively. These two schemes are compared with existing survivability approaches based on p-cycles and shared path, which shows clear superiority of our approaches in terms of energy efficiency and bandwidth blocking. Larger the reduction in bandwidth blocking ratio more is the allocation of connections. As spectrum allocation increases with an increase in the number of connections, usage of network elements also increases, which in turn increases total power consumption. Thus there exists a trade-off between bandwidth blocking ratio and network power consumption. In addition, CMDE-RSCA/ (FMDE-RSCA) reduces most of the crosstalk among multiple cores/ (fragmentation within the core itself while limiting inter-core crosstalk below the threshold level) in comparison with those approaches. In between these two approaches, CMDE-RSCA leads to consume lesser energy, whereas FMDE-RSCA blocks a lesser amount of bandwidth.

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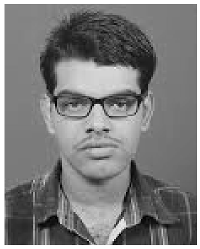

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