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# Core Arrangement based Spectrum-Efficient Path Selection in Core-Continuity Constrained SS-FONs

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**Abstract.** In this work, we exploit the spatial dimension of spectrally-spatially flexible optical networks (SS-FONs) to perform path selection. The existing path selection schemes in SS-FONs predominantly use  $k$ -shortest paths (KSP) method. However, in this work, we demonstrate that in SS-FONs, consideration of core selection along with link selection between source and destination nodes can significantly increase the spectrum utilization efficiency. We propose a  $k$ -core arrangement based paths (KCAP) scheme that performs path calculation and prioritization on the basis of core arrangement in different multicore fiber (MCF) structures, threshold crosstalk (XT) values, distance adaptive modulation (DAM), and the number of MCF links. The proposed KCAP achieves better spectrum utilization than the existing XT-aware and predefined core-prioritization schemes.

## 1 Introduction

The introduction of elastic optical network (EON) [1] brought flexibility in the spectral domain, which significantly increased the spectrum efficiency of optical networks. The main enabling technologies of EON are distance adaptive modulation (DAM), bit-rate adaptive transceivers, flexible spectrum grids, and multicarrier transmission techniques. EON has been accepted as a promising solution to satisfy the ever-increasing bandwidth demands in near-future. EON requires technology migration only at the nodes, while utilizing the existing fiber infrastructure. However, it is predicted that the bandwidth supported by the existing single-core fiber (SCF)/ single-mode fiber (SMF) technology will soon fall short to satisfy the future bandwidth intensive applications in the 5G and beyond era [2–7]. Thus, with a view to further increase the optical network capacity, spectrally-spatially flexible optical networks (SS-FONs) (also known as space division multiplexed (SDM)-EONs) have been researched in the recent past. The SS-FONs expand the capacity of optical networks in the spatial domain (along with the spectral domain flexibility of EON) through multi-core and/or multi-mode fibers (MCF/MMF) [6]. This work is focussed on MCF SS-FONs.

The routing, spectrum, core and/or mode assignment (RSCMA) problem in SS-FONs is subdivided in to the routing (R), and spectrum, core and/or mode assignment (SCMA) sub-problems [2–7]. Various schemes have been proposed in the literature in recent past for SCMA to improve spectrum utilization and manage crosstalk (XT) levels in SS-FONs. However, for the routing sub-problem,  $k$ -shortest paths (KSP) routing has been predominantly used [2–7] in SS-FONs. To perform RSCMA, paths are first calculated and

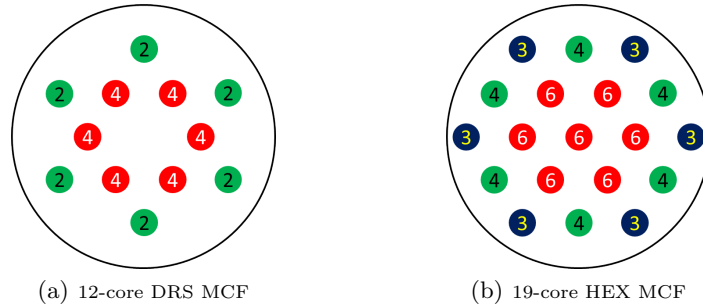


Fig. 1: Core grouping in MCFs on the basis of number of surrounding cores: (a) Two core groups with  $\alpha = 4$ , and  $\alpha = 2$ , shown by red, and green color, respectively; (b) Three core groups with  $\alpha = 6$ ,  $\alpha = 4$ , and  $\alpha = 3$ , shown by red, green, and blue color, respectively.

prioritized (on the basis of KSP) offline for different node-pairs in an optical network topology, and then SCMA is done on the calculated routes. In SCF/SMF optical networks, routing deals with the selection of fiber links to be used from source  $s$  to destination  $d$  nodes in a network. However, in SS-FONs, the added dimension (i.e., spatial dimension) can significantly affect the spectrum utilization efficiency of path selection schemes. In this work, for the first time, we exploit the spatial dimension of SS-FONs for path selection and prioritization.

In different MCF structures [2–8], multiple cores are arranged in different pattern. Fig. 1 above shows the core arrangement in a 12-core dual ring structure (DRS) MCF, and a 19-core hexagonal (HEX) MCF structure. A lightpath traveling between  $s$  to  $d$  in an SS-FON may be routed through any of the cores in MCF. Further, using fully non-blocking reconfigurable optical add/drop multiplexers (FNB-ROADMs) [9], lightpaths may switch cores at intermediate nodes. Thus, in SS-FONs, routing is not limited to the selection of only links between the  $s$ - $d$  pair, rather it is two-dimensional, where selection of both links and cores is to be performed to define the end-to-end path between an  $s$ - $d$  pair of nodes. Thus, in this work, we propose a  $k$ -core arrangement based paths (KCAP) scheme that calculates and prioritizes paths in terms of both links and cores on the basis of core arrangement, DAM, threshold XT levels, and number of links between  $s$ - $d$  pairs in an SS-FON.

FNB-ROADMs require enormous node complexity and very high CAPEX, hence core-continuity constrained (CCC) SS-FONs (where core switching is not possible at intermediate nodes) have been proposed in the literature [9] as a solution to satisfy the increasing bandwidth demands in short- and mid-term future. Thus, in this work, we consider CCC SS-FONs. In an SCF optical network, if  $P$  number of possible paths exist between an  $s$ - $d$  pair, the number of possible paths between that  $s$  –  $d$  pair in an  $n$ -core CCC SS-FON will be  $n \cdot P$  (one possible path through each core). In the existing RSCMA approaches, core selection is performed under SCMA sub-problem, however, in this work we show that consideration of core selection while calculating paths can significantly improve the spectrum utilization.

*Related work:* Inter-core XT in SS-FONs is a major consideration to perform RSCMA. The existing RSCMA approaches ensure acceptable threshold XT levels through various SCMA schemes [2–7], and do not consider XT values during route calculation. Hence, we review the existing schemes used to manage XT levels in SS-FONs. In [10], an overview

of existing XT estimation methods is given. A frequently used method to ensure acceptable XT levels performs worst case (WC)-XT calculations, where the maximum possible XT that can occur in any core of an MCF is calculated offline. Based on the WC-XT calculations for different modulation formats (MFs) and  $s$ - $d$  pairs, SCMA is done. A straightforward approach to ensure acceptable XT levels is XT-avoid [11], where allocation of same frequency slot (FS) in any two adjacent cores in an MCF is avoided, thereby resulting in no XT amongst cores. Another approach to manage acceptable XT levels in SS-FONs is strict-XT [10,11], which require complex calculations for strict XT level check of all the existing lightpaths on the arrival of every new lightpath demand.

Both the WC-XT and XT-avoid methods are proactive approaches to deal with XT as they do not require any complex calculation depending on the dynamic changes in spectrum usage in different cores. The XT-avoid approach is highly spectrum inefficient as it leads to a large number of unused FSs in SS-FONs due to XT avoidance criteria [11]. However, the WC-XT approach has higher spectrum utilization efficiency as compared to XT-avoid method since WC-XT allows spectrum overlapping between adjacent cores considering acceptable XT levels. Hence, we consider WC-XT with KSP (referred to as KSP-WC-XT) as one of the benchmark schemes to compare its spectrum utilization efficiency with the proposed KCAP.

As we exploit the spatial flexibility and core arrangement in the proposed KCAP, we study another benchmark scheme (referred to as KSP-WC-XT-CP) that performs core-prioritization (CP). Fig. 1 shows the number of surrounding cores  $\alpha$  for each core in the 12-core DRS MCF and the 19-core HEX MCF. As the XT value in a core depends on the number of surrounding cores [6, 10, 11], a predefined CP approach can enhance spectrum utilization while ensuring acceptable XT levels. In [2], a CP scheme has been proposed for spectrum allocation (SA) in SS-FONs, where non-adjacent cores with low  $\alpha$  have been preferred first to allocate spectrum. However, as spectrum gets allocated in all the cores with increasing network load, effects of XT will be observed due to all surrounding cores, thereby making it difficult to allocate future lightpath demands with acceptable XT levels and/or efficient MFs. We apply a similar CP scheme for path selection in KSP-WC-XT-CP, where the cores with minimum  $\alpha$  are preferred first for path prioritization. The proposed KCAP scheme is detailed in Section II with a comparative description with the benchmark KSP-WC-XT and KSP-WC-XT-CP schemes. It should be noted that all the three schemes, i.e., KSP-WC-XT, KSP-WC-XT-CP, and the proposed KCAP are the proactive schemes that do not require complex dynamic XT calculations depending on the spectrum information.

*Notations:* Let  $Z$  be the set of lightpath demands, with index  $z$ , in a given SS-FON mesh connected network graph  $G(V, W, C, P)$ , where  $V$  is the set of nodes, with index  $v$ ,  $W$  is the set of fiber links present in a network, with index  $w$ ,  $C$  is the set of cores available per fiber link, with index  $c$ , and  $P$  is the set of link distances, with index  $p$ . A lightpath request is denoted by  $Z\{s_z, d_z, r_z\}$ , where  $s_z$ , and  $d_z$  are the source and destination nodes, respectively, of request  $z$ , and  $r_z$  is the bitrate required by request  $z$ . Let  $I$  be the set of all possible paths between all  $s - d$  pairs in a network, with index  $i$ . The FS granularity, and the number of guard slots per lightpath are denoted by  $\Delta f$ , and  $N_g$ , respectively. Let  $M$  (b/s/Hz) denotes the modulation spectral efficiency.

## 2 Proposed: $k$ -core arrangement based paths (KCAP)

The proposed KCAP leverages spatial flexibility of SS-FONs along with spectral flexibility (i.e., DAM and bit-rate adaptive SA) for path calculation and prioritization while ensuring acceptable XT levels of paths. In the proposed KCAP, core grouping is performed on the basis of the number of surrounding cores ( $\alpha$ ) for each core in an MCF. Cores with the same  $\alpha$  are grouped in one core group  $G_i$ . For example, in Fig. 1(a), the 12 cores can be categorized into two core groups;  $G_1$ : consisting of the six cores of outer ring with  $\alpha = 2$ , and  $G_2$ : consisting of the six cores of inner ring with  $\alpha = 4$ . Similarly, the cores of 19-core HEX MCF, shown in Fig. 1(b), can be categorized into three core groups,  $G_1$  (consisting of six cores with  $\alpha = 3$ ),  $G_2$  (consisting of six cores with  $\alpha = 4$ ), and  $G_3$  (consisting of seven cores with  $\alpha = 6$ ).

In the analytical model based on coupled-power theory [6,10,11], the mean XT ( $XT_\mu$ ) value in an MCF is given by

$$XT_\mu = \frac{\alpha - \alpha \exp(-(\alpha + 1) \cdot h \cdot L)}{1 + \alpha \exp(-(\alpha + 1) \cdot h \cdot L)}, \quad (1)$$

where,  $L$  is the length of MCF, and  $h$  is a constant, which is calculated as

$$h = \frac{2 \cdot \kappa^2 \cdot R}{\beta \cdot \Lambda}, \quad (2)$$

where,  $\kappa$  is the coupling-coefficient,  $R$  is the bending radius,  $\beta$  is the propagation constant, and  $\Lambda$  is the core pitch. To determine the transmission reach with acceptable XT levels given the value of threshold XT ( $XT_{th}$ ), (1) can be rewritten as

$$L = \frac{1}{(\alpha + 1) \cdot h} \ln \left( \frac{\alpha(1 + XT_\mu)}{\alpha - XT_\mu} \right). \quad (3)$$

Substituting the typical values of  $XT_{th}$  [10] for binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-quadrature amplitude modulation (8QAM), and 16QAM modulation schemes in (3), we calculate the transmission reach  $L$  for different core groups in 12-core DRS MCF and 19-core HEX MCF, as shown in Table I. For BPSK, QPSK, 8QAM, and 16QAM MFs,  $M = 1$ ,  $M = 2$ ,  $M = 3$ , and  $M = 4$ , respectively. The value of  $h$  in (3) is calculated using (2) by substituting the MCF-specific values [10] specified in Table V.

It can be observed from Table I that for different core groups, the value of  $L$  is different. Using DAM, the shortest physical path is preferred for lightpath establishment since it offers highest possible MF, thereby increasing spectrum efficiency. However, from Table I, it can be observed that a lightpath of same physical distance, if routed through different cores in an MCF will result in selection of different MFs. Hence, the KSP scheme, where paths are calculated and prioritized on the basis on increasing physical lengths, will not be suitable for efficient spectrum utilization in SS-FONs.

In WC-XT method, the maximum possible XT value (i.e., the worst case transmission reach  $L_{wc}$ ) in an MCF is considered. Hence, for 12-core DRS MCF,  $L_{wc} = L(G_2)$ , and for 19-core HEX MCF  $L_{wc} = L(G_3)$ , as shown in Table I. Using, DAM and bit-rate adaptive SA, the number of FS  $N_i^w$  required on each  $w \in |W(i)|$  is given by (4) for a lightpath demand  $z$  with required bit rate  $b_z$  (in Gbps) [12]. Here,  $|W(i)|$  is the subset of links in path  $i \in I$ . Highest supported  $M$  is chosen according to the physical distance of the chosen path.

Table 1: Transmission reach  $L$  (km) for different core groups in 12-core DRS MCF and 19-core HEX MCF

MCF-type		BPSK	QPSK	8QAM	16QAM
	$XT_{th}$ (dB)	-21.7	-26.2	-28.7	-32.7
12-core	$L(G_1)$	3347.74	1189.11	668.86	266.33
DRS MCF	$L(G_2) = L_{wc}$	1672.45	594.38	334.37	133.16
19-core	$L(G_1)$	2230.57	792.58	445.86	177.55
HEX	$L(G_2)$	1672.45	594.38	334.37	133.16
MCF	$L(G_3) = L_{wc}$	1114.66	396.21	222.9	88.77

$$N_i^w = \left\lceil \frac{b_z}{\Delta f \cdot M} \right\rceil + N_g \quad (4)$$

The number of FS required in the network ( $N_i^n$ ) for different paths  $i \in I$  can be obtained as the product of  $N_i^w$  and the number of links used in the  $i^{th}$  path [13],

$$N_i^n = N_i^w \cdot |W(i)|. \quad (5)$$

Consider the network topology shown in Fig. 2. The value of  $N_i^n$  for a lightpath demand of  $b_z = 150$  Gbps between F-G and R-W node pairs is calculated in Table II-IV considering  $k = 4$  paths and 12-core DRS MCF for the benchmark KSP-WC-XT and KSP-WC-XT-CP schemes, and the proposed KCAP scheme. In Table II, highest possible MF has been selected as per  $L_{wc}$  such that the path length does not exceed  $L_{wc}$  for the selected MF. The encircled values denote path priority obtained by KSP-WC-XT, where paths are prioritized on the basis on physical fiber lengths. From Table I, it is observed that the path priority obtained results in the increasing order of the value of  $N_i^n$ , which indicates that the path that requires minimum FS in the network has been preferred the most.

However, as we calculate  $N_i^n$  on the basis of core arrangement, i.e., depending on the value of  $\alpha$  for different cores in Table III, it is found that the obtained paths are not in

Table 2: Path calculation and prioritization using KSP-WC-XT scheme

Demand		Path 1	Path 2	Path 3	Path 4
F-G	Path	FG	FDG	FADG	FNG
	Length (km)	289	426	540	618
	MF	8QAM	QPSK	QPSK	BPSK
	$N_i^n$	6 ①	14 ②	20 ③	26 ④
R-W	Path	RUSW	RUYW	RUSPW	RUSPQW
	Length (km)	581	663	687	801
	MF	QPSK	BPSK	BPSK	BPSK
	$N_i^n$	20 ①	38 ②	50 ③	62 ④

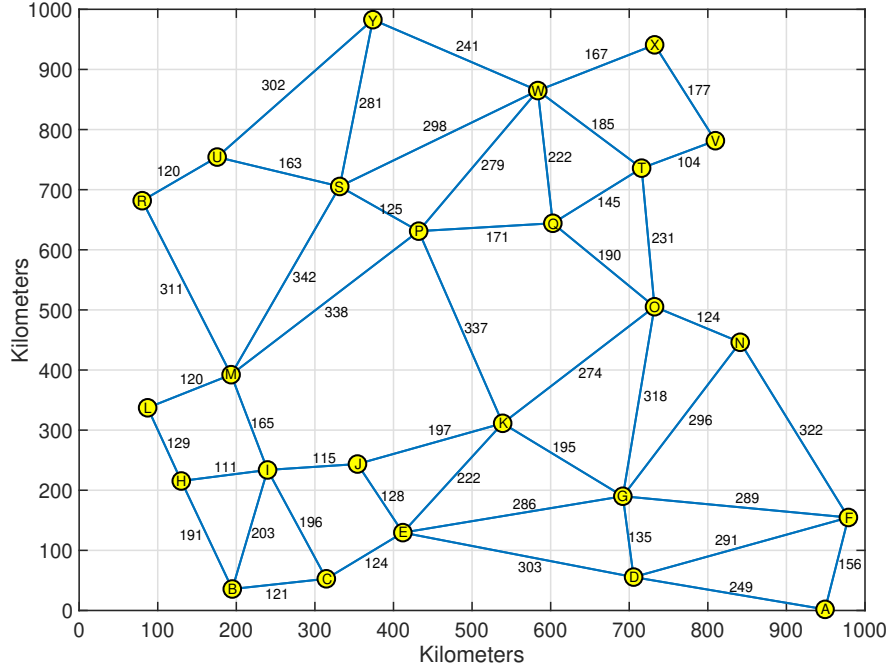


Fig. 2: A 25-node test network topology randomly generated in a 1000 km  $\times$  1000 km area using GG.

the increasing order of  $N_i^n$ . It can be observed that for lightpath establishment through Path 4 using a core with  $\alpha = 2$ , the  $N_i^n$  required is 10, whereas for Path 3,  $N_i^n$  required is 14. Further, it can be observed that for Path 1 (with  $\alpha = 4$ ), the  $N_i^n$  required is 6, and for Path 2 (with  $\alpha = 2$ ), the  $N_i^n$  required is 10. This indicates that preferring the cores with lesser  $\alpha$  for lightpath establishment until they are fully allocated is also not a spectrum-efficient approach. The encircled values denote path prioritization using KSP-WC-XT-CP, where predefined core prioritization on the basis of increasing values of  $\alpha$  has been done for lightpath establishment. From Table III, it can be observed that the paths prioritized using KSP-WC-XT-CP are not in the increasing order of the value of  $N_i^n$ . Thus, in SS-FONs, neither core prioritization, nor shortest path selection results in path prioritization in the increasing order of spectrum consumption (i.e.,  $N_i^n$ ).

The  $N_i^n$  required in SS-FONs depend on the value of  $\alpha$ , the length of fiber, and the number of links between  $s - d$ . Hence, in the proposed KCAP, we perform core grouping on the basis of the value of  $\alpha$ . Offline path calculation based on  $XT_{th}$ , core groups, DAM, and number of fiber links is performed in the proposed KCAP, and  $N_i^n$  is calculated for various possible paths between different  $s - d$  pairs in an SS-FON. The routes are then prioritized on the basis of the increasing values of  $N_i^n$ , as shown in Table IV. The encircled values in Table IV denote path prioritization using the proposed KCAP. It can be observed from Table I that  $G_1$  (having  $\alpha = 2$ ) of 12-core DRS MCF, offers twice the  $L$  as that obtained using  $G_2$ . Alternatively, it can be said that  $G_1$  is more spectrum efficient as it allows the selection of higher MF than  $G_2$  for a particular value of  $L$ . For example, to establish a lightpath of 1000 km in a 12-core DRS MCF SS-FON, QPSK can be used using  $G_1$ , however, BPSK has to be used if the lightpath is established using  $G_2$  since it exceeds  $L$  possible with QPSK using  $G_2$ , as observed from Table I. Hence, in case of a tie between the value of  $N_i^n$  for two paths with different core groups, the proposed KCAP prefers  $G_i$

with higher  $\alpha$  in order to save the spectrum efficient cores for future lightpath demands. In case of a tie between the value of  $N_i^n$  for two paths of different physical length, the path with shorter physical length is preferred in the proposed KCAP.

It is worth noting that the existing RSCMA schemes first obtain the paths, and then XT-estimation, DAM, and CP is performed under the SCMA subproblem for allocating spectrum on the chosen path/s. However, the proposed KCAP calculates the paths on the basis of core arrangement, threshold XT levels, DAM, and number of links used. It may also be noted here that though bit rate  $b_z$  appears in (4), KCAP can find the path preference without the knowledge of bit rate requirements of lightpath demands, and is thus applicable to perform dynamic lightpath provisioning. From (4), it can be seen that for a particular  $s - d$  pair in a given SS-FON with certain MCF structure, the physical distance is constant,  $\alpha$  is constant, and hence  $M$  corresponding to different  $s - d$  pairs and core groups is also constant. FS granularity  $\Delta f$  is also fixed to a typical value of 12.5 or 6.25 GHz. The numbers of guard slots  $N_g$  per lightpath are also constant. The number of links  $|L(i)|$  for a path between any  $s - d$  pair is also constant. Thus, the  $N_i^n$  required in the network by a path  $i \in I$  can be represented as  $N_i^n = \lceil x_i \cdot b_z \rceil$ , where  $x_i$  is constant for any route  $i \in I$ . Hence, route prioritization can be done using the proposed KCAP by sorting routes on the basis of increasing values of  $N_i^n = \lceil x_i \cdot b_z \rceil$  considering any arbitrary value for  $b_z$ .

The proposed KCAP is summarized in the following steps as follows:

**Step 1:** Perform core grouping on the basis of  $\alpha$  in MCF used.

**Step 2:** Calculate  $L$  for different core groups using (2),(3) on the basis of  $XT_{th}$  values corresponding to different MFs.

**Step 3:** Calculate  $N_i^n$  using (4),(5) for different possible paths, and prioritize them on the basis of increasing value of  $N_i^n$ .

### 3 Performance evaluation

In this section, a comparative performance evaluation of the proposed KCAP, and the benchmark KSP-WC-XT and KSP-WC-XT-CP schemes has been done. To perform a

Table 3: Path calculation and prioritization using KSP-WC-XT-CP scheme

Demand		Path 1	Path 2	Path 3	Path 4
F-G	Path	FG	FDG	FADG	FNG
	Length (km)	289	426	540	618
	MF( $\alpha = 2$ )	8QAM	8QAM	8QAM	8QAM
	$N_i^n(\alpha = 2)$	6 ①	10 ②	14 ③	10 ④
	MF( $\alpha = 4$ )	8QAM	QPSK	QPSK	BPSK
	$N_i^n(\alpha = 4)$	6 ⑤	14 ⑥	20 ⑦	26 ⑧
	R-W	Path	RUSW	RUYW	RUSPW
Length (km)		581	663	687	801
MF( $\alpha = 2$ )		8QAM	8QAM	QPSK	QPSK
$N_i^n(\alpha = 2)$		14 ①	14 ②	26 ③	32 ④
MF( $\alpha = 4$ )		QPSK	BPSK	BPSK	BPSK
$N_i^n(\alpha = 4)$		20 ⑤	38 ⑥	50 ⑦	62 ⑧



Table 4: Path calculation and prioritization using the proposed KCAP

Demand		Path 1	Path 2	Path 3	Path 4
F-G	Path	FG	FDG	FADG	FNG
	Length (km)	289	426	540	618
	MF( $G_1$ )	8QAM	8QAM	8QAM	8QAM
	$N_i^n(G_1)$	6 ②	10 ③	14 ⑥	10 ④
	MF( $G_2$ )	8QAM	QPSK	QPSK	BPSK
	$N_i^n(G_2)$	6 ①	14 ⑤	20 ⑦	26 ⑧
R-W	Path	RUSW	RUYW	RUSPW	RUSPQW
	Length (km)	581	663	687	801
	MF( $G_1$ )	8QAM	8QAM	QPSK	QPSK
	$N_i^n(G_1)$	14 ①	14 ②	26 ④	32 ⑥
	MF( $G_2$ )	QPSK	BPSK	BPSK	BPSK
	$N_i^n(G_2)$	20 ③	38 ⑤	50 ⑦	62 ⑧

comprehensive assessment of the proposed KCAP on network topologies of different size and connectivity, we generate random network topologies based on Gabriel graph (GG) [14] instead of few standard network topologies. In this approach, a number of nodes are randomly located in a given geographical area following uniform distribution, and then the nodes are connected through fiber links using GG theory. As per GG theory, any two nodes  $o_1$  and  $o_2$  are connected by a link iff there is no other node lying in a circle obtained with center as the mid-point of the straight line joining  $o_1$  and  $o_2$ , and diameter equal to the length of that straight line. We generate random network topologies, where the number of nodes is varied in each iteration, uniformly selected from the set specified in Table V. Thus, network topologies of varying node/link density, link-lengths and connectivity is obtained in each iteration. The simulation results shown have been averaged over 100 iterations. One such instance of the random network topology for 25 nodes is shown in Fig. 2.

In each iteration, a total of 5000 lightpath demands for 12-core DRS MCF, and 10000 lightpath demands for 19-core HEX MCF, respectively, have been generated uniformly among different node pairs. The lightpaths with heterogeneous data rate requirement (given in Table V) are established incrementally in the randomly generated network topologies. Each link in the network is assumed to be a MCF bidirectional link. For spectrum allocation, first-fit (FF) scheme has been employed in which for each core, all the available frequency slots are indexed, and then spectrum allocation is done starting from the lowest index of frequency slots. Lightpath establishment using all the considered schemes is subject to the spectrum continuity, spectrum contiguity, and non-overlapping spectrum allocation with CCC. Simulation parameters are summarized in Table V.

Performance has been evaluated in terms of spectrum utilization ratio ( $SUR$ ) versus the number of accepted lightpath demands.  $SUR$  is defined as the ratio of the number of FS utilized in the network to the total number of available FS in the network. Thus, a low value of  $SUR$  indicates better spectrum utilization for a certain number of accepted lightpath demands. In the literature [10, 15], modulation selection ratio has been used in SS-FONs for performance evaluation, where selection of higher MFs indicate better

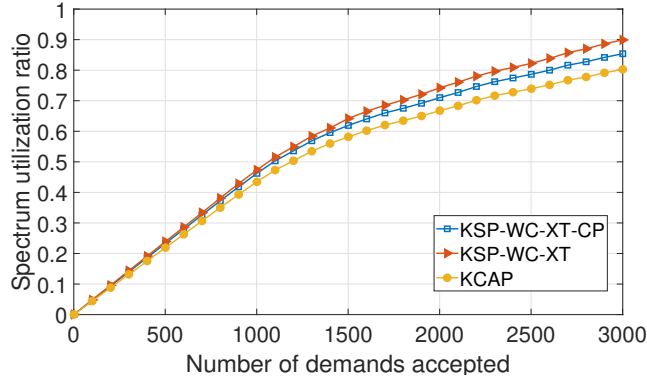


Fig. 3: Spectrum utilization ratio ( $SUR$ ) with increase in the number of accepted lightpath demands in 12-core DRS MCF SS-FON.

spectrum utilization. However, as we observe in Table III-IV, the  $N_i^n$  depends on MF selection as well as core group selection. Hence, establishing lighpaths using high MF initially on cores with less values of  $\alpha$  (such as in KSP-WC-XT-CP) may lead to much lower MF selection for future lightpath demands. To analyze the pattern of MF selection with varying network load, we analyze different path selection schemes on the basis of average modulation spectral efficiency ( $M_{avg}$ ). It is defined as the ratio of the sum of  $M$  of all the accepted lightpath demands to the number of accepted lightpath demands.

Fig. 3 shows the  $SUR$  with increase in the number of accepted lightpath demands. As more and more demands gets established in the network, spectrum consumption in all the cores and links increases. The proposed KCAP performs better than both the benchmark schemes, achieving an average improvement of 7.5%, and 11.55% in  $SUR$  as compared to the KSP-WC-XT-CP, and KSP-WC-XT schemes, respectively. The KSP-WC-XT-CP performs better than the KSP-WC-XT scheme since it considers core arrangement based

Table 5: Simulation parameters

Parameter	Value
Number of lightpath demands for 12-core DRS MCF SS-FON	5000
Number of lightpath demands for 19-core HEX MCF SS-FON	10000
Heterogeneous data rate set	{40, 200, 500, 1000} Gbps
Number of available FS per core	320
FS granularity	12.5 GHz
Geographical area where random network topology is obtained	1000 km $\times$ 1000 km
Set of number of nodes in random network topologies	{20, 30, 40}
$\kappa$	$1.27 \times 10^{-3}$
$\beta$	$4 \times 10^6 m^{-1}$
$R$	50 mm
$\Lambda$	40 $\mu m$

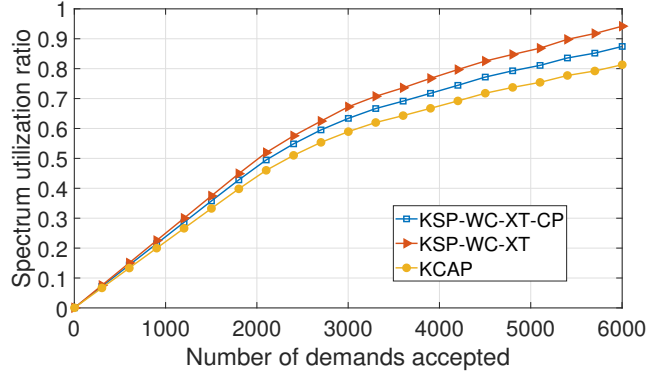


Fig. 4: Spectrum utilization ratio ( $SUR$ ) with increase in the number of accepted lightpath demands in 19-core HEX MCF SS-FON.

CP utilizing the spatial dimension for path calculation and prioritization, whereas KSP-WC-XT does not utilize the core arrangement in MCFs.

In Fig. 4,  $SUR$  for 19-core HEX MCF has been evaluated. The increased number of cores offered acceptance of higher number of lightpath demands in SS-FONs. Further, the number of core groups in 19-core HEX MCF is three, as shown in Fig. 1 and Table I. Thus, core grouping increases the average  $SUR$  improvement of the proposed KCAP to 9.66% and 14.35%, as compared to the KSP-WC-XT-CP, and KSP-WC-XT, respectively, in Fig. 4.

In Fig. 5,  $M_{avg}$  for 12-core DRS MCF at different values of spectrum utilized is shown, which describes the pattern of MF selection by different path selection schemes. At 30% spectrum utilization, the KSP-WC-XT-CP scheme performs better than the KSP-WC-XT and the proposed KCAP in terms of  $M_{avg}$ , indicating higher MF selection. However, with the increase in spectrum utilization,  $M_{avg}$  for KSP-WC-XT-CP decreases, whereas for the proposed KCAP,  $M_{avg}$  increases slightly. This is because in KSP-WC-XT-CP, the spectrum efficient cores (with low  $\alpha$ ) have been preferred first for lightpath establishment. However, as the spectrum utilization increases, the lightpath establishment using cores with higher  $\alpha$  increases, resulting in low MF selection for future demands.

Fig. 6 shows  $M_{avg}$  for 19-core HEX MCF. The pattern of  $M_{avg}$  using different schemes in 19-core HEX MCF is similar to that observed in 12-core HEX MCF. However, the value of  $M_{avg}$  for all the schemes is lesser in 19-core HEX MCF as compared to that in 12-core DRS MCF. This is due the higher  $\alpha = 6$  for the inner seven cores in the 19-core HEX MCF, which affects  $L$ , and hence MF selection. The value of  $M_{avg}$  for KSP-WC-XT almost remains the same with increase in spectrum utilization for both the 12-core DRS MCF, and 19-core HEX MCF. This is due to the reason that KSP-WC-XT does not prioritize routes on the basis of core arrangement.

As the demands arrive in the network, and the spectrum is utilized beyond 50%, it can be observed that the proposed KCAP performs better than both the KSP-WC-XT-CP and KSP-WC-XT schemes. It is worth noting that higher  $M_{avg}$  for KSP-WC-XT-CP at 30% – 50% spectrum utilization does not indicate a directly proportional relation with spectrum utilization efficiency. This can be observed from the lower values of  $SUR$  for KSP-WC-XT-CP as compared to the proposed KCAP for different number of demands accepted, since  $N_i^n$  depends on the core group selection and the number of links as well along with MF selection.

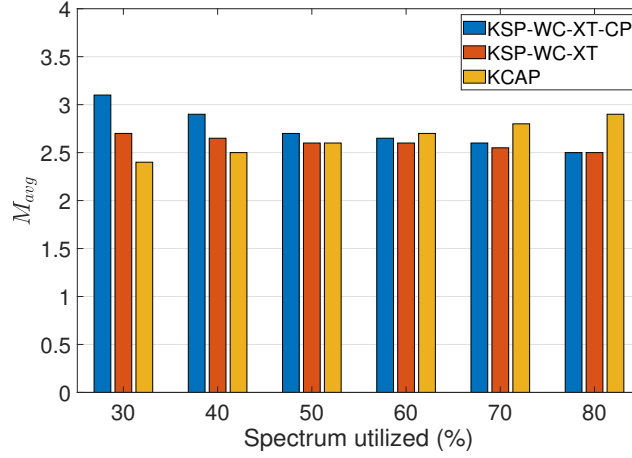


Fig. 5: Average modulation spectral efficiency ( $M_{avg}$ ) with increase in spectrum utilization in 12-core DRS MCF.

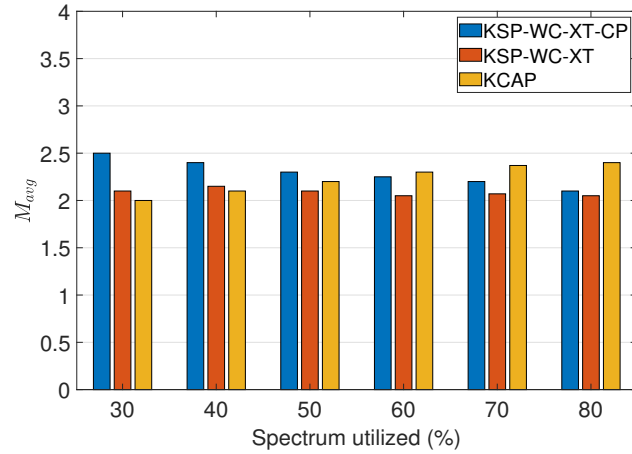


Fig. 6: Average modulation spectral efficiency ( $M_{avg}$ ) with increase in spectrum utilization in 19-core HEX MCF.

## 4 Conclusion

In SS-FONs, consideration of spatial dimension (i.e., core arrangement in MCF) during path selection can significantly improve the spectrum utilization efficiency, as demonstrated in this work. Hence, two-dimensional paths between  $s - d$  pair should be calculated in SS-FONs that specify: (a) the fiber links to be used in the network, and (b) the core to be used in the MCF. The proposed KCAP calculates and prioritizes paths on the basis of core arrangement,  $XT_{th}$ , DAM, and the number of links between  $s - d$  pair. The proposed KCAP performs better than the existing KSP-WC-XT scheme which does not consider core arrangement of MCFs. Furthermore, the proposed KCAP has also been compared with KSP-WC-XT-CP scheme that utilizes the core arrangement to perform core prioritization on the basis of  $\alpha$ . The proposed KCAP achieves an average improvement of up to 9.66%, and 14.35% in *SUR* as compared to the KSP-WC-XT-CP, and KSP-WC-XT schemes, respectively. In future, we plan to show the effects of core arrangement based path selection for short-reach and intra-datacenter applications with CCC relaxation.

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