The RBCMLSA Problem on EONs with Flexible Transceivers

Der-Rong Din
Computer Science & Information Engineering
National Changhua University of Education
Changhua City, Taiwan, R. O. C.
deron@cc.ncue.edu.tw

Meng-Xun Zhan
Computer Science & Information Engineering
National Changhua University of Education
Changhua City, Taiwan, R. O. C
moncky2000@gmail.com

***Abstract*—Benefiting from the development of coherent detection and digital signal processing, innovative optical transceivers enable the dynamic adaptation of the baud rate, modulation level and Forward Error Correction (FEC) coding to the optical transmission properties. Next generation optical networks will require high levels of flexibility, being able to fit rate, bandwidth, FEC coding and optical reach requirements of different connections. For serving transmission on an Elastic Optical Network (EON), the flexible lightpath routing and the spectrum allocated for the connection request should be developed to meet the traffic requirement. In this paper, the Routing, Baud rate, FEC Coding, Modulation Level, Spectrum Allocation (RBCMLSA) problem is defined and studied. A heuristic algorithm, which integrates single/multiple path routing schemes, is proposed. The proposed algorithm is examined through simulations and the results show that the proposed algorithms can achieve good results.**

Keywords-routing; baud rate; FEC code; modulation level; spectrum allocation (RBCMLSA); flexible transceiver; elastic optical network (EON).

I. INTRODUCTION

Recently, the *Elastic Optical Network* (EON) has attracted intensive research because of employing *Optical-Orthogonal Frequency Division Multiplexing* (O-OFDM) technology, which has been used to scale the demands by efficiently utilizing the spectrum. A key feature of EON is that the modulation format and the spectrum can be adaptively adjusted and allocated according to the distance and capacity requirements [1] [2]. Based on variable bandwidth devices (such as Bandwidth-Variable Transponders (BVTs) and Bandwidth-Variable Wavelength Cross-Connects (BV-WXCs)), EONs require more sophisticated bandwidth allocation mechanisms. The spectrum of a fiber on an EON is divided into *Frequency Slots* (FSs) and the necessary amount of consecutive FSs are assigned to support the connection request [1] [2]. The number of required FSs is determined by the requested bandwidth, the modulation format, the (fixed) slice width and the Guard Band (GB) introduced to separate two spectrum adjacent connections, among others. The controller should find Routing, Modulation Level and Spectrum Assignment (RMLSA) for the connection request.

In EONs, the transmitting rate of the transmitter ranges from 2.5 Gb/s to 400 Gb/s. Benefiting from the development of coherent detection and digital signal processing, innovative optical transceivers enables the dynamic adaptation of the baud rate, modulation level and Forward Error Correction (FEC) coding to the optical transmission properties.

Sambo et al. [3] proposed a programmable controller on the Software Definition Network (SDN)-EONs. Several parameters (such as channel types, number of carries, transmitting rate, modulation format, central frequency, channel wide, FEC types, and number of FSs) can be dynamically determined to meet the connection request on the network. Cugini et al. [4] proposed the idea of the plug and play auto-configuring transmitters of the optical network. In the proposed environment, the control plane should be capable of performing effective routing and spectrum assignment as well as proper selection of the transmission parameters (e.g., baud rate, modulation format, coding type) depending on the required *Transmission Reach* (TR) or maximum transmission distance.

A. Multipath Routing

For online provisioning, it is difficult to serve certain large *bandwidth* (BW) requests with single-path routing due to the BW or TR limitation. Thus, it results in high request blocking probability [17] [18]. Lu et al. [18] suggested that a connection's traffic could be split over multiple paths without causing significant bandwidth waste. They proposed a dynamic multi-path algorithm, which considers the differential delay constraint. Zhu et al. [17] proposed two dynamic algorithms that incorporate a Hybrid Single-/Multi-path Routing (HSMR) scheme on the RMLSA model (denoted as RMLSA-HSMR). They considered dynamic RMLSA problem with various path selection policies for multipath provisioning in EONs [17]. The simulating results showed that the proposed hybrid single-/multi-path routing scheme could effectively reduce the blocking probability, by comparing to the single-path routing scheme.

B. Studied Problem

In the future, the next generation optical networks will require high levels of flexibility. Based on the new provided capabilities of the transponders, the controller will be able to adjust baud rate, bandwidth, FEC coding, modulation format and optical reach requirements of different connections. In this paper, the dynamic routing problem on EONs with flexible transceivers is studied. In the given EONs, the parameters of transceivers (including baud rate, modulation format, and FEC type) can be determined and selected by the

 ISBN: 978-1-61208-650-7

network controllers. For a given EON and a sequence of connection requests, the goal is to find lightpaths and assigned suitable channels to lightpaths and meet the traffic and TR requirement such that the performance measure can be optimized. Since for each request, the baud rate, modulation format, and FEC type should be determined and find suitable spectrum, this problem is denoted as the **Routing, Baud rate, Code, Modulation Level, and Spectrum Allocation (RBCMLSA) problem**. Unlike previous works in RCMLSA and RMLSA, the proposed algorithm selects not only the route and the spectrum but also the baud rate, FEC type, and modulation format best suited to establish an optical connection.

In the paper, the hybrid single-/multi-path routing scheme is considered. The blocking performance of the proposed algorithm is evaluated in comparison to the RCMLSA and RMLSA approaches. Based on the survey, there is no article that considered the RBCMLSA problem with flexible transceivers for multipath routing. In this paper, a heuristic algorithm is proposed to solve the RBCMLSA problem with dynamic traffic. The proposed algorithm is examined through simulations and the results show that the proposed algorithm can achieve good results.

The remainder of this paper is as follows: Section 2 describes the related works; Section 3 defines the new RBCMLSA problem; Section 4 presents the details of the proposed algorithm; Section 5 gives performance evaluation by means of simulation; Section 6 concludes the paper.

II. RELATED WORKS

In this section, several studies related to the RBCMLSA problem will be stated.

A. FEC

In an optical network, the Optical Signal to Noise Ratio (OSNR) of a high data rate optical signal would degrade significantly over long transmission distances. This degradation can be compensated by using the FEC coding techniques [5]. FEC technologies were first proposed for fiber-optic communications, before signal modulation and transmission. In FEC coding, redundant *overhead* (OH) bits are added to the information bits [6]. FEC techniques with different error correcting capabilities were studied to evaluate both the performance of different FEC types and corresponding tradeoffs between their Net Coding Gains (NCGs) and their coding overheads. The future trends expected for FECs to combat even higher transmission impairments were presented in [7]. The evolution of FEC technologies can be classified into three generations [7] [8]. The first generation used block codes. A typical example is Reed-Solomon (RS)[255, 239]. The second generation used concatenated codes. An example is RS[255, 239]+Bose-Chaudhuri-Hocquenghem (BCH)[1023, 963]. The third generation used the more powerful soft decision decoding technique. The Block Turbo Code (BTC) and Low Density Parity Check (LDPC) code are two representatives of this generation. The OH, NCG, data rate and OSNR values are summarized in Table 1 [6]. Guo et al. [6] considered Shared Backup Path Protection (SBPP)-based EONs with the adaptive FEC allocation strategy. They developed an Integer Linear Programming (ILP) optimization model as well as a Spectrum Window Planes (SWPs)-based heuristic algorithm. The results showed that the adaptive FEC allocation strategy is very effective in significantly increasing the network capacity of an EON [6].

TABLE I. FEC TYPES OF OPTICAL NETWORK

FEC type	OH(%)	NCG(dB)@10^{-13}	Data Rate (Gb/s)	OSNR limit
RS[255, 239]	6.69	5.8	106.69	14.5
RS[255, 239] + BCH[1023, 963]	13.34	7.3	113.34	12.6
LDPC[4161, 3431, 0.825]	21.2	11.27	121.2	9.1

TABLE II. PARAMETERS OF TRANSCEIVER

Parameter	value	Modulation	SNR_{min}
P_S	1 mW	QPSK	2.031 dB
L_{span}	100 km	8 QAM	3.367 dB
h	6.626×10^{-34} m^2 kg/s	16 QAM	4.955 dB
fs	1.935×10^{14} Hz	32 QAM	6.722 dB
AG	20 dB QPSK	64 QAM	9.020 dB
NF	5.5 dB		
R_S	1.0×10^9		

B. RCSA vs. RCMLSA

Sambo et al. [9] [10] studied the Routing, Code, and Spectrum Assignment (RCSA) problem. For a given connection request and fixed modulation format, a set of candidate paths is constructed and the coding scheme with minimal extra information is selected, and then the required spectrum is allocated. Sambo et al. [9] [10] considered the *Time Frequency Packing* (TFP) [11] as the coding scheme.

Garrido et al. [12] considered the Routing, Code, Modulation Level, and Spectrum Allocation (RCMLSA) problem. In RCMLSA, not only the route and spectrum but also the pair FEC code-modulation format best suited are selected to establish an optical connection in EONs. In [12], the provided data rates (10, 40, 100, 400, 1000 Gb/s), modulation formats (Binary Phase Shift Keying (BPSK)/ Quadrature Phase Shift Keying (QPSK)) /8 Quadrature Amplitude Modulation (QAM)/16QAM/32QAM/64QAM) and different FEC codes (non-FEC/type 1 FEC/type 2 FEC/type 3 FEC) are considered. They proposed an algorithm to determine the route/modulation level/FEC type to minimize the number of required FSs for the connection request. Simulating results showed that the blocking probability of the RCMLSA model is lower than that of the RMLSA and RCSA models. However, in [12], the baud rate of the transceiver was fixed and cannot be selected by the network controller. In this paper, we use the RCMLSA problem as a base and extend it by considering the baud rate selection. The TR of a transmitting parameter may change if the baud rate change, thus this results in a new and more practical routing problem.

Alvarado et al. [13] found that joint optimization of the constellation and FEC OHs can yield large gains in terms of overall network throughput. They also studied the performance of the EON whose transmitters with two baud rates and a single constellation. The result in [13] suggested that one low baud rate could be used for the worst performing connection, while the other rate is used to increase the overall network throughput. Moreover, the results are quite close to the optimal baud rate of the corresponding one-rate scheme [14].

C. *Transmission Reach*

The TR or maximum distance of a single-core optical-amplified fiber is determined by several factors. The major impairments are Amplified Spontaneous Emission (ASE) noise and fiber nonlinearities [15]. The TR of a fiber-optic link can be estimated by the following formula [15]:

$$TR = P_S \times L_{span} / (SNR_{min} \times h \times fs \times AG \times NF \times R_S), \quad (1)$$

where P_S is the optical power at the transmitter. L_{span} is the distance between amplifiers. SNR_{min} is the required *Signal to Noise Ratio* (*SNR*) at the receiver side, which is related to the selected modulation format and Bit Error Ratio (BER) rate. For example, QPSK is 2.031dB, 8 QAM is 3.367 dB at BER 10^{-3}, etc. (shown in Table II)) [15]. *AG* is the gain of the amplifiers, *h* is Planck's constant, *fs* is the optical signal frequency, *NF* is the noise factor of the amplifiers, and R_S the symbol rate including the coding overhead (optimum Nyquist pulses are assumed).

Gho et al. [16] proposed a rate-adaptive transmission scheme using variable-rate FEC codes (concatenated RSs) with a fixed signal constellation and a fixed symbol rate. They studied the problem that how achievable bitrates vary with distance in a long-haul fiber system. They found that, with zero margins, an information bitrate could be realized up to 2000 km, with the achievable rate decreasing by approximately 40% for every additional 1000 km.

III. PROBLEM DEFINITION

In the following, the assumptions, constraints, notations and the definitions of the studied problem are given.

A. *Assumption*

- For each link, there is a fiber connecting the end-nodes and signal can be transmitted bidirectional.
- All nodes in the network are equipped with BV-WXC and BVT.
- For simplicity, the numbers of FSs provided by links are all equal.
- A GB should be allocated between two lightpaths.
- The bandwidth requirement between nodes can be transmitted by using multiple lightpaths with the same or different routes and numbers of FSs [18].

B. *Constraints*

Three constraints are considered in this paper, they are *spectrum continuity constraint*, *subcarrier consecutiveness constraint*, and *non-overlapping spectrum constraint*. Due to space limitation, the definition of these constraints can be found in [1]. To avoid a request from being split over too many lightpaths and causing too many guard bands, a *BW allocation granularity* (denoted as *g* FSs) is included [17]. Specifically, when the request is provisioned over more than one routing path, the minimum number of the FSs, which can be allocated on each path, is *g* [17].

C. *Notations*

- $G=(V, E, l)$: The physical topology of the network, where V= {$v_1, v_2, ..., v_n$} is the set of nodes (|V| = n), E= {$e_1, e_2, ..., e_m$} is the set of links (|E| = m), and $l(e)$ is the distance (kilometers) of the link e in E.
- $r=(s, d, BW_{sd})$: The connection request, where *s* in *V* and *d* in *V* is the source and destination node of the request, respectively. BW_{sd} is the required bandwidth (Gb/s) of the lightpaths between nodes *s* and *d*.
- *B*: the set of baud rates.
- *M*: the set of modulation formats {PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM, PM-64QAM} in the network.
- *F*: the set of FEC types, and *F*={no-FEC, Type 1 with RS[255, 235], type 2 with RS[255, 239]-BCH[1023, 963], type 3 with LDPC[416, 3431, 0.825], type 4 rate-adaptive code}.
- $R_{sd} = \{R^1_{sd}, R^2_{sd}, ..., R^k_{sd}\}$: The set of *k* routing paths between *s* and *d*. This set can be computed by performing the Eppstein algorithm [19] in $O(|E|+k|V|+|V|\log|V|)$.
- $OH[b, f, m]$: A 3-dimensional matrix, where the element $OH[b, f, m]$ represents the required overhead when the baud rate $b\in B$, the modulation format $m\in M$ and the FEC scheme $f\in F$ are used.
- $D[b, f, m]$: A 3-dimensional matrix, where the element $D[b, f, m]$ represents the TR when $b\in B$, $m\in M$ and $f\in F$.
- $FM(R^i_{sd}, BW_{sd})$: A priority queue, which contains all the triples (b, f, m) whose transmission reach is equal to or higher than the length of routing path. That is, $FM(R^i_{sd}, BW_{sd})=\{(b, f, m) | \text{dist}(R^i_{sd}) \le D[b, f, m]\}$ for $b\in B$, $m\in M$ and $f\in F$ and $\text{dist}(R^i_{sd})$ is the distance of the path R^i_{sd}.
- P^{new}: The set of routing paths, $P^{new} = \{(p^i_{sd}(b_i, f_i, m_i, N_i), i = 1, 2, ..., z\}\}$, where $b_i\in B$, $f_i \in F$, $m_i\in M$ and N_i is the number of allocated FSs of the i^{th} lightpath.

The values of $OH[b, f, m]$ can be obtained from Table I, which are assumed independent with the *b* and *m*. Moreover, for the type 4 rate-adaptive FEC coding, the overhead is set to 66.66% for extending the TR to 1000 km from non-FEC coding [16]. The values of $OH[b, f, m]$ can be calculated by using the formula (1) for the non-FEC type and estimated by using linear interpolation based on the observation in [16] and shown in Table IV. Each flexible transceiver was assumed capable of operating with five modulation formats and five FEC coding levels and several possible baud rates (shown in Table IV). For some baud rates, several modulation formats and some data rates are not supported. For example, consider Table IV, for baud rates 28, 30, 32, only the PM-QPSK and PM-16QAM and data rates (10, 40, 100) are supported.

After selecting the routing path $R^i_{sd} \in R_{sd}$ the number of required FSs for different bandwidth (10, 40, 100, 400, 1000) of the request can be determined by using *b*, *f*, *m*. If the

 ISBN: 978-1-61208-650-7

request is supported by a single lightpath, the minimal number of required FSs of the lightpath (denoted as N_{sd}) can be computed by

$$N_{sd} = \left\lceil \frac{BW_{sd} \times (1 + OH[b, f, m])}{C_f \times m} \right\rceil + GB, \quad (2)$$

where C_f is the bandwidth (Gb/s) provided by each FS. If the connection request is supported by z (>1) multiple lightpaths and the set of routing paths are $path_1$, $path_2$, ..., $path_z$, then the minimal number of required FSs for the demand BW_{sd} by using the multipath routing can be computed by the formula:

$$N_{sd} = \sum_{i=1}^{z} \left(\left\lceil \frac{BW^i_{sd} \times (1 + OH[b_i, f_i, m_i])}{C_f \times m_i} \right\rceil \right) + z \times GB, \quad (3)$$

where b_i, f_i and m_i are the selected parameters of the path_i, and subjects to constraints $\Sigma^z_{i=1} BW^i_{sd} \geq BW_{sd}$ and $\lceil BW^i_{sd} \times (1+OH[b_i, f_i, m_i])/(C_f \times m_i) \rceil \geq g$, $\forall i = 1, 2, ..., z$.

IV. PROPOSED ALGORITHM

In this section, the details of the proposed RBCMLSA-HSMR algorithm are described. For a new connection request $r = (s, d, BW_{sd})$, the set $P^{new} = \{p^i_{sd} | i = 1, 2, ..., z\}$ of lightpaths should be established to route the request.

A. RBCMLSA-HSMR

For the connection request $r = (s, d, BW_{sd})$, the k-shortest paths algorithm is performed on the network $G(V, E, l)$ to find a set of candidate paths $R = \{R^i_{sd}, i = 1, 2, ..., k\}$. Paths in P are sorted in ascending order according to the distances of the paths $dist(R^i_{sd})$ on the network $G(V, E, l)$. The shortest path is selected first because more efficient modulation format and better FEC type can be selected such that the number of required FSs can be reduced. For the selected path R^i_{sd}, $1 \leq i \leq z$ the following steps are performed.

- The priority queue $FM(R^i_{sd}, BW_{sd})$, which contains all possible triples (b, f, m) is obtained. All triples in list $FM(R^i_{sd}, BW_{sd})$ are sorted increasingly according to the number of required FSs (if there is a tie, the order is determined by the smaller $OH[b, f, m]$ and larger m).
- If the list $FM(R^i_{sd}, BW_{sd})$ is empty, the next candidate path ($i=i+1$) in P is selected and analyzed.
- If the list $FM(R^i_{sd}, BW_{sd})$ has at least one element, the pair (b, f, m) corresponding to the minimum value in $OH[b, f, m]$ is selected. That is, those parameters (the baud rate, modulation format, and FEC type) requiring the lowest OH for the given bit ate BW_{sd} is selected.
- Next, a spectrum allocation algorithm (first-fit method) is executed to allocate the selected number of FSs along the route if possible.
- If the spectrum allocation algorithm succeeds, the found resources will be allocated. Otherwise, a new route is analyzed ($i=i+1$). Since it is impossible to find available resources on the same path for more required resources.
- If no more candidate paths are available in R, i.e., all paths in R are examined and there is no single-path can be allocated to the lightpath, and then the multipath routing scheme will be applied if possible.
- If multipath routing paths cannot be found, the request will be rejected.
- In multipath routing scheme, the path with the best parameter (b, f, m) is selected and maximal available number of FSs is selected and allocated.
- The remaining unsupported bandwidth is selected from the same path first (with the same parameter or different parameters) if possible.
- Otherwise, other paths in R are examined repeatedly until the required bandwidth is satisfied.

The request is first routed by a single path, if possible. After checking all possible paths for single-path routing and the request cannot be routed by a single path, then the multi-path routing scheme is applied. It is worth noting that the same candidate path can be selected as the routing path more than once but with different FS index. The bandwidth BW^i_{sd} allocated to the selected path $p^i_{sd} \in P^{new}$ is determined based on the network status and should satisfy the constraint $BW_{sd} \leq \sum_{\forall p^i_{sd} \in P^{new}} BW^i_{sd}$.

When the connection request is routed by multiple paths, more FSs will be used for the guard band. In the context of this study, we assume that $GB = 1$ and this guard band is inserted as the highest indexed slot in the spectrum assignment of each connection. The request $r = (s, d, BW_{sd})$ is blocked, if a feasible set of routing paths $P^{new} = \{p^i_{s,d} (b_i, f_i, m_i, N_i), i = 1, 2, ..., z\}$ cannot be found. The details of the RBCMLSA-HSMR algorithm are shown in Algorithm 1.

V. SIMULATION RESULTS

The proposed algorithms were coded by using C++ programming language. All simulations were run on a notebook computer with Intel Core i7-4710 HQ CPU 2.5 GHz, 16.0 GB RAM and with Windows 10 pro 64-bit operating system. The COST239 network (showed in Figure 2), which is a famous and widely used network topology, was used for simulations. The distance between nodes in COST239 can fit the parameters provided in Table IV. Other well-known network topologies will be examined in the future study. In Figure 2, the number nears the link is the length (km.) of the fiber.

In the simulation, the static traffic is simulated for different sets with different numbers (50, 100, 150, and 200) of requests. The number of candidate paths for a request is $k = 20$. The connection request is randomly generated uniformly for different pairs of nodes, the number of required bandwidth (Gb/s) is within [10, 2000]. For each fiber of the network, 320 FSs are provided and $C_f = 12.5$ Gb/s. Two algorithms for different models are implemented for comparison; they are RCMLSA model [12] and RMLSA model [17].

Algorithm 1 RBCMLSA-HSMR Algorithm

Input: $G(V, E, l)$, $r = (s, d, BW_{sd})$;
Output: the set of lightpaths $P^{new} = \{(p^i_{s,d}(b_i, f_i, m_i, N_i), i = 1, 2, ..., z\}$, subject to $\sum_{i=1}^{z} BW^i_{sd} \geq BW_{sd}$ and $N_i \geq g$.
$P^{new} = \emptyset$, $B = BW_{sd}$;
sort the paths in R in ascending order based on the distances $dist(R^i_{sd})$, $\forall R^i_{sd} \in R$, $R' = R$;
//single-path routing
while (($R \neq \emptyset$) and (found == **false**)) **do**
  {
  select and remove a path R^i_{sd} from R;
  construct the list $FM(R^i_{sd}, BW_{sd})$;
  select a triple $(b, f, m) \in FM(R^i_{sd}, BW_{sd})$ with the minimum number of required FSs which is computed by $N_{sd} = \left\lceil \frac{BW_{sd} \times (1+OH[b,f,m])}{C_f \times m} \right\rceil + GB$, for the selected modulation level m, baud rate b and FEC type f;
  if (the required resources of the path R^i_{sd} can be allocated on the network) **then**
    allocate resources and add path $p^i_{sd} = R^i_{sd}$ with parameters (b, f, m) to P^{new};
    found = **true**, **return success** and P^{new};
  end if
  }
end while

//multi-path routing
$BW = 0$; //currently allocated bandwidth of the request
while (($R' \neq \emptyset$) and ($BW < BW_{sd}$)) **do**
  {
  select and remove a path R^i_{sd} from R';
  construct the list $FM(R^i_{sd}, BW_{sd} - BW)$, which is implemented by the priority queue according to the number of required FSs of the selected parameter (b, f, m) increasingly;
  while (($FM(R^i_{sd}, BW_{sd} - BW) \neq \emptyset$) and ($BW < BW_{sd}$)) **do**
    {
    select the first triple (b, f, m) from the list $FM(R^i_{sd}, BW_{sd} - BW)$;
    determine the number of required FSs (N^i_{sd}) to route the required bandwidth $(BW_{sd} - BW)$ with parameters (b, f, m);
    if ($N^i_{sd} < g$) **then**
      $N^i_{sd} = g$; //check for constraint
    end if
    check the maximum number of allocatable FSs N^i of the path R^i_{sd} on the network;
    if ($N^i \geq N^i_{sd}$) **then**
      temporarily allocate N^i_{sd} FSs on the network and add path $p^i_{sd} = R^i_{sd}$ with parameters (b, f, m, N^i_{sd}) to P^{new};
      $BW = BW + \frac{1}{1+OH[b,f,m]} \times N^i_{sd} \times m \times C_f$;
    else if ($N^i_{sd} > N^i \geq g$) **then**
      temporarily allocate N^i FSs on the network and add path $p^i_{sd} = R^i_{sd}$ with parameters (b, f, m, N^i) to P^{new};
      $BW = BW + \frac{1}{1+OH[b,f,m]} \times N^i \times m \times C_f$;
    else
      break; //current path cannot be used
    end if
    }
  end while
  }
end while
if ($BW \geq BW_{sd}$) **then**
  allocate spectrum, **return success** and P^{new};
else
  recovery all the spectrum allocations for paths in P^{new};
  remove all paths from P^{new}, mark the request as block and **return false**;
end if

Figure 1. RBCMLSA-HSMR

For each algorithm, both the single-path routing and the hybrid simple-/multi-path routing schemes are implemented. The parameters for RMLSA model are shown in Table III, which are the same as the best parameters for RBCMLSA (shown in Table IV), but without FEC overhead. The maximum distance or TR limits by 1,292 km. The parameters for RCMLSA model are selected from the central part of Table IV, but the highest bandwidth limitation is released (i.e. it can support up to 1000 Gb/s).

Several performance criteria are considered in this paper, they are:

- Blocking Ratio (BR), which is defined as the ratio of the number of blocked requests versus the number of total requests.
- Multipath Ratio (MR), which is the ratio of the number of requests routed by multiple paths to that of the number of successful requests.
- The average number of allocated FSs per lightpath,
- the average hops per lightpath,
- the average number of lightpaths per request, and
- computation time.

In the COST239 network, the simulation results are shown in Figure 3. Figure 3(a) shows the average number of paths per request of the RCMLSA method is greater than that of the other methods. The average number of paths per request increases as the number of requests increases. Figure 3(b) shows the average number of FSs per lightpath of the RCMLSA single path routing method is greater than that of the other methods. The average number of FSs per lightpath decreases as the number of requests increases. The average number of FSs per lightpath for single-path routing scheme is higher than that of the multipath routing scheme. Figure 3(c) shows the average number of hops per lightpath of the RMCMLSA multipath routing method is greater than that of the other methods.

The average number of hops per lightpath decreases as the number of requests increases from 50 to 150. The average number of hops per lightpath for multipath routing scheme is higher than that of the single-path routing scheme. Figure 3(d) shows that the BR of the RBCMLSA multipath routing is lower than that of the other methods. For single-path routing, the BR of the RBCMLSA method is lower than that of the other methods. The result also shows that multipath routing scheme can reduce the BR about 40%. The BR increases as the number of requests increases. Figure 3(e) shows that the MR of the RCMLSA multipath routing is higher than that of the other methods. The MR increases as the number of requests increases. Figure 3(f) shows that the CPU time in seconds of the RCMLSA multipath routing is higher than that of the other methods. The RBCMLSA multipath is the second highest.

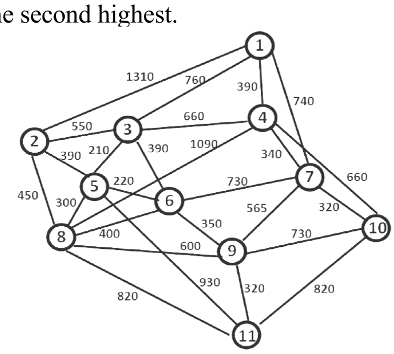

Figure 2. COST239 network.

 ISBN: 978-1-61208-650-7

VI. CONCLUSIONS AND FUTURE WORK

In this paper, the Routing, Baud rate, FEC Coding, Modulation Level, and Spectrum Allocation (RBCMLSA) problem has been defined and studied. For serving transmission on an EON, the goal is to design a routing and spectrum assignment algorithm to establish lightpaths. In the studied problem, the hybrid single/multipath routing scheme has developed to increase the spectrum efficiency. A heuristic algorithm denoted as RBCMLSA-HSMR, which integrates single/multiple paths routing scheme has been proposed. The proposed algorithm has been examined through simulations on the COST239 network and the results show that the proposed algorithms can reduce the blocking probability about 40%.

The results show that using flexible transmitters and adaptive transmitting parameters, the proposed algorithm can get lower blocking probability both in single-path and multiple-path routing schemes. Thus, the performance for routing in the RBCMLSA model is better than that of RMLSA and RCMLSA models. This is because of that controller can find a better routing path together with better parameters in RBCMLSA model, such that the required number of FSs can be reduced and the spectrum of the network can be used more efficiently. Simulation results also show that multipath-routing scheme does reduce the blocking probability whatever in RMLSA, RCMLSA, or RBCMLSA models.

In the future, the performance of the proposed algorithm on different networks will be simulated, and more feasible transmitting parameters of the flexible transceivers will be collected and examined. Moreover, the more problems in the RBCMLSA model that are important will be studied. For example, the survival routing problem, de-fragmentation problem on the single-fiber network or the multi-fiber network.

TABLE III. PARAMETERS OF RMLSA

Transmission Reach (km)	b	m	modulation format
1292	120	2	PM-QPSK
1147	1147	3	PM-8QAM
1031	64	4	PM-16QAM
937	51	5	PM-32QAM
840	43	6	PM-64QAM

ACKNOWLEDGMENT

This work was supported in part by the MOST project under Grant 106-2221-E-018-002.

REFERENCES

[1] G. Zhang, M. D. Leenheer, and A. Morea, “A survey on OFDM-based elastic core optical networking,” IEEE Commun. Surv. & Tut. vol. 15, First Quarter 2013, pp. 65-87, doi: 10.1109/SURV.2012. 010912.00123.

[2] M. Klinkowski and K. Walkowiak, “Routing and spectrum assignment in spectrum sliced elastic optical path network,” IEEE Commun. Lett., vol. 15, Aug. 2011, pp. 884-886, doi: 10.1109/ LCOMM.2011.060811.110281.

[3] N. Sambo, et al., “Programmable transponder, code and differentiated filter configuration in elastic optical networks,” J. Lightw. Technol., vol. 32, June 2014, pp. 2079-2086, doi:10.1109/JLT.2014.2319859.

[4] F. Cugini, et al., “Toward plug-and-play software-defined elastic optical networks,” J. Lightw. Technol., vol. 34, Mar. 2016, pp. 1494-1500, doi:10.1109/JLT.2015.2511802.

[5] W. D. Grover, “Forward error correction in dispersion-limited lightwave system,” J. Lightw. Technol., vol. 6, May 1988, pp. 643-654, doi:10.1109/50.4049.

[6] H. Guo, et al., “OSA benefit of adaptive FEC in shared backup path protected elastic optical network,” Optics Express, vol. 23, July 2015, pp. 20158-20175, doi:10.1364/OE.23.020158.

[7] T. Mizuochi, “Next generation FEC for optical transmission systems,” Proc. IEEE Symp. Optical Fiber Communications Conference (OFC 2003), IEEE Press, Feb. 2004, paper ThN1, doi:10.1109/ OFC.2003.315927.

[8] T. Mizuochi, “Recent progress in forward error correction and its interplay with transmission impairments,” IEEE J. Sel. Top. Quantum Electron. vol. 12, July, 2006, pp. 544-554, doi: 10.1109/JSTQE. 2006.876597.

[9] N. Sambo et al., “Routing, code, and spectrum assignment (RCSA) in elastic optical networks,” Proc. IEEE Symp. of Optical Fiber Communications Conference and Exhibition (OFC 2015), IEEE Press, Mar. 2015, page W1l.1, doi:10.1364/OFC.2015.W1I.1.

[10] N. Sambo et al., “Routing code and spectrum assignment (RCSA) in elastic optical networks,” J. Lightw. Technol., vol. 33, Dec. 2015, pp. 5114-5121, doi:10.1109/JSTQE.2006.876597.

[11] M. Secondini, et al., “Optical time-frequency packing: principles, design, implementation, and experimental demonstration,” J. Lightw. Technol., vol. 33, Sept. 2015, pp. 3558-3570, doi:10.1109/JLT. 2015.2443876.

[12] D. Garrido, A. Leiva, A. Beghelli, R. Ahumada, and R. Olivares, “Routing, code, modulation level and spectrum assignment (RCMLSA) algorithm for elastic optical networks,” Proc. IEEE Symp. Transparent Optical Networks (ICTON 2016), IEEE Press, Aug. 2016, pp.Tu. B3.4, doi:10.1109/ICTON.2016.7550388.

[13] A. Alvarado, D. J. Ives, S. J. Savory, and P. Bayvel, “On the impact of optimal modulation and FEC overhead on future optical networks,” J. Lightw. Technol., vol. 34, May 2016, pp. 2339-2352, doi: 10.1109/JLT.2016.2517699.

[14] D. J. Ives, P. Wright, A. Load, and S. J. Savory, “Using 25GbE client rates to access the gains of adaptive bit- and code-rate networking,” J. Opt. Commun. Netw., vol. 8, July 2016, pp. A86-A91, doi:10. 1364/JOCN.8.000A86.

[15] R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, “Capacity limits of optical fiber networks,” J. Lightw. Technol., vol. 28, Feb. 2010, pp. 662-701, doi:10.1109/JLT. 2009.2039464.

[16] G.-H. Gho, L. Klak, and J. M. Kahn, “Rate-adaptive coding for optical fiber transmission systems,” J. Lightwave Technol., vol. 29, Jan. 2011, pp. 222-233, doi:10.1109/JLT.2010.2099208.

[17] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, “Dynamic service Parameters of RMLSA provisioning in elastic optical networks with hybrid single-/multi-path routing,” J. Lightw. Technol., vol. 31, Jan. 2013, pp. 15-22, doi: 10.1109/JLT.2012.2227683.

[18] W. Lu, X. Zhou, L. Gong, M. Zhang, and Z. Zhu, “Dynamic multi-path service provisioning under differential delay constraint in elastic optical networks,” IEEE Commun. Lett., vol. 17, Jan. 2013, pp. 158-161, doi:10.1109/LCOMM.2012.120612.121343.

[19] D. Eppstein, ``Finding the k shortest paths,” SIAM J. Comput., vol. 28, Apr. 1999, pp. 652-673, 1999, doi:10.1137/S0097539795290477.

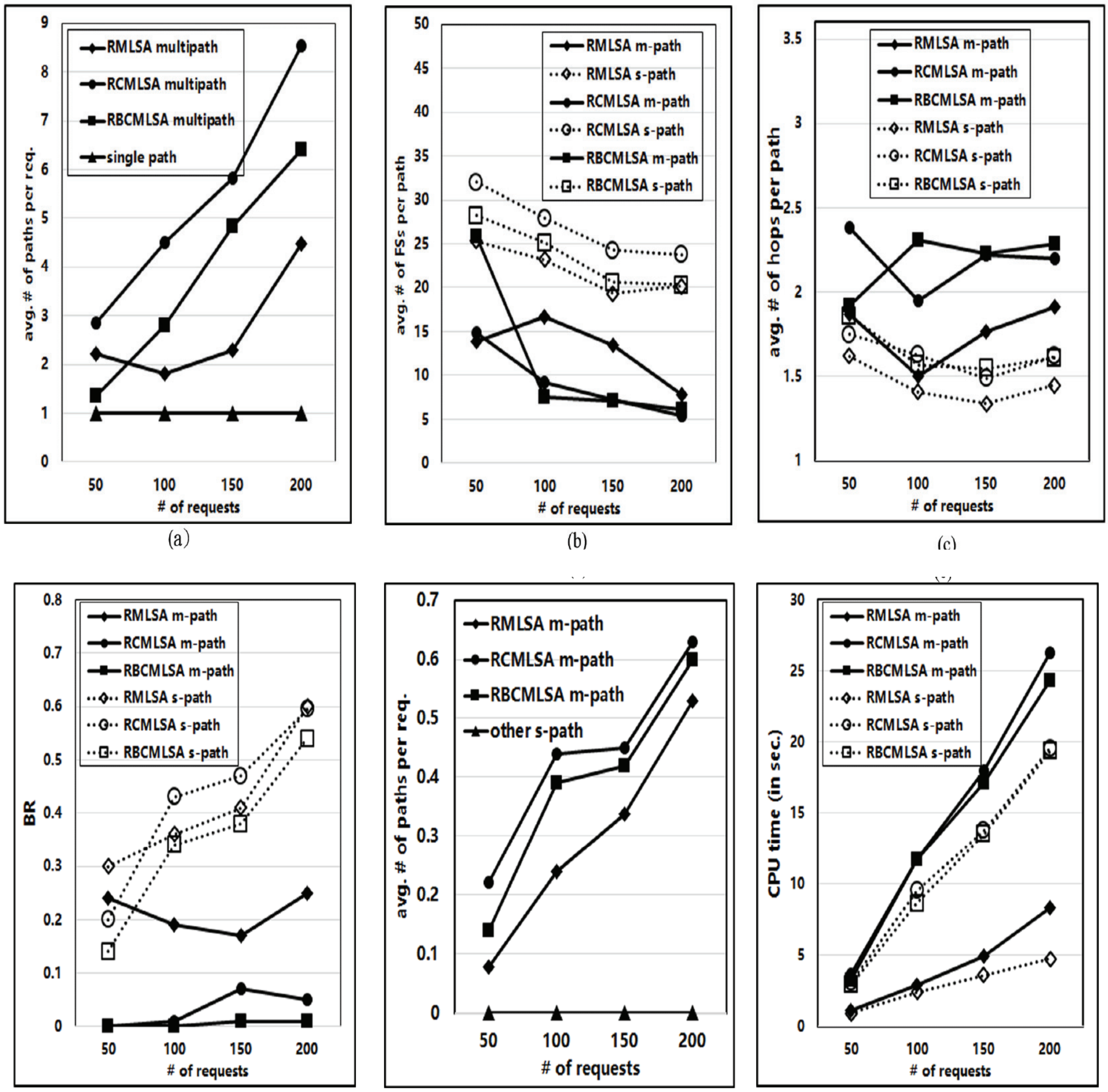

Figure 3. Simulation results on the COST239 network (a) the average number of path per request, (b) the average number of paths per request, (c) the average number of hop per path, (d) BR, (e) MR, (f) CPU time.

TABLE IV. THE NUMBER OF REQUIRED FSS FOR THE SELECTED PARAMETER, DATA RATES, AND TRANSMISSION REACH

m	b	FEC Type f Trans. reach (km)				
(10,40,100) $D[b, f, m]$		no-FEC	Type 1	Type 2	Type 3	Type 4
PM-QPSK	FSs	(1,2,4)	(1,2,5)	(1,2,5)	(1,2,5)	(1,3,7)
	28	1674	1774	1874	1992	2674
	30	1856	1956	2056	2174	2856
	32	2084	2184	2284	2402	3084
PM-16QAM	FSs	(1,1,2)	(1,1,3)	(1,1,3)	(1,1,3)	(1,2,4)
	28	1064	1164	1264	1382	2064
	30	1134	1234	1334	1452	2134
	32	1216	1316	1416	1534	2216
(10, 40, 100, 400) $D[b, f, m]$		no-FEC	Type 1	Type 2	Type 3	Type 4
PM-QPSK	FSs	(1,2,4,16)	(1,2,5,18)	(1,2,5,19)	(1,2,5,20)	(1,3,7,27)
	112	1122	1222	1322	1440	2122
	120	1201	1301	1401	1519	2201
	128	1292	1392	1492	1610	2292
PM-8QAM	FSs	(1,2,3,11)	(1,2,3,12)	(1,2,4,13)	(1,2,4,13)	(1,2,5,18)
	75	1011	1111	1211	1329	2011
	80	1075	1175	1275	1393	2075
	85	1147	1247	1347	1465	2147
16 QAM	FSs	(1,1,2,8)	(1,1,3,9)	(1,1,3,10)	(1,1,3,10)	(1,2,4,14)
	56	920	1020	1120	1238	1920
	60	972	1072	1172	1290	1972
	64	1031	1131	1231	1349	2031
PM-32QAM	FSs	(1,1,2,7)	(1,1,2,7)	(1,1,2,8)	(1,1,2,8)	(1,2,3,11)
	45	844	944	1044	1162	1844
	48	888	988	1088	1206	1888
	51	937	1037	1137	1255	1937
64 QAM	FSs	(1,1,2,6)	(1,1,2,6)	(1,1,2,7)	(1,1,2,7)	(1,1,3,9)
	37	765	865	965	1083	1765
	40	801	901	1001	1119	1801
	43	840	940	1040	1158	1840
(10, 40, 100, 400,1000)		no-FEC	Type 1	Type 2	Type 3	Type 4
PM-32QAM	FSs	(1,1,2,7,16)	(1,1,2,7,18)	(1,1,2,8,19)	(1,1,2,8,20)	(1,2,3,11,27)
	112	724	824	924	1042	1724
	120	756	856	956	1074	1756
	128	791	891	991	1109	1791
PM-64QAM	FSs	(1,1,2,6,14)	(1,1,2,6,15)	(1,1,2,7,16)	(1,1,2,7,17)	(1,1,3,9,23)
	93	665	765	865	983	1665
	105	692	792	892	1010	1692
	117	722	822	922	1040	1722

 ISBN: 978-1-61208-650-7