A RMLSA Algorithm with Modulation Format Conversion at Intermediate Nodes

César Garrido, Ariel Leiva, Alejandra Beghelli*
Pontificia Universidad Católica de Valparaíso, Av. Brasil 2147, Valparaíso, Chile
** Universidad Adolfo Ibañez, Padre Hurtado 750, Viña del Mar, Chile*
Tel: (+56) 322273682, e-mail: ariel.leiva@pucv.cl

ABSTRACT
In this paper a new RMLSA (Routing, Modulation Level, and Spectrum Assignment) algorithm is presented. The proposal leverages on the potential usage of intermediate modulation format conversion to increase the optical reach or being able to use route segments with lower available capacity.

To do so, the proposal first attempts to establish a full transparent connection on the shortest path. If this is not possible (due to optical reach limits or capacity availability), the algorithm resorts to modulation format conversion at an intermediate node. If modulation format conversion is not enough to establish the connection on the shortest path, up to two additional routes are explored.

By means of simulation, the performance of the algorithm was evaluated on a dynamic elastic optical network. Results show that, at low traffic loads (<0.4), resorting to modulation format conversion significantly decreases the rejection rate of connection requests compared to not applying such conversion.
Keywords: Dynamic resource allocation, RMLSA algorithms, elastic optical networks.

1. INTRODUCTION

Elastic allocation of spectrum (central frequency and spectral width) has been proposed as a medium/long term alternative to the inefficient spectrum usage of fixed grid operation [1,2]. However, elastic operation requires new optical devices: flexible transponders to select different transmission rates, modulation formats and central frequencies [1,2] as well as flexible optical switches, as Flexible-Wavelength Selective Switches [1,2]. Also, new algorithms able to allocate the central frequency and the spectral width to different connection requests are required.

Flexible spectrum allocation algorithms work based on the fact that the spectrum is divided in small spectrum units called FSUs (Frequency Slot Units), with a width of 12.5 GHz each. Thus, to establish a new optical connection a route and the same set of contiguous FSUs in each link of that route must be found. Most resource allocation algorithms proposed for elastic optical networks belong to the RMLSA (Routing, Modulation Level and Spectrum Assignment) type [1-3]: they solve the problem of finding a route (R), a modulation level (ML) and a spectrum portion (S) for each new connection. Usually, the RMLSA algorithms work sequentially: first, they solve the routing problem to then assign a modulation format and finally, a spectrum segment (number and position of FSUs).

The most used routing algorithm is k-SP: the k shortest paths are considered for connection establishment (with k typically ranging from 1 to 3), attempting first the shortest one. If the shortest path is not available, the 2nd shortest is attempted and so on [3]. The usual modulation format assignment technique selects the modulation format with the lowest FSU requirement with an optical reach equal to or higher than the length of the route under consideration [1-3]. The number of FSU required is given by the combination bit rate - modulation format. Finally, the most common spectrum allocation method is First-Fit (FF) [3], where the first (either from the lowest or the highest part of the spectrum) number of contiguous FSUs available in all the route links is selected.

Most RMLSA algorithms proposed to date attempt to establish a connection in a transparent way [1-3], using the same modulation format and the same spectrum portion along the whole route. In such case, the rejection of a connection request is due to two reasons: because of a lack of the same set of continuous FSUs in all the links of the route or because of a short optical reach. To overcome these problems, a few RMLSA algorithms take into account the capability of regenerating the optical signal at some or all nodes along the route [4,5] (giving up on the transparency). However, such benefit comes at a cost of significantly higher computational processing [4] or cost [5].

In this paper, we propose a new RMLSA algorithm that works in a sequential manner (to keep a low computational cost) and resorts to modulation format conversion in just one node along the route (decreasing blocking at a lower cost than converting modulation format at each node as in [5]).

The rest of this paper is as follows: Section 2 describes the algorithm. Section 3 presents the performance evaluation results. Section 4 concludes the paper.

2. RMLSA ALGORITHM

The algorithm proposed is termed as RMLSA+MCA (*Modulation Conversion Assignment*). For the routing problem, it uses a k-SP (k-Shortest Path) approach. For the modulation format assignment, it selects the format requiring the lowest number of FSUs such that the optical reach equals or exceeds the length of the selected route. Finally, for the spectrum allocation, *First Fit* is applied.

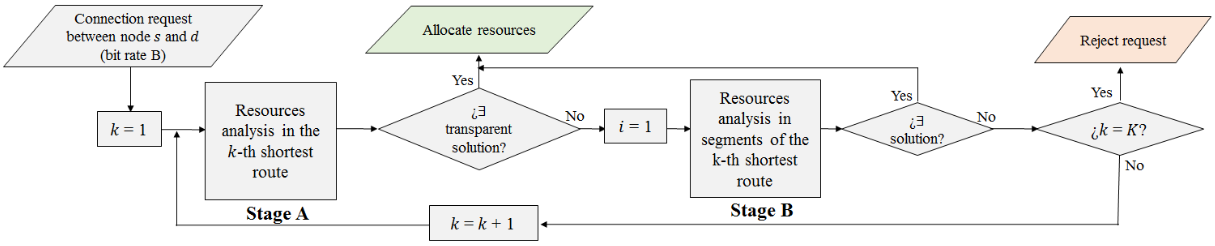

Fig. 1: Flowchart for the RMLSA-MCA algorithm

Fig. 1 shows a flowchart with the mains steps of RMLSA+MCA. Upon the reception of a connection request between nodes s and d with a bit rate of $B_{s,d}$, the algorithm operates in 2 stages (A and B), described in the following.

Stage A: In this stage, the feasibility of establishing the connection transparently using one route is evaluated. The pseudo-code for Stage A is shown in Fig. 2. Let:

- s be the source node; d be the destination node.
- $B_{s,d}$ the bit rate for the connection between s and d;
- $\beta = \{B^1, B^2, \ldots B^u, .., B^U\}$ be the set made of the transmission rates available at the flexible transponders.
- $\mathcal{M} = \{M^1, M^2, \ldots, M^j, .., M^J\}$ be the set made of the J modulation formats available at the flexible transponders.
- $\mathcal{R}_{s,d} = \{R^1_{s,d}, R^2_{s,d}, ., R^k_{s,d}, \ldots, R^K_{s,d}\}$ be the set of the K candidate routes (pre-computed) between nodes s and d. $R^k_{s,d}$ denotes the k-th shortest route.
- $\mathcal{L}_{s,d} = \{L^1_{s,d}, L^2_{s,d}, \ldots, L^k_{s,d}, \ldots, L^K_{s,d}\}$ be the set of the route lengths, in km. $L^k_{s,d}$ is the length of route $R^k_{s,d}$.
- $\mathcal{FM}(L^k_{s,d}, B_{s.d})$ be the set of the modulation formats in $\mathcal{M}$ that, along with the transmission rate $B_{s,d} \in \beta$, have an optical reach equal to or higher than $L^k_{s,d}$.
- $\mathbb{FSU}[\mathcal{M}, \beta]$ be a matrix, where element $\mathbb{FSU}[m, b]$ stores the number of FSUs required when using modulation format m and transmission rate b, $\forall m \in \mathcal{M}$ y $b \in \beta$.
- $\mathbb{U}(R^k_{s,d})$ be the availability vector of route $R^k_{s,d}$. The number of elements of this vector is equal to the number of FSUs in any link. The j-th element of this vector is equal to 0 if the j-th FSU in the route is available, 1 otherwise.
- $\mathcal{FSU}[\mathbb{U}(R^k_{s,d})]$ be the set of FSUs available and spectrally continuous in vector $\mathbb{U}(R^k_{s,d})$.
- $\left\|\mathcal{FSU}[\mathbb{U}(R^k_{s,d})]\right\|_{\max}$ be the maximum number of contiguous and available FSUs in vector $\mathbb{U}(R^k_{s,d})$.

Build the set $\mathcal{FM}(L^k_{s,d}, B_{s,d})$ **IF** $\mathcal{FM}(L^k_{s,d}, B_{s,d}) \neq \emptyset$ ▪ Select the modulation format $m \in \mathcal{FM}(L^k_{s,d}, B_{s,d})$ requiring the minimum number of FSUs (this is done by identifying the minimum value in the column $B_{s,d}$ of matrix $\mathbb{FSU}[m, b]$). ▪ Calculate $\mathbb{U}(R^k_{s,d})$, $\mathcal{FSU}[\mathbb{U}(R^k_{s,d})]$ and $\left\|\mathcal{FSU}[\mathbb{U}(R^k_{s,d})]\right\|_{\max}$	▪ **IF** $\left\|\mathcal{FSU}[\mathbb{U}(R^k_{s,d})]\right\|_{\max} \geq \mathbb{FSU}[m, b]_{min}$ - Execute the SA algorithm, if successful establish connection. If not, end stage A **ELSE** - End stage A **ELSE** End stage A

Fig. 2: Stage A (Checking availability of route $R^k_{s,d}$)

For route $R^k_{s,d}$, the algorithm calculates the set of the modulation formats $\mathcal{FM}(L^k_{s,d}, B_{s.d})$ complying with the required optical reach for transparent communication. If this set has at least one element, then the modulation format requiring the lowest number of FSUs is selected (by searching in the column $B_{s.d}$ of matrix $\mathbb{FSU}[m, b]$). Next, the spectrum allocation (SA) algorithm is executed to find a set of contiguous and continuous FSUs (as many as the number determined in the previous step) in the analysed route. If the SA algorithm finds a solution, resources are reserved and the connection is established. Otherwise, stage A ends and stage B is started.

Stage B: This stage is executed when it is not possible establishing a transparent connection between nodes s and d using route $R_{s,d}^k$. In this case, a node in $R_{s,d}^k$ where modulation format conversion can be carried out is searched for. The pseudo-code of Stage B is shown in Fig. 3. Let:

- $N(R_{s,d}^k)$ be the number of nodes in route $R_{s,d}^k$.
- $\mathcal{S}(R_{s,d}^k) = \left\{S^1(R_{s,d}^k), \ldots, S^i(R_{s,d}^k), \ldots, S^{N(R_{s,d}^k)-2}(R_{s,d}^k)\right\}$ be the set of segments in route $R_{s,d}^k$, such that segment $S^i(R_{s,d}^k)$ originates at the source node of route $R_{s,d}^k$ (that is, node s) and ends at the i-th node previous to node d along the route. Fig. 4 shows an example of a route ($R_{A,D}$) made of 4 nodes between nodes A and D. In this case, the set $\mathcal{S}(R_{A,D})$ has 2 elements: segments $S^1(R_{A,D})$ and $S^2(R_{A,D})$.
- $\mathcal{S}(R_{s,d}^k)^* = \left\{S^1(R_{s,d}^k)^*, \ldots, S^i(R_{s,d}^k)^*, \ldots, S^{N(R_{s,d}^k)-2}(R_{s,d}^k)^*\right\}$ be the set of segments in $R_{s,d}^k$ such that segment $S^i(R_{s,d}^k)^*$ starts at the i-th node previous to destination node d and ends at node d. Fig 4. shows these segments for the 4-node route between nodes A and D.
- $L[S^i(R_{s,d}^k)]$ and $L[S^i(R_{s,d}^k)^*]$ be the length, in km, of segments $S^i(R_{s,d}^k)$ y $S^i(R_{s,d}^k)^*$, respectively.
- $\mathcal{FM}(L[S^i(R_{s,d}^k)], B_{s,d})$ and $\mathcal{FM}(L[S_s^i(R_{s,d}^k)^*], B_{s,d})$ be the sets of modulation formats in $\mathcal{M}$ that, along with the bit rate $B_{s,d} \in \beta$, have an optical reach equal to or higher than $L[S^i(R_{s,d}^k)]$ y $L[S^i(R_{s,d}^k)^*]$, respectively.
- $\mathbb{U}(S^i(R_{s,d}^k))$ and $\mathbb{U}(S^i(R_{s,d}^k)^*)$ be the FSU availability vectors of segments $S^i(R_{s,d}^k)$ y $S^i(R_{s,d}^k)^*$, respectively.
- $\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k))]$ and $\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k)^*)]$ be the sets of available and spectrally contiguous FSUs in vectors $\mathbb{U}(S^i(R_{s,d}^k))$ and $\mathbb{U}(S^i(R_{s,d}^k)^*)$, respectively.
- $\|\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k))]\|_{\max}$ and $\|\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k)^*)]\|_{\max}$ be the maximum number of FSUs contiguous and available in vectors $\mathbb{U}(S^i(R_{s,d}^k))$ and $\mathbb{U}(S^i(R_{s,d}^k)^*)$, respectively.

IF $i \leq N(R_{s,d}^k)$-2
- ❖ Calculate $S^i(R_{s,d}^k)$, $L[S^i(R_{s,d}^k)]$ and $\mathcal{FM}(L[S^i(R_{s,d}^k)], B_{s,d})$
- ❖ **IF** $\mathcal{FM}(L[S^i(R_{s,d}^k)], B_{s,d}) \neq \emptyset$
  - ▪ Select modulation format $m \in \mathcal{FM}(L[S^i(R_{s,d}^k)], B_{s,d})$ requiring minimum number of FSUs (minimum value in column $\mathbb{U}[m, B_{s,d}]$), $\mathbb{FSU}[m,b]_{min}$.
  - ▪ Calculate $\mathbb{U}(S^i(R_{s,d}^k))$, $\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k))]$ and $\|\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k))]\|_{\max}$
  - ▪ **IF** $\|\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k))]\|_{\max} \geq \mathbb{FSU}[m,b]_{min}$
    - • Execute SA in $S^i(R_{s,d}^k)$ and reserve resources.
    - • Calculate $S^i(R_{s,d}^k)^*$, $L[S^i(R_{s,d}^k)^*]$ and $\mathcal{FM}(L[S_s^i(R_{s,d}^k)^*], B_{s,d})$
    - • **IF** $\mathcal{FM}(L[S^i(R_{s,d}^k)^*], B_{s,d}) \neq \emptyset$
      - ~ Select modulation format $m \in \mathcal{FM}(L[S^i(R_{s,d}^k)^*], B_{s,d})$ requiring minimum number of FSUs ($\mathbb{FSU}[m,b]_{min}$)
      - ~ Calculate $\mathbb{U}(S^i(R_{s,d}^k)^*)$, $\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k)^*)]$ and $\|\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k)^*)]\|_{\max}$
      - ~ **IF** $\|\mathcal{FSU}[\mathbb{U}(S^i(R_{s,d}^k)^*)]\|_{\max} \geq \mathbb{FSU}[m,b]_{min}$
        - * Execute SA in $S^i(R_{s,d}^k)^*$ and reserve resources
        - * End stage B.
      - ~ **ELSE**
        - * Release reserved resources.
        - * i=i+1
        - * Re-start stage B.
    - • **ELSE**
      - ~ Release reserved resources.
      - ~ i=i+1
      - ~ Re-start stage B.
  - ▪ **ELSE**
    - • i=i+1
    - • Re-start stage B.
- ❖ **ELSE**
  - ▪ i=i+1
  - ▪ Re-start stage B.

ELSE
End stage B.

Fig 3: Stage B (Selecting 2 segments to connect s and d, with one intermediate modulation format conversion)

In this stage route $R_{s,d}^k$ is divided in 2 segments. Next, the algorithm attempts to establish two connections (one per segment, assuming that a modulation format conversion as well as a change in the spectral position is performed at the final node of the first segment). If the connection between s and d cannot be established using these 2 segments, stage B re-starts considering a different set of segments. This procedure is repeated until the connection can be established or until all combinations of segments in the route have been unsuccessfully attempted. In this latter case, the algorithm goes back to stage A to analyse the next candidate route. If after analysing all routes (and combination of segments in those routes) the connection cannot be established, the request is rejected.

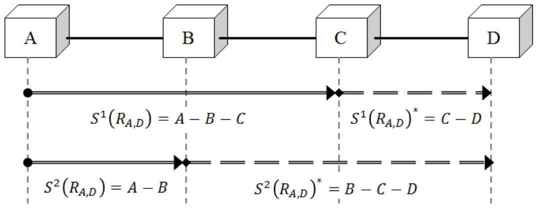

Fig. 4: Set of segments associated to a 4-node route.

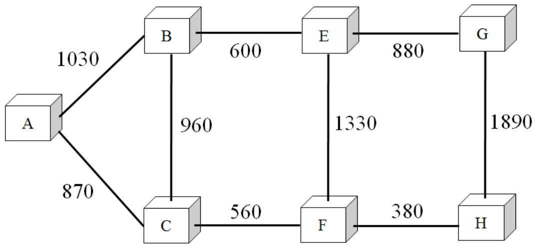

Fig. 5: Test topology. Link lengths in km.

3. NUMERICAL EXAMPLE

The blocking performance of RMLSA+MCA was evaluated using an C++ ad-hoc simulator. The network topology used is shown in Fig. 5 (link lengths in km). A total number of 450000 connections requests uniformly distributed among all node pairs were generated. Each connection (defined by a source-destination pair and a bit rate) follows an ON-OFF traffic model. ON(OFF) periods are exponentially distributed, with mean value denoted by T_{off} and T_{on}, respectively. The traffic load, ρ, is given by $T_{on}/(T_{on} + T_{off})$. Link capacity was assumed equal to 75 FSUs. The set of available bit rates in the flexible transponders of the network is β={10, 40, 100, 400 y 1000} Gbps. Bit rates requests are also uniformly distributed. Table 1 [6] was used to build the sets $\mathcal{FM}(\cdot)$ and matrix $\mathbb{FSU}[\mathcal{M},\beta]$, assuming OFDM channels.

Table 1: FSU requirements and optical reach of OFDM signals for different combinations of modulation formats and bit rates

	Number of FSUs required					Optical reach [km]
	10 Gbps	40 Gbps	100 Gbps	400 Gbps	1000 Gbps	
BPSK	1	4	8	32	80	4000
QPSK	1	2	4	16	40	2000
8-QAM	1	2	3	11	27	1000
16QAM	1	1	2	8	20	500
32QAM	1	1	2	7	16	250
64QAM	1	1	2	6	14	125

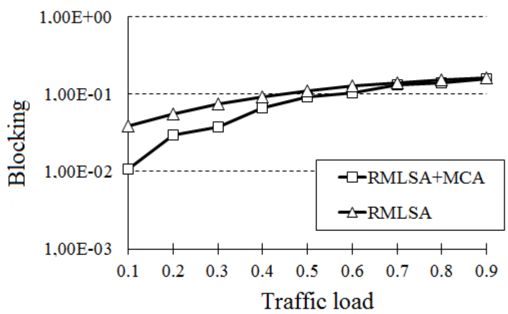

Fig. 6: Blocking as a function of the traffic load for RMLSA+MCA and RMLSA.

A 3-SP routing algorithm and the *First-Fit* SA algorithm were applied. The modulation format with the lowest FSU requirement such that the optical reach is equal to or higher than the length of the route/segment analysed was selected. Fig. 6. shows the results, including the performance of the same algorithm without the modulation format conversion (RMLSA). It can be seen that RMLSA+MCA exhibits a lower blocking than RMLSA for all operational traffic loads (under 0.7) thanks to the intermediate modulation format conversion.

4. CONCLUSIONS

A new RMLSA algorithm with intermediate modulation format conversion capability was proposed. Results show that, at traffic loads under 0.7, the proposal exhibits a lower blocking than RMLSA classical. Future research will focus on studying the performance of RMLSA+MCA on more realistic network topologies as well as on optimal location of modulation format converters.

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