Algorithm for Energy Efficient Routing, Modulation and Spectrum Assignment

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Resumo

Information and Communication Technology activities consumed 4% of the world energy in 2009, and such consumption will continue to increase due to the traffic growth of the Internet predicted for the next years. Techniques to make the core of the network more energy efficient has been proposed, among them, green routing has been considered a promising technique. This technical report proposes a novel Routing, Modulation Level and Spectrum Assignment (RMLSA) algorithm for elastic optical networks that considers the energy consumption of potential routes. Results indicate that this algorithm can save up to 34% energy and produce bandwidth blocking ratio two orders of magnitude lower than existing energy aware RMLSA algorithms.

1 Introduction

One of the main characteristics of the Internet architecture is to impose no constraint on the application layer which allows the fast emergence of new applications. These applications have heterogeneous bandwidth demands. While some applications have low bandwidth requirements, others such as IPTV and grid applications can demand bandwidth of the order of Gbits per second [1]. Such diversity of bandwidth demands calls for a rate-flexible transport network.

The Wavelength Division Multiplexing (WDM) technique brought great capacity to the Internet link layer by allowing the multiplexing of several wavelengths in a single fiber. Traditional WDM employs a fixed-size frequency allocation per wavelength with a guard-band frequency separation between two wavelengths. In WDM, the fixed capacity of a wavelength accommodates demands of different sizes. This leads to underutilization of the spectrum since demands rarely match the exact capacity of a wavelength. Sub-wavelength demands are usually groomed to decrease the capacity wastage. On the other hand, supra-wavelength demands require inverse multiplexing and the allocation of multiple independent WDM wavelength with wasteful allocation. Moreover, the necessary guard band between wavelengths contributes to spectrum underutilization. Although multi-rate

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WDM introduces some flexibility in resource allocation, its coarse allocation granularity can only ameliorate the problem in a limited way.

Such rigidness has recently led to the emergence of spectrum-sliced elastic optical path networking. In this technology, (Optical) Orthogonal Frequency Division Multiplexing (OFDM) is employed. OFDM is a multi-carrier transmission technology that slits high data rate channels into a number of orthogonal channels, called subcarriers, each with (sub-wavelength) low data rates. In flexible grid (elastic) networks, sub wavelength demands are directly supported in the optical domain and super-wavelength demands are granted by the aggregation of several carriers in a super-channel maintaining orthogonality among channels to save spectrum.

Similar to the routing and wavelength assignment (RWA) problem in WDM networks, solutions for the routing and spectrum assignment (RSA) problem in elastic optical networks are needed to accommodate traffic demands. Besides the spectrum continuity constraint that imposes the allocation of the same spectrum in each fiber along the route of a lightpath, in an RSA formulation, slots (carrier) must be contiguously allocated in the spectrum (the spectrum contiguity constraint).

To better utilize the spectrum available in elastic optical networks, different modulation formats can be used to achieve the highest possible transmission rates. However, the transmission of a high number of bits per symbol depends on the length of the path since the distance impacts the receiver capacity of decoding the received signal. Such restriction imposes another component to the RSA problem, since besides spectrum continuity and contiguity constraints, decision need to be made to choose the best modulation level to be used along the lightpath. Such problem is called Routing, Modulation Level and Spectrum Assignment (RMLSA). The choice of modulation opens opportunities to increase the energy efficiency of the network operations since each modulation scheme produces different transmission rates and energy consumption.

The Information and Communication Technology (ICT) activities consumed 4% of the world energy in 2009 [2], and it is estimated that such consumption will grow to 8% by 2020 [3]. Moreover, such energy consumption strongly impacts environmental issues, with ICT activities contributing with 2 to 2.5% of the global Green House Gases (GHG) emissions. Due to such impact of energy consumption, energy aware (green) mechanisms have been proposed to reduce the energy consumption in network transmissions.

One way to employ energy awareness in RMLSA problem is to consider the power consumption of the network devices during the route computation. Moreover, this paper proposes an algorithm called Energy Aware Multigraph Shortest Path (EAMGSP), which extends the Multigraph Shortest Path (MGSP) proposed by the authors in [4] to incorporate the modulation level choice as well as energy awareness. A cost function to account the power consumption of network devices in the RMLSA computation is proposed. Results indicate that the EAMGSP jointly used with this cost function can produce blocking probabilities 2 orders of magnitude lower when compared to other energy aware solutions as well as save up to 34% energy.

This paper is organized as follows. The next section describes related work. Section III introduces the EAMGSP algorithm and the new cost function. Section IV shows the energy consumption model employed in the paper. Section V introduces the cost function. Section

VI evaluates the performance of the EAMGSP algorithm. Section VII concludes the paper.

2 Related Work

Several papers have proposed energy aware RWA algorithms for WDM networks. In [5], strategies for energy efficiency in optical networks were presented, including green routing. In [6], the use of an auxiliary graph to represent the power consumption of network components was proposed so that routes with low energy consumption could be searched in the graph. Traffic grooming was formulated as an Integer Linear Programming (ILP) in [7], considering several components such as active router ports and traffic volume. Another ILP and a heuristic were proposed, to minimize the power consumption of packet switching and processing [8].

A traffic grooming algorithm was proposed in [9] which uses an auxiliary graph to represent the energy consumption of the network devices. It tries routing the paths inside zones of lower energy consumption. A multipath energy aware grooming scheme was proposed in [10]. It promotes energy savings by splitting the bandwidth demand of requests among several paths and aggregating established lighpaths with residual available bandwidth.

The RMLSA solution in [11] uses K shortest paths to calculate routes and a policy to allocate spectrum using the lowest starting slot available in the spectrum, the modulation is chosen based on the length of the paths, in a way that the chosen modulation uses less spectrum and can be successfully decoded by the destination.

In [12], two Integer Linear Programming for the RMLSA problem were proposed. In the first solution, the modulation choice is based on the length of each candidate route. In the second formulation, the problem is formulated as an ILP for choosing the route and modulation level, and the solution found is used as input for the solution of a spectrum assignment ILP problem.

An energy efficient RMLSA algorithm named EEKSP is proposed in [13]. The algorithm also uses a K shortest paths algorithm to find the candidate routes and it estimates the energy consumption of each route by using a formulation named $MetricPC$, which accounts spectrum usage, energy consumption of modulation schemes and energy consumption of Optical Cross Connectors (OXCs) and signal amplifiers. The algorithm produces higher energy efficiency than the ones proposed for WDM networks. The algorithm considers only the number of hops as parameters in the K shortest paths algorithm.

In this paper, it is introduced an RMLSA algorithm that tries to allocate lighpaths considering energy consumption parameters to choose paths with the least energy consumption. Such consideration was not made in previous papers [11]- [13]. The proposed approach also leads to lower blocking probabilities since it is not restricted to the K shortest paths algorithm that limits potential candidate paths.

3 The Energy Aware Multigraph Shortest Path Algorithm

The RMLSA algorithm was designed to operate in networks with dynamic arrival of requests for the establishment of lightpaths. It is assumed it is implemented in ideal Path Computation Elements (PCE) and that information about the status of spectrum availability is stored in PCEs databases.

It has been proved that the Routing and Spectrum Allocation problem is an NP-hard problem and heuristics are needed to solve the problem [12]. The proposed algorithm models the spectrum availability in the network as labelled multigraph. A multigraph is a graph which is permitted to have multiple edges (also called parallel edges), that is, edges that have the same source and destination vertex. In this auxiliary graph, vertices represent OXCs and edges the slots in the link connecting OXCs. All vertices are connected by N edges which is the number of slots in the spectrum of each network link. The label on an edge represent a metric related to slot availability. An ∞ value means that the slot is already allocated whereas the value 1 means that the slot is available for allocation. These values were defined to facilitate the employment of traditional shortest path algorithms.

The multigraph is transformed in $M \times (N - b_m)$ graphs where b_m is the bandwidth demand in slot of the requested channel using the modulation m and M is the number of possible modulation schemes. Actually, a multigraph per modulation level is created and $N - b_m$ graphs are generated for the multigraph associated with the m^{th} modulation scheme. These graphs are generated by fixing an edge of the multigraph and considering the b_m consecutive edges to the fixed edge. This set of b_m edges of the multigraph are mapped onto a single edge of the generated graph. Its cost is given by applying a specific cost function that considers the b_m edges. Figure 1 illustrates the multigraph representing the spectrum and one of the generated graph. For each of the generated graph, a shortest path algorithm is executed and the chosen path is the one that has the lowest cost among all the shortest paths found.

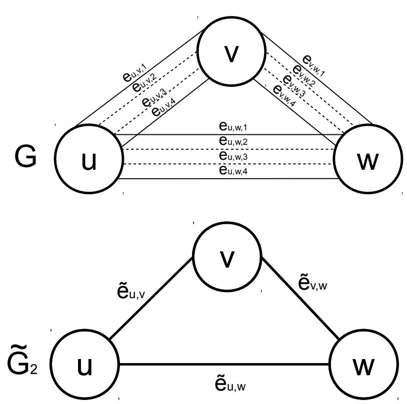

Figura 1: Multigraph representation of the spectrum

The following notation will be used to describe the algorithm:
s: source node;
d: destination node;
b: bandwidth demand;
$r(s, d, b)$: request from the node s to the node d with bandwidth demand b;

c: slot capacity in GHz;

$b_m = \left\lceil \frac{b}{m} \right\rceil \times c$: b_m is the ratio between the requested bandwidth b and the transmission rate of the modulation level m, multiplied by the capacity of the slots c, which gives the number of slots needed to allocate b using the modulation m;

N: number of slots between two nodes;

M: number of possible modulation levels;

$G = (V, E, C)$: labelled multigraph composed by a set of nodes V, a set of edges E and a set o edge costs C. The edges connecting two vertices of G represent the N slots in the link connecting two network nodes;

$E = \{e_{u,v,n}\}$: the set of edges connecting u and v;

$c(e_{u,v,n})$: cost of the edge $e_{u,v,n}$; $c(e_{u,v,n}) = 1$ if the n^{th} slot in the link connecting the OXCs u and v is not in use; $c(e_{u,v,n}) = \infty$ if the slot is in use;

$\widetilde{G}_m = (V, E_m, C_m)$: the m^{th} multigraph in which E_m is the set of edges connecting $\{u, v\} \in V$ and C_m is the set of costs associated with E_m using modulation level m,

$\widetilde{G}_{m,n} = (V, \widetilde{E}_{m,n}, \widetilde{C}_{m,n})$: the n^{th} graph of the multigraph $\widetilde{G}_m$, in which $\widetilde{E}_{m,n} = \{\widetilde{e}_{u,v,m,n}\}$ is the set of edges, and $\widetilde{C}_{m,n}$ is the set of costs associate with the edges;

$\widetilde{e}_{u,v,m,n}$: the n^{th} ordered set of edges such that $e_{u,v,m,n}$ is the least ordered edge and $e_{u,v,m,n+b_m}$ is the greatest ordered edge;

$\widetilde{c}(\widetilde{e}_{u,v,m,n})$: the cost of the set $\widetilde{e}_{u,v,m,n}$;

$\widetilde{C}_{m,n} = \{\widetilde{c}(\widetilde{e}_{u,v,m,n})\}$: the set of edge costs;

$SP(\widetilde{G}_{m,n}, r(s, d, b))$: shortest path in the graph $\widetilde{G}_{m,n}$ between nodes s and d;

$P_{m,n}$: a chain of $\widetilde{G}_{m,n}$ such that the source node s is the least ordered node and d is the greatest ordered node;

$C(P_{m,n}) = \sum_{\widetilde{e}_{u,v,m,n} \in \{P_{m,n}\}} c(\widetilde{e}_{u,v,m,n})$: the cost of the path $P_{m,n}$ is the sum of the cost of all the edges in the chain;

$C_{s,d}$: cost of the shortest path between s and d;

For a demand of b_m slots, $M \times (N - b_m)$ $\widetilde{G}_{m,n}$ graphs will be created, with edges corresponding to the mapping of b_m edges of G, starting with the n^{th} edge of G. Since the same ordered edges connecting any two nodes in G are mapped onto the edges of $\widetilde{G}_{m,n}$, the spectrum continuity is assured.

Algorithm 1 shows the EAMGSP algorithm. In Lines 1-3, the shortest paths are calculated, for each modulation level and for each set of b_m edges of the the multigraph. In the execution of the shortest path algorithm (SP), the number of slots needed to fulfil the traffic demand is calculated as a function of the transmission rate of the modulation m. The shortest path is chosen by comparing the cost of all chains $C(P_{m,n})$ and selecting the least cost chain (Line 4). If the shortest path found has infinite cost, there is no available path between s and d, with sufficient spectrum using any possible modulation level and the request should be blocked (Line 6). If the path has cost lower than infinity a new lightpath is established using the path $P_{m,n}$ and the modulation m. The allocated edges have their costs set to ∞ to represent the allocation (Line 9).

Since the Algorithm executes a shortest path algorithm $N - b$ times for each modulation, and considering the use of the Dijkstra Shortest Path algorithm, the computational complexity of the proposed algorithm is $M \times N \times (|V| + |E|) \times \log(|V|)$. As the number of

Algorithm 1 EAMGSP

$\forall m = 1...M$
  $\forall n = 1...N{-}b_m$
    $(C(P_{m,n}), P_{m,n}) = SP(\widetilde{G}_{m,n}, r(s,d,b_m))$
$C_{s,d} = C(P_{m,n}) \mid \forall i \forall j \; C(P_{m,n}) \leq C(P_{i,j})$
if $C_{s,d} = \infty$ **then**
  block $r(s,d,b_m)$
else
  establish $r(s,d,b_m)$ *as* $P_{m,n}$
  $C(e_{u,v,i}) = \infty \quad \forall \{u,v\} \in P_i \quad n = n...i{+}b_m$
end if

modulation schemes available are limited, and the number of slots are fixed for a network topology, the value of M and N can be expressed as constants, then the computational complexity of the algorithm is $(|V| + |E|) \times \log(|V|)$.

4 Energy Consumption Model

This section presents the energy consumption model introduced in the paper [13], which considers the energy consumption of multiple modulation levels, OXCs and optical Erbium Doped Fiber Amplifiers (EDFAs).

The modulation levels considered are presented in Table 1, along with their transmission rate, their power consumption and maximum feasible distance. The modulation used implies on a maximum possible distance, since the higher the number of bits per symbol, the stronger is the signal attenuation which can cause wrong decoding of the signal at the receiver. Although modulation levels with high bits per symbol consume more power, they are more efficient since the ratio of power consumed per bit is also higher.

Tabela 1: Slots capacity, power consumption and maximum distance of transmission for the modulation levels

Modulation format	Slots capacity (Gb/s)	M (W)	Maximum distance (m)
BPSK	12.5	47.13	4000
QPSK	25	62.75	2000
8QAM	37.5	78.38	1000
16QAM	50	94	500
32QAM	62.5	109.63	250
64QAM	75	125.23	125

The power consumption of OXCs is also accounted in the model, and it is a function of its node degree, the number of active ports of OXCs. OXCs consume $150 Watts$ and each port $85 Watts$ [13]. EDFAs have a constant power consumption of $200 Watts$.

The energy consumption of the network is given by:

$$EC_{trans} = \sum_{r \in R} S_r \times PC_m \times H_r \quad (1)$$

$$EC_{OXCs} = \sum_{o \in O} (D_o \times 85 + 150) \times T_o \quad (2)$$

$$EC_{EDFAs} = \sum_{a \in A} 200 \times T_a \quad (3)$$

$$EC_{total} = EC_{trans} + EC_{OXCs} + EC_{EDFAs} \quad (4)$$

where:
$R = \{r\}$: Accepted requests;
$O = \{o\}$: Set of OXCs;
$A = \{a\}$: Set of EDFAs;
PC_m: Power consumption of a slot according to its used modulation;
EC_{req}: Energy consumption of all the requests;
H_r: Lifetime of the r^{th} request;
S_r: Number of slots allocated by request r, without the band guards;
EC_{OXCs}: Energy consumption of all OXCs;
T_o: Time of operation of the o^{th} device;
D_o: Degree of connectivity of o^{th} the OXC;
EC_{EDFAs}: Energy consumption of all EDFAs;
EC_{total}: Total energy consumption of the network.

Equation 1 expresses the energy consumption of all the requests (EC_{req}) which is given by the sum of the power consumptions of all transmissions multiplied by their lifetimes. The energy consumption of the OXCs (EC_{OXCs}) is expressed in Equation 2 as the sum of all OXCs power consumption multiplied by their operation times. Equation 3 expresses the energy consumption of the EDFAs (PC_{EDFA}) as the sum of their power consumption multiplied by the operation time. Finally, Equation 4 expresses the total energy consumption of the network, which is given by the sum of the energy consumption of all accepted requests, OXCs and EDFAs.

5 Cost Function

In this section, we propose a cost function used by the EAMGSP algorithm. The power consumption of the modulation schemes is used to decide which paths to choose, so that paths with required capacity of transmission and which consume less power are prioritized. This is done by estimating the power consumption of the new path to be established by accounting the power consumption of the used network devices as well as the modulation levels employed.

The cost function is given by:

$$\widetilde{c}_m(\widetilde{e}_{u,v,m,n}) = \sum_{i=n}^{n+b_m} F_{u,v,m,i} \quad (5)$$

$$F_{u,v,m,i} = \begin{cases} D_v * 85 + 150 + \frac{b_m}{m \times c} \times PC_m \\ \qquad\qquad if\ c(e_{u,v,i}) = 1\ and\ d_{s,v} \leq\ MD_m \\ \infty \qquad otherwise \end{cases} \tag{6}$$

where:

c: Bandwidth capacity of a slot in GHz;

m: Modulation level, i.e. number of bits per symbol transmitted by the modulation scheme;

$d_{s,v}$: Distance between nodes s and v .

PC_m: Power consumption in Watts of the modulation level m;

MD_m: Maximum distance in Kilometres of a path using the modulation level m so that the received signal can be correctly decoded at the destination;

$$(PC_m, MD_m) = \begin{cases} (47.13, 4000) & for\ m = 1 \\ (62.75, 2000) & for\ m = 2 \\ (78.38, 1000) & for\ m = 3 \\ (94.00, 500) & for\ m = 4 \\ (109.63, 250) & for\ m = 5 \\ (125.23, 125) & for\ m = 6 \end{cases} \tag{7}$$

The cost $\widetilde{c}(\widetilde{e}_{u,v,m,n})$ is given by the sum of the cost of all edges of the chain (Equation 5). The function $F_{u,v,m,i}$ (Equation 6) expresses both the availability of the edges and if the distance feasible for decoding the signal at the receiver. In case one of the conditions is not satisfied the function has an infinite value. In case both are satisfied, the function assumes the value of power consumption given by the sum of the power consumption of the OXC plus $\frac{b}{m \times c}$ which represents the power consumption of the transmission using modulation m.

6 Numerical Evaluation

To assess the performance of the proposed algorithm, simulation experiments were employed and results compared with those given by the EEKSP algorithm [13] which uses a K shortest paths algorithm to compute routes. The parameter $k = 3$ was used since no significant gain were observed with higher values. The FlexGridSim [14] simulator was employed in the simulations, each with 100,000 requests as input. Confidence intervals with 95% confidence level were generated. The NSF (Figure 3) and the USA (Figure 2) topologies were used in the simulations. The NSF topology has 16 nodes and 25 links whereas the USA topology has 24 nodes and 43 links. The spectrum was divided in 240 slots of 12,5GHz each. The load varied between 25 erlangs and 800 erlangs, in steps of 25 erlangs, following the same pattern used in [13], for a matter of comparison between the two algorithms.

The metrics utilized in the comparison are the Bandwidth Blocking ratio, the total energy consumption and the energy efficiency which is the ratio between total data transmitted and the total energy consumed in the network, expressed in Mbits per Joule.

Figure 4 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. The proposed algorithm produces lower blocking ratios under low loads

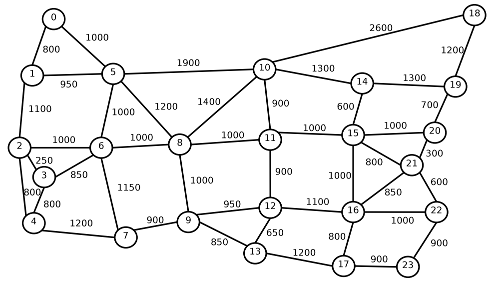

Figura 2: The USA topology

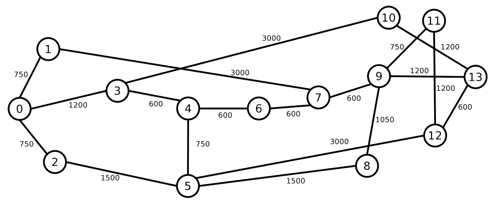

Figura 3: The NSF topology

and it starts to block only under 75 erlangs, while the EEKSP algorithm starts blocking requests under 25 erlangs. Under 75 and 100 erlangs, the proposed algorithm produces BBR values that can be two orders of magnitude lower. Under loads between 150 and 200 erlangs, the proposed algorithm produces BBR one order of magnitude lower than those given by EEKSP. The difference decreases for loads higher than 300 erlangs, and the BBR values are similar under loads higher than 350 erlangs.

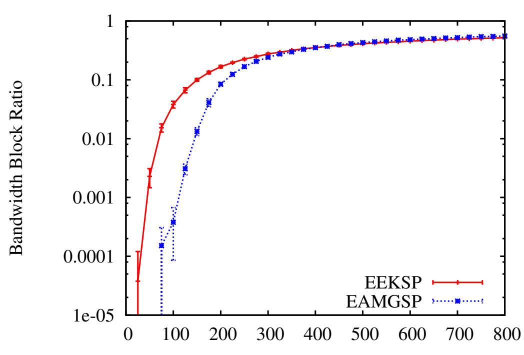

Figura 4: Bandwidth Blocking Ratio as a function of the load for the USA topology

Figure 5 shows the network energy consumption, in KJ as a function of the load for the USA topology. Under loads lower than 200 erlangs the EEKSP and the proposed algorithm have similar energy consumption. Under loads lower than 200 erlangs the difference between EEKSP and the proposed algorithm can be up to 2%. Under loads higher than 200 erlangs, the proposed algorithm consumes 11% less energy than does EEKSP. Under loads higher than 400 erlangs it consumes 27% less energy than does EEKSP.

The EAMGSP algorithm consumes less energy since the choice of the path considers the energy consumption of all elements, while the EEKSP algorithm find routes based only on the number of hops, which results in larger energy consumption solutions.

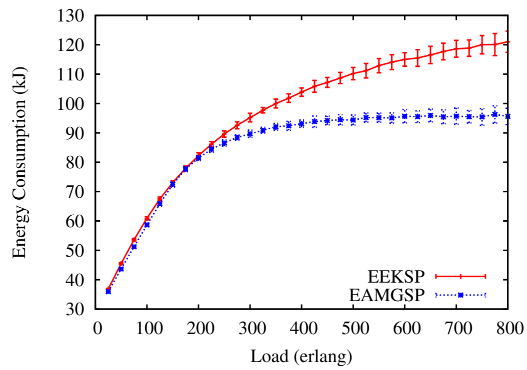

Figura 5: Energy consumption for the USA topology

Although the difference in energy consumption between EEKSP and EAMGSP under lower loads is not substantial, the EAMGSP algorithm produces significantly lower blocking ratios under these loads, which makes it more energy efficient. Figure 6 illustrates the energy efficiency of the algorithms for the USA topology. Under loads below 100 erlangs the EAMGSP consumes 7% less energy per bit than does the EEKSP algorithm, such difference increases to 11% under loads of 200 erlangs and to 17% under loads of 800 erlangs.

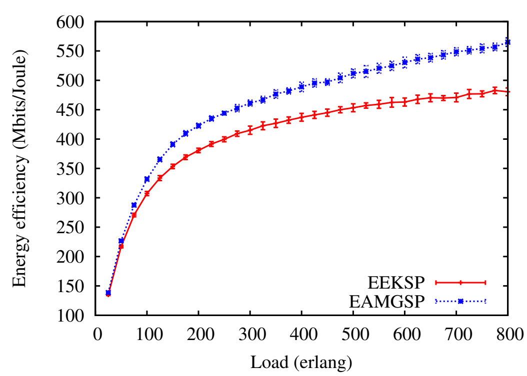

Figura 6: Energy Efficiency as a function of the load for the USA topology

Figure 7 shows the BBR as a function of the load for the NSF topology. The proposed algorithm blocks requests under loads of 125 erlangs while the EEKSP blocks requests under loads of 25 erlangs. Under loads of 125 erlangs, the difference between the BBR produced is two orders of magnitude and under 200 erlangs the difference is of one order of magnitude. Under loads higher than 300 erlangs, the BBR given by EEKSP and by the proposed algorithm differ slightly.

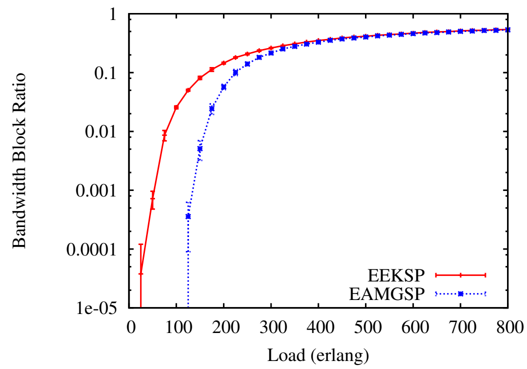

Figura 7: Bandwidth Blocking Ratio as a function of the load for the NSF topology

Figure 8 shows the energy consumption of the network in KJ for the NSF topology. The energy consumption behaviour is similar to that of the USA topology, with the maximum difference between EEKSP and EAMGSP being 6% under loads lower than 200 erlangs. EAMGSP saves up to 17% energy consumption under loads of 400 erlangs and up to 31% under loads of 800 erlangs.

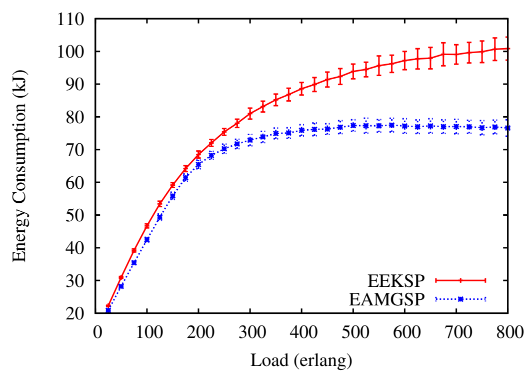

Figura 8: Energy consumption for the NSF topology

Figure 9 illustrates the energy efficiency of the algorithms for the NSF topology, in which the EAMGSP produces higher energy efficiency when compared to EEKSP, consuming 12%, 15% and 34% less energy per bit under loads of 100, 200 and 775 erlangs, respectively.

7 Conclusion

This paper introduced the Energy Aware Multigraph Shortest Path algorithm which represents the spectrum availability using multigraphs. Different modulation levels can be employed and the chosen modulation is the one which leads to the lowest energy consumption and which has as restriction a link length that allows the decoding if the signal at the destination.

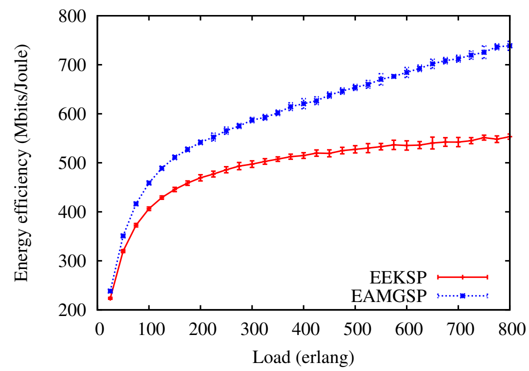

Figura 9: Energy Efficiency as a function of the load for the NSF topology

The EAMGSP algorithm can save up to 31% of energy, produces blocking ratio two orders of magnitude lower achieving up to 34% higher energy efficiency compared to EEKSP for the NSF topology. With those energy savings optical network providers can avail economic savings and diminish green house gasses emission.

8 Acknowledgements

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