Technological Forecasting & Social Change 127 (2018) 310–316

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

The capacity expansion approach in optical transport networks with fixed and flexible grids

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A R T I C L E I N F O

Keywords:
Technology upgrade, WDM networks
Capacity planning
Demand forecasting

A B S T R A C T

This paper addresses the issue of the backbone infrastructure capacity planning of WDM optical network related to upgrading of the existed fixed grid with the flexible grid technology. In order to determine the appropriate time for making the technology migration we propose a novel approach that is based on the penalty function as well as on the Blocking Bandwidth Ratio (BBR) metric. The penalty function depends on the forecasted traffic demands and relates to the congestion level of the considered link. According to these indicators the upgrade plan is determined. Through the case study the proposed approach is demonstrated.

1. Introduction

The expansion of network capacity became the standard part of the network operators' strategic decisions, considering the constant rise of the Internet traffic volumes caused by the rapid development of the digital market. The correlation between the growth of highly consuming Internet services and the growth of internet traffic volumes could be confirmed by many global reports, such as (Akamai Technologies, 2016; Cisco Systems, 2014). This fact creates the need for developing of the efficient tool for network upgrade decision timing, which leads to the significant cost savings for network operators.

Existing backbone/long-haul WDM networks which connect different regions and/or metro areas operate mostly using the fixed spectrum grid at the 50 GHz granularity (ITU-T G.692) (International Telecommunications Union (ITU), 1998), regardless of real throughput carried by each channel. This might lead to inefficient spectrum utilisation that reflects to the revenues for network operators. By slicing the spectrum into finer configurable slots of 12.5 GHz granularity, the flexible-grid technologies can efficiently overcome these limitations for the purpose of the on-demand provisioning. Considering the investments needed for the new technology implementation, it is not cost effective to make technology upgrade of the whole network. Rather, the partial network capacity expansion realized through the upgrade of certain number of bottleneck nodes by forming the "flexible islands" (Yu et al., 2015) makes a more acceptable scenario from the network operator's perspective. In this way, the already-implemented fixed-grid WDM equipment could be preserved. This implies the coexistence of fixed and flexible grid technologies, making it challenging from the network planner's perspective, in both, the space and time domain. The interoperability of fixed-grid and flexible-grid technologies is an actual issue that is analysed in the recent works (Yu et al., 2015; Ruiz et al., 2014).

The next-generation broadband networks will enable access to the applications (the Internet of things, big data, mobile technologies, cloud computing and data storage). In order to achieve these targets it is necessary to provide broadband Internet access at a speed of at least 100 Mbps to 96% of households by 2020 and a speed of not less than 30 Mbps to the remaining percentage of households (Skouby et al., 2014; Zhao et al., 2013a). Our investigation is according to this perspective. Considering this future level of demands at the broadband services market, the capacity upgrading of the network resources becomes the crucial task of the network planning process.

The reliable demand forecast is very important input for capacity upgrading of the optical network resources. For this purpose, we applied the diffusion theory to forecast traffic demand (Mahajan et al., 2000). The basic Bass diffusion model was chosen to forecast the future traffic growth of total fixed broadband access services/technologies at the telecommunication market (Bass, 1969). Considering the coexistence of above-mentioned optical technologies and the need for effective return on investments, it could be worth to investigate how long the already installed fixed-grid network equipment could be used on the certain network link.

This paper proposes a novel approach for determination the input parameters for the capacity expansion plan of the backbone WDM link. Due to a high speed of traffic changes we introduced the penalty function as well as the Bandwidth Blocking Ratio (BBR). The main innovative aspect of our research is related to combine these two metrics in order to decrease uncertainty of the forecasted demands. The

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http://dx.doi.org/10.1016/j.techfore.2017.10.009
Received 29 May 2017; Received in revised form 26 September 2017; Accepted 6 October 2017
Available online 14 October 2017

proposed approach gives the appropriate time for making decision about the capacity expansion of a certain fixed-grid WDM link during the considered period, regarding the scenario of the enlargement of "flexible island(s)". The proposed approach is demonstrated in the case of a given optical network. The forecasted fixed broadband traffic is obtained by diffusion theory.

The remainder of this paper is organized as follows. Section 2 surveys the related works. Section 3 gives the statement of the WDM link capacity expansion problem. The proposed approach is presented in Section 4. The case study provides the experimental results in Section 5, followed by the conclusions at the end of the paper.

2. Related works

Different approaches were proposed for the network capacity expansion/upgrade problem. Some of them related to fixed-grid WDM technology (Pickavet and Demeester, 1999) considered the long-term WDM network planning problem. These authors proposed three different models in order to compare the cost implications of these approaches on network expansion decisions, depending on different dynamic characteristics of network planning. Also, in (Melián et al., 2004) authors developed the optimal upgrading plan by mixed integer programming (MIP) model with the aim to find the best solutions to place the additional optical fibers, optical cross-connects (OXCs) and other WDM components within the given network at minimal costs. However, this model did not treat the traffic demands as uncertain. Considering the previous approaches related to the flexible-grid technologies, in (Papanikolaou et al., 2015) authors proposed integer linear programming (ILP) model that considered the capital expenditure of modular IP/MPLS routers at the optical network edges in the multilayer flex-grid network planning model. Shakya et al. (2015) proposed an ILP model to formulate the time-varying traffic assignment problem in flex-grid networks. The authors also proposed three novel spectrum assignment schemes heuristics based on the interference graph (IG) technique.

Recent researches consider deployment of the flexible-grid technology covering various aspects. In (Meusburger and Schupke, 2009) the impact of including forecast knowledge to the routing and aggregation decisions has been investigated, in terms of overall capital expenditures. However, this approach did not include the traffic demand forecast. In (Tahon et al., 2013) the problem of partial deployment of flexible-grid technology within the existing fixed-grid network has been considered in term of traffic grow uncertainty impact on the upgrade investment decision. The different technologies migration scenarios have been introduced. However uncertainty is considered only in general. In (Ruiz et al., 2014) the flexible-grid island is introduced as a key element of such a technology migration. This research introduced the migrating flowchart regarding the all-term planning process, also identified certain optimization issues related to the network reconfiguration, as well as key drivers needed to make the successful planning process. Yu et al. (2015) introduced different migration strategies, which have been discussed in the presence of several scenarios regarding the concept of "flexible islands". The coexistence of fixed-grid and flexible-grid technologies within the same optical network has been identified by these authors as research challenge, leaving some issues still opened.

However, abovementioned works have been mostly technology perspective oriented. Some other papers like (Peres et al., 2010; Todd and Doucette, 2017) pay attention to the market drivers and social influences. Generally the diffusion models have been proposed for capturing the lifecycle dynamics of new product/services (Mahajan et al., 2000). The most important model in this stream of research is the basic Bass model (Bass, 1969). In (Turk and Trkman, 2012) it has been shown that the basic Bass model is well suited to estimate broadband diffusion. The main advantages of the basic Bass model are given in (Bass et al., 1994). The later models mainly represented the modifications of the existing one, such as (Krishnan et al., 2000). The paper

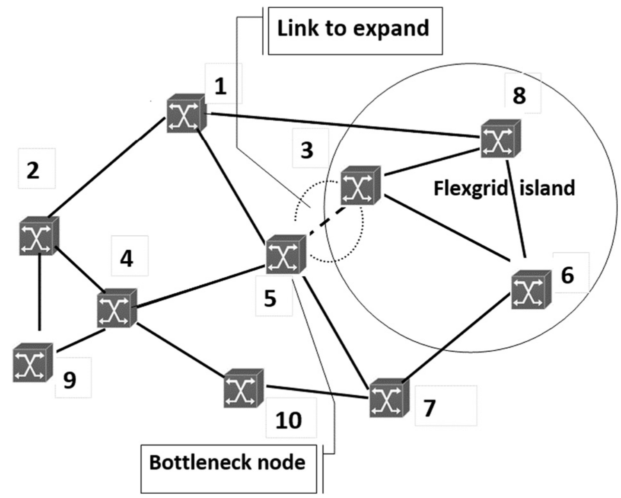

Fig. 1. The topology of gradually upgraded fixed-grid network.

(Mahajan and Peterson, 1978) gives the necessary assumptions which should be satisfied for the Bass model application. Further, the cumulative number of fixed broadband users function has been used to obtain the forecasted traffic demands according to Stordahl's traffic forecast model for the transport network (Stordahl et al., 2002). Similar approach is applied in (Radojicic et al., 2012) and (Jensen, 2003). In our research, we applied the basic Bass diffusion model as suitable approach to forecast the fixed-broadband market.

3. The capacity expansion problem

We study the capacity expansion problem of the critical link in the gradually upgraded fixed-grid optical network example, shown by Fig. 1. It connects a number of larger regions/metro areas (represented as nodes) with different broadband service demands. Several nodes, identified as bottlenecks are upgraded with flexible-grid technologies. In this way, the "flexible island" is created due the coexistence of fixed-grid and flexible-grid nodes.

The illustration of such coexistence is shown by Fig. 2, where the fixed-grid node is located between two flexible-grid nodes. In this example, the flexible-grid node generates demand of 200 Gbps toward the other flexible-grid node (through the fixed-grid node) by setting up two lightpaths, each with the capacity of 100 Gbps.

The link is considered as "critical" if it connects fixed-grid node to the flexible-grid node. The 50 GHz granularity certainly imposes the fixed-grid node to become a candidate for the "flexible island" enlargement. Such node becomes the network bottleneck when it begins to suffer due to exhaustion of available wavelengths. Thus, it becomes unable to participate in the process of establishing new lightpaths. If such an issue occurs, it is necessary to upgrade it to the flexible-grid technology by the "flexible island". In this way the traffic losses could be overcome. Besides, it is important to determine an appropriate time when upgrading procedure should be initiated. If the upgrading is realized too early, the available resources utilisation couldn't be at the satisfactory level. In addition, the equipment price could be higher considering the price decline in general. On the contrary, if the upgrading comes too late, the traffic losses will be significant, which might lead to the customers' dissatisfaction and the loss of service provider's revenue.

4. The proposed approach of capacity expansion plan

The main goal of this approach is to determine the best capacity expansion plan considering the future traffic demand. Unlike previous research, the proposed approach introduces two metrics, which are

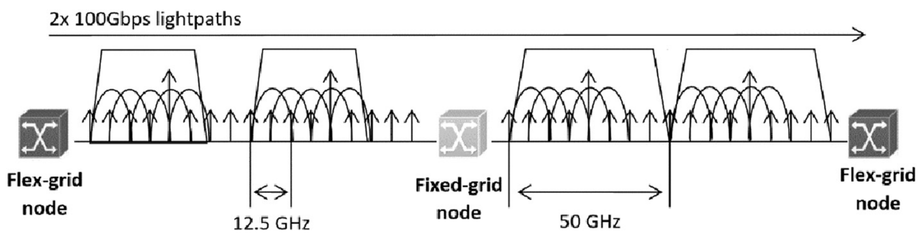

Fig. 2. The coexistence of flexible-grid and fixed-grid nodes – an example of 200 Gbps demand initiated by the flexible-grid node.

used as upgrading indicators: the penalty function that relates to the congestion level of the considered link, as well as the Bandwidth Blocking Ratio (BBR) (Keyao et al., n.d.). By reaching certain thresholds these metrics, synergistically, could indicate the appropriate time when the fixed-grid node upgrade should be done.

The main objective of medium-term planning is the capacity upgrading according to the forecasted demands for each planning period. Typically, the medium-term planning time scale is one year. In this approach, the traffic demands are forecasted by combining the basic Bass model (Bass, 1969) and the traffic forecast model for the transport network (Stordahl et al., 2002). The basic Bass model has three key parameters: the innovation parameter or external influence, the imitation parameter or internal influence and the market potential. The innovators follow the development of new service or technology and easily accept it. The imitation parameter reflects the influence of those users who have already adopted a new service/product by spreading "word of mouth" communication. The Bass model offers a very good tool for forecasting the broadband market (Turk and Trkman, 2012). In our research, it satisfied necessary assumptions: the user decision process is binary (user either adopts, or waits to adopt); the market potential remains constant (m); no repeat purchase; the impact of the word-of-mouth is independent of adoption time; sales of innovation are considered to be independent of the adoption or non-adoption of other innovation; the marketing strategies supporting the innovation are not explicitly included (Mahajan and Peterson, 1978).

The mathematical structure of the Bass model is derived from a hazard function corresponding to the conditional probability that an adoption will occur at time t given that it has not occurred yet. If $f(t)$ is the density function of time to adoption and $F(t)$ is the cumulative fraction of adopters at t, the basic hazard function underlying the Bass model is given by:

$$\frac{f(t)}{1 - F(t)} = p + q \cdot F(t) \tag{1}$$

This model has three key parameters: the parameter of innovation, p, the parameter of imitation, q and the market potential m. Parameter q reflects the influence of those users who have already adopted the new technology, while p captures the influence that is independent from the number of users. By assuming the constant value for the market potential, the cumulative number of fixed broadband users at time t, $N(t) = F(t)m$, could be given by following equation (Bass, 1969):

$$N(t) = m \cdot \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \tag{2}$$

A number of estimation procedures have been suggested for estimating the parameters p and q, such as the ordinary least squares (OLS), maximum likelihood estimation (MLE), nonlinear least squares (NLS), algebraic estimation (AE), etc. The market potential, m, could be estimated by analysing demographic statistical data for the observed traffic area, taking into account the birth rate and migration rate of population. Since this paper considers the broadband technologies related to the fixed users, the market potential could be determined as the ratio between total observed population and the average number of household members.

The forecasted traffic demands generated by broadband users in time t, denoted as x_t, could be obtained by using (Radojicic et al., 2012):

$$x_t = N(t) \cdot C(t) \cdot A(t) \cdot b(t) \cdot u(t) \cdot HP(t) \tag{3}$$

where: $C(t)$ is the mean downstream access capacity, $A(t)$ is the mean access capacity utilisation, $b(t)$ is the busy hour concentration factor, $u(t)$ is the packet switching concentration, $HP(t)$ is the fixed broadband access technology penetration. All these parameters are fully explained in (Radojicic et al., 2012).

The penalty function, $p_t(x_t/c_t)$, depends on the forecasted traffic demands, x_t, as well as on the capacity of the link c_t, connected to the observed fixed-grid node (Zhao et al., 2013b):

$$p_t(x_t/c_t) = \frac{x_t}{c_t - x_t},\ 0 < \frac{x_t}{c_t} < 1,\ x_t < c_t \tag{4}$$

The penalty level is used as the first indicator of reduced network performance, as well as users' dissatisfaction and potential loss of the service provider's revenue.

Apart from a reliable demand forecast, the Bandwidth Blocking Ratio (BBR) is additional indicator of the link performance deterioration. It is defined as the ratio of the bandwidth usage related to rejected traffic flows and the total bandwidth usage of all offered traffic on the observed link. In the case of WDM optical network the rejected traffic flows relates to lack of the available wavelengths.

Considering built-in parameters analogy from (Pavon-Marino and Izquierdo-Zaragoza, 2015), the Bandwidth Blocking Ratio of the observed link at the time t, BBR_t, could be obtained by:

$$BBR_t = \frac{\sum_{p_t \in P} x_{p_t} - c_t}{c_t} \tag{5}$$

where: $\sum_{p_t \in P} x_{p_t}$ is equal to the sum of the occupied capacity of each route traversing the observed link, x_{p_t}; P is the subset of the routing paths p_t that traverse the observed link at the time t.

5. Case study

The proposed approach is demonstrated in the case of a link that belongs to the gradually upgraded fixed-grid network (Fig. 1). The WDM optical network consists of 10 regions/metro-areas (MA) represented by corresponding nodes interconnected with backbone links. It is assumed that the network is partially upgraded with flexible-grid technologies at three nodes thus forming the "flexible island".

The fixed-grid node of the observed region/metro-area (MA5) is directly connected by the critical link to the abovementioned "flexible island" (i.e. to the node MA3). It is considered as candidate node for upgrading with flexible-grid technologies. The main goal of the case study is to determine the appropriate time for upgrading by using the reliable demand forecast as input parameter.

5.1. Forecasting the diffusion of fixed broadband services

In order to determine the appropriate time for upgrading considered link it is necessary to obtain the reliable demand forecast. For this purpose the official broadband market reports (2004 to 2016, (Republic of Serbia - Regulatory Agency for Electronic Communications and Postal Services (RATEL), 2016a, 2016b), (An overview of the telecom

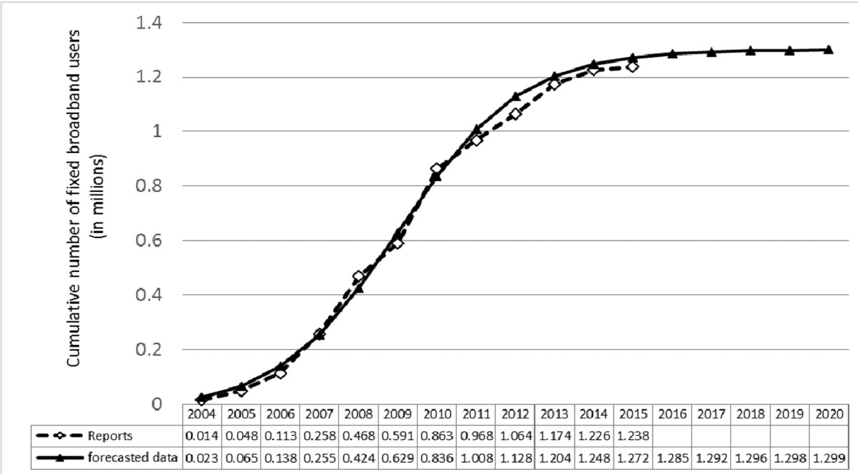

Fig. 3. Reported and forecasted cumulative number of fixed broadband users for the period (2004–2020).

market 2016 - Quarterly reports Q1–Q4 2016), (Overviews of Telecom Market 2006)) for the observed region/metro-area (MA5) are used (Fig. 3). The time scale of long-term planning is normally few years (from 3 to 5). The medium-term planning time scale should be equal to the one for long-term planning and is subdivided into several shorter periods typically around one year each. Concerning the overall broadband penetration the Bass model exhibited a well fitting performance to the observed data. The model parameters (m, p and q) are estimated by simple linear regression (Bass, 1969). The additional adjustment procedures were made to obtain the best matches of the real data and forecasted values. The following parameter values are obtained: $p = 0.013$, $q = 0.63$ and $m = 1.3$ (in millions), which are further used to forecast the corresponding cumulative numbers of the fixed broadband users for the period 2017–2020, by the Eq. (2), as shown in Fig. 3.

The precision of forecasted diffusion process is analysed by performing three tests: MAE (Mean Absolute Error, (Hamilton, 1994)), MAPE (Mean Absolute Percentage Error, (Lewis, 1982)), as well as The Durbin-Watson test (Montgomery et al., 2001). In order to quantify deviation in the data units, MAE and MAPE tests are conducted. If the value of MAE or MAPE is smaller, then better fit of the curve is achieved. The values obtained by MAPE could be also evaluated by using the Lewis scale of judgment of forecast accuracy (Lewis, 1982), as shown in Table 1.

In order to check for the existence of the systematic errors, the third test (Durbin-Watson) has been conducted, by using following equation:

$$DW = 2 - 2\frac{w}{v}, \tag{6}$$

where parameters w and v could be obtained by using Eqs. (7) and (8):

$$w = \sum_{t=1}^{n-1} (F(t) - \widehat{F}(t))(F(t+1) - \widehat{F}(t+1)) \tag{7}$$

$$v = \sum_{t=1}^{n} (F(t) - \widehat{F}(t))^2 \tag{8}$$

The values of DW test belong to the range of 0–4, where the scope

Table 1
A scale of judgment of forecast accuracy (Lewis, 1982).

MAPE	Judgment of forecast accuracy
Less than 10%	Highly accurate
11 to 20%	Good forecast
21 to 50%	Reasonable forecast
51% or more	Inaccurate forecast

Table 2
The evaluation of the forecasted values.

Test	Evaluation results
MAE	0.029
MAPE (%)	12.702
DW	1.53846

1.5–2.5 indicates the absence of first-order autocorrelation (the best case is the DW value of 2).

The evaluation of the forecasted results for considered access technologies is performed by the above-mentioned tests (Table 2).

The evaluation of the forecasted values conducted by the usage of MAPE test shows very low value indicating that the Bass model has the good forecast, which is also confirmed with very low value, obtained by conducting the MAE test. Additionally, the Durbin-Watson test shows the absence of first-order autocorrelation, indicating there are no systematic errors within forecasted data.

5.2. *Forecasting traffic demands generated by broadband users*

In order to obtain forecasted traffic demands generated by the fixed broadband users, the Eq. (3) has been used and following parameters has been assumed:

- the mean downstream access capacity, $C(t)$, is continuously increasing to higher access capacities especially in order to offer new and enhanced applications, so according to (Republic of Serbia - Regulatory Agency for Electronic Communications and Postal Services (RATEL), 2006, 2016a, 2016b), it is assumed that it will polynomial increase in the future with following rule: $C(t) = 487.62\,t^2 - 1011.8\,t + 1974.9$ (Fig. 4)
- measurement results show that the mean access capacity utilisation is changing over with linear trend $A(t) = 0.0231\,t + 0.0657$, $R^2 = 0.983$ (Fig. 5)
- by examining data obtained from the available traffic monitoring system, it is found that the packet switched concentration factor, $u(t)$, is nearly constant value: $u(t) = u = 0.78$, while the busy hour concentration factor, $b(t)$ is changing over with linear trend $b(t) = 0.0028\,t + 0.2431$, $R^2 = 0.9973$ (Fig. 6).
- based on the official telecommunication reports (An Overview of Telecom Market in the Republic of Serbia in 2015 2016), (An overview of the telecom market 2016 - Quarterly reports Q1–Q4 2016), (Overviews of Telecom Market 2006), the fixed broadband access technology penetration, $HP(t)$, shows logarithmic trend $HP(t) = 18.189 ln(t) - 22.214$, $R^2 = 0.9821$ (Fig. 7). The service

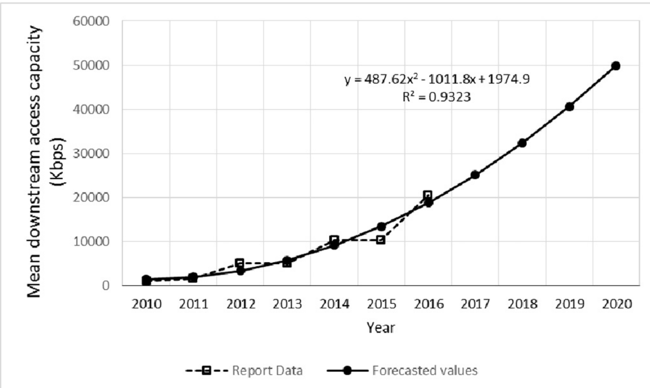

Fig. 4. Mean downstream access capacity.

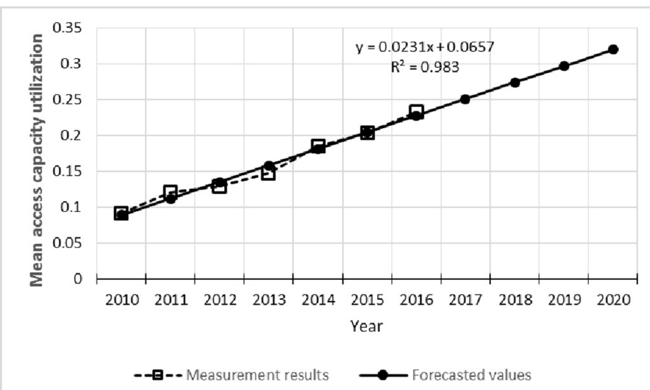

Fig. 5. Mean access capacity utilisation.

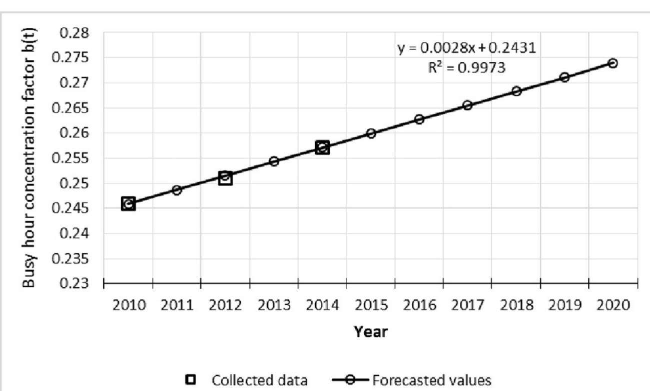

Fig. 6. Busy hour concentration factor.

penetration should not exceed the ICT Development Index (IDI) - "g - reference value" (International Telecommunication Union, 2012).

In this way the forecasted cumulative traffic demand for single metro-area (MA5) regarding the access technologies, which are present in the broadband market could be obtained (Fig. 8).

In order to generate any-pair connection requests across the network the following setup of parameters and traffic profiles are adopted from (Yu et al., 2015):

- It is assumed that fixed-grid link has 80 wavelengths, while flexible-grid link has 320 frequency slots, as well as the spectrum allocation for the both, fixed-grid and flexible-grid, regarding demands up to 40 Gbps, 100 Gbps, 200 Gbps and 400 Gbps, respectively (Table 3).

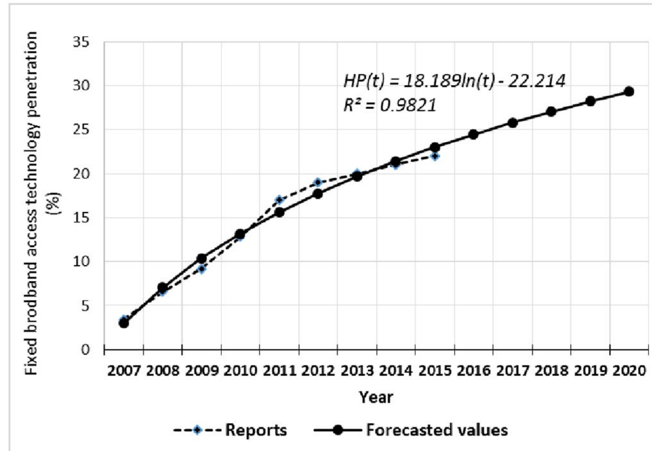

Fig. 7. Fixed broadband access technology penetration.

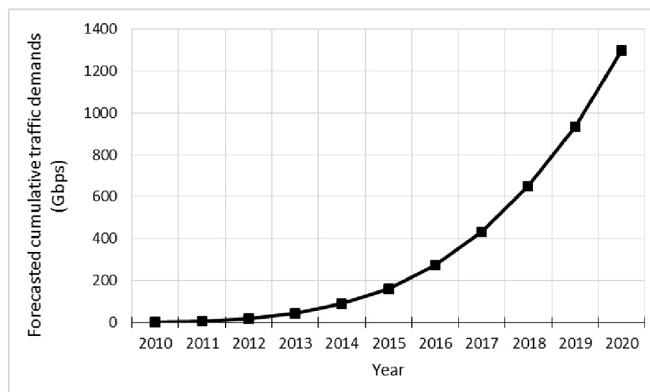

Fig. 8. The forecasted cumulative traffic demand for single metro-area (MA5) regarding the access technologies, which are present in the broadband market.

Table 3
Spectrum allocation regarding bandwidth demand (Yu et al., 2015).

Channel	Fixed grid		Flexible grid	
	Spectrum	Wavelengths	Spectrum	Slots
40 Gbps	50 GHz	1	25 GHz	2
100 Gbps	50 GHz	1	37.5 GHz	3
200 Gbps	100 GHz	2	75 GHz	6
400 Gbps	200 GHz	4	125 GHz	10

Table 4
Traffic profiles regarding traffic demand ratios (Yu et al., 2015).

Demand	Profile P1	Profile P2	Profile P3
40 Gbps	50%	20%	0%
100 Gbps	30%	50%	40%
200 Gbps	15%	20%	40%
400 Gbps	5%	10%	20%

- Three traffic profiles denoted as P1, P2 and P3 are assumed, as shown in Table 4.
- For the traffic generation purposes, it is assumed that connection demands are generated following the Poisson arrival with requirements, which are uniformly chosen among the values of 40 Gbps, 100 Gbps, 200 Gbps and 400 Gbps.
- It is assumed that connection arrivals follows the Poisson process (Pavón Mariño, 2016) with the arrival rate, λ, and exponentially

Table 5
Metro-area (MA5) - Bandwidth Blocking Ratio and utilisations regarding the traffic profile and year.

Year	Traffic profile	BBR	Utilisation (x_t/c_t)
2016	P1	0	0.425
	P2	0	0.500
	P3	0	0.588
2017	P1	0	0.575
	P2	0	0.663
	P3	0	0.750
2018	P1	0	0.850
	P2	≈ 0	0.863
	P3	≈ 0	0.975
2019	P1	0.002838	0.987
	P2	0.013798	0.988
	P3	0.044178	0.989

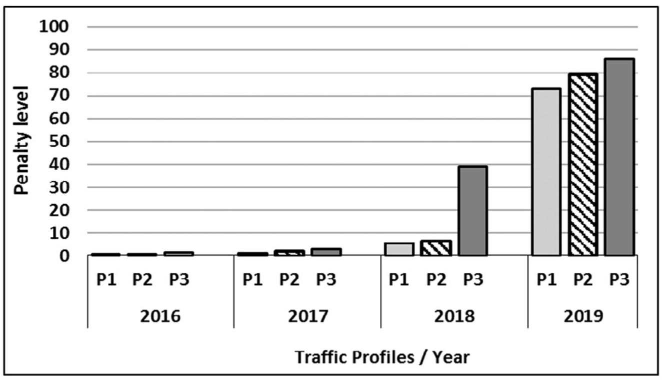

Fig. 9. The penalty levels of the observed bottleneck link for the forecasted period (2016–2019).

distributed holding time with the mean value normalized to $1/\mu = 1$. Hence, the traffic load could be expressed as $\rho = \lambda/\mu = \lambda$ Erlangs. In this approach, the Net2Plan 0.4.2 (Pavon-Marino and Izquierdo-Zaragoza, 2015) is used to determine parameters needed to calculate BBR ratios. We supposed that BBR threshold for the fixed grid upgrade is 0.01.

Based on these parameters, the Net2Plan custom script has been created. Traffic matrices are generated (using external editing tool) in incremental manner according to the forecasted cumulative number of demands for each metro-area and to fit each of the abovementioned traffic profiles.

By loading these traffic matrices, offline network planning tool has been applied separately for each year, using the algorithm based on ILP (Integer linear programming) solving of the RSMA (Routing Spectrum Modulation Assignment) problem, in the presence of the fixed-grid and flexible-grid WDM networks (Pavón Mariño, 2016, GIRTEL research group, n.d.).

Upon series of the offline planning tool executions, the results related to the node 5 (MA5) have been gathered in order to obtain utilisations per each year and per each traffic profile. Further, using the eq. (5) the corresponding BBR values per year and per traffic profile are calculated (Table 5).

Finally, the obtained utilisations are used for calculating penalty levels using the Eq. (4) and results are shown in Fig. 9.

From Table 5 and Fig. 9 certain similarities could be noticed:

- BBR values are equal/nearly equal to zero until the year of 2019, due to absence of the traffic overload. Further, in 2019, BBR values, which correspond to the traffic profiles P2 and P3, reached the trigger value (0.01); According to this metric only, the upgrade has to be realized in 2019 regarding these two profiles;
- The significant increase of the penalty level for the traffic profile P3 indicates the link performance deterioration in the year of 2018;
- Further increase of the penalty levels happened in the year of 2019 indicating further performance deterioration, regardless of the traffic profile.

According to these facts, the following capacity expansion plan for the metro-area MA5 should be suggested:

- The upgrading process should be initiated in the year of 2018 for the traffic profile P3. The whole upgrade process has to be finished by the end of the year of 2019, because of high BBR value (0.044178);
- The upgrading process should be performed in the year of 2019 for the traffic profiles P1 and P2 according to the high penalty levels for both profiles as indicated in the Fig. 9, as well as high BBR value for profile P2 (0.013798).

Note that this paper considers simultaneously only one critical link as the network bottleneck. Also, our approach for determination the appropriate time for network upgrading does not take into account the component costs i.e. installation, upgrading and un-installation costs of the different systems, etc. In addition, it should be considered the price decline during the time as further research. Although our approach is general, we analysed it considering through the selected traffic profiles.

6. Conclusions

In this paper, the problem of coexistence of the WDM fixed-grid and flexible-grid nodes within the same optical network is considered. For this purpose, two indicators are employed: the Bandwidth Blocking Ratio and the penalty level of the observed link load. These two metrics indicate the appropriate time when the observed node should be merged with the flexible island, such expanding the capacity of its corresponding link. In this way, the uncertainty of the decision making process is decreased. Our further research could include additional metrics related to further improve of the upgrade decisions as well as other traffic profiles.

The statistical indicators concerning the forecasting behaviour of the Bass model, namely, MAE, MAPE and DW showed very satisfactory results. Future study about the comparison of the Bass model for the broadband penetration should be considered. In any case, in the future a better estimation of the Bass model's parameters and the correlation with network externalities and social indices is necessarily.

It could be noticed that our proposed approach takes care about the usage of the currently available fixed-grid resources as much as possible. By identifying the appropriate time for node upgrade, the link performance deterioration is avoided. Such scenario could be more acceptable from the network operator's perspective. In this way, the benefit of the proposed approach is reflected to prevention of the potential loss of service provider's revenues considering the time of return on investment, as well.

Acknowledgement

This paper is partially supported by the Serbian Ministry of Education and Science under projects No. 036012 and No. 032025.

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