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# Ultra-Wideband WDM Optical Network Optimization

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**Abstract:** Ultra-wideband wavelength division multiplexed networks enable operators to use more effectively the bandwidth offered by a single fiber pair and thus make significant savings, both in operational and capital expenditures. The main objective of this study is to minimize optical node resources, such as transponders, multiplexers and wavelength selective switches, needed to provide and maintain high quality of network services, in ultra-wideband wavelength division multiplexed networks, at low cost. A model based on integer programming is proposed, which includes a detailed description of optical network nodal resources. The developed optimization tools are used to study the ultra-wideband wavelength division multiplexed network performance when compared with the traditional C-band wavelength division multiplexed networks. The analysis is carried out for realistic networks of different dimensions and traffic demand sets.

**Keywords:** Ultra-Wideband WDM System Design; Optical Network Optimization; CDC-F technology; Optical Node Model; Network Congestion; Linear Programming (LP); Integer Programming (IP)

## 1. Introduction

Optical networks based on Wavelength Division Multiplexing (WDM) technology that operate within the C-band are near the limit of their capacity. New ideas are hence explored to increase the data transmission rates in WDM networks. These include especially the use of transmission wavelengths adjacent to the C-band, i.e. the Ultra Wideband WDM (UW-WDM) systems, and systems that rely on use of optical fibers with a larger number of cores, i.e. Space Division Multiplexing (SDM) systems. Of these two approaches to increasing the telecommunication network transport capacity the former one is at the moment much nearer to the practical implementation since the latter is linked with the need to deploy multicore fibers. Hence, the analysis of routing in UW-WDM systems is the main subject of this contribution.

From the network operator point of view, the ever-increasing demand for high-speed data services translates into the need to continually upgrade the networks to increase the data transmission rate per optical fiber. In currently deployed optical networks, which are based on single core fibers, the data transmission rate can be increased by using either a larger per-channel bit rate or by increasing the number of available channels. Further, increase of transmission rate can be achieved by using transponders with advanced modulation formats or by adding polarization multiplexing. All these means of increasing the data transmission rate within the C-band will reach soon the limits set by the

31 information theory and the physics of the optical pulse propagation within silica glass optical fibers.  
32 Thus the WDM network equipment providers have to expand the system capacity by reaching out to  
33 other segments of the optical spectrum that are available in silica glass optical fibers, i.e. the S-band  
34 and L-band.

35 Existing fiber optic networks that operate in C-band (1530 nm to 1565 nm) typically support up to  
36 96 channels of 50 GHz bandwidth. The selection of the C-band for optical long-haul communications  
37 was justified by the presence of low light attenuation in silica glass fiber and by the availability of high  
38 quality, low cost erbium ion doped fiber amplifiers (EDFAs) pumped by semiconductor lasers. One  
39 option for gaining additional capacity in C-band WDM systems is to use flexible grid, which enables  
40 provisioning flexible size WDM channels (flexible grid) with bandwidth as small as 12.5 GHz and the  
41 carrier wavelength step of 6.25 GHz. This allows for a more effective use of the available bandwidth  
42 within the C-band, mainly by effectively reducing the guard bands. However, once all transmission  
43 channels of the C-band are filled, the only way of further increasing the link capacity is through adding  
44 on a new pair of fibers. Since many backbone network service providers lease fiber pairs, adding a  
45 new fiber pair translates into a significant increase of the network operating cost and thus may prove  
46 prohibitively expensive. Considering that the fiber lease prices are usually quoted per fiber length unit  
47 [1], a large increase of operational costs may prevent further network expansion particularly in the  
48 network sections that use long routes.

49 An alternative approach that provides additional capacity to the optic network operators is the  
50 use of L-band (1565 nm to 1625 nm). The throughput obtained using both C and L bands is significantly  
51 larger than that obtained using C band only [2,3], and recently it was shown to exceed 100 Tb/s [4],  
52 reaching even 150 Tb/s when C, L, and S bands are used [5]. The L-band shares the main characteristics  
53 with the C-band, i.e. low attenuation in silica glass fibers and availability of good quality and cost  
54 effective EDFAs pumped by semiconductor lasers. The network equipment providers already offer  
55 solutions that allow taking advantage of the C-band and L-band in one fiber pair. Such UW-WDM  
56 solution provides up to 192 50 GHz bands instead of 96 channels available in the traditional C-band  
57 WDM systems. Thus in this paper we explore the advantages of UW-WDM system using C+L-band  
58 when compared with the traditional C-band based WDM system.

59 The currently available UW-WDM routing architecture provides channels with minimum  
60 bandwidth of 12.5 GHz and the carrier wavelength step of 6.25 GHz (flexible grid) over the C+L  
61 bands along with colorless, directionless and contentionless operation (CDC-F). In modern optical  
62 WDM networks based on CDC-F Reconfigurable Optical Add Drop Multiplexer (ROADM) operating  
63 within C+L band wavelength routing improves to the point whereby practically every segment of the  
64 available bandwidth can be accessed by a transponder with an almost arbitrary carrier wavelength  
65 and operating bandwidth. Thus the overall network flexibility increases and potentially reduces the  
66 operational costs. CDC-F ROADMs allow for simple adding, dropping and express routing traffic  
67 through network nodes and hence offer benefits such as simple planning, simple and robust bandwidth  
68 utilization and low cost network maintenance since CDC-F ROADMs conform with Software Defined  
69 Network (SDN) paradigm. Finally, the advantages of the CDC-F ROADM structure enable operators  
70 to offer a flexible service, which may translate into reduction of Operational Expenditure (OpEx) and  
71 Capital Expenditure (CapEx) when compared with other solutions [6,7].

72 During the last decade attention of the telecommunication community has been concentrated on  
73 Routing and Wavelength Assignment (RWA) and Routing and Spectrum Allocation (RSA) problems.  
74 Consequently, numerous exact and heuristic methods are now available to solve RWA and RSA  
75 problems in static [8–11] and dynamic [12–14] environment. However, only recently the relevance of  
76 the ultra wideband networks has been considered. This study concentrates on the optimization  
77 of UW-WDM networks. The problem is formulated using Mixed Integer Programming (MIP).  
78 A comparative study of UW-WDM and classical C-band WDM network is performed. Network  
79 topologies used in the simulations are realistic and representative for optical DWDM networks for

80 selected countries [15]. Traffic demands are typical for DWDM networks and are represented using a  
81 traffic matrix.

82 The rest of the paper is organized as follows. In the second section, the mathematical background  
83 relevant to the applied optimizing procedures is provided. In the third section, a discussion of the  
84 results is provided, which is followed by a concise summary given in the last section.

## 85 2. Problem formulation

86 In this section, UW-WDM network optimization problem is formulated using MIP. For this  
87 purpose the following sets are defined:

88  $\mathcal{N}$  set of all nodes

89  $\mathcal{T}$  set of transponders

90  $\mathcal{S}$  set of frequency slices

91  $\mathcal{E}$  set of edges

92  $\mathcal{P}_{(n,n')}$  set of paths between nodes  $n, n' \in \mathcal{N}$ ;  $p \subseteq \mathcal{E}$

93  $\mathcal{B}$  set of bands

94  $\mathcal{S}_b$  set of frequency slices used by band  $b \in \mathcal{B}$ ;  $\mathcal{S}_b \subseteq \mathcal{S}$ ;  $\bigcup_{b \in \mathcal{B}} \mathcal{S}_b = \mathcal{S}$

95  $\mathcal{S}_t$  set of frequency slices that can be used as starting slices for transponder  $t \in \mathcal{T}$ ;  $\mathcal{S}_t \subseteq \mathcal{S}$

96 The following objective cost function is optimized using an IP algorithm subject to the listed  
97 below constraints:

$$\min \sum_{b \in \mathcal{B}} (\zeta(b) \sum_{e \in \mathcal{E}} y_{be} + \sum_{t \in \mathcal{T}} \zeta(t, b) \sum_{n, n' \in \mathcal{N}} \sum_{p \in \mathcal{P}_{(n,n')}} \sum_{s \in \mathcal{S}_t} x_{tnn'ps}) \quad (1)$$

98 where,  $\zeta(b)$  is a cost of using band  $b$  at a single edge (equipment like: ETFAs, preamplifiers, and  
99 boosters are considered),  $y_{be}$  is a binary variable, equals 1 if band  $b$  is used on edge  $e$  and 0 otherwise,  
100  $\zeta(t, b)$  is a cost of using a pair of transponders  $t$  in band  $b$  and  $x_{tnn'ps}$  is a binary variable that equals 1 if  
101 transponders  $t$  are installed between node  $n$  and node  $n'$ , routed on path  $p$ , and starting on frequency  
102 slice  $s \in \mathcal{S}_t$  and 0 otherwise.

103 In the cost model ETFAs, preamplifiers, boosters, and transponders are included but not WSSs,  
104 ILAs, and filters since the latter devices are not a subject of optimization.

105 In the model the following three constraints have been included:

$$\sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}_{(n,n')}} \sum_{s \in \mathcal{S}_t} v(t) x_{tnn'ps} \geq d(n, n') \quad \forall n, n' \in \mathcal{N} \quad (2)$$

106 where,  $v(t)$  is a bitrate provided by transponder  $t$  and  $d(n, n')$  is a bitrate demanded from node  $n$  to  
107 node  $n'$ .

$$x_{tnn'ps} h \nu(b) c(t) \Delta(t) \sum_{e \in \mathcal{E}} w(n, n', p, e) \cdot (f(e) (e^{\frac{\lambda(s)l(e)}{1+f(e)}} + V - 2) + (e^{\frac{\lambda(s)l(e)}{1+f(e)}} + W - 2)) \leq P_0 \quad (3)$$

$$\forall t \in \mathcal{T}, \forall n, n' \in \mathcal{N}, \forall p \in \mathcal{P}_{(n,n')}, \forall b \in \mathcal{B}, \forall s \in \mathcal{S}_b$$

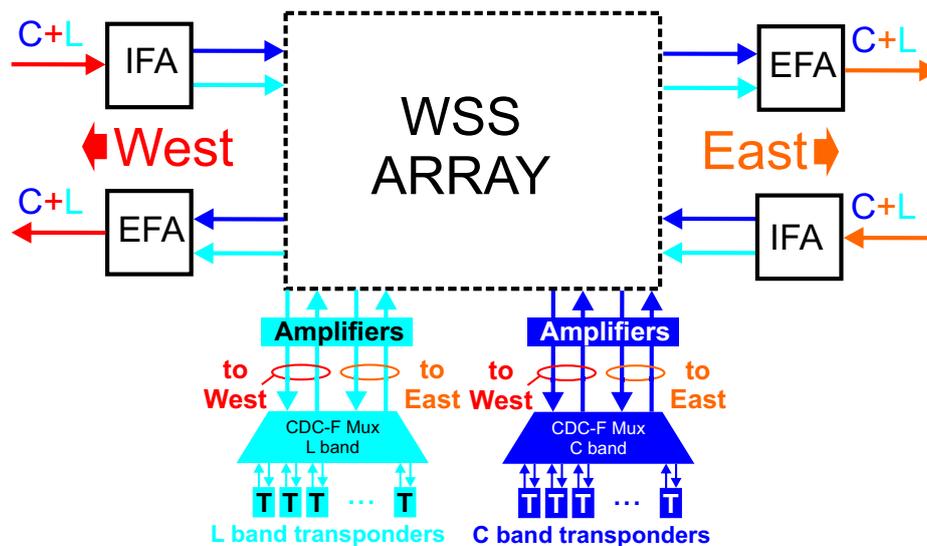
108 where,  $h$  is the Planck constant equal to  $6.62607004 \cdot 10^{-34} m^2 kg/s$ ,  $\nu(b)$  is a frequency of band  $b$ ,  $c(t)$   
109 is an OSNR of transponder  $t$ , which has been calculated using the standard formula, c.f. [16–19].  
110  $\Delta(t)$  is the bandwidth used by a transponder  $t$ ,  $f(e)$  is a number of In-Line Amplifiers (ILAs) evenly  
111 distributed over edge  $e$  to re-amplify the signal in order to prevent OSNR from dropping to a very  
112 small value,  $\lambda(s)$  is a loss per km using slice  $s$ ,  $l(e)$  is a length of edge  $e$ ,  $V$  is the gain of ILA,  $W$  is the  
113 gain of fibre amplifier that compensates the nodal loss while the transmitter output power for a single  
114 WDM channel is assumed to equal to 1 mW and is represented by  $P_0$ . Finally, a constraint is added for  
115 avoiding duplicate allocation of the same wavelength in an edge:

$$\sum_{t \in \mathcal{T}} \sum_{n, n' \in \mathcal{N}} \sum_{p \in \mathcal{P}_{(n, n')}} \sum_{s \in \mathcal{S}_t} w(n, n', p, e) u(t, s, s') \cdot x_{tnn'ps} \leq y_{be} \quad \forall e \in \mathcal{E}, \forall b \in \mathcal{B}, \forall s' \in \mathcal{S}_b \quad (4)$$

116 where,  $w(n, n', p, e)$  is a binary constant that equals 1 if a path  $p$  between nodes  $n$  and  $n'$  uses edges  $e$   
 117 and 0 otherwise,  $u(t, s, s')$  is a binary constant that equals 1 if transponder  $t$  using bandwidth starting  
 118 at frequency slice  $s$  also uses frequency slice  $s'$  and 0 otherwise.

119 The subject of minimization is the cost of installed amplifiers and transponders in (1). Constraints  
 120 (2) ensure that all demands are satisfied. Constraints (3) ensure that all installed transponders are  
 121 routed in such a way that their power budgets are not exceeded. Notice that these constraints can  
 122 be precalculated and reduced to  $x_{tnn'ps} = 0$  for some combinations of indices and removed for other  
 123 combinations. Finally, (4) ensure that using a band results in installing appropriate amplifiers. Notice  
 124 that these constraints also ensure that each frequency slice at each edge is not used more than once. It  
 125 is noted that the constraints included do not allow for considering nonlinear interactions and resulting  
 126 signal impairments.

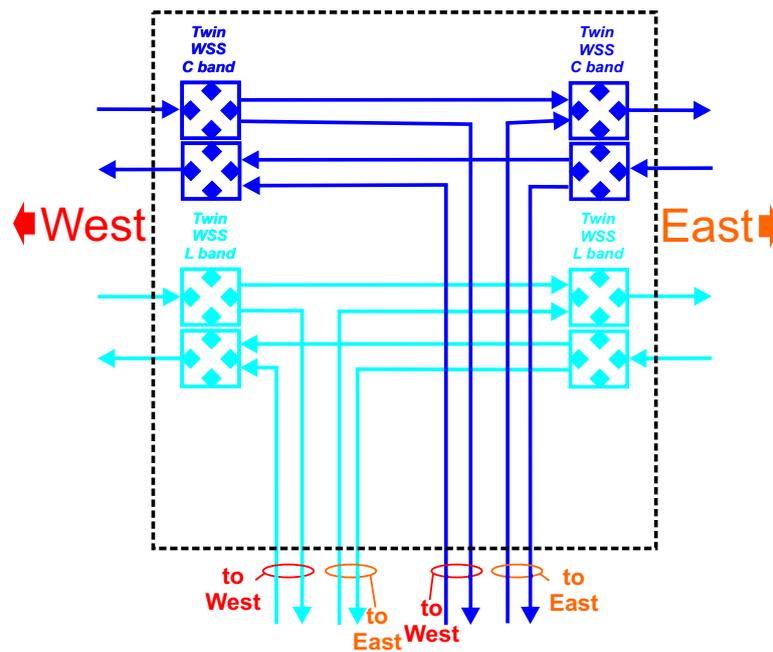
127 Fig. 1 shows a schematic diagram of a two dimensional CDC-F Reconfigurable Optical Add Drop  
 128 Multiplexer (ROADM) architecture for an UW-WDM optical network operating within C+L-band that  
 129 has been assumed whilst performing optimization. Higher dimensional nodes are arranged in an  
 130 analogous manner.



**Figure 1.** Schematic diagram of a two-dimensional colourless, directionless, contentionless, flexible grid (CDC-F) ROADM used in C+L WDM systems; WSS - Wavelength Selective Switch, IFA - Ingress Fiber Amplifier, EFA - Egress Fiber Amplifier.

131 In Fig. 1 Ingress Fiber Amplifier (IFA) amplifies the signal entering the ROADM from a  
 132 transmission line. In IFA the C and L band are separated using a C/L band splitter and the C  
 133 and L band signals are fed separately to C and L band fiber amplifiers. After amplification the C and L  
 134 band signals are fed separately to Wavelength Selective Switch (WSS) array. The inner structure of the  
 135 WSS array is shown in Fig. 2.

136 The C and L band signals are handled separately by C-band and L-band WSSs that connect the  
 137 signals entering and leaving the node with the CDC-F multiplexers and transponders (Fig. 1). The  
 138 signals leaving the node are boosted by the Egress Fiber Amplifiers (EFAs). In an EFA similarly as



**Figure 2.** Schematic diagram of Wavelength Selective Switch (WSS) array used in CDC-F ROADM from Fig.2.

139 for IFA and C-band and L-band signals are amplified separately and combined together using a C/L  
 140 band combiner before being sent into the transmission line. The overall network node attenuation for  
 141 transit traffic and for add-drop channels has been assumed equal to 15 dB and independent of the  
 142 node dimensionality up to the maximum node dimensionality considered in the networks studied, i.e.  
 143 6 (Fig. 3 - Fig. 5). This assumption is well justified by the fact that the actual architecture of optical  
 144 node equipment is based on a fixed maximum node dimensionality.

### 145 3. Results and Discussion

146 Computational results were obtained for three optical networks, Polish (Fig. 3), American (Fig.  
 147 4) and German (Fig. 5) that have different characteristics. The networks correspond to actual optical  
 148 networks stemming from specified countries and were taken from [15]. Table 1 and Fig. 3 – Fig. 5  
 149 provide the relevant parameters for both networks and their topologies.

**Table 1.** Analyzed network parameters.

network	# nodes	# link	# demand
Polish	12	18	66
USA	12	15	66
German	17	26	136

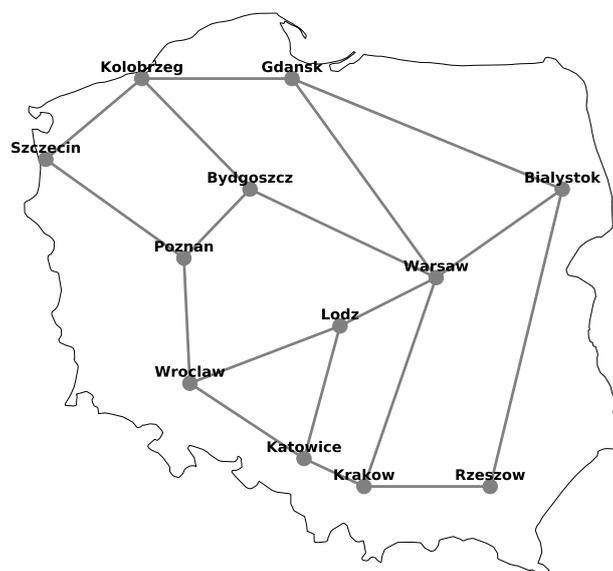
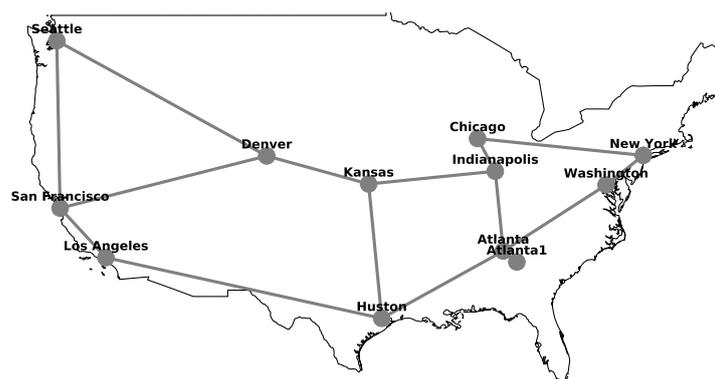
150 The demands that were used in optimization of network cost, are given by demand matrix, which  
 151 provides the values of traffic flow between selected nodes expressed in Gbps. An example demand  
 152 matrix for the network from Fig. 3 is presented in Table 2.

153 The calculations were carried out using a linear solver engine of CPLEX 12.8.0.0 on a 2.1 GHz  
 154 Xeon E7-4830 v.3 processor with 256 GB RAM running under Linux Debian operating system. The  
 155 average calculation time for Polish, American and German networks was approximately equal to  
 156 respectively 56000 s, 36000 s and 72000 s.

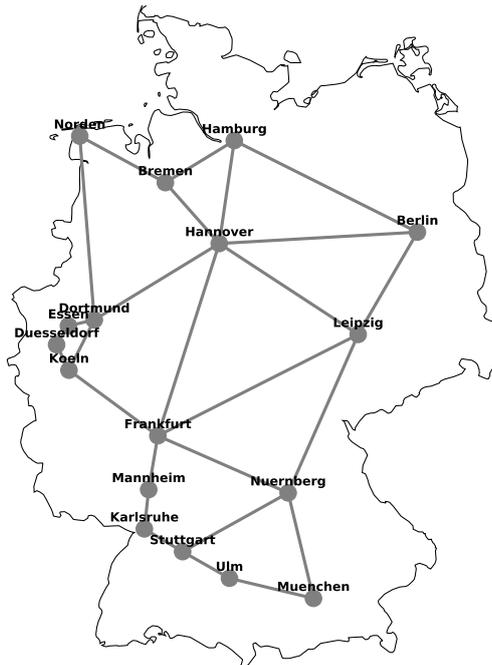
157 The increase of traffic in an analyzed DWDM network was simulated by increasing the values of  
 158 demand matrix elements (demands between initial and end nodes). It was assumed that all elements

**Table 2.** An example demands matrix.

	2	3	4	5	6	7	8	9	10	11	12
1	50	50	50	50	50	50	50	50	50	50	50
2		50	50	50	50	50	50	50	50	50	50
3			50	50	50	50	50	50	50	50	50
4				50	50	50	50	50	50	50	50
5					5	50	50	50	50	50	50
6						50	50	50	50	50	50
7							50	50	50	50	50
8								50	50	50	50
9									50	50	50
10										50	50
11											50

**Figure 3.** Schematic diagram of Polish national transmission optical backbone network.**Figure 4.** Schematic diagram of American national transmission optical backbone network.

159 of the demand matrix were equal, i.e., set initially to 50 and then increased to 100, 300 and so on, as  
 160 presented in Fig. 7 – Fig. 9. The channels from C band were utilized first and L band channels were  
 161 used only when C band ones were no longer available. For the sake of clarity it is noted that on the  
 162 abscissa axis the demand volume is measured using the value of a single demand matrix element, i.e.  
 163 it is initially set to 100 and then increased to 300, 500, etc. until an integer solution is not feasible taking



**Figure 5.** Schematic diagram of German national transmission optical backbone network.

**Table 3.** Sets description

Set	Set settings
$\mathcal{N}$	in Table 1
$\mathcal{E}$	in Table 1
$\mathcal{S}$	768 slots
$\mathcal{B}$	2 bands
$\mathcal{T}$	3 transponders
$\mathcal{S}_b$	$\mathcal{S}_1 = \{1 \dots 384\}, \mathcal{S}_2 = \{385 \dots 768\}$
$\mathcal{S}_t$	$\mathcal{S}_1 = \{1 \dots 380\} \cup \{385 \dots 764\}$ $\mathcal{S}_2 = \{1 \dots 378\} \cup \{385 \dots 762\}$ $\mathcal{S}_3 = \{1 \dots 376\} \cup \{385 \dots 760\}$

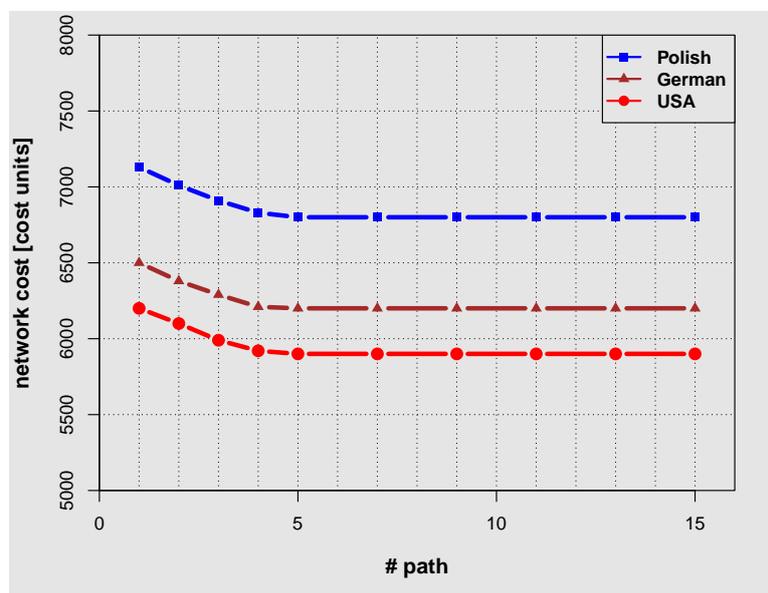
164 into account the available resources of the physical layer, i.e. a path for at least one of the demands  
 165 cannot be provided.

**Table 4.** Modelling parameters

Constant	Constant settings
bitrate [Gbps]	$v(1) = 100, v(2) = 200, v(3) = 400$
OSNR[dB]	$c(1) = 12, c(2) = 15, c(3) = 22$
$d(n,n')$ [Gbps]	an example in Table 2
$\zeta(b)$	$\zeta(1) = 1, \zeta(2) = 2$
$\zeta(t,b)$	$\zeta(1,1) = 5, \zeta(2,1) = 7, \zeta(3,1) = 9$ $\zeta(1,2) = 6, \zeta(2,2) = 8.4, \zeta(3,2) = 11.8$
$\Delta(t)$ [GHz]	$\Delta(1) = 25, \Delta(2) = 50, \Delta(3) = 75,$
$\nu(b)$ [THz]	$\nu(1) = 193.8, \nu(2) = 188.5$
$\lambda(s)$ [dB/km]	$\lambda(s) = 0.046$ for $b = 1$ and $\lambda(s) = 0.055$ for $b = 2$
$W$ [dB]	15
$V$ [dB]	15
$P_0$ [W]	$10^{-3}$

166 Table 3 describes in detail the sets and their settings and Table 4 presents constant settings used  
 167 during computational process.

168 Fig. 6 shows the dependence of network cost on the number of paths for Polish, American and  
 169 German network calculated at the maximum value of the demand volume, which was  $d = 4500$ ,  
 170  $d = 3000$  and  $d = 2500$  for Polish, German and American network, respectively. The paths were  
 171 selected using Yen's K-shortest path algorithm [20].



**Figure 6.** The dependence of network cost on the number of paths for Polish, American and German networks.

172 In these calculations both C and L bands were used. The results from Fig. 6 show that the network  
 173 cost initially decreases with the increasing number of paths and then gradually levels off and settles to  
 174 a constant value for the number of paths larger than 5. This indicates that increasing the number of  
 175 available paths beyond 5 does not result in further significant reduction of the network cost whilst  
 176 may significantly increase the calculation time. Therefore the results shown in Fig. 7 – Fig. 12, were  
 177 calculated with the number of paths set to 5.

178 Fig. 7 – Fig. 9 present the dependence of network cost on the network capacity for Polish,  
 179 American and German network. In Fig. 7 – Fig. 9 color coding is used to differentiate between lines  
 180 representing the network costs obtained using C band only (blue thin line) and C + L band (red thick  
 181 line). ILA were placed every 160 km, 120 km, 80 km and 40 km in each link of the network. The results  
 182 shown in Fig. 7 – Fig. 9 indicate that utilizing C and L band allowed more than doubling the amount  
 183 of the allocated demand volume when compared with C band only. Interestingly, especially for cases  
 184 with ILA spaced at 40 km and 80 km, the cost only doubles at most, when comparing the values for  
 185 maximum allocated demand volume for C and L band (the end of red thick line) with C band only  
 186 (the end of thin blue line). This is the case despite of the fact that nodal components (e.g., transponders  
 187 and amplifiers) are by 20% more expensive for band L than for band C [21]. A closer inspection of the  
 188 results shown in Fig. 7 – Fig. 9 reveals that the dependence of the network cost on the demand volume  
 189 for Polish network is nearly linear for ILA spacing of 40 km and 80 km. However, for the German  
 190 and American network the dependence of the network cost on the demand volume deviates more  
 191 from a straight line. The ratio of the network cost to the demand volume for German network with  
 192 ILA spacing of 80 km at demand volume of 1000 Gbps (maximum capacity for C band only) is equal  
 193 approximately to 3.4 cost units/Gbps whilst for maximum capacity achievable using both C and L  
 194 band it reduces to 2.4 cost units/Gbps whereas for the American network the ratio of the network cost  
 195 to the demand volume reduces from 2.5 to 2 cost units/Gbps. For the Polish network however, the  
 196 ratio of the network cost to the demand volume in both cases remains nearly constant and equal to  
 197 1.5 cost units/Gbps. Thus in terms of the ratio of the network cost to the demand volume the largest

198 benefits of using C and L band are obtained for American and German network. However, when  
 199 one compares the maximum allocated demand volume for all three networks one can notice that the  
 200 largest benefits from using C and L band are achieved for Polish and German network. For Polish  
 201 and German network at ILA spacing of 80 km, the maximum allocated demand volume for C and  
 202 L band is approximately 2.5 times that for C band only. For the American network only a twofold  
 203 increase is observed. It is also noted that the results presented in Fig. 7 – Fig. 9 show that using ILAs  
 204 too densely only increases costs without increasing the maximum allocated demand volume. In fact  
 205 the best results for all three networks were obtained at the ILA spacing of 80 km, which agrees with  
 206 engineering practice.

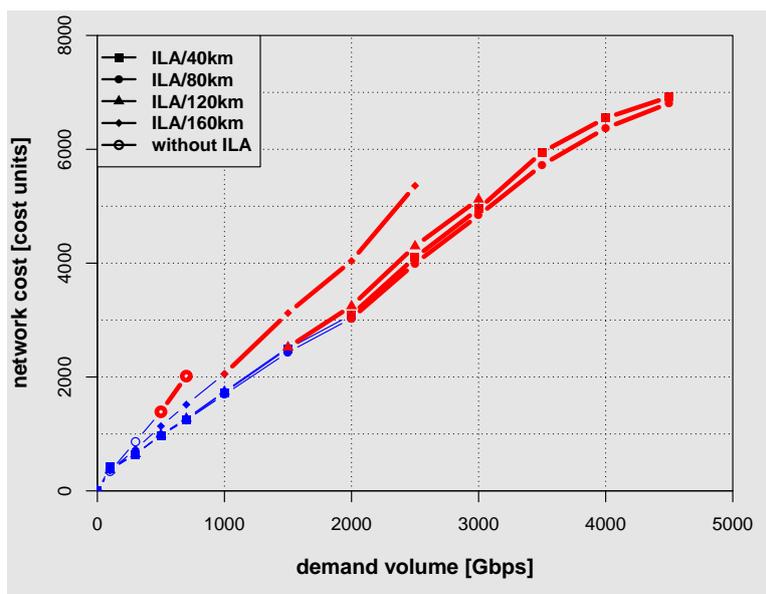


Figure 7. The dependence of network cost on the demand volume for Polish network.

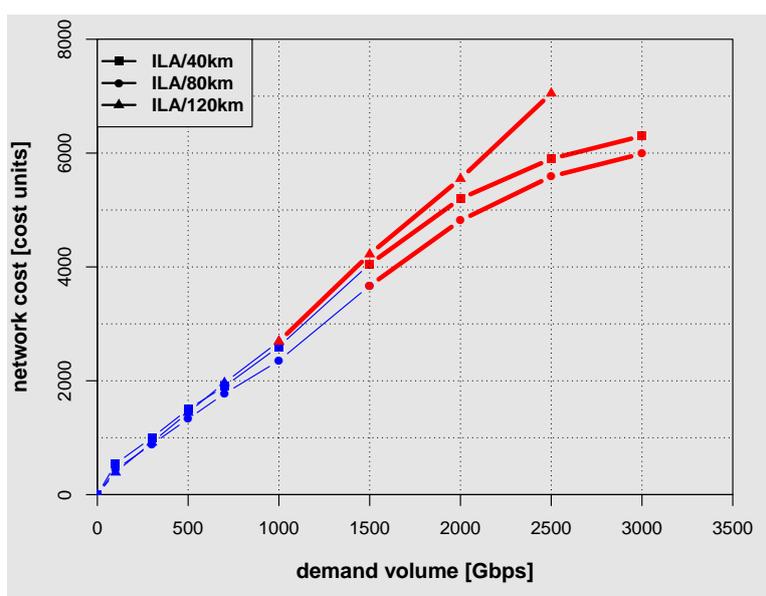


Figure 8. The dependence of network cost on the demand volume for American network.

207 The last point that needs to be explained is the lack of the results for large ILA spacing in the  
 208 case of German and American network in (Fig. 8 and Fig. 9). This is due to a presence of long links.

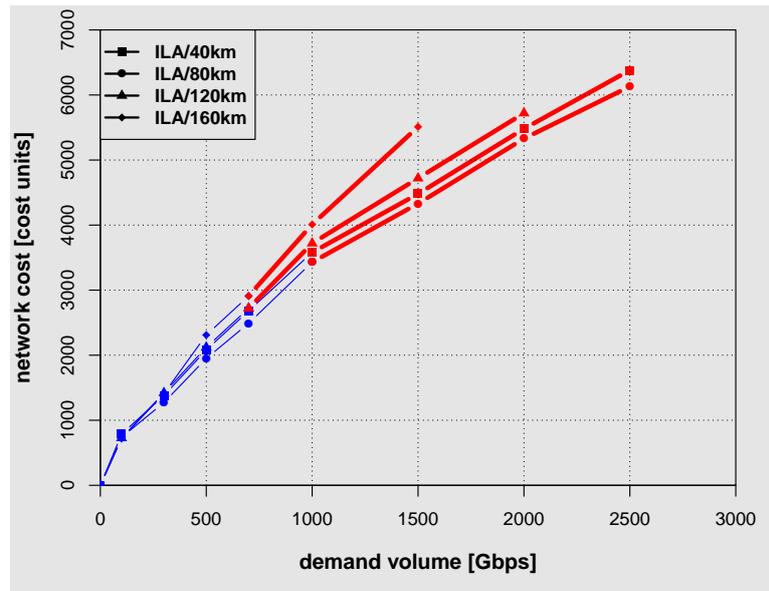


Figure 9. The dependence of network cost on the demand volume for German network.

209 Specifically, in the case of American and German network results (Fig. 8 and Fig. 9) links with the  
 210 length above 200 km for German network and most links for American network cannot be used  
 211 without ILAs due to excessive signal attenuation and hence an unacceptably low OSNR. This in the  
 212 context of the optimization procedures corresponds to an unfeasible solutions. Therefore, in order  
 213 to make these links available for allocation it is necessary to place an ILA in the middle of a link to  
 214 improve OSNR. Especially in the American network, which is a long-distance network, there is a need  
 215 to use ILAs.

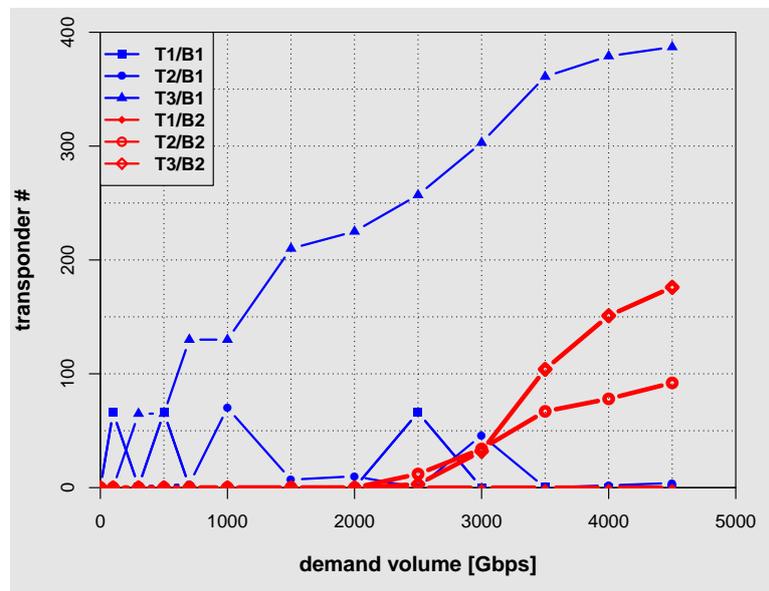


Figure 10. The dependence of number of transponders on the demand volume for Polish network.

216 Results shown in Fig. 10 – Fig. 12 give the dependence of the number of transponders used on  
 217 the demand volume and thus provide further insight into the optimal allocation of network resources  
 218 with the increasing demand volume. Blue line corresponds to C band (B1) transponders while the  
 219 red one to the L band (B2) transponders. Transponder bit rate for T1, T2 and T3 is given in Table 4

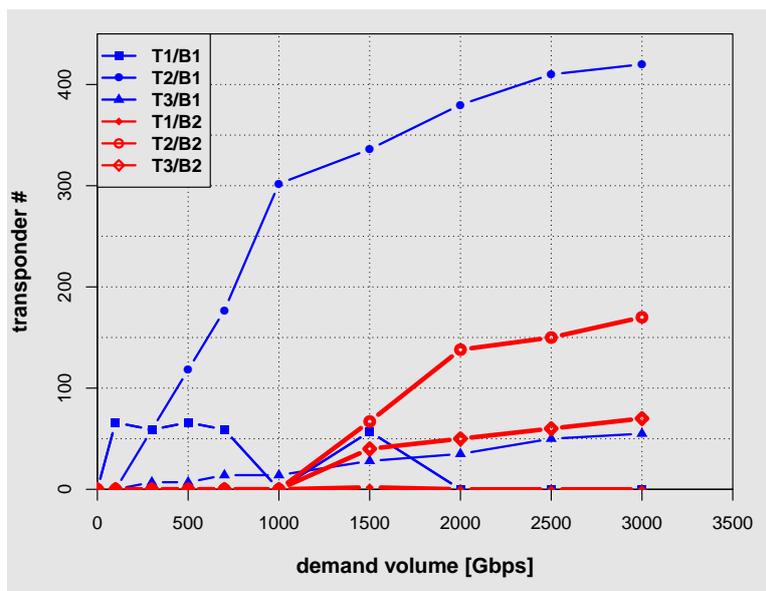


Figure 11. The dependence of number of transponders on the demand volume for American network.

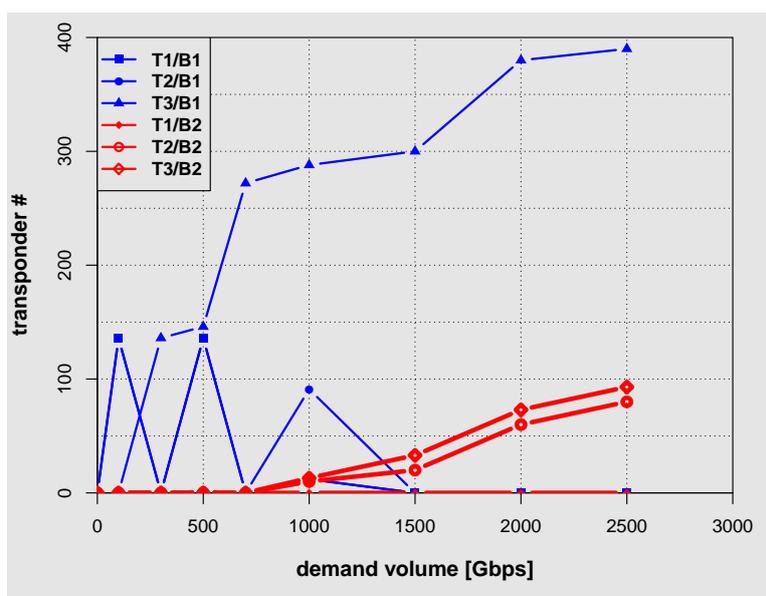
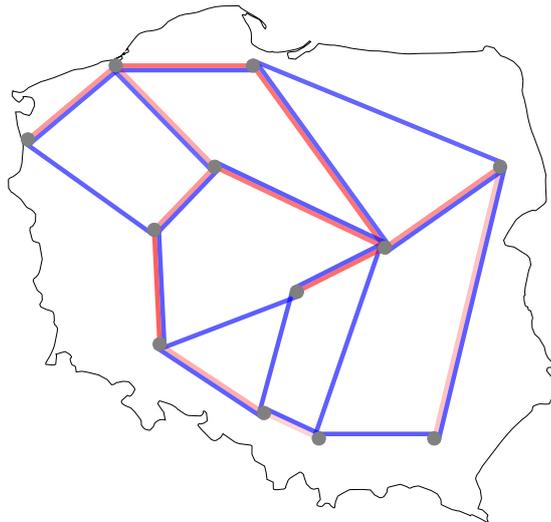


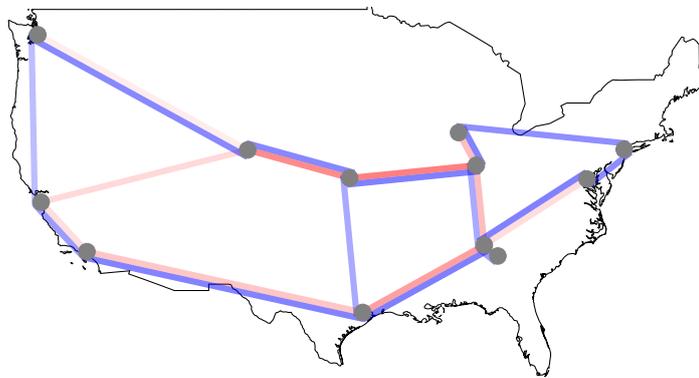
Figure 12. The dependence of number of transponders on the demand volume for German network.

220 and is respectively 100, 200 and 400 Gbps. For the Polish and German network the dependence of the  
 221 number of transponders on the demand volume (Fig. 10 and Fig. 12) shows similar trends. In the case of  
 222 Polish and German network at large values of the demand volume the dominant role is played by  
 223 T3 transponder (for both C band and L band). In the case of American network (Fig. 11) on the other  
 224 hand, T2 transponder is mostly exploited at large values of the demand volume. Such behavior is  
 225 related to the fact that in the American network distances between nodes are large when compared  
 226 with Polish and German network and therefore transponders with higher throughput, characterized  
 227 by larger required minimal OSNR value, cannot be used.

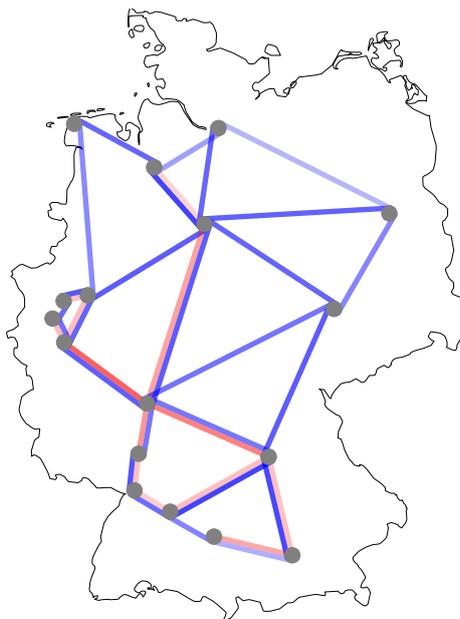
228 Finally, to gain more insight into the bandwidth usage for all links in Fig. 13 – Fig. 15 a diagram is  
 229 plotted in a form of a map showing the percentage of the bandwidth used for each link. The legend for  
 230 Fig. 13 – Fig. 15 is given in Fig. 16. The red line intensity corresponds to the percentage use of the  
 231 C-band whilst the red line to the L band, consistently with the colour coding used in the preceding



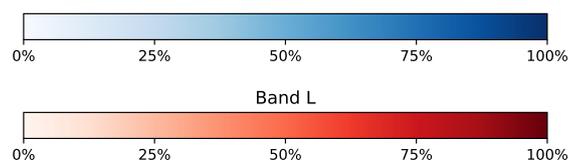
**Figure 13.** Wavelength assignment for band C and L (with max demand) for Polish network.



**Figure 14.** Wavelength assignment for band C and L (with max demand) for American network.



**Figure 15.** Wavelength assignment for band C and L (with max demand) for German network.



**Figure 16.** The scale showing the use of the C and L bands for the networks shown on the maps Fig. 13 – Fig. 15

232 figures. The results shown in Fig. 13 – Fig. 15 allow identifying the links that are used most and  
 233 separate them from the links that are almost unused. For instance there is a very limited use of the  
 234 link between Denver and San Francisco in the case of American network (Fig. 14) whilst the links  
 235 between Denver and Kansas and Kansas and Indianapolis are near the capacity limit. Also for the  
 236 German and Polish networks the bandwidth usage in links is more evenly distributed than for the  
 237 American network.

#### 238 4. Conclusion

239 An optimization of an UW-WDM network that takes into account details of supported bands has  
 240 been performed. The study focuses particularly on the comparison of an UW-WDM network using  
 241 both C and L band with a standard WDM network using C band only.

242 The obtained results show that the UW-WDM network allows for nearly doubling the allocated  
 243 demand volume when compared with the standard WDM network operating within the C band only.

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 245 S.S.; software, S.K. and M.Z.; validation, S.K. and S.S.; formal analysis, S.K., S.S. and M.Z.; resources, S.K., M.Z.  
 246 and S.S.; writing–original draft preparation, S.K. and S.S.; writing–review and editing, S.K. and S.S.; visualization,  
 247 S.K. and S.S.; supervision, S.K.”

248 **Conflicts of Interest:** The authors declare no conflict of interest.

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